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TESIS DOCTORAL

MOTOR SKILL TRAINING USING VIRTUAL REALITY AND HAPTIC INTERACTION

A CASE STUDY IN INDUSTRIAL MAINTENANCE

Matthieu Poyade

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CERTIFICAMOS:

Que D. Matthieu Poyade, MSc., ha realizado en el Departamento de Tecnología Electrónica de la Universidad de Málaga, bajo nuestra dirección, el trabajo de investigación correspondiente a su Tesis Doctoral titulada:

"MOTOR SKILL TRAINING USING VIRTUAL REALITY AND HAPTIC INTERACTION
A CASE STUDY IN INDUSTRIAL MAINTENANCE"

Revisado el presente trabajo, estimamos que puede ser presentado al Tribunal que ha de juzgarlo.

Y para que conste a efectos de lo establecido en el Real Decreto 1393/2007 regulador de los estudios de Tercer Ciclo-Doctorado, AUTORIZAMOS la presentación de esta Tesis en la Universidad de Málaga.

Málaga, a 24 de abril de 2013

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DEDICATION

This thesis is dedicated to Gemma Martinez Lara and Fito who were always by my side throughout these tough years, my parents and all my family who never stopped believing in me.

In loving memory of Jean Claude Poyade & José Lara Moreno.

Matthieu

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ABSTRACT

The primary aim of this study is to evaluate the effectiveness of a Virtual Reality (VR)-simulated system in training fine motor skills that can be transferred to the performance of manual tasks in the real world. The VR system presented in this thesis enables training following fundamental methods such as part-task and whole-task training, in realistic simulations which are enhanced through haptic interaction. A fundamental advantage of using virtual reality in training is the ability to provide specific types of augmented feedback which cannot be provided in the real world.

The work presented in this thesis fits within the scope of ManuVAR (Manual work support throughout system lifecycle by exploiting Virtual and Augmented Reality), a European Union (EU) funded Seventh framework programme project which, among other things, aimed to support motor skill training in high value high knowledge manual work by using Virtual Reality technologies. A case study in industrial maintenance is presented: the metallographic replica, a nondestructive inspection technique that requires fine grinding and polishing of the inspected area. The motor skills required for the performance of these tasks must be particularly accurate. However, those motor skills consist of a tacit knowledge which is hard to transfer from experts to trainees.

This thesis focuses on the design and the evaluation of a VR training system which aims to supplement the motor skill training traditionally carried out for the performance of fine grinding and polishing tasks. The VR training system was designed on the basis of functional and customer requirement analyses which enabled defining the functionalities that allow solving the issues that arise when training in the real world.

Two experimental studies were designed to investigate whether a training program inspired by part-task and whole-task training methods, along with the provision of augmented feedback, enabled training the motor skills that are relevant for the performance of fine grinding and polishing tasks. The first experimental study explored the effectiveness of part-task training on the performance of a polishing task in a virtual environment. The second study evaluated the effectiveness of the complete training program for both tasks and investigated the capability of the VR training system to discriminate between several levels of expertise.

The outcomes of the experimental studies show the effectiveness of the training carried out on the VR training system, showing meaningful accuracy improvements throughout the performance of motor skills. This proves the internal validity of the proposed training. Moreover, the construct validity of the system is also suggested through the discrimination between expert and non-expert operators. On the basis of these findings, the external validity of the VR training system to train the fine motor skills that are relevant for the performance of fine grinding and polishing tasks in real operating environments can be established.

This work supports the hypothesis that VR enhanced with haptic force feedback can be useful for training fine motor skills, complementing the traditional training, which is carried out in real operating environments.

RESUMEN

El objetivo principal de este estudio es evaluar la eficacia de un sistema de entrenamiento de Realidad Virtual en el adiestramiento de habilidades motoras finas, transferibles al desempeño de tareas manuales en el mundo real. Este sistema permite ejercitar siguiendo métodos fundamentales de entrenamiento como el método analítico (*part-task training* en inglés) y el método global (*whole-task training* en inglés), a través de simulaciones realistas que incluyen la interacción háptica. Una de las principales ventajas del entrenamiento en sistemas de Realidad Virtual como el que se presenta en esta tesis es la posibilidad de suministrar una retroalimentación aumentada que no puede ser proporcionada en entornos reales.

El trabajo presentado en esta tesis se inscribe en el ámbito de ManuVAR (Manual work support throughout system lifecycle by exploiting Virtual and Augmented Reality), un proyecto europeo del 7º programa Marco, que, entre otras cosas, tiene por objetivo fomentar el entrenamiento de habilidades motoras finas en el trabajo manual de alta cualificación y de alto valor, mediante el uso de la Realidad Virtual.

El término Realidad Virtual se refiere tradicionalmente a una interfaz informática que proporciona unas simulaciones gráficas interactivas e inmersivas, permitiendo que un usuario tenga la sensación de estar perceptualmente involucrado en un entorno virtual. Con frecuencia se ha empleado para apoyar la formación de habilidades motoras y de procedimiento en campos de la cirugía y de la industria.

Este trabajo presenta un caso de uso en el mantenimiento industrial: la réplica metalográfica, una técnica de inspección no destructiva que permite reproducir la topografía de la superficie de un material sobre una fina película de plástico como si fuera un negativo de la misma. El proceso de realización de la réplica metalográfica resulta adecuado para la obtención de reproducciones de la microestructura en campo y su posterior análisis en el laboratorio. La obtención de la réplica metalográfica requiere la preparación previa de la superficie de los materiales que se tiene previsto inspeccionar. El objetivo es eliminar las escamas de óxido e impurezas, con el fin de revelar la microestructura de la superficie del material libre de deformaciones, arañazos y otros defectos que pueden alterar la calidad de la réplica. Esta fase de preparación consiste en una serie de procesos abrasivos que se llevan a cabo a través de varias tareas

de desbaste grueso y fino y de pulido así como de un tratamiento químico. Esta tesis se centra tan sólo en la realización de tareas de desbaste fino y de pulido en el contexto previamente explicado.

La realización de una tarea de desbaste fino permite eliminar las capas de óxido residual de la superficie del material inspeccionado utilizando una herramienta rotativa de precisión a la que se le acoplan discos de lija de diámetro pequeño de distinta granulometría. La orientación de la herramienta al aplicarse sobre la superficie del material debe modificarse 90 grados en comparación con la tarea precedente de desbaste fino. Por otra parte, la realización de una tarea de pulido permite alisar mecánicamente la superficie del material inspeccionado utilizando la misma herramienta rotativa de precisión equipada con paños de pulido a los que se les aplica una pequeña cantidad de pasta de diamante. La granulometría de la pasta de diamante que se aplica va disminuyendo a medida que se repita la tarea de pulido. El objetivo es obtener una superficie especular totalmente libre de rayas. Las habilidades motoras que se necesitan para la ejecución de dichas tareas deben ser particularmente finas.

La enseñanza de dichas tareas se produce típicamente bajo la supervisión de un experto en metalurgia que previamente ha llevado a cabo demostraciones prácticas y ha proporcionado directrices verbales acerca de las características de los movimientos a realizar. Mientras el alumno ejercita una tarea, el experto a veces destaca los errores de movimiento cometidos en forma de comentarios. Sin embargo, debido a la naturaleza de las tareas de desbaste fino y de pulido que impiden la observación de la superficie del material mientras se están llevando a cabo, el experto no puede proporcionar información acerca del estado de cumplimiento de la tarea. Este tipo de retroalimentación solo puede ser facilitada en cuanto la tarea haya sido completada. Además, algunas de las habilidades motoras que se requieren en ambas tareas, tales como la aplicación de una fuerza y una inclinación adecuada de la herramienta sobre la superficie del material inspeccionado, son difíciles de evaluar con exactitud. Dichas habilidades constituyen un conocimiento tácito que es difícilmente transferible de los expertos a los alumnos mediante directrices verbales. Por lo tanto, el experto puede difícilmente proporcionar una retroalimentación precisa al alumno.

En esta tesis se propone que el uso de las tecnologías de Realidad Virtual permite resolver algunos de los problemas que surgen durante el entrenamiento convencional en tareas de desbaste fino y de pulido. Estudios previos han demostrado que la Realidad Virtual permite:

1. La evaluación del cumplimiento de los objetivos de la tarea y de las habilidades motoras ejercitadas de una manera objetiva.
2. El uso de métodos fundamentales de entrenamiento de habilidades motoras que difícilmente se pueden implementar en el entorno real.
3. El suministro de información aumentada precisa que no puede ser facilitada en el mundo real.
4. La simulación realista de modelos físicos de interacción.

Esta tesis se centra en el diseño y la evaluación de un sistema de entrenamiento de Realidad Virtual que tiene por objetivo reforzar el adiestramiento que tradicionalmente se lleva a cabo para el desarrollo de las habilidades motoras finas necesarias durante la realización de trabajos de desbaste fino y de pulido. El estudio se centra en las habilidades motoras finas de fuerza aplicada y de inclinación de una herramienta de trabajo sobre la superficie de un material.

Diseño y desarrollo de un sistema de entrenamiento en Realidad Virtual

El sistema de entrenamiento fue diseñado basándose en el análisis de requisitos funcionales y de usuario, permitiendo definir las funcionalidades que solucionan los problemas que surgen durante el entrenamiento en el mundo real. El desarrollo resultante propone, junto con el sistema de entrenamiento de Realidad Virtual, un conjunto de ítems que permiten la elaboración de unos programas de entrenamiento de manera flexible.

El programa de entrenamiento permite parametrizar el adiestramiento que se lleva a cabo en el sistema de Realidad Virtual, con el objetivo de ejercitar las habilidades motoras de fuerza aplicada y de inclinación de la herramienta siguiendo métodos fundamentales de entrenamiento como el método analítico y el método global. El método analítico de entrenamiento permite ejercitar las habilidades motoras que componen una tarea de manera independiente y conjunta. Este método se basa en primer lugar en la descomposición de una tarea en un sub-conjuntos de componentes con el fin de practicar estos elementos de forma independiente. Una revisión de la literatura científica ha permitido identificar varias técnicas de descomposición:

1. La segmentación, que consiste en separar habilidades motoras que suelen realizarse de manera secuencial.
2. El fraccionamiento, que consiste en separar habilidades motoras que se suelen realizar conjuntamente.
3. La simplificación, que consiste en actuar sobre una característica de una habilidad motora con el fin de facilitar su ejecución.

El método analítico de entrenamiento también se caracteriza por la manera con la cual las habilidades motoras aisladas o simplificadas según una de las técnicas de descomposición presentadas se recombinan con el fin de poder ser ejercitadas conjuntamente permitiendo así la reconstrucción de la tarea global. Tres métodos de recombinación destacan en la literatura:

1. El método analítico-global, que permite entrenar cada habilidad motora de manera independiente y una vez la ejecución es lo bastante fina, se reconstruye la tarea global con el fin de ser ejercitada. Este método es apropiado para habilidades motoras organizadas de manera sequencial.
2. El método analítico progresivo permite en primer lugar practicar dos habilidades motoras de forma independiente que luego se asocian con el fin de ser ejercitadas conjuntamente. Cuando el rendimiento se vuelve óptimo, se entrena una nueva habilidad aparte y luego se añade a la asociación de habilidades existentes. De esta manera, la tarea global se reconstruye de manera gradual incluyendo nuevas habilidades motoras. Se considera que este método de recombinación permite una mejor conprensión de las habilidades motoras que componen la tarea. Este método se considera apropriado para ejercitar habilidades motoras que se suelen realizar de manera concurente en la tarea global.
3. El método analítico repetitivo permite ejercitar una primera habilidad motora de manera independiente. En cuanto el rendimiento de dicha habilidad se vuelve óptimo, se le añade una segunda habilidad, luego una tercera y así sucesivamente, con el fin de practicar el nuevo conjunto hasta que la tarea global esté completamente reconstruída. Al igual que el método analítico progresivo, este método permite una mejor comprensión de las habilidades motoras que componen la tarea global.

> Sin embargo, este método es más apropriado para ejercitar aquellas habilidades motoras cuyos componentes son dependientes de otras. Por ejemplo, para aprender a tocar el piano, se ejercita en un primer lugar con una mano, luego se añade la otra mano y al final se puede hacer uso de los pedales.

Por otra parte, el método global permite ejercitar una tarea tal y como se haría en un entorno real.

Asimismo, un programa de entrenamiento permite gestionar el suministro de retroalimentación aumentada a lo largo del proceso de adiestramiento. La información proporcionada puede ser relativa a la evaluación del cumplimiento de los objetivos de la tarea o al rendimiento, es decir, a la medida en que las habilidades motoras que se requieren en dicha tarea se realizan con éxito. La literatura científica hace referencia a la retroalimentación aumentada que proporciona información acerca del cumplimiento de los objetivos de la tarea como conocimiento de los resultados (*Knowledge of Results* (KR) en inglés). Por otra parte, se refiere a la retroalimentación aumentada que informa acerca de la realización de las habilidades motoras como conocimiento del rendimiento (*Knowledge of Performance* (KP) en ingles). Estas retroalimentaciones pueden ser en tiempo real y terminales en cual caso se proporciona al final de la tarea.

A lo largo del entrenamiento siguiendo el método analítico, se puede emplear un conjunto de indicadores visuales y auditivos que proporcionan una retroalimentación aumentada en forma de conocimiento del rendimiento y de los resultados en tiempo real así como de conocimiento de los resultados de manera terminal. El sistema de Realidad Virtual permite además favorecer el aprendizaje durante el entrenamiento con el método global, utilizando un indicador visual en forma de mapa de color que proporciona conocimiento de los resultados en tiempo real.

El desarrollo presentado en esta tesis también incluye un modelo de interacción háptica que permite la simulación de las sensaciones intrínsecas resultantes a la manipulación de una herramienta rotativa de precisión real sobre la superficie de un material. También ha sido implementado en el sistema de entrenamiento de Realidad Virtual un modelo matemático, desarrollado con el fin de apoyar la simulación de la interacción de la herramienta sobre la superficie del material inspeccionado. Dichos modelos se han desarrollado y verificado de manera heurística. Dos expertos en la realización de la réplica metalográfica, provenientes de la empresa madrileña Tecnatom

S.A., una empresa de ingeniería que presta servicios de mantenimiento a plantas industriales y químicas, han participado en la elaboración de dichos modelos.

Evaluación del sistema de entrenamiento en Realidad Virtual

Se diseñaron dos estudios experimentales con el fin de investigar si un programa de entrenamiento inspirado en un adiestramiento que sigue los métodos analítico y global, junto con el suministro de información aumentada, permite entrenar algunas de las habilidades motoras finas que se requieren en las tareas de desbaste fino y de pulido.

Estudio experimental 1

El primer estudio experimental explora la eficacia del entrenamiento siguiendo el método analítico en el desempeño de una tarea de pulido en un entorno virtual. Para este estudio experimental, se formularon dos hipótesis experimentales:

1. El método analítico de entrenamiento permite al alumno ser más eficaz en la realización de las habilidades motoras que se requiren en una tarea de pulido tales como la inclinación de la herramienta y la fuerza que se aplica sobre la superficie del material inspeccionado.
2. El método analítico de entrenamiento permite transferir estas habilidades motoras al desempeño de una tarea completa de pulido en un entorno virtual.

El experimento fue realizado con un total de 30 sujetos (14 hombres, 16 mujeres). Todos eran estudiantes o personal de servicio de la Universidad de Nottingham (Reino Unido), y sus edades estaban comprendidas entre 18 y 65 años (Media = 30,21, SD = 2,85). Ninguno de ellos presentaba defecto visual no corregido o problema fisiológico en al brazo o antebrazo. Todos los participantes eran diestros excepto uno, y eran novatos en la manipulación de herramientas eléctrica así como de dispositivos hápticos. La participación en el experimento se hizo de manera voluntaria.

Los sujetos se sentaron delante de una pantalla LCD bidimensional de gran tamaño con la mirada a la altura del centro del monitor. Un dispositivo háptico del tipo Phantom Desktop se encontraba delante de ellos posicionado en medio del ancho del monitor. Este dispositivo les permitía interactuar sobre un área de inspección que se encuentra sobre una tubería industrial simulada en un entorno de Realidad Virtual, a través de una herramienta rotativa de precisión virtual. La herramienta estaba simulada visualmente y mediante el dispositivo háptico. Varios sonidos de entornos industriales así como de dicha herramienta en funcionamiento se reprodujeron durante la realización del estudio experimental.

El experimento se compone de una fase de familiarización con la tecnología háptica, una fase de entrenamiento siguiendo el método analítico y de una fase de evaluación durante la cual los sujetos intentaban llevar a cabo una tarea de pulido en el área de inspección. En esta última fase, se hizo uso de un ejercicio de entrenamiento siguiendo el método global.

Por una parte, el método analítico propone entrenar las habilidades de fuerza y de inclinación de manera independiente y conjunta a través de una serie de ítems. Durante este entrenamiento, se le pidió al sujeto que tratase de mantener de manera continua una habilidad individual o bien un conjunto de habilidades motoras entrenadas dentro de unos rangos durante un tiempo de 15 segundos. Se suministraba información aumentada en forma de conocimiento del rendimiento en tiempo real durante la realización de cada ítem con el fin de facilitar el desarrollo de estas habilidades motoras finas. También se proporcionaba información aumentada (conocimiento terminal de los resultados) al final de cada ítem. Por otra parte, el método global permite realizar una tarea de pulido tal y como se hace en el mundo real. Aquí se añadió información aumentada que permitía ir conociendo los resultados en tiempo real; en concreto, un mapa de color que indica el ratio de cumplimento de la tarea en cada punto del área inspeccionado. Se utilizó un rango de colores que abarcaba desde el verde intenso, para indicar un cumplimento completo, hasta el rojo vivo, para una tarea no empezada. En medio de este rango, se observan matices de naranja y amarillo para señalar el estado inacabado de la tarea.

El estudio sigue un diseño entre-sujetos. Se repartieron los participantes de manera aleatoria en tres grupos. Cada grupo estaba asignado a una condición única de entrenamiento: "*Full Training*" (FT), "*Haptic familiarization Training*" (HT) y "*Control Training*" (CT). Cada condición incluye una fase de familiarización a la tecnología háptica, una fase de adiestramiento y una fase final de evaluación. Antes de cada fase, el sujeto recibe unas explicaciones verbales, textuales y gráficas acerca del objetivo de la fase, de la información que se le presenta en la pantalla y de las fuerzas que genera el dispositivo háptico.

Los sujetos que pertenecían al grupo FT primero llevaron a cabo unos ejercicios de familiarización, y luego el entrenamiento siguiendo el método analítico. Este entrenamiento se compone de diez ejercicios organizados en 4 ítems de 60 segundos cada uno. Con el fin de hacer la práctica más factible al principio, la componente de movimiento se quitó durante los cinco primeros ejercicios. Sin embargo, para que la dificultad del entramiento sea más equilibrada, una vez que las habilidades motoras se han consolidado, dicha componente se reincorpora en los ejercicios 6 a 10. Primero, se sugirieron tres patrones de movimientos a través de los ejercicios 6 a 8; posteriormente los sujetos eran libres de escoger el patrón de movimiento que más les convenía.

En cada ítem, el sujeto debía mantener de manera continua las habilidades motoras entrenadas dentro unos rangos durante un tiempo de 15 segundos. Estos rangos incluyen una inclinación de la herramienta virtual entre 0º y 10º, y una fuerza aplicada entre 1N y 5.3N. En el ítem 1, se entrenaba únicamente la inclinación de la herramienta mientras que en el ítem 2, se ejercitaba la fuerza que se aplicaba de manera independiente. En el ítem 3, ambas habilidades motoras se practicaban de forma simultánea. En estos tres ítems, se suministró información aumentada en tiempo real en forma de conocimiento del rendimiento, que indicaba el valor de las habilidades ejercitadas con respeto a los rangos, y de conocimiento de los resultados, que consistía en el tiempo restante para cumplir el objetivo del ítem. El ítem 4 era idéntico al ítem 3 pero la información aumentada en forma de conocimiento del rendimiento no se proporcionaba.

Al igual que los sujetos que pertenecían al grupo FT, los de grupo HT primero llevaron a cabo unos ejercicios de familiarización. Sin embargo, ellos no fueron adiestrados físicamente siguiendo el método analítico sino que vieron una película que les enseñaba una captura de pantalla durante una sesión de entrenamiento llevada a cabo por un usuario experto.

Los sujetos del grupo CT no fueron familiarizados con la manipulación háptica sino que vieron una película de un experto llevando a cabo los ejercicios de familiarización. Tampoco recibieron entrenamiento físico, sino que vieron el mismo vídeo de entrenamiento que los sujetos del grupo HT.

Finalmente, todos los sujetos llevaron a cabo a una tarea de pulido simulada en un entorno virtual con la ayuda de información aumentada de tipo conocimiento de los resultados en tiempo real, en forma de un mapa de color posicionado por encima del área de inspección y magnificado en una ventana localizada a la derecha de la pantalla. Esta evaluación permite valorar el efecto de la condición de entrenamiento siguiendo el método analítico sobre la realización de las habilidades motoras que se requieren en una tarea de pulido.

Durante la fase final de evaluación, se midieron el rendimiento en la realización de la tarea de pulido y la precisión en la realización de las habilidades motoras de fuerza y de inclinación. También, se pidió a los sujetos valorar una serie de puntos y dar su opinión acerca de su condición de entrenamiento, y de las simulaciones gráficas y hápticas, entre otras cosas.

Se realizó un análisis estadístico (ANOVA) de las mediciones de rendimiento y de precisión. Los resultados indican que los sujetos que fueron asignados la condición de entrenamiento FT resultaron significativamente mejores que los otros sujetos. Dichos sujetos fueron capaces de alcanzar un grado de cumplimiento de la tarea de pulido significativamente más alto. Se encontraron diferencias significativas en cuanto a la precisión de las habilidades motoras ejercitadas, aunque solo se encontró una diferencia marginalmente significativa entre los sujetos de FT y CT en cuanto a la precisión de la inclinación de la herramienta. Por otra parte, se realizo un análisis de tipo no paramétrico (Kruskal-Wallis H-Test) de las valoraciones proporcionadas, que demostró una diferencia significativa entre los sujetos de FT y los de HT en cuanto a la facilidad de la interacción háptica, la percepción del rendimiento y la percepción de la eficacia del entrenamiento. Sin embargo no se encontraron diferencias entre los sujetos de los grupos FT y CT y tampoco entre HT y CT.

Se realizaron también un análisis de los comentarios siguiendo una metodología de clasificación de contenido en temas, "*Theme-Based Content Analysis*" (TBCA). El análisis de aquellos comentarios sugiere la complejidad de llevar a cabo las habilidades motoras de fuerza aplicada y de inclinación de la herramienta en ausencia de entrenamiento físico previo con el método analítico.

Estos resultados sugieren la eficacia del entrenamiento siguiendo el método analítico para apoyar al desarrollo de habilidades motoras finas tales como la fuerza aplicada y la inclinación de la herramienta sobre la superficie del material y la transferencia a una tarea simulada de pulido. Sin embargo, el vídeo asociado a la fase de familiarización a la tecnología háptica en la condición de entrenamiento CT parece tener un efecto leve sobre el aprendizaje de la inclinación de la herramienta. Aunque es necesaria más investigación para determinar con mayor exactitud el efecto de aquel vídeo.

Estudio experimental 2

El segundo estudio experimental evalúa la efectividad de todo el programa de entrenamiento para ambas tareas, e investiga la capacidad del sistema para diferenciar entre varios niveles de experiencia. Este estudio experimental se llevó a cabo en las instalaciones de Tecnatom S.A. en San Sebastián de los Reyes (Spain), dentro del ámbito de la fase de demostración del proyecto europeo ManuVAR. Seis técnicos no expertos (1 mujer y 5 hombres) con edad incluida entre 30 y 55 años, acostumbrados a manipular herramientas eléctricas, participaron en el estudio. Ninguno de ellos tenía conocimientos previos de manipulación con dispositivos hápticos. Aquellos sujetos se repartieron de manera aleatoria en dos grupos. A cada grupo se le asignó una tarea de desbaste fino o de pulido. También dos expertos (hombres) en reproducción de la técnica de replica metalográfica de edad 31 y 35 años estuvieron involucrados en el proceso de evaluación.

Este estudio experimental estuvo compuesto de dos experimentos. El primer experimento evalúa la eficacia del entrenamiento siguiendo el método analítico para tareas de desbaste fino y de pulido. Para este experimento, se planteó la hipótesis de que el método analítico de entrenamiento, además de permitir al alumno ser más eficaz en la realización de las habilidades motoras finas que se requieren en una tarea de pulido como se ha demostrado en el primer estudio experimental presentado en esta tesis, también sirve en el caso de una tarea de desbaste fino. El segundo experimento investiga la eficacia del entrenamiento siguiendo el método global y examina la capacidad del sistema para diferenciar entre expertos y no expertos. Para este experimento, se formularon dos hipótesis:

1. El método global de entrenamiento lleva de manera efectiva a una mejoría de rendimiento en la realización de unas tareas de desbaste fino y de pulido.

2. Las simulaciones de tareas de desbaste fino y de pulido propuestas en el entrenamiento con el método global proporcionan en una representación realista del trabajo en el mundo real permitiendo distinguir entre differentes niveles de experiencias acquiridos en el mundo real.

En ambos experimentos, cada sujeto se colocaba de pie enfrente de una gran pantalla tridimensional a través de la cual se podía visualizar el entorno virtual relativo al entrenamiento con los métodos analítico y global. Los sujetos llevaban gafas de visión estereoscópica pasiva que les permitía percibir la profundidad en dicho entorno. Los mecanismos de cambio de punto de vista estaban implementados en la simulación para evitar que la visualización tridimensional sufriera distorsiones. Para ello se hizo uso de unos sensores reflectantes de luz infrarroja, montados sobre las gafas. Se rastreó la posición de dichos sensores utilizando un conjunto de cámaras infrarrojas repartidas alrededor de la sala de experimentación. Un dispositivo háptico del tipo Phantom Desktop se dispuso delante de pantalla, elevado de tal manera que el espacio de manipulación en el mundo real cuadrara con el espacio de trabajo en el entorno virtual. Este dispositivo permitía controlar en posición y orientación una herramienta rotativa de precisión virtual con el fin de interactuar sobre un área de inspección que se encontraba en el lateral de una tubería industrial simulada en un entorno de Realidad Virtual. Al igual que en el primer estudio experimental, varios sonidos de entornos industriales así como de la herramienta en funcionamiento se reprodujeron durante la realización de las tareas.

Experimento 1: Evaluación del entrenamiento con el método analítico

En el primer experimento, los sujetos de cada grupo llevaron a cabo una fase de pre-evaluación, una fase de adiestramiento siguiendo el método analítico y finalmente una fase de post-evaluación. La fase de pre-evaluación se compone de 6 ejercicios durante los cuales se evaluaron las habilidades motoras de fuerza aplicada y de inclinación de la herramienta sobre la superficie del material. El entrenamiento fue reducido, por falta de tiempo para realizar un estudio más completo, a dos ejercicios compuestos de 4 ítems cada uno. Al igual que en el primer estudio experimental propuesto en esta tesis, cada ítem permitía ejercitar independientemente o conjuntamente las habilidades motoras de fuerza aplicada y de inclinación de la herramienta. Se le pedía al sujeto que intentase mantener la o las habilidades ejercitadas dentro de unos rangos propios a la tarea que le estaba asignada de manera continua por un periodo de tiempo de 10 segundos. Estos rangos incluían una inclinación entre 75º y 90º, y una fuerza entre 1N y 5N para una tarea de desbaste fino y de 0º hasta 20º y 1N a 5N para una tarea de pulido. Los ítems se presentaron al igual que en el primer estudio experimental. También se suministraba información aumentada en forma de conocimiento del rendimiento para apoyar al desarrollo de dichas habilidades motoras durante los tres primeros ítems y en forma de conocimiento de los resultados durante y después de cada ítem.

Finalmente, los sujetos llevaron a cabo una fase de post-evaluación de igual diseño que la fase de pre-evaluación. Durante ambas fases, se midieron el numero de ítems correctamente cumplidos así como el tiempo de cumplimento con el fin de subrayar el efecto del entrenamiento con el método analítico para ambas tareas. También se recopilaron las impresiones de los sujetos mediante cuestiones abiertas y cerradas con respuestas tipo Likert.

Los resultados de aquel experimento señalan que el entrenamiento con el método analítico permite a los sujetos cumplir todos los ítems en la fase de post-evaluación con un tiempo medio mejorado de manera relevante. La hipótesis inicial queda entonces verificada. Además, todos los sujetos han valorado positivamente la retroalimentación aumentada en forma de conocimiento del rendimiento que informa del valor de las habilidades motoras finas ejercitadas, que se suministró en tiempo real a través de unos indicadores gráficos así como al entrenamiento en general. Sin embargo, se ha observado que el realismo de los entornos virtuales en cuanto a grafismo y precisión en la interacción háptica podrían ser mejoradas.

Experimento 2: Evaluación del entrenamiento con el método global

En el segundo experimento, se mantuvo la repartición de los sujetos en sus respectivos grupos y se incluyeron a los dos expertos en el diseño experimental.

En un primer lugar, se investigó la eficacia del entrenamiento con el método global para apoyar el aprendizaje a través de la realización de unas tareas de desbaste fino y de pulido. En primer lugar, los sujetos no expertos llevaron a cabo una breve tarea de familiarización seguida de una fase de pre-evaluación de 3 minutos. Durante esta fase, se le pidió a los sujetos que realizaran la tarea que les había sido asignada al principio del estudio experimental. Posteriormente los sujetos ensayaban la realización de dicha tarea a través de dos ejercicios de tres minutos cada uno. Adicionalmente, se podía suministrar el mapa de color, bajo petición, durante 10 segundos seguidos.

Finalmente, los sujetos llevaron a cabo una fase de post-evaluación diseñada de igual manera que la fase de pre-evaluación. En ambas fases, se midió el nivel de cumplimiento de la tarea asociada a cada sujeto con el fin de destacar la eficacia de aquel entrenamiento.

Los resultados ponen de manifiesto la tendencia general a la mejora del rendimiento después después del entrenamiento con el método global. Aunque, las mejoras son leves en el caso de la tarea de desbaste fino, el rendimiento de los aprendices en general tiende a mejorar. Sin embargo, basándose sobre trabajos previos, se puede esperar una mejoría más relevante en ambas tareas con un tiempo de entrenamiento más largo. En este caso, se puede considerar que la hipótesis inicial se ha verificado.

En un segundo lugar, se investigó si las simulaciones propuestas eran una representación fiel de la realidad en el sentido que el sistema de entrenamiento en Realidad Virtual permite diferenciar entre varios niveles de experiencias: expertos y no expertos. Por eso, se comparo el rendimiento de los dos expertos en ambas tareas con la de los técnicos no expertos. Esta comparación se hizo basándose en las medidas realizadas durante la fase de pre-evaluación. Como resultado se obtuvo que los expertos fueron capaces de llegar a un nivel más alto de cumplimiento que los técnicos no expertos en ambas tareas. Por lo tanto, el sistema de entrenamiento permite distinguir entre ambos niveles de experiencia y, por tanto, las simulaciones propuestas constituyen unas representaciones fieles a la realización de ambas tareas en el mundo real. La segunda hipótesis inicial queda entonces demostrada.

Finalmente, con los datos subjetivos recopilados a lo largo del experimento, se demostró que todos los sujetos tuvieron una buena opinión del entrenamiento propuesto, insistiendo sobre el realismo de la ejecución de ambas tareas.

Conclusiones

Los resultados de estos estudios experimentales resaltan la eficacia del programa de entrenamiento implementado en el sistema de Realidad Virtual, mostrando mejoras relevantes en la ejecución de las habilidades motoras durante la realización de las tareas de desbaste fino y de pulido. Esto señala la validez interna del entrenamiento propuesto. Por otra parte, la validez de constructo del sistema también se sugiere a través de la discriminación entre los niveles de experiencia de operadores expertos y no expertos. Estos resultados proporcionan indicios de la validez externa del sistema de entrenamiento en Realidad Virtual para desarrollar las habilidades motoras finas que son relevantes para el desempeño de tareas de desbaste fino y de pulido en entornos reales.

En definitiva, este trabajo de investigación da soporte a la idea de que la Realidad Virtual mejorada con la interacción háptica puede ser útil para el entrenamiento de habilidades motoras, en complemento al entrenamiento que tradicionalmente se lleva a cabo en el mundo real.

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ACRONYMS AND ABBREVATIONS

3D	*Three-dimension*
AARBA	*Association for the Advancement of Radical Behavior Analysis*
ANOVA	*Analysis of Variance*
API	*Application Programming Interface*
AR	*Augmented Reality*
AT	*Application Tool*
CPU	*Central Processing Unit*
CT	*Control Training condition*
DOF	*Degree of Freedom*
EU	*European Union*
FT	*Full Training condition*
GMP	*Generalized Motor Program*
GUI	*Graphical User Interface*
HDAPI	*Haptic Device Application Programming interface*
HLAPI	*High Level Application Programming interface*
HSD	*Honesty Significant Difference*
HT	*Haptic familiarization Training condition*
KP	*Knowledge of Performance*
KR	*Knowledge of Results*
LCD	*Liquid Crystal Display*
ManuVAR	*Manual work support throughout system lifecycle by exploiting virtual and augmented reality*
NDT	*Non Destructive Technique*
PC	*Personal Computer*
PLM	*Product Lifecycle Management*
RAM	*Random Access Memory*
RAS	*Robotic Assisted Surgery*
S.A.	*Sociedad Anonima (Anonymous Society)*
SME	*Small Medium Enterprise*
SPSS	*Statistical Package for the Social Sciences*

SysML	*Systems Modeling Language*
TBCA	*Theme-Based Content Analysis*
UML	*Unified Modeling Language*
USL	*User Specific Logic*
VR	*Virtual Reality*
VRPN	*Virtual-Reality Peripheral Network*

PART 1

INTRODUCTION

OF THE THESIS

Chapter 1. Introduction

Manual work is a paramount and expensive component of the EU industrial activity. With the evolution of technologies since the early eighties, unskilled manual work has been mostly automated. Industries have been thus able to maintain competitively their activity in the globalized market by lowering their manufacturing costs. In contrast, high value high knowledge manual work cannot be automated. The practical knowledge of workers which is required for the performance of highly skilled manual operations represents a serious competitive advantage for EU industries. Such knowledge is tacit to the extent that in contrast to explicit knowledge, it cannot be uttered in sentences or captured in drawings but rather refers to skills acquired through practical experience (Nonaka & Von Krogh, 2009). Tacit knowledge is thus difficult to transfer to other people.

For many years now, industries have demonstrated great interest in using computer-aided solutions for training high value high knowledge manual work in order to increase their competitiveness (Mujber et al., 2004; Abate et al., 2009). One of these solutions is Virtual Reality (VR), which allows improving the training on manual work operations by providing realistic and interactive simulations of industrial procedures and offering additional informational contents that cannot be not provided otherwise.

The research presented in this thesis investigates the use of VR technologies to enable the successful development of complex motor skills that are required in the performance of highly skilled manual operations. A case study in an industrial maintenance task is presented.

The purpose of this chapter is to introduce this thesis. Section 1.1 defines the framework of this thesis, starting with a brief overview of the training of motor skills in the context of industrial maintenance (Section 1.1.1), then, a short review of the use of VR technologies for training motor skills (Section 1.1.2) and an introduction to the research project which has supported this work (Section 1.1.3). Secondly, section 1.2 presents the research problems which have motivated this study. Thirdly, section 1.3 describes the overall objectives of this work. Finally, section 1.4 describes the structure of the thesis.

1.1 FRAMEWORK OF THE STUDY

1.1.1 Motor skill training in industrial maintenance

The maintenance of operating components which are subject to critical process conditions as in industrial and nuclear power plants is crucial for ensuring the safety and the reliability of industrial activities. However, maintenance tasks carried out in such critical environments may be compromising for the safety of the operators that perform them. For this reason, the execution of those maintenance tasks must be efficient. Maintenance operators usually dedicate a considerable effort to train the motor skills that are required for the performance of those tasks.

Behavioral psychologists have traditionally highlighted two fundamental methods for training motor skills: part-task and whole-task training (Teague et al., 1994, Utley & Astill, 2008; Browne et al., 2009, Coker, 2009). Part-task training consists of breaking down motor skills required for the performance of a manual task into simpler components in order to be practised separately whereas whole-task training proposes a holistic approach of the target task.

This thesis presents a case study of the metallographic replica, an in-situ non-destructive inspection technique that aims to evaluate the integrity of materials exposed to critical process conditions. In the course of that inspection technique, several abrasive processes such as fine grinding and polishing operations for which accurate motor skills are needed (Hulsholf et al., 2005), are carried out (ASTM E 3 - 01, 2001). Those motor skills are traditionally trained following the whole-task training method under the supervision of an expert metallurgist who makes demonstrations and provides verbal guidelines to the trainee. However, for reasons that are presented later, conventional training has issues and limitations, especially for inexperienced trainees. In particular, part-task training can be very effective for beginners, to the extent that it allows focusing independently on each of the motor skills that are required throughout those tasks. However, arranging such part-task training in the real world may be complicated. VR is believed to enable solving this and other issues that arise throughout the training carried out in the real world, allowing effective part-task and whole-task training.

1.1.2 Virtual Reality, haptic interaction and motor skill training

VR has been traditionally defined as a computer graphics interface that involves real-time, immersive and interactive simulation, enabling a user to be physically and perceptually involved in a virtual environment (Burdea & Coiffet, 2003). It has been frequently employed to support the training of procedural and motor skills using haptic force feedback devices (Bhatti et al., 2009; Gutiérrez et al., 2010).

In VR, motor skills can be practised through multiple rehearsals of training exercises, designed according to part-task and whole-task training methods carried out in realistic virtual environments in which, according to Bossard et al. (2008), Abate et al. (2009) and Wang, Y. et al. (2009), the performer's safety is not compromised. Moreover, VR allows defining a series of objective performance metrics (i.e. completion time, error ratio, efficiency of performance …) which can be used to assess the development of motor skills throughout the training process (Haque & Srinivasan, 2006; Van der Meijden & Schijven, 2009; Johanesson et al., 2010; Rhienmora et al., 2011). Task performance-related information that is usually not available in the real world can be thus provided throughout VR training. The provision of such information is referred as augmented feedback, which aims to supplement the sensory information perceived during the performance of the task with additional multimodal information. Many research studies have investigated the effect of augmented feedback to support the learning of complex motor skills in VR (Solis et al., 2003; Esen et al., 2004; Morris et al., 2007; Sewell et al., 2007; Johannesson et al., 2010). According to Johanesson et al. (2010) and Gopher (2012), augmented feedback is a prominent feature of motor skill training in VR. Thus, the use of VR is believed to be beneficial for training those motor skills that are relevant in an industrial maintenance task.

Haptic interaction enables providing tactile and kinesthetic intrinsic information. This is given in the form of force feedback resulting from the computation of object contact and manipulation in virtual environments (Hayward et al., 2004). According to Abate et al., (2009), the addition of haptic force feedback within virtual environments allows bringing the concept of VR interaction closer to realistic physical models. Haptic force feedback has been shown to be profitable for training fine motor skills at all levels of expertise (Tholey et al., 2005, Wagner et al., 2007). For this reason, it has been frequently employed to support motor skill training in medical (Morris et al., 2006; Sternberg et al., 2007; for a comprehensive list of examples see the review presented by Coles et al., 2011) and dentistry procedures (Steinberg et al., 2007; Suebnukarn et al., 2010; Rhienmora et al., 2011). In contrast, fewer studies have proposed using haptic force feedback for training the fine motor skills that are involved in industrial tasks (Balijepalli & Kesavadas, 2003; He & Chen, 2006; Wang, Y. et al. 2006; Wang, Y. et al., 2009; Sung et al., 2011). Moreover, the effect of the suggested haptic-based training on the development of those skills has not been investigated in depth.

This thesis presents a VR training system enhanced with haptic force feedback which aims to train some of the fine motor skills that are involved in the performance of an industrial maintenance task. The system proposes practical training exercises inspired by part-task and whole-task training methods and enhanced with augmented feedback.

1.1.3 The ManuVAR Project

ManuVAR (Manual work support throughout system lifecycle by exploiting Virtual and Augmented Reality) is an EU funded project from the Seventh framework programme (http://manuvar.eu/) which aimed to develop a technological and methodological framework using virtual and augmented reality technology (VR/AR) for supporting high value high knowledge manual work through the product life cycle in order to enhance the competitiveness of EU industries (Krassi et al., 2010b, Krassi et al., 2010c).

Several industrial use cases distributed across the whole product life cycle were implemented. One of these industrial use cases consisted of procedural training for the performance of the metallographic replica technique and motor skill training on fine grinding and polishing operations. A cluster formed by the University of Malaga, Tecnatom S.A., a Spanish company that delivers advanced engineering services in industrial facilities and nuclear power plants, the Association for the Advancement of Radical Behavior Analysis

(AARBA) and the Human Factors Research Group from the University of Nottingham was in charge of the definition, design, development and evaluation of that use case.

Several fundamental teaching and training methods were implemented on the ManuVAR platform in order to enable procedural and motor skill training using VR technologies (Poyade et al., 2011). However, the research presented in this thesis only focuses on the training of motor skills (Figure 1).

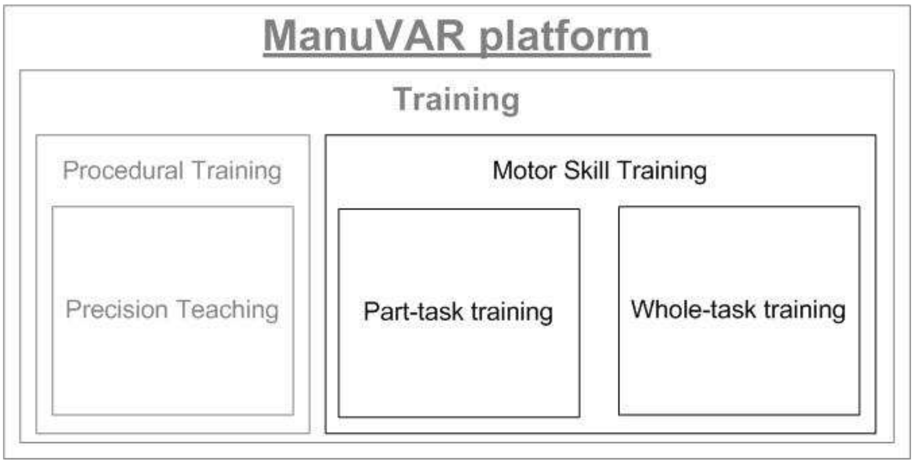

Figure 1. The work presented in this thesis was part of the implementation and evaluation of a training framework on the ManuVAR platform.

More information about the ManuVAR project is available in Appendix C.

1.2 MOTIVATION

As mentioned in section 1.1.1, the motor skills that are relevant in fine grinding and polishing tasks are traditionally trained following the whole-task training method under the supervision of an expert metallurgist. That training aims at the successful development of fine motor skills that are required in both tasks. However, as addressed later in this thesis, practices inspired by the whole-task training method are often too challenging for inexperienced trainees. Therefore, the learning of motor skills occurs with difficulty. In this work, two of the fine motor skills that are required in fine grinding and polishing tasks are considered. These are *angle skill* for the inclination of the power tool on the surface of the material being inspected, and *force skill* for the force exerted on the surface of the material through the tool.

Motor skill training inspired by the part-task training method can be more profitable to the extent that it enables dissociating a sub-set of motor skills into several independent components which can be practised separately. However, the dissociation of motor skills that are usually performed simultaneously is not easy to implement in the real world.

In many occasions, VR has been employed to train motor skills following part-task and whole-task training methods. However, to the best knowledge of the author, an analysis of the effectiveness of part-task training on fine motor skills usually performed simultaneously is still missing. Thus, the question arises whether the VR training of those fine motor skills is effective for improving performance in real operating environments.

Fine motor skills such as those required in fine grinding and polishing tasks belong to the domain of tacit knowledge and are therefore difficult to describe verbally. On the one hand, force skill is not directly observable. Thus, the expert metallurgist in charge of the supervision of the training is not able to monitor the force being exerted. Therefore, verbal guidelines provided to assist the performance of that skill difficulty lead to effective refinements of the exerted force. On the other hand, angle skill is observable. However, refinements of that skill require a high degree of accuracy that is difficult to describe verbally. Thus, refinements of both skills suggested through verbal guidelines are not sufficient to reach a high degree of accuracy during the performance of the tasks proposed in this thesis.

To the extent that VR allows the provision of augmented feedback which bring additional performance-related information to the process of motor skill training, the question arises as to whether this feature of VR training is sufficient to enable motor skills to gain in proficiency in the real world.

1.3 OBJECTIVES

The purpose of the research presented in this thesis is to explore the effect of VR training based on haptic interaction along with the use of augmented feedback to support the development of fine motor skills, and more specifically of angle and force skills in the context of fine grinding and polishing tasks. To do so, it is first necessary to design and develop a VR training system which enables training those motor skills. Then, the effectiveness of that system must be evaluated in order to investigate the validity of the system to train motor skills in the suggested context.

The design of the VR training system should be based on a description of the functionalities of that system in order to enable the resulting development to resolve the research problems presented in section 1.2. Throughout the design stage, a functional analysis based on the extraction of customer requirements was carried out in order to highlight those functionalities. The resulting development proposes a training toolkit which allows building flexible training programs. Each training program enables configuring a series of exercises inspired by part-task and whole-task training methods and enhanced with augmented feedback.

This work presents two experimental studies which aim to assess the effectiveness of the VR training system to support motor skill training. The first study aims to demonstrate that part-task training enables novice trainees to become more proficient when performing fine motor skills in a whole-target task in VR. The second study aims to demonstrate the effectiveness of VR training inspired by part-task and whole-task training methods for non-expert trainees. The external validity of the VR training system is subsequently investigated. The external validity of the system refers to its ability to effectively train motor skills which can be transferred to the real environment.

On the basis of the addressed objectives and the previous research, which is reviewed in the following chapters of the thesis, two initial hypotheses are presented:

1. Hypothesis 1: The implementation of fundamental training methods such as part-task and whole-task training in the context of VR training, along with the provision of augmented feedback, is valid for training fine motor skills that are required in the suggested tasks.
2. Hypothesis 2: The suggested VR training enables transferring the trained motor skills to real operating environments.

The evaluation proposed in this work is limited to a specific case of motor skill training. Fine grinding and polishing performance in real operating environments may be altered by ergonomic and environmental factors such as body posture, lighting, and external disturbances caused by surrounding operational activities. Studying the effect of these factors on task performance is out of the scope of this thesis. Moreover, the impact of immersive VR technologies such as stereoscopic display and point of view tracking on the training of motor skills is not investigated.

1.4 STRUCTURE OF THE THESIS

On the basis of the objectives described in section 1.3, this thesis is structured as shown below (Figure 2).

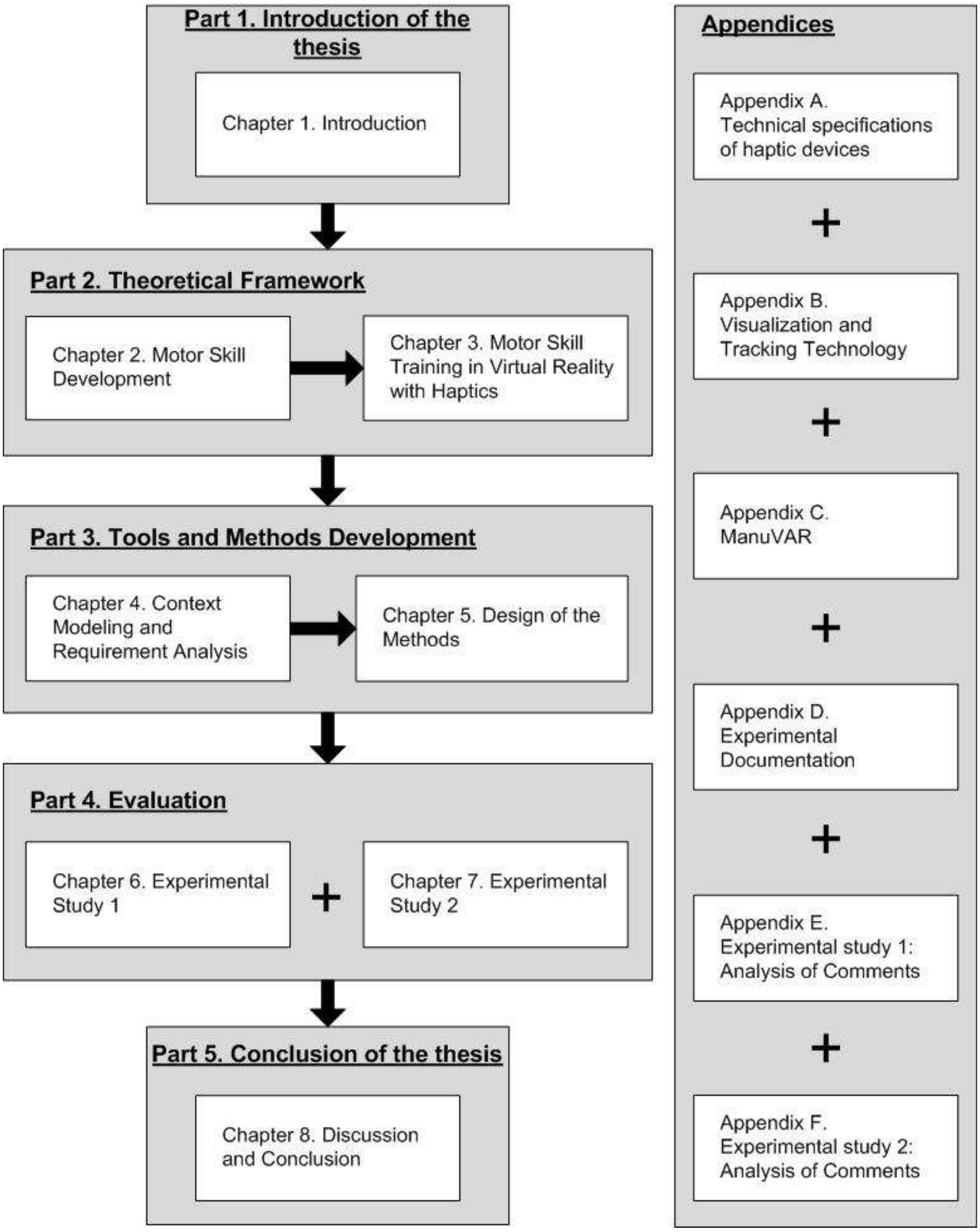

Figure 2. Structure of the thesis.

The remainder of the thesis starts with a presentation of the relevant theoretical background. Chapter 2 provides a description of fundamental concepts in motor skill training used later in the thesis, giving emphasis to the factors that lead to the successful development of motor skills. Chapter 3 presents the research background of this thesis, including the use of haptic force feedback and the fundamental training methods and types of augmented feedback that support motor skill training in VR.

The third part of the thesis describes the design and development of the VR training system. Chapter 4 defines the context for the modelling and the development of the VR training system. It introduces the maintenance tasks supported by the VR training system and highlights the motivations for such development. It then proceeds to functional and requirement analysis in order to provide a coherent description of the functionalities of the system. Chapter 5 describes the resulting design and development of the VR training system. It presents a training toolkit which supports the functionalities of the system. Finally, it presents a novel task performance model along with the methodology followed to construct it.

The fourth part of the thesis presents two experiments that aim at evaluating and validating the VR training system. Chapter 6 investigates the effectiveness of part-task training in order to enable inexperienced performers to gain in proficiency while performing a simulated polishing task. Chapter 7 assesses the effectiveness of part-task and whole-task training methods on non-expert performers to improve their motor skills for the performance of both tasks and investigates the external validity of the system.

Finally, Chapter 8 proposes a general discussion on experimental results with regards to previous research and concludes the thesis.

Additionally, six appendices are provided at the end of this thesis. Appendices A and B focus on the VR technologies used in the experimental studies presented in chapters 6 and 7. Appendix C presents the architecture of the ManuVAR platform and helps to set in context the current work. Appendix D reports all the documentation provided to participants in the experiments. Finally, appendices E and F present the qualitative data collected throughout both experimental studies.

PART 2

THEORETICAL FRAMEWORK

Chapter 2. Motor Skill Development

Humans are able to perform a wide range of complex movements that are crucial to ensure our independence and interaction with our surroundings (Utley & Astill, 2008). Several definitions of the term skill have been proposed in an attempt to explain what are motor skills. For instance, Guthrie (1952) (reported in Schmidt & Wrisberg, 2008; Utley & Astill, 2008) has defined such skill as the ability to achieve an end-result with a maximum certainty of goal achievement, minimum energy expenditure and movement completion time; Newell (1991) has suggested that motor skills are those skills in which the emphasis is given to the movement and the outcome of the action; Schmidt & Wrisberg (2008) have defined motor skill as the ability to reliably and consistently perform sequences of organized movements considering the perceptual sensory information. However, all these definitions converge towards the fact that motor skills aim to achieve specific goals set as motor problems that arise from the interaction of an individual with its surroundings (Higgins, 1991). These motor problems are solved through the execution of coordinated movements onto one or several degrees of freedom of the human body.

This chapter introduces the concepts of motor skills, motor learning and gives emphasis to the factors that lead to the successful development of motor skills. Section 2.1

presents common taxonomies used to classify motor skills. Section 2.2 introduces several theories to support the acquisition of motor skills and describes how motor learning occurs through performance improvements. Finally, sections 2.3 and 2.4 propose several improvements in the design of the learning experience that aim to enhance the acquisition of motor skills.

2.1 CLASSIFICATION OF MOTOR SKILLS

Motor skills are complex to describe and evaluate. For this reason, several taxonomies have been proposed, aiming to organize motor skills according to specific characteristics. Most popular classifications tend to conceptualize motor skills regarding to a task-centered approach. Other taxonomies propose classifying motor skills according to an approach centered in the performance proficiency defined by maximum certainty of goal achievement, minimum energy expenditure and movement completion time. Thus, these taxonomies support the definition of motor skill as proposed by Guthrie (1952). However, classifications centered in performance proficiency are strongly dependent on the level of expertise of the performer and remain less frequently used.

Task-centered taxonomies approach motor skills from the perspective of the task organization (Section 2.1.1), the importance of the cognitive load in the achievement of the goals (Section 2.1.2), the involvement of muscular activity (Section 2.1.3) and the predictability of the environment (Sections 2.1.4 & 2.1.5).

2.1.1 Task organization

Classification following task organization proposes a one-dimensional system in which motor skills are arranged from discrete to continuous skills, with serial skills set in-between. According to Schmidt & Wrisberg (2008), discrete skills are generally those skills involved in actions of short duration with a well-defined beginning and end (i.e. punching, hammering, screwing, etc…). Serial skills describe a group of ordered discrete skills that compose more complex and long lasting movements (i.e. sequence of the triple jump, throwing a javelin, mechanical assembling, polishing, grinding, etc…). In many occasions, serial skills are decomposed into several discrete skills in order to be more efficiently learned through practice. In this thesis, emphasis will be given to the decomposition of motor skills that are relevant for the performance of fine grinding and polishing tasks, into several discrete skills to support motor skill training. Section 2.3 introduces the concept of breaking down motor skills into several discrete skills. Continuous skills are those repetitive skills that compose rhythmic actions (i.e. running, swimming, cycling, assembly line work, etc…). Continuous skills have no concrete beginning or end and can be stopped at any moment of the realization of the action.

2.1.2 Importance of cognitive load

Motor skills can also be classified according to the relevance of cognitive abilities in the success of goals achievement. This classification defines a one-dimensional system in which motor skills are arranged from simple to complex skills as a function of the importance of decision-making during the performance of those skills. Simple skills require little concentration and are not cognitively demanding (i.e. walking, hammering, screwing, etc…). In contrast, complex skills are cognitively complicated. They often require the development of a strategy in order to be efficiently performed. Thus, they are attention demanding and need to be practiced repeatedly in order to achieve a smooth performance. For instance, motor skills involved in complex machinery assembly tasks as those proposed by Abate et al., (2009) and Gutiérrez et al. (2010) are usually considered as complex skills.

Of course, after a sufficient period of training, the performance of the practised motor skills gets automatized (Section 2.2.2.1) and the cognitive load is reduced to a minimum. However, this thesis will focused on the training period during which those motor skills that are required in industrial maintenance tasks are acquired (Section 4.2). Those motor skills would rather tend to be complex skills to the extent that during that period their performance in industrial facilities requires a high level of concentration over a prolonged period of time.

2.1.3 Involvement of muscular activity

The classification with regard to the involvement of the muscular activity in the course of the performance defines a one-dimensional system in which motor skills are arranged from fine to gross motor skills. On the one hand, fine motor skills involve groups of small muscles devoted to the performance of precision movements for which a high degree of sensory coordination is required (Magill, 2007). Fine motor skills are generally performed in manipulation tasks that require arm-hand-eye coordination such as in electronic component mounting and soldering tasks (Sung et al., 2011). Similarly, the motor skills that are focused in this thesis for the performance of fine grinding and polishing tasks consist of fine motor skills. On the other hand, gross motor skills involve groups of large muscles requested for the performance of not precise movements often achieved in wide workspaces (i.e. hammering, lifting weight, etc…). However, in many occasions, fine and gross motor skills are performed simultaneously.

2.1.4 Predictability of the environment

Knapp (1967) (reported in Schmidt & Wrisberg, 2008) has proposed a one-dimensional classification of motor skills based on the level of variability and predictability of the environment in which they are usually performed. Motor skills are ranged from open to closed skills. Open skills are those skills in which performance is affected by external factors because they are carried out in variable and unpredictable environments. Thus, the performer must be able to quickly evaluate the environment characteristics based on the information obtained from perceptual sensory cues, and must rapidly adapt movement patterns. Motor skills involved in the performance of fine grinding and polishing tasks conducted during a maintenance campaign of an industrial plant, can be considered as open skills to the extent that the stillness of the environment is usually altered by surrounding maintenance activities. In contrast, closed skills are performed in stable and predictable environments. Closed skills are not affected by environment characteristics, so performers can organize their movements with no rush. For instance, motor skills involved in the performance of fine grinding and polishing tasks carried out at the laboratory for training purposes are thus considered as closed skills.

2.1.5 Gentile’s Two-dimensional classification

Gentile (1987) (seen in Magill, 2007; Utley & Astill, 2008) have highlighted that most common taxonomies restrict the classification of motor skills onto a unique dimension, without considering the movements complexity in their context. In response to such criticism, Gentile (1987) has proposed a two-dimensional classification which considers action requirements and environmental demands (Table 1). However, in the context of this thesis, this taxonomy is conceived as strongly inspired by the classification based on the predictability of the environment in which motor skills are arranged as open and closed skills (Section 2.1.4).

Gentile´s taxonomy is traditionally referred as a two-dimensional classification model. Nonetheless, that model can be argued to be composed of more dimensions to the extent that motor skills are arranged according to two states of variability of the action (states 1 & 2) and two other states of variability of the environment (states 3 & 4). In state 1, the body can be stationary or in movement, whereas in state 2, an object manipulation can be engaged or not. Moreover, the degree of variability of the environment in which the action is performed, referred as the regulatory condition, can be (state 3) intra-trial and (state 4) inter-trial.

Table 1. Gentile's two-dimensional classification system (Utley & Astill, 2008).

			Action Function			
			Body orientation stable		**Body orientation changing**	
			No object manipulation	Object manipulation	No object manipulation	Object manipulation
Environmental context	**Regulatory condition: stationary**	No-inter-trial variability	Watching a football game	Writing	Walking or running	bowling
		inter-trial variability	Using sign language	Shooting in archery	Performing step-up in gym	Running over an obstacle course carrying a ball
	Regulatory condition: variable	No-inter-trial variability	Standing in a elevator	Standing and bouncing a ball	Walking on a moving walkway	Dribbling a ball around a set of cones
		inter-trial variability	Standing on one leg when wearing roller skates	Catching balls thrown at different speeds	Crossing the road	Playing rugby, football, etc…

Motor skills required in fine grinding and polishing tasks are usually part of actions in which the body orientation remains relatively stable and object manipulation is engaged. Moreover, the laboratory in which those skills are traditionally trained consists of an environment with stationary regulatory conditions and no variability between trials. In contrast, industrial plants in which those skills are commonly performed for inspection purposes, the environment can be considered as highly changing with a high degree of variability between rehearsals.

2.2 MOTOR SKILL ACQUISITION

Motor skills are developed through the process of motor learning during which an unskilled performer passes through different phases to become a highly skilled performer. Schmidt & Wrisberg (2008) have described the learning of a motor skill as an internal process associated to practice that leads to relatively permanent changes in the capability to perform an action. Those changes appear in the form of a slow and progressive retention during which the skill is gradually consolidated passing from an initial and fragile state in which it tends to be easily forgotten, to a more permanent and automatized state (Brashers-Krug et al., 1996). Section 2.2.1 presents the mechanisms that support the process of acquisition and development of motor skills and section 2.2.2 gives emphasis to the consolidation of those motor skills through several stages.

2.2.1 Theories of motor skill acquisition

For a long time, researchers have attempted to explain how the process of motor learning was achieved. Traditionally, cognitive theories of skill acquisition placed the emphasis on the mechanisms used by the central nervous system to plan and control movements. These mechanisms are centralized and organized in motor programs as a set of prescriptive sub-processes in charge of stimulus identification using perceptual sensory cues, selection and organization of the response, in order to enable modifying and performing an action. Basically, motor programs enable storing a representation of the dynamics of movements previously performed in the movement memory and compare it with the characteristics of the movement being currently produced. Adams, J. A. (1971) (reported in Schmidt, 1975, Lee & Schmidt, 2008; Utley & Astill, 2008; Rosenbaum, 2009) and Schmidt (1975) have proposed two approaches of motor learning based on prescriptive motor control theories.

According to Newell (2003) and Schmidt (2003) common thoughts concerning motor control theories have changed over the time. A more contemporary theory than those presented above has suggested an ecological approach to the acquisition of motor skills in which motor skill acquisition is more than just a set of processes reproduced in a sequential fashion as a function of stimuli (Newell, 1991). This theory implies that the development of motor skill emerges naturally through an exploratory phase in which a performer searches for optimal movement characteristics in accordance with his/her own capabilities to perform the movement, and restrictions imposed by the task and the environmental context.

2.2.1.1 Adam's closed-loop theory

Adam, J. A. (1971) (reported in Schmidt, 1975; Lee & Schmidt, 2008; Utley & Astill, 2008; Rosenbaum, 2009) has proposed a closed-loop theory to support motor skill acquisition during slow, graded and linear positioning tasks. A paramount principle of Adam's closed-loop theory is the frequent need of feedback providing information about goal achievement, in order to enable a performer to adjust the movement coordination pattern. Section 2.4.2 refers to that kind of extrinsic information as Knowledge of Results (KR).

Adam, J. A. (1971) suggested that learning a motor skill occurs based on two memory states, referred to as memory trace and perceptual trace. The memory trace consists of a simple motor program responsible for selecting and initiating the appropriate motor response based on the representation of prior actions stored in movement memory. The perceptual trace supports accurate performance of a movement by guiding body limbs towards correct position and along appropriate trajectory. The perceptual trace consists of a unique representation of the action based on past experience, which encompasses perceptual sensory information, and provides the most accurate reflection of the movement performance. It acts as a reference of correctness and enables error adjustments for next attempts of the movement. During and after movement performance, a performer's central nervous system compares the actual intrinsic feedback (Section 2.4.2) with the information provided by the perceptual trace and consequently enables adjustments of the movement to achieve an optimal performance. The perceptual trace is in general strengthened by an increased exposure to extrinsic feedback, more especially to KR, and errors decrease with practice until the representation of the action in the trace is accurate.

However, Schmidt (1975) highlighted some criticisms to Adam's theory. First, it was developed from slow positioning movements and presented inherent problems for rapid movement learning. Second, Adam predicted incorrectly that the amount of KR would enhance movement performance and the effect of withdrawing such information feedback might disrupt motor learning and corrupt the accuracy of the trace (Winstein & Schmidt, 1990). Third, Adam's theory states that the perceptual trace acts as a reference of correctness based on feedback from previous experience, without which the trace cannot be developed. Thus, Adam's theory hardly accounts for the development of accurate novel movements (reported in Utley & Astill, 2008). And finally, Schmidt (1975) argued a storage problem in the movement memory as Adam's theory supports the storage of every sequence of movements as a unique representation of an action. It is referred as a one-to-one mapping and suggests the storage of a considerable amount of information.

2.2.1.2 Schmidt's theory of schema

Schmidt (1975) attempted to generalize motor learning to a wide range of movements involving discrete, rapid, open and closed skills through the theory of schemas. Schmidt's theory incorporates much of Adam's closed loop theory but organized in a different way. It provides a solution to the memory storage issue due to the one-to-one mapping. The approach of Schmidt proposes a one-to-many mapping between the movement being produced and a conceptualized representation of the action that includes a description of a movement coordination pattern using both variant and invariant features.

A schema defines a set of rules that describe a class of movement as a structure of information parameterized by several specification variables that yield to a specific response outcome (Schmidt, 1975). Basically, Schmidt suggests that actions are programmed in advance and stored in a generic way in movement memory as Generalized Motor Programs (GMP).

Schmidt's schema is based on the assumption that when an individual attempts to perform a movement to achieve a specific objective, the information indicating the initial conditions of the performance, the response specifications for the motor program, the sensory consequences of the response and the response outcome are recorded once the action is complete. The recorded information can be thus reused aiming to be attuned when attempting to perform a similar movement coordination pattern with different characteristics. For instance, the performance of a fine grinding or a polishing task as a movement pattern is ruled by a set of variables that are proper to the task being performed (i.e. range of applied force and tool inclination). However, when performing on distinct areas of an industrial plant, the characteristics of that movement pattern may be different. Thus, the GMP stores a generic representation of the movement pattern that can be reused and attuned for further performances.

The initial conditions encompass all the preliminary available intrinsic and extrinsic information prior to the response (i.e. initial posture of body limbs, environmental conditions, etc…). This information remains crucial for movement planning in the environmental context. The response specifications consist of the characteristics of the produced movement. These characteristics can be variant (i.e. force, angle, speed, duration, etc…) and invariant (i.e. right hand, left hand, both hands, etc…). The sensory consequences gather the intrinsic and extrinsic information feedback perceived during the response (i.e. proprioceptive, visual, auditory, etc…). And finally, the response outcome consists of the KR and other sources of feedback that report the success of the performance regarding to the original movement objectives.

Schmidt’s theory suggests that after several trials of a novel movement coordination pattern, the central nervous system formulates two schemas that abstract the information resulting from past experiences. These schemas are named recall and recognition schemas.

The recall schema considers the relationship between the initial conditions of the action, the past experiences outcomes and response specifications, to address new action goals and determine most appropriate response specifications to achieve the movement coordination pattern to the desired outcome. Response specifications to be determined can be novel or already existing. Therefore, the recall schema produces a motor response.

At the same time, the recognition schema compares the actual sensory consequences and response outcome with the expected sensory consequences and outcomes based on conceptualized information from past experiences. The recognition schema accounts accurately for error detection in case the actual sensory consequences and response differ from the expected sensory consequences and response. And therefore, it indicates that the actual motor response must be adjusted in order to achieve the action goal.

2.2.1.3 Newell’s constraint theory

Newell (1986) (reported in Utley & Astill, 2008) proposed a dynamic system theory based on an ecological approach of the process of motor learning in which movement coordination patterns naturally emerge self-organized as a function of an interaction with a set of possibly changing constraints. Newell (1986) suggested that motor skill acquisition consists of an exploratory phase that stands through practice. During this phase, an individual searches for optimal motor coordination solutions to meet the demand of the task, by interacting with three major constraints: organismic, task and environmental constraints.

Organismic constraints refer to the individual capability to perform coordinated movements (i.e. body shape, weight, height, emotional, cognitive and agility constraints, etc…). Task constraints refer to all task aspects that limit the interaction (i.e. task’s rules, equipment in use, and objective of the action, etc…). And finally, environmental constraints consist of the information obtained through all perceptual sensory cues (visual and auditory cues, proprioceptive information, information feedback, etc...) that characterize the environment context. In that sense, the implementation of haptic force feedback in VR training simulations is paramount to provide realistic environmental constraints and therefore enhance the exploration of appropriate motor coordination patterns.

At the beginning of the exploration, when learning a novel motor skill, movement coordination patterns present a high degree of variability. However, through practice and using the available information feedback that reflects the interaction with all constraints, the performer is naturally able to gradually adapt the movement coordination pattern to the desired response outcome. Therefore, the coordination becomes progressively more stable and the practiced skill gets progressively consolidated and automatized. The behaviour resulting from the stabilized movement coordination pattern is referred as attractor. For instance, Kelso & Schöner (1988) have demonstrated that when performing out of phase fingertip movements and increasing progressively the pace, movement coordination pattern was naturally stabilized to in-phase or anti-phase movement. In-phase and anti-phase synchronisms were the natural attractor states for the coordination of finger movement. However, newer attractor states can be developed through practice.

2.2.2 Stages of motor learning

The learning of a motor skill viewed from the perspective of a process in which a performer improves a skill through practice, is traditionally described as a model composed of several hierarchically organized stages.

2.2.2.1 Fitts and Posner three-stage model

Fitts & Posner (1968) proposed a model nowadays considered as the most popular framework for understanding motor skill acquisition (Kolozsvari et al., 2011). According to them, the learning of motor skills as those required in fine grinding and polishing tasks, occurs through three stages: cognitive, associative or intermediate and autonomous. It is assumed that through practice, motor skills progressively gain in proficiency along one phase and gradually merge into another (Figure 3).

Figure 3. The three-stage model proposed by Fitts and Posner represented as a one-dimensional system (figure as proposed by Utley & Astill, 2008). Motor learning occurs gradually through practice as the considerable mental demand required at the cognitive stage progressively decreases until the skill becomes fully automatized.

The cognitive stage is characterized by learners trying to understand the task and testing several strategies to efficiently perform the task. Often, the learner engages self conversations to promote verbal guidelines in order to support the performance. The learner devotes considerable cognitive activity to the performance and initially tends to commit a large number of errors without being able to identify and solve them. Motor skill performance is generally unsure, awkward and with little consistency. However, performance improvements tend to be important and generally occur rapidly. Throughout this stage, instructions, demonstrations, assistance (Section 2.4.1), and information feedback (Section 2.4.2) are considered to be particularly beneficial for performance improvements.

In the associative or intermediary stage, the learner organizes motor skill patterns more effectively which results in significant improvements in the performance. The learner is able to associate environmental cues with motor skill characteristics enabling him or her to anticipate and time skills resulting in smoother and more stable movements. For instance, during a fine grinding and polishing tasks, the learner is able to associate tool inclinations and exerted forces with the outcome of task performance. Moreover, self-verbal guidance tends to be less frequent and performance progressively becomes cognitively effortless. The learner drastically commits fewer errors and is able to refine their motor skills to solve these errors. Generally, the learner does not require as much assistance to efficiently perform the task. This stage usually lasts considerably longer than the cognitive stage.

The autonomous stage is characterized by the absence of cognitive load during the performance of the task. Motor skill patterns are performed more consistently and almost automatically. The learner is able to efficiently detect errors and refine movements with proper adjustments. The learner generally shows a high degree of self confidence while performing the task.

In this thesis, an experimental study will be conducted in order to evaluate the effectiveness of a VR training system to carry novice performers with no knowledge of the motor skills that are relevant in a polishing task, from the cognitive to a more advanced stage of motor learning (Chapter 6).

2.2.2.2 Gentile's two-stage model

Gentile (1987) (reported in Magill, 2007; Utley & Astill, 2008) modeled motor learning from the perspective of the goal achievement. The model is composed of two stages: the verbal-cognitive and the motor stages (Schmidt & Wrisberg, 2008).

In the verbal-cognitive stage of learning, the performer aims to acquire a pattern of movement coordination that allows completing the action with a certain degree of success. Gentile stated that the learner determines the most appropriate movement coordination pattern by exploring a wide variety of movement possibilities through practice and error making. The performer must develop movement characteristics as a function of the variability of the environment, referred in section 2.1.5, as regulatory conditions of the environment. This suggests the existence of an explicit mapping process that matches movement characteristics with regulatory conditions of the environment. To do so, the performer must be able to discriminate environmental features in order to differentiate between regulatory conditions that determine how the movement must be produced and non-regulatory conditions that do not influence the performance of the movement. In the verbal-cognitive stage of the motor learning, the learner dedicates an important cognitive activity which often encompasses a self-conversation in order to establish the most appropriate movement coordination pattern to achieve the task goal. When reaching the end of this stage, the learner has developed the appropriate movement coordination pattern that allows achieving the goal even though performance is not consistent and efficient.

In the motor stage of learning, the learner must acquire three basic characteristics in order to keep on improving the skill. First, the learner must generalize the movement coordination pattern acquired during the verbal-cognitive stage to any environmental contexts that he or she can be eventually confronted. For instance, a technical worker must be able to perform fine grinding and polishing tasks on any material surface he/she might be confronted. Secondly, the learner's performance must become more consistent in order to achieve the action goal on demand. Thus, the technical worker must be able to perform several rehearsals of a maintenance task with the same degree of efficiency. Thirdly, the learner must be able to economize physical and cognitive efforts while performing the skill. In that case, the motor skill becomes almost automatic and the performer has acquired a high level of expertise. In that sense, fine grinding and polishing operations are instinctual (automatic) for expert metallurgists but physically and cognitively demanding for unskilled performers.

In this last stage, Gentile's model aims to adjust and generalize a movement coordination pattern in order to meet the task demand in all possible environmental contexts. However, the learner's goal for refinement and generalization of a movement may differ depending on the nature of the skill being performed. Gentile has proposed a classification of movements based on the complexity of the action and the predictability of the environment (Section 2.1.5). However, in order to simplify this approach, motor skills can be arranged as open and closed skills (Section 2.1.4).

On the one hand, the practice of open skills usually implicates the performance of rapid movements in ever-changing environments. The performer is often required to quickly adapt the movement during the trial in order to almost immediately meet the task demand. On the basis of the provided information feedback during and after the performance (Section 2.4.2), the performer attempts to diversify the movement characteristics dependently to the dynamics of the environment. In industrial plants where fine grinding and polishing tasks are carried out, a performer must rapidly adapt task performance to possible disturbances caused by surrounding maintenance activities. For instance, a decrease of environmental lighting may lead to change working posture and movement patterns in order to enable the achievement of the task. This is referred as the diversification stage (Schmidt & Wrisberg, 2008).

On the other hand, the practice of a closed skill usually involves performance of movements in a stationary environment. The performer is given the opportunity to use the information feedback (Section 2.4.2) to fixate the movement coordination pattern from trial to trial. During the performance of fine grinding and polishing tasks in a laboratory, the performer has the opportunity to refine angle and force skills with no rush with regards to the available information feedback. This is referred as the fixation stage (Schmidt & Wrisberg, 2008).

In this thesis, emphasis will be given only to motor skill training for fine grinding and polishing tasks in stationary environments. Moreover, as mentioned previously in section 1.3, ergonomic considerations (i.e. arm and full body posture) are out of the scope of this research work.

2.2.2.3 The Bernstein's stage theory

Bernstein (1967) (reported in Newell & Vaillancourt, 2001; Magill, 2007; Utley & Astill, 2008) proposed a dynamic approach of motor learning. In fact, Bernstein's model is based on an ecological approach of motor skill acquisition which argues that motor programs provide an excessive emphasis on the organization of actions in the central nervous system and omit the dynamics of body limbs to meet the task demand in accordance with environment constraints.

Bernstein suggests that the complexity of learning a novel motor skill remains in the development of a movement coordination pattern that enables a performer to progressively master multiple degrees of freedom of the human movement system.

The development of a pattern of coordination over several degrees of freedom in order to efficiently perform a motor skill occurs through three stages of learning: novice, advanced and expert.

In the novice stage, the learner temporarily reduces the number of active degrees of freedom by freezing out body limbs at the periphery of the movement. The learner explores the perceptual motor workspace by interacting with task and environmental constraints aiming to acquire the most appropriate pattern of coordination for active degrees of freedom resulting in the desired kinematic response.

In the advanced stage, the learner keeps on exploring the workspace and gradually releases all restrictions enabling the progressive integration of previously frozen degrees of freedom to the movement coordination pattern. Usually, searching for optimal movement coordination pattern remains highly challenging as the combination of proprioceptive cues increases with the number of released degrees of freedom.

And finally, in the expert stage, the fluidity during the performance of a skill results from a coordinated structure of body limbs. The performer exploits outcomes from the interaction of all possible degrees of freedom to optimize the completion of the skill.

Vereijken et al. (1992) (reported in Newell & Vaillancourt, 2001; Utley & Astill, 2008) have argued the Bernstein's stage theory in a study in which participants were given several days to master a gross motor skill which consisted of body balancing on a ski simulator. The authors have demonstrated that the evolution of the dynamics of participants' limbs over days of practice was consistent with the freezing-freeing-exploiting stages proposed by Bernstein. In contrast, Newell & van Emmerik (1989) have highlighted no evidence of freeing peripheral degrees of freedom in learning a fine motor skill as signature handwriting. Thus, the Bernstein's stage theory can be questioned for learning fine motor skills. For this reason, that theory won´t be considered to explain the learning of those fine motor skills that are required in fine grinding and polishing tasks as suggested in this thesis.

2.3 DESIGNING THE LEARNING EXPERIENCE

As mentioned in section 2.2, motor learning consists in an internal process associated to practice that leads to relatively permanent improvements in the capability to perform an action (Schmidt & Wrisberg, 2008). However, practising the target action does not always lead to a successful development of motor skills (Schmidt & Wrisberg, 2008). In many occasions, motor skills are better acquired through attuned practice proposed as a set of specifically designed exercises. Many authors (Teague et al., 1994, Utley & Astill, 2008; Browne et al., 2009, Coker, 2009) have given emphasis to two training methods (Section 2.3.1):

1. Whole-task training which refers to practising a task in its integrity.
2. Part-task training which consists of breaking down motor skills involved in the performance of a complex task into simpler part-task components in order to be practiced separately, and then recombining them to reconstruct the whole target skill.

Sections 2.3.2 & 2.3.3 present respectively several methods to break down a skill into part-task components and integrate those components to reconstruct the whole target skill.

2.3.1 Part vs. whole-task training

One of the main difficulties for practitioners is to decide whether it is better to practise a movement pattern using one or the other training method (Utley & Astill, 2008). In the early 60's, Adams, J. A. (1960) explored the effectiveness of part-task and whole-task training methods for sequential skills involved in cockpit procedures. However, the motivation for decomposing training of a whole-task into several subroutines remained unclear. Later, Naylor & Briggs (1963) (reported in Utley & Astill, 2008; Coker, 2009) hypothesized that decision making for appropriate training format should take into consideration two inherent features of the task: the complexity which stands for the number of sub-components that composed the task, and consequently how demanding would be that task; and the organization of the task which refers to the degree of dependence between sub-components.

Conditions of practice that enable trainees to optimize their performance are considered to be paramount for the acquisition of motor skills. On the one hand, whole-task training is considered to be particularly appropriate for those motor skills that are not too complex and remain highly organized. Effectively, the breaking down of those motor skills into many part-task components for training purposes would be ineffective as the dynamics of the whole target skill would be altered. On the other hand, part-task training is believed to be particularly profitable for training complex motor skills that are composed of many independent sub-components. The effectiveness of part-task training to support the motor learning of complex motor skills such as those involved in medical and rehabilitation procedures have been widely discussed (Johnson et al., 2008; De Visser et al., 2011; Kolozsvari et al., 2011; Klein et al., 2012). However, simple skills for which whole-task training is usually employed might often appear relatively complicated for novices. Effectively, at the early stage of motor learning, even for simple skills, the task demand is important (Section 2.2.2.1), and whole-task training may often lead to unsuccessful development of motor skills as it does not allow isolating relevant task components and prevents error recognition (Utley & Astill, 2008; Coker, 2009). In that case, part-task training may have a strong motivational role as it enables reducing task demand. In contrast, an advanced performer might be bored by part-task training as it may not be challenging enough. Therefore, the level of expertise of performers should also be taken into consideration when designing a training experience to enhance motor learning (Utley & Astill, 2008; Coker, 2009).

In this thesis, the development of two independent discrete skills such as angle and force skills is being investigated. Those skills are relevant for the performance of fine grinding and polishing tasks for which whole-task training is traditionally carried out (Section 4.2). However, such training often appears too challenging for inexperienced workers (Section 4.2.2). It is believed that part-task training would contribute to enhance the training traditionally carried out (Section 4.2). Nonetheless, the implementation of such part-task training procedure in the real world may be troublesome. It is proposed that VR training would enable solving this issue.

This research work presents and evaluates a VR training system which aims to support motor learning through part-task and whole-task training.

2.3.2 Breakdown of skills

Wightman & Lintern (1985) (reported in Roessingh et al., 2002; Utley & Astill, 2008) defined three techniques to break down skills into part-task components: segmentation (Figure 4.a), fractionation (Figure 4.b) and simplification (Figure 4.c).

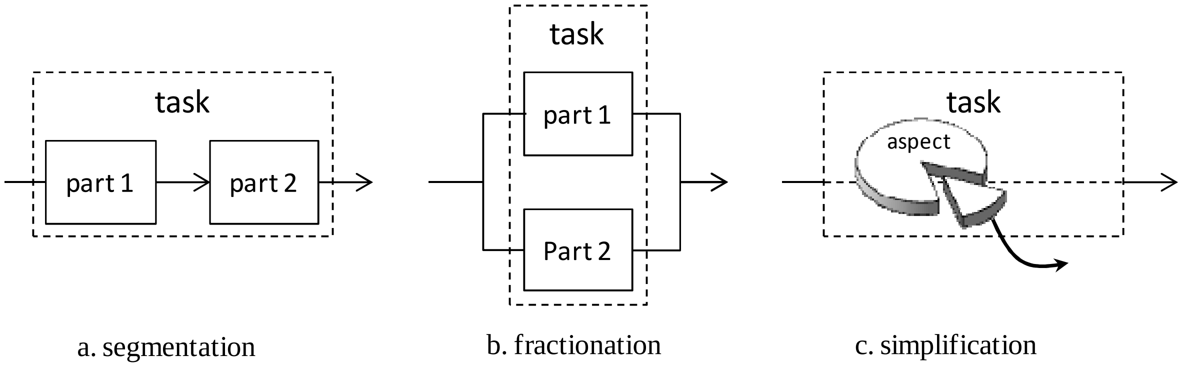

Figure 4. Three techniques for part-task training (segmentation and fractionation techniques appeared as proposed by Roessingh et al. (2002))

The segmentation technique (Figure 4.a) consists of separating serial skills into parts according to spatial or temporal considerations. For example, when learning to interpret a sequence of Morse code (Clawson et al., 2001), novices first trained on identifying the dot and hash pattern proper for each letter.

The fractionation technique (Figure 4.b) consists in separating skills that are usually executed simultaneously. For instance, motor skills involved in car driving are performed simultaneously. An advanced driver can easily perform several actions at a time. However, a novice driver may hardly be able to focus on handling the wheel, pressing the clutch pedal and simultaneously changing the gear. Therefore, the novice driver only focuses on handling the wheel whereas the instructor changes the gear using the shared control clutch. Nevertheless, the effectiveness of the fractionation technique is questionable for training rhythmic skills involving antagonist body limbs (Coker, 2009). For instance, Klapp et al. (1998) demonstrated that fractionation of practice to train a rhythmic bimanual coordination pattern resulted in a poor accuracy compared to whole-task training technique. They have investigated the effectiveness of fractioned part practice to train each hand on tapping a singular rhythm. Results revealed that trainees who received whole-task training were more accurate at performing the bimanual tapping compared to those who received part-task training.

The simplification technique (Figure 4.c) consists of acting on some characteristics of the task to decrease the level of difficulty and ease the performance. Coker (2009) proposed three ways to implement this part-task training technique: the modification of the equipment (i.e. using a lighter bat to ease the baseball swing), the reduction of the coordination requirements (i.e. training wheels on a bicycle assist the learner to maintain the balance) and the modification of the environment characteristics to make an open skill become more closed (i.e. training baseball batting of a ball placed on a tee-support). The reduction of coordination requirements often leads to provide physical assistance during the performance. Section 2.4.1 introduces several assistance concepts commonly used to enhance the practice and therefore the learning experience.

The achievement of complex maintenance procedures such as fine grinding and polishing tasks requires an accurate performance of force, angle and motion skills (Section 4.2). Those skills are performed simultaneously. In this thesis, part-task training inspired by the concepts of fractionation of angle and force skills and simplification of the motion pattern is believed to be profitable for the achievement of an efficient performance of fine grinding and polishing tasks. However, the dissociation of those concurrent motor skills in the real world may be complicated.

2.3.3 Integration scheme

Roessingh et al. (2002) and Coker (2009) highlighted three main schemes or methods of part-task integration that enable reconstructing the whole target task throughout the training process: the part-whole method (Figure 5.a), the progressive-part method (Figure 5.b) and the repetitive-part method (Figure 5.c).

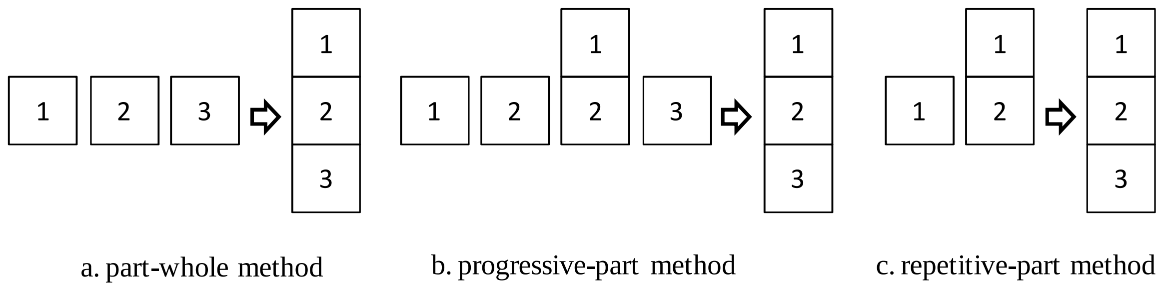

Figure 5. Schemes of integration of part-task components (all schemes are as proposed by Roessingh et al. (2002))

In the part-whole method (Figure 5.a), all part-tasks are practised separately. When a performer is proficient in all part-tasks, the whole target task is reconstructed from all part-task components so the whole target task can finally be practised. The part-whole method is appropriate for training those skills which are usually performed sequentially. For example, when training on heavy machinery manipulation as in an excavation task simulated in a virtual environment, operators usually practise separately essential sub-components of the task such as carrier positioning, trenching, and truck skills, and once all skills are consolidated, part-task components are combined in order to train the whole target task (So et al., 2012).

The progressive-part method (Figure 5.b) enables simplifying the task and provides a better understanding of the integration of part-task components. In the progressive-part method, the performer starts practising independently two part-tasks. When the skills are mastered, both part-tasks are combined and practised together. Once the performer becomes proficient, an additional part component is practised separately and subsequently integrated into the previous association so the performer can practise the new combination. This process lasts until the whole target task is completely reconstructed. The progressive-part method is appropriate for the practice of independent skills that are usually performed simultaneously. For example, in many occasions in ski learning, hip movement and knee flexion are often practised separately when the performer is stopped on the side of the ski track and then combined with other skills in order to be practised on the ski run.

The repetitive-part method (Figure 5.c) also provides a better understanding of the integration of part-task component. However, in contrast with the progressive-part method, the performer is not given the opportunity to practise each part-task independently. The performer only practises the first part-task component independently. When the skill is mastered, the performer integrates an additional part-task in order to practise them together.

This process continues until the whole task is fully reconstructed. The repetitive-part method is especially suitable when the practice of one part-task component is inseparable from the previous one. For instance, a novice piano player first practices with one hand, then incorporates the second hand in order to develop a bimanual coordination pattern and finally implements foot coordination to press the pedals.

Part-task training aims to support the acquisition of several independent skills. Nevertheless, combining those motor skills in order to be practiced as a whole is strongly recommended for an effective performance of the whole target task. In this thesis, the integration of angle, force and motion skills inspired by the progressive-part method is believed to be profitable to transfer those motor skills to the performance of a whole target task.

2.4 ASSISTING THE LEARNING EXPERIENCE

2.4.1 Physical guidance

Physical assistance during the performance of movement coordination patterns may be particularly beneficial for the learner. Schmidt & Wrisberg (2008) have referred to such assistance as physical guidance, a temporarily aid to the performance of movement coordination patterns that aims to enhance motor learning. Physical guidance is generally assumed to provide a clear view of the goals, increasing safety and minimizing fear of failing during the movement performance (Wulf et al., 1998b). Schmidt & Wrisberg (2008) have proposed two types of physical guidance: active and passive guidance.

Active guidance enables the proactive performance of movement coordination patterns but physically constraints erroneous movements. The active guidance paradigm is considered to support the proactive learning of movement coordination patterns. Wulf et al. (1998b) have demonstrated the effectiveness of training with active guidance on the performance of complex ski movements compared to training with no physical aid. They have presented a study which investigated the effect of active guidance on the learning of a slalom-like movement coordination pattern practised on a ski simulator. The active guidance consisted of two ski poles fixed to the floor, which aimed to aid novice performers to achieve body balance movements. Performances after training with and without active guidance were assessed. Results reported that training with active guidance led to significant improvements of body balance movement compared to the other training condition. Those results suggested that active guidance enhances motor learning by facilitating the exploration of the movement workspace proposed by Newell (1991). On the other hand, the passive guidance literally guides the movement through correct performance. With the passive guidance, the learner assumes a passive control of the movement preventing him/her to make errors. Hornby et al. (2008) showed interest in employing passive physical guidance during gait training for rehabilitation purposes. In their study, the passive guidance provided assistance to stroke patients by continuously tutoring lower limbs towards correct gait performance.

However, several researches have demonstrated that both active and passive physical guidance when provided too frequently tended to alter the process of motor learning by making the learner becoming dependent on it. Winstein et al. (1994) have shown that active guidance when provided too frequently while training a lever placement task prevented a learner from constructing an accurate representation of movement coordination patterns in order to be stored in GMP (Section 2.2.1.2). The authors have presented experimental results which suggested that training with frequent active guidance did not lead to significantly accurate performance recall once physical assistance was withdrawn. In contrast, when the active guidance was faded, which means frequently provided at the early stage of learning and gradually withdrawn in the course of the training, recall performance was significantly more accurate. In a more recent study, Hornby et al. (2008) have drawn similar conclusions concerning passive guidance. In their study, the authors looked at the effectiveness of gait training with passive guidance when provided continuously and as-needed. Their results suggested that passive assistance when provided as-needed was more effective. Subsequently, the authors pointed out some drawbacks of passive guidance previously highlighted by Schmidt & Wrisberg (2008): (1) it tended to change the nature of the movement as several degrees of freedom remained constrained during the training and not during the performance recall; (2) it minimized the involvement of the performer; and (3) did not promote error recognition and correction. Hence, Hornby et al. (2008) have suggested gradually withdrawing passive guidance in the course of training in order to enable proactive learning and error correction mechanisms. Conclusions from this study are in agreement with those formulated by Crespo & Reinkensmeyer (2008). In their study, they have investigated the effectiveness of such physical guidance in a steering task. Results showed that learning occurs better when the assistance allows increasingly challenging learners in order to enable them to perform the task on their own.

Physical guidance has been extensively employed to support motor learning in VR (Feygin et al., 2002; Srimathveeravalli & Thenkurussi, 2005; Yang et al., 2008). Criticism mentioned about the dependence trend in such physical assistance can also be applied to the context of motor learning in VR (Liu et al., 2005).

In the context of this thesis, physical active guidance when provided in virtual environments in the form of composite forces supplied through a haptic device which drives back the performance towards the correctness is rather considered as a type of concurrent augmented feedback as it is only provided once performance becomes erroneous (Section 3.1.2). Section 2.4.2 provides a description of augmented feedback. Moreover, physical active guidance can be considered as a prescriptive feedback of performance as it provides a solution to committed errors. In contrast, physical passive guidance is a purely assistive technique which brings the performance closer to the concept of demonstration.

2.4.2 Information feedback

Researchers agree that information feedback is a paramount factor for training to support the development of motor skills (Magill, 2007; Schmidt & Wrisberg, 2008; Utley & Astill, 2008). Feedback refers to the sensory information that states the outcome of a movement performance or the causes of that outcome to the performer. Two categories of feedback are distinguished: intrinsic and extrinsic feedback.

The intrinsic feedback, sometimes called sensory feedback (Utley & Astill, 2008) or inherent feedback (Schmidt & Wrisberg, 2008) refers to the perceptual sensory information that naturally arises from the performance of a movement. Intrinsic feedback can be exteroceptive in which case the information comes from sources located outside the body, or interoceptive, also referred as proprioceptive, in which case the information comes from sources located inside the body primarily based on kinesthetic and vestibular information cues.

The extrinsic feedback, commonly referred as augmented feedback (Newell, 1991; Magill, 2007; Schmidt & Wrisberg, 2008; Utley & Astill, 2008) provides task-dependent information related to movement performance that supplements the available intrinsic information feedback by adding an external source of information. Augmented feedback, for example in the form of comments from an instructor, indications of performance scores and movement characteristics, and recorded performance in videotape format, is considered as an important component of motor skill training (Utley & Astill, 2008).

Augmented feedback can be used to positively reinforce correct performance in order to encourage accurate performance rehearsal. It can also directly or indirectly provide error correction information enabling performers to minimize errors and therefore enables bringing movement performance closer to the objective of the action. Augmented feedback can be either prescriptive, which means that the information describes committed errors and specifies a way to solve them, or descriptive in which case the information provides only a description of errors produced during the performance (Schmidt & Wrisberg, 2008). Prescriptive augmented feedback is considered to be very useful at the early stage of learning, until the learner acquires the capability to interpret descriptive feedback (Schmidt & Wrisberg, 2008). Moreover, augmented feedback is usually believed to play an important motivational role in the process of motor learning. Motivation is usually considered as an important organismic constraint (Section 2.2.2.3), which energizes the learner to strive for the achievement of action's goals (Young et al., 2001; Schmidt & Wrisberg, 2008; Utley & Astill, 2008).

Augmented feedback can be concurrent, which means that it is provided during the performance of the movement, or terminal, in which case it is provided once the movement is finished. Two types of terminal augmented feedback are typically distinguished: knowledge of results (KR) and knowledge of performance (KP) (Magill, 2007; Schmidt & Wrisberg, 2008; Utley & Astill, 2008). Differences between both types remain in the nature of the information conveyed to the performer. KR provides information about movement outcome or goal achievement after the completion of the movement (Schmidt & Wrisberg, 2008). For example, an instructor may inform a performer after the practice of an industrial maintenance task that the outcome of the performance is either appropriate or not. KR is considered to be particularly helpful when part of the intrinsic feedback is not available or too weak. However, sometimes KR can be redundant and augment intrinsic feedback providing sensory information already perceived. In contrast, KP provides prescriptive or descriptive information about kinematic characteristics of the movement that lead to a specific performance outcome (Schmidt & Wrisberg, 2008). For instance, an instructor may inform an operator after the completion of a polishing task that *"the inclination of the tool was too little"* (descriptive) and eventually include advices to facilitate error correction, such as the way the tool should be grasped to ease refinements of inclination (prescriptive). KP often leads to quicker achievement of objectives due to error correction information and it is considered particularly useful for learning serial skills composed of complex movements on several degrees of freedom (Mononen, 2007; Utley & Astill, 2008).

KP has been traditionally employed as terminal augmented feedback (Magill, 2007; Schmidt & Wrisberg, 2008; Utley & Astill, 2008) and several studies have extended the concept of providing prescriptive or descriptive augmented feedback in the form of concurrent KP (Konttinen et al., 2004; Mononen, 2007). In a recent study (Ranganathan & Newell, 2009), concurrent KP has been presented in the form of a vertical bar which showed in real-time about the exerted force with regards to a target force. In this thesis, a similar concept of augmented feedback will be used to inform about applied angle and force throughout part-task training (Chapter 5). Moreover, motor skill training in VR is believed to enable approximating the concept of KR to concurrent augmented feedback.

Several studies have highlighted the asset of training with augmented feedback as it enables guiding towards the correct performance of motor skills through practice (Todorov et al., 1997; Young et al., 2001; for review see Wulf & Shea, 2004). However, it is believed that augmented feedback when provided too frequently during practice tends to generate dependence which impedes the processing of intrinsic information feedback (Salmoni et al., 1984). Therefore, performers do not attempt to develop the capability to produce a movement on their own, and performance results tend to worsen when augmented feedback is withdrawn (Schmidt & Wrisberg, 2008). This has been commonly referred as the guidance hypothesis of augmented feedback (Salmoni et al., 1984; Schmidt & Wulf, 1997; Wulf & Shea, 2004; Schmidt & Wrisberg, 2008). For this reason, many studies have proposed scheduling augmented feedback throughout the practice period (Winstein & Schmidt, 1990; Wulf et al., 1998a; Mononen, 2007; Ranganathan & Newell, 2009). Nonetheless, the guidance hypothesis of augmented feedback is a controversial topic. Findings from these research studies have suggested that the effect of training motor skills with augmented feedback is more complex than what it seems (Wulf & Shea, 2004).

A study conducted by Winstein & Schmidt (1990) investigated the effect of frequency of terminal KR to support motor learning of a lever placement task which involved movements on one degree of freedom. The authors compared the effectiveness of training with faded terminal KR which consists of providing frequent terminal KR at early stage of learning and gradually reducing it throughout the training, and frequent terminal KR. Their results showed that training with faded KR led to significantly more accurate performance recall when compared to that with frequent KR. These findings suggested that exposure to such augmented feedback without withdrawing it throughout the learning process may have a detrimental effect on performance and thus confirmed the guidance hypothesis. In contrast, a study proposed by Wulf et al. (1998a) have not found any benefits for providing faded KR to novice participants during the training of complex task such as a slalom-like movements on a ski simulator. The authors compared the effect of providing frequent terminal KR and faded terminal KR equivalent to providing feedback after the completion of every two trials. A control group practising without augmented feedback was also considered in that experiment. Results highlighted undoubtedly the effectiveness of training with augmented feedback to support motor learning. However, faded KR did not lead to higher performance improvements when compared to the frequent KR condition. Similarly, Mononen (2007) explored the benefits of training novices on a precision rifle shooting task with all augmented feedback. The shooting task encompasses fine motor skills of a particular complexity as it required a high degree of eye-hand-arm coordination. In that study, the author looked at the effect of frequent and reduced exposure to terminal KP along with frequent terminal KR on motor learning. As in the study of Wulf et al. (1998a), results suggested a significant effect of augmented feedback on the acquisition of motor skills. However, no significant differences were found between both KP conditions.

The findings from these studies suggested that the complexity of the task in terms of the number of degrees of freedom involved in the performance of the skills are determinant for the effectiveness of training enhanced with augmented feedback. Apparently, more frequent augmented feedback seems to be required for the learning of complex motor skills (Schmidt & Wrisberg, 2008). Although the performance of a lever placement task as that proposed by Winstein & Schmidt (1990) appeared to be relatively complicated, it only required movements on a single degree of freedom. In that sense, task complexity was minimum compared to those proposed by Wulf et al. (1998a) and Mononen (2007).

Although the guidance hypothesis of KR and KP is questionable (Wulf & Shea, 2004), Schmidt & Wulf (1997) highlighted the strong dependence trend inherent to concurrent augmented feedback when provided too frequently throughout training. In their study, Schmidt & Wulf (1997) investigated the effect of training a lever placement task with continuous concurrent feedback. Their results showed that performance dropped down once concurrent feedback was withdrawn. Continuous concurrent feedback tended to restrict motor learning to the extent that it hinders the processing of intrinsic feedback for the development of an accurate representation of the movement coordination pattern stored in motor programs

(Section 2.2.1.2). In a more recent study, Ranganathan & Newell (2009) have demonstrated that frequent concurrent KP was effective to support acquisition of motor skills throughout training, but resulted to be detrimental for task performance once it was withdrawn. The authors looked at the effectiveness of several augmented feedback conditions to support learning of a discrete force task which implicated movements on two degrees of freedom. Results showed that motor learning was significantly lower when training was enhanced with frequent concurrent feedback when compared to reduced and frequent terminal feedback conditions. These findings confirmed the strong guidance property of concurrent augmented feedback. On the other hand, Konttinen et al. (2004) and Mononen (2007) have shown the effectiveness of reduced exposure to concurrent augmented feedback to support learning of a rifle shooting task. The authors compared the effect of practice with concurrent auditory KP scheduled on half of training trials and with terminal KR. Their results showed that concurrent auditory KP when provided in reduced frequency led to significant performance improvements compared to terminal KR. These findings suggest that concurrent augmented feedback when provided in a reduced frequency may be an appropriate solution to the guidance hypothesis.

In this thesis, a VR training system to train some of the motor skills that are relevant in fine grinding and polishing tasks will be evaluated (Chapters 6 & 7). The suggested training will follow a training program which will enable scheduling concurrent KR and KP and terminal KR throughout part-task training, and concurrent and terminal KR throughout whole-task training.

2.5 CONCLUSION

In this chapter, several relevant concepts for the acquisition of motor skills have been reviewed. For the sake of providing an explicit definition of motor skill terminologies, a review of most common classifications of motor skills has first been conducted. Second, typical theorical approaches which define motor learning as an internal process associated to practice giving emphasis to the gradual consolidation and automatization of motor skills have been described. Third, emphasis has been given to the design of the training experience introducing two fundamental training methods: part-task & whole-task training. Proper combinations of these training methods are believed to be particularly profitable to enhance training of motor skills involved in the performance of fine grinding and polishing tasks.

Finally, relevant assistance techniques such as physical guidance and augmented feedback to support motor learning throughout training have been approached. A literature review has enabled focusing on the limitations of these techniques. Previous research studies have demonstrated that both techniques are beneficial for motor learning to the extent that they enable guiding the practice of motor skills towards correctness. However, when provided too frequently, performers tend to become dependent to them. Thus, too frequent exposure to these techniques may prevent the processing of intrinsic information feedback required for the development of accurate motor programs. For this reason, physical guidance and augmented feedback are recommended to be frequently provided at the early stage of learning, but gradually withdrawn once performance gains in proficiency.

In this thesis, a VR training system enhanced with haptic force feedback will be presented along with a training toolkit which will enable building training programs to support the development of fine motor skills that are relevant in fine grinding and polishing tasks (Chapter 5). A training program will be designed for the evaluation of the VR training system (Chapters 6 & 7). That training program will allow applying fundamental training methods such as part-task and whole-task training to the context of VR training. On the one hand, part-task training will be inspired by fractionation of angle and force skills and simplification of the motion pattern at early stage of learning (Section 2.3.2). The integration of part-task components will be based on the progressive-part method (Section 2.3.3). On the other hand, whole-task training will allow performing the suggested tasks as in the real world. Moreover, both training methods will be enhanced with concurrent and terminal augmented feedback.

Chapter 3. Motor Skill Training in Virtual Reality with Haptics

The potential of VR technologies to support learning and training in educational (Bossard et al., 2008), industrial (Mujber et al., 2004) and clinical fields (Van der Meijden & Schijven, 2009; Coles et al., 2011) has been widely investigated. VR can provide support to fundamental training methods such as part-task and whole-task training (Section 2.3), demonstrating effective motor learning and transfer to real operational environments. VR also offers the possibility to enhance motor learning with augmented feedback (Section 2.4.2) which is often not available in the real world. Moreover, VR technologies such as haptic devices which are able to provide force feedback on several degrees of freedom enable interacting within virtual environments alike in real physical contexts.

This chapter describes the research background for the use of VR and haptic force feedback to support the development of a VR training system which aims to train and transfer angle and force skills to the performance of fine grinding and polishing tasks in real operating environments. Figure 6 presents the components that are relevant to motor skill training in VR.

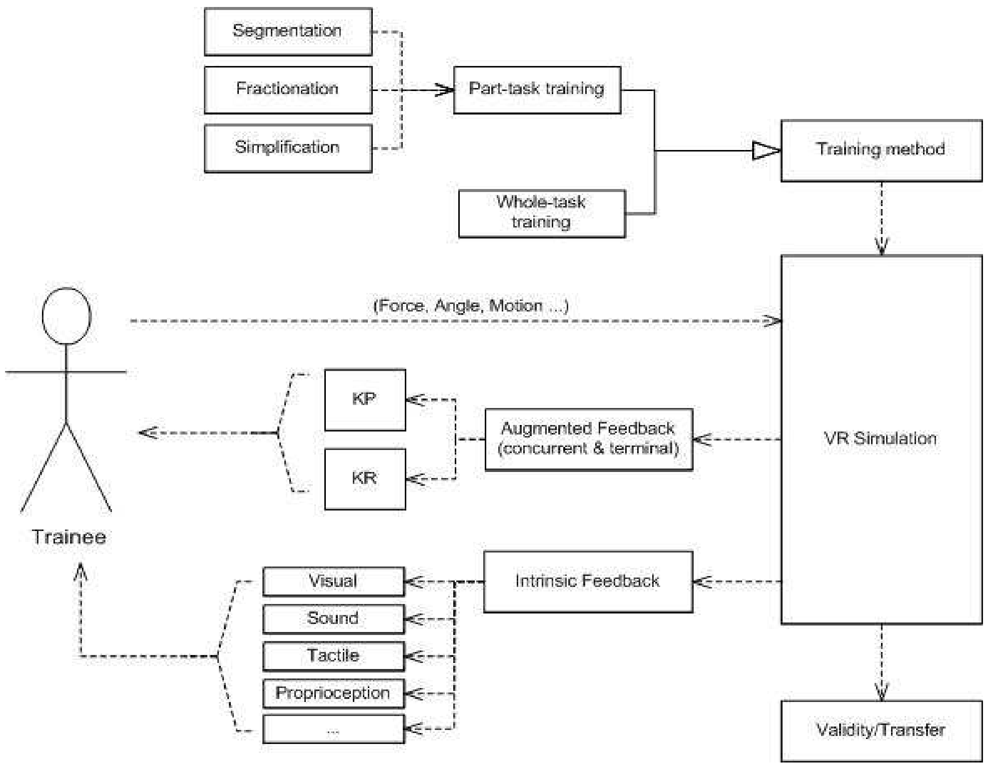

Figure 6. Diagram of components that are relevant to motor skill training in VR.

This chapter presents a literature review of:

1. The current state of motor skill training in VR giving emphasis to the effect of haptic force feedback to improve interaction within virtual environments (Section 3.1).
2. The application of relevant concepts employed in conventional motor skill training such as fundamental training methods (Section 3.2) and augmented feedback (Section 3.3), to the context of VR training.
3. The validity of transferring motor skills from virtual to real environments (Section 3.4).

3.1 HAPTICS: INTRINSIC FEEDBACK VS. AUGMENTED FEEDBACK

Although many VR simulators, especially those dedicated to motor skill training for clinical procedures, are devoid of haptic force feedback, significant training effect (Bajka et al., 2009; Selvander & Åsman, 2012) and effective transfer of skills to operating room contexts (Jordan et al., 2001; Ahlberg et al., 2002; Seymour et al., 2002) have been demonstrated. However, the absence of haptic force feedback has been often considered as a drawback in VR training simulations (Verdaasdonk et al., 2006; Bajka et al., 2009). The addition of haptic force feedback is believed to be profitable to the extent that it enables reducing the need of conventional training on patients, improving motor skills competence and enabling effective transfer of motor skills to real world situations (Van der Meijden & Schijven, 2009; Coles et al., 2011). However, the use of haptic technologies for training technical motor skills such as those required in industrial procedures has not been yet generalized and remains for the moment, commercially unsuccessful. Nonetheless, according to Abate et al. (2009), industries show an increasing interest in employing computer-aided solutions to sustain competitively their activities and the addition of haptic force feedback is believed to be relevant for training procedures that require human intervention such as highly skilled maintenance operations.

On the one hand, haptic force feedback is considered to bring the concept of VR interaction closer to realistic physical models supplying intrinsic information that cannot be provided otherwise (Abate et al, 2009; Aziz & Mousavi, 2009; Dalto et al., 2010). On the other hand, haptic force feedback allows improving motor learning through VR training proposing augmented feedback (Section 2.4.1) in the form of an assistance technique (Wang, Y. et al., 2006; Srimathveeravalli et al., 2007; Hassan & Yoon, 2010a).

3.1.1 The role of haptics as intrinsic feedback

Despite a growing interest for the use haptic force feedback in VR simulations since the beginning of the last decade, few research studies have compared the effectiveness of VR training with and without haptic force feedback (Basdogan et al., 2004; Van der Meijden & Schijven, 2009). In this thesis, VR training enhanced with haptic force feedback is believed to be profitable for motor learning enabling the development of novel motor programs (Section 2.2.1).

Moody et al. (2001) demonstrated that the addition of haptic force feedback while training suturing tasks in a virtual environment led to significant performance and accuracy improvements in task completion time and exerted forces on tissues.

Tholey et al. (2005) analyzed the effect of providing haptic force feedback in a palpation task performed in robotic assisted surgery (RAS) procedures which usually lack haptic intrinsic information. Additional force feedback was found to positively affect task performance at all levels of expertise providing intrinsic information that was essential for accurate characterization of tissue stiffness. Similarly, Wagner et al. (2002; 2007) have shown how the performance of a RAS dissection task for which applied forces are relevant, is improved when haptic intrinsic information was provided through a haptic device. In concurrence with Tholey et al. (2005), the addition of haptic force feedback was shown to significantly improve the accuracy of applied forces and decrease committed errors at all stages of motor learning (Wagner et al., 2007). Nonetheless, haptic force feedback appeared to be particularly profitable at an early learning stage. Several research studies (Ström et al., 2006; Zhou et al., 2012) have supported similar statements showing that haptic force feedback enabled moving performance further on the learning curve at early learning stage.

Panait et al. (2009) remarked that the effectiveness of haptic force feedback is dependent on the nature of the task. In their study, they investigated the effect of providing haptic force feedback on the performance of manipulation and force-based tasks throughout VR training. No significant training effect of haptic force feedback task was found on a basic manipulation task. However, performance of a force-based task appeared to be significantly improved by haptic force feedback. These findings suggest that haptic force feedback is particularly beneficial for training force control-based tasks.

The realism issue of haptic force feedback has been approached through several research studies. Realistic haptic force feedback is considered to provide important intrinsic information that could not be emulated otherwise. Haptic force feedback has been shown to increase the overall realism of VR simulations and is crucial for an effective practice of force-based skills (Moody et al., 2001; Zhang et al., 2009; De Visser et al., 2011; Zhou et al., 2012). However, there is very little knowledge concerning the degree to which the realism of haptic force feedback supports effective motor learning (Van der Meijden & Schijven, 2009). Several studies have pointed out that the lack of realism of haptic interaction in VR training could hamper the development of motor skills (Adams, J. R. et al., 2001; Zhang et al., 2009; Muresan III et al., 2010). Adams, J. R. et al. (2001) investigated the effect of haptic interaction in VR training on an assembly task. They found that a low degree of realism of the haptic interaction was a factor for a weak motor learning. In more recent studies, Zhang et al. (2009) and Muresan III et al. (2010) reported that the lack of realism of haptic interaction in VR training with regards to conventional training techniques was critical for the effectiveness of motor learning in VR.

Haptic force feedback has been shown to positively affect the performance of motor coordination and more particularly force control-based tasks at all levels of expertise. Thus, haptic force feedback enables the development of novel motor programs and also allows generalizing existing motor programs with haptic intrinsic information. Moreover, haptic force feedback has been shown to be particularly profitable at an early learning stage supporting effectively motor learning for force control-based tasks. However, the effectiveness of VR training has been argued to strongly depend on the degree of realism of haptic interaction. Nonetheless, the degree of realism of haptic interaction required to ensure effective VR training is relatively hard to determine.

This work will present a VR training system enhanced with haptic force feedback which aims to support the successful development of angle and force skills required in the performance of fine grinding and polishing tasks (Chapter 5). The effectiveness of such system to provide realistic haptic intrinsic information will be highlighted among other things through the collection of qualitative data in the experimental study described in chapter 7.

3.1.2 The role of haptics as augmented feedback

Apart from simulating intrinsic information as perceived in the real world, haptic force feedback has also been extensively employed in VR training to provide augmented feedback in the form of an active physical guidance that aids to the performance of complex tasks for which motor coordination in term of position and orientation, and force control are important. For instance, Solis et al. (2002, 2003), Eid et al. (2007), Šustr (2010) and Nishino et al. (2011) presented several implementations of haptic-based guidance that provide a correcting force which rectifies the user’s movement and actively support the development of motor coordination patterns for the handwriting of calligraphy characters. Basdogan et al. (2004) proposed a model of active haptic guidance for a needle insertion procedure. They emulated the force produced by an instructor’s hand correcting needle position mismatches. Morris et al. (2006) presented a haptic physical assistance technique that enables providing adjustment of exerted forces in bone drilling operations. Wang, Y. et al. (2006, 2009) presented a haptic arc welding training method that provides an active haptic guidance to emulate human tutoring on welding distance, speed and electrode position along a predefined trajectory. Gutiérrez et al. (2010) have developed a VR multimodal training system to practice fine motor skills involved in delicate manipulation tasks, which proposed among other things, a haptic-based guidance that provides force constraints to attract or repel an individual’s hand towards a target area.

In the context of this thesis, active haptic guidance is considered as an instantaneous and prescriptive augmented feedback equivalent to concurrent Knowledge of Performance

(KP) (Section 2.4.2). It supports proactive motor learning and physically steers movement performance towards correctness when it becomes erroneous.

Several research studies have investigated the value of such haptic augmented feedback to support effective motor learning for force control and motor coordination-based tasks. Morris et al. (2007) have demonstrated that active haptic guidance in the form of a correcting force of opposite direction enabled effective learning of vertical force patterns while being passively guided along a horizontal trajectory in a proactive manner. However, several research studies have reported the complexity of interpreting active haptic assistance at an early learning stage (Saga et al., 2005; Srimathveeravalli & Thenkurussi, 2005; Esen et al., 2008a; Esen et al., 2008b). Esen et al. (2008a, 2008b) have designed an active haptic assistance paradigm in the form of a correcting force provided by a human instructor in order to learn force patterns of similar complexity as those proposed by Morris et al. (2007). Saga et al. (2005) and Srimathveeravalli & Thenkurussi (2005) have presented two VR training systems that support learning of handwriting of calligraphic characters using active haptic guidance on the performance of character shape and exerted pencil pressure. Both studies found that active haptic assistance led to high accuracy in path tracing but low efficiency to recall force patterns. These findings suggest that when the task demand is high, for example when motion is actively engaged, active haptic guidance is not sufficient to support the learning of forces.

Avizzano et al. (2002) and Rodriguez et al. (2010) have demonstrated that the addition of active haptic guidance for training respectively bi-dimensional and tri-dimensional path tracing produce significant performance improvements compared to more conventional training assistance based on visual cues. However, Yang et al. (2008) found that active haptic guidance tended to discourage proactive error correction, and therefore hampered motor learning. Similarly, Liu et al. (2005) have given emphasis to the outcome of the dependence trend of the physical assistance technique in the form of a rapid deterioration of tri-dimensional trajectory performance when active haptic guidance is withdrawn. For this reason, haptic augmented feedback should be provided differently in order to encourage proactive motor learning. However, there is currently no clear compromise concerning an effective way of providing haptic augmented feedback throughout VR training. Rodriguez et al. (2010) compared the effectiveness of active haptic assistance provided continuously and systematically when error rate became too high, to support tri-dimensional trajectories learning, but did not find any significant differences. Similarly, Li et al. (2009) proposed a gradual withdrawing of active haptic guidance in the course of VR training in order to support the performance of a placement task (O'Malley et al., 2006). However, no higher motor learning has been observed compared to non-assisted practice.

Several research studies have discussed the value of active haptic guidance to support motor learning in motor coordination and force control-based tasks. However, no clear consensus has been apparently found concerning an effective provision of active haptic assistance.

As mentioned previously, this work aims to develop and evaluate a VR training system to train angle and force skills required for the performance of fine grinding and polishing tasks. Nonetheless, considering the lack of effectiveness of active haptic guidance to support force skill learning when motion is engaged, and the absence of consensus to effectively provide haptic assistance, the implementation of such haptic augmented feedback is discarded.

3.2 PART-TASK TRAINING VS. WHOLE-TASK TRAINING

Conventional training based on the whole-task training method is often too challenging for the development of novel clinical and technical motor skills (Section 2.3). Moreover, such training is often conducted in conditions in which the safety of patients or operators is compromised. For this reason, despite the importance of repetitive tasking is paramount for motor learning, it remains delicate. Furthermore, prior to whole-task practice, clinical motor skills are frequently isolated in a part-task training procedure (Section 2.3) in order to be practised separately throughout basic exercises carried out on physical training workbenches, which contain inanimate objects and lack the feel and the dynamics of handling real tissues (Fried, G. M. et al., 2004; Ritter & Scott, 2007; Pan et al., 2011). Such training workbenches are usually referred to as part-task trainers (Youngblood et al., 2005) and remain critical with regards to the objective assessment of performance metrics (Pan et al., 2011).

VR training improved with haptic force feedback is believed to efficiently support part-task and whole-task training procedures offering the possibility of repetitive and safe tasking conducted in realistic simulated environments with variable degrees of complexity (Bossard et al., 2008; Johannesson et al., 2010; Mishra et al., 2010; Pan et al., 2011; Bhatti et al., 2012). Moreover, VR training enables objective measures of performance and accuracy for real-time and terminal evaluation (Haque & Srinivasan, 2006; Van der Meijden & Schijven, 2009; Pan et al., 2011; Rhienmora et al., 2011). Performance and accuracy assessment can be provided in the form of augmented feedback (Section 3.3) which aims to support motor learning during and after VR tasking (Gopher, 2012).

Several developments have supported motor learning for the performance of educational, medical and industrial procedures by applying fundamental training methods such as part-task and whole-task training to the context of VR (Basdogan et al., 2004; Morris et al., 2006; Abate et al., 2009; Wang, Y. et al., 2009; Gutiérrez et al., 2010; Nishino et al., 2011; Sung et al., 2011). Table 2 presents a review of the current state of the art of training methods and augmented feedback employed in VR training to support motor learning in dentistry, educational, industrial and medical fields. The importance of augmented feedback in VR training will be argued in section 3.3.

As it will be discussed later, this thesis presents a VR training system which enables applying fundamental training methods such as part-task and whole-task training along with the provision of augmented feedback in order to support the development of those motor skills that are required in specific industrial maintenance tasks.

Table 2. Current status of motor skill training in VR.

Task	**Training Method**	**Integration method to whole-task**	**Practiced skills**	**Augmented Feedback**	**Study purpose**	**Conclusion**	**Authors**
Dentistry task	Whole-task Training		Perceptual force skills		Assess of the realism of the VR training simulator.	Realistic simulation of periodontal task but some limitations in the collision model of the 3 DOF haptic interaction were found. Thus, a 6 DOF haptic interface would be required.	Steinberg et al. (2007)
Dentistry task: access opening	Whole-task Training		Motor coordination (position, orientation) & force control skills	Terminal KR	Evaluate the effectiveness of the repetitive practice of an access opening dental task throughout VR training.	VR training leads to significantly shorten completion time and lead to significant force refinements.	Suebnukarn et al. (2010)
Dentistry task: teeth drilling in crown preparation procedure	Whole-task Training		Motor coordination (position, orientation) & force control skills	Terminal KP & KR	Evaluate the accuracy of the VR training system to assess skills involved in a crown preparation procedure. Performance from expert dentists and novices was compared.	The VR training system enables discriminating different level of expertise. Also, the system has demonstrated a high degree of acceptance from experts	Rhienmora et al. (2011)
Educational task: assembly of 3D LEGO plane	Whole-task Training		Motor coordination (position, orientation)		Present a VR training simulation for assembly task and assessment of the value of force feedback in assembly	VR training with haptics enables the early formation of mental model of assembly task	Adams, J. R. et al. (2001)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Educational task: assembly of 3D pieces	Whole-task Training		Motor coordination (position, orientation)		Compare of the effectiveness of VR training with conventional training to transfer skills involved in a 3D puzzle assembly task to real world context	VR training effectively supports transfer of assembly skills to the real world. VR training substantially improve task performance in the real world much better that conventional training.	Oren et al. (2012)
Educational task: handwriting task: Japanese calligraphy	Part-task Training (Simplification)		Positional skills	Concurrent KP (KP + Active guidance)	Present and evaluate the effectiveness of a Japanese handwriting teaching system (Solis et al., 2002) to satisfy motor learning throughout the cognitive and associative stages.	The implementation of visuohaptic information in the system enables to significantly decrease task completion time and performance.	Solis et al. (2003)
Educational task: handwriting task	Part-task Training (Simplification)		Positional & force control skills	Concurrent KP (Active guidance)	Present and assess of a haptic teaching system to assist the performance of handwriting character shape and pencil pressure.	High accuracy in path tracing but low efficiency to recall pressure patterns.	Saga et al. (2005)
Educational task: handwriting task: Chinese calligraphy	Part-task Training (Simplification)		Positional & force control skills	Concurrent KP (Active guidance)	Present a Chinese calligraphy VR training system	The training system is helpful to reduce handwriting error and to improve writing speed.	Wang, D. et al. (2006)
Educational task: handwriting task: multi-language calligraphy	Part-task Training (Simplification)	Repetitive-part	Positional skills	Concurrent KP (Active guidance)	present and assess a handwriting learning and evaluation tool which proposes task simplification through 3 modes of guidance (none, partial & full) to support motor learning(Mansour et al., 2007), to transfer handwriting skills	The system enables transferring handwriting skills to the performance of a writing task on a sheet of paper.	Eid et al. (2007)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Educational task: handwriting task: artistic calligraphy	Part-task Training (Simplification)		Motor coordination (position, orientation) & force control skills		Present a simulation of calligraphic creation called Haptic Calligraphy	No experimental study - development with no aim of training (only for artistic performance)	Šustr (2010)
Educational task: handwriting task: Japanese calligraphy	Part-task Training (Simplification)	Repetitive-part	Motor coordination (position, orientation) & force control skills	Concurrent KP (Active guidance)	Assess the realism of a haptic-based system for learning handwriting of calligraphic characters and explore the effectiveness of passive & active haptic guidance to support motor learning.	The system provide realistic simulation of handwriting task and both guidance techniques led to improvements of writing speed although passive guidance was more effective.	Nishino et al. (2011)
Industrial task: arc Welding Task	Part-task Training (Simplification)		Motor coordination (position, orientation) & force control skills	Concurrent KP (KP + Active guidance)	Present a part-task training method to practice arc welding using realistic haptic force feedback to simulate the interaction of a welding electrode on a metal workpiece in a virtual environment.	No experimental results have been provided.	Wang, Y. et al. (2006, 2009)
Industrial task: assembly of peg on wooden table	Part-task Training (Simplification)		Motor coordination skills (position) for placement task		Present a bi-manual Mixed Reality assembly training system enhanced with passive haptic guidance, and conduct a usability test.	Passive haptic guidance was an efficient technique to support placement in assembly procedure	Ott et al. (2007)
Industrial task: assembly for maintenance of aircrafts	Part-task Training (Simplification)		Motor coordination (position, orientation) for assembly		Present a VR training system to approach path planning and in assembly/disassembly of mechanics in aircraft maintenance procedures.	No experimental results on training have been provided.	Hassan & Yoon, (2010a, 2010b)

Task	**Training Method**	**Integration method to whole-task**	**Practiced skills**	**Augmented Feedback**	**Study purpose**	**Conclusion**	**Authors**
Industrial task: assembly/disassembly for maintenance and repairing task in aerospace industry	Whole-task Training		Motor coordination (position, orientation)		Present a visuo-haptic VR system used to carry out among others, simulations of assembly, disassembly and repairing tasks during maintenance operations targeted to the aircraft industry.	No experimental results on training have been provided.	Abate et al. (2009) & Nappi et al. (2009)
Industrial task: assembly task in mechanical car industry	Part-task Training (Simplification)	Repetitive-part	procedural motor coordination skills (position, orientation)	Terminal KR	Present an interactive training system (Bhatti et al., 2008) to support learning of assembly sequences. VR training occurs through an integration of simplified part-task which included various degrees of difficulties to whole-task. A user evaluation test was carried out	The VR training system was user-friendly and realistic.	Bhatti et al. (2009)
Industrial task: assembly in industrial maintenance operations	Part-task Training (Simplification)	Repetitive-part (Rodriguez et al., 2010)	Procedural, bimanual motor coordination (position, orientation) & force control skills for assembly	Concurrent KP (Active guidance)	Present a VR training system that aim to support transfer of procedural, fine motor skills and bi-manual coordination skills that are relevant for assembly and maintenance operations.	No experimental results on training have been provided.	Gutiérrez et al. (2010)
Industrial task: assembly for maintenance tasks of nuclear reactor	Whole-task Training		Motor coordination (position, orientation) for assembly		Present a VR simulator for procedures training in complex manufacturing tasks as those performed during the remote handling maintenance of the ITER	No experimental results on training have been provided.	Hermskerk et al. (2011)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Industrial task: assembly for maintenance of aircraft engines	Part-task Training (Simplification)		Motor coordination (position, orientation) for assembly	Concurrent KP (Active guidance)	Present a VR system which aimed to train on engines assembly for maintenance procedures. Engine components motion was supported by active haptic guidance.	No experimental results have been provided.	Lu et al. (2012)
Industrial task: electronic component soldering	Whole-task Training		Motor coordination (position, orientation) & force control skills		Present a preliminary development of a VR training system to practice soldering skills.	No experimental results on training have been provided.	Sung et al. (2011)
Industrial task: forklift driving	Whole-task Training		Motor coordination skills (position, orientation) for handling task		Present and evaluate a VR haptic-based system for training non-motorized forklift driving.	Forklift driven with haptics was a realistic interaction paradigm compared to joystick driving.	Martin et al. (2012)
Industrial task: polishing and grinding task	Part-task Training (Simplification)		Force control skills	Concurrent KP & Concurrent KR	Present a VR training system for machine operators performing polishing and grinding tasks, and explore the effect of path constraint on applied force.	Applied forces were more stable when path relief was more constant.	Balijepalli & Kesavadas (2003)
Industrial task: metal machining (grinding, cutting, pressing, milling….)	Whole-task Training		Force control skills		Present the Virtual Technical Trainer (Mellet-d'Huart et al., 2004) using haptic and pseudo haptic feedback for training milling techniques (process of grinding, cutting, pressing, or crushing in a mill).	The force feedback was well appreciated at early stage of learning. However, the grasping of the haptic device was not satisfactory	Crison et al. (2004)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Industrial task: turning machining operation (cutting-grinding)	Whole-task Training		Force control skills		Present a VR system to practice turning operation.	No experimental results have been provided.	He & Chen (2006)
Medical task: palpation task in cardiovascular surgery	Whole-task Training		Perceptual force control skills		Present a haptic simulator for learning palpation of aorta in cardiovascular surgery and test the value of the system for stiffness recognition	The VR system was perceived as realistic as Haptic interface enabled applied force close to real force model. No experimental results on training have been provided.	Nakao et al. (2003)
Medical task: Palpation task of spine bone	Part-task Training (Simplification)		Positional & force control skills	Terminal KR (on demand)	Explore the effect of training on palpation diagnosis with haptic playback which consists of passive haptic guidance that allows following and feeling an expert's motions.	Haptic playback led to a significant training effect.	Williams II et al. (2004a, 2004b)
Medical task: Palpation task of breast tumour	Whole-task Training		Perceptual force control skills		Present a VR system which supports training of palpation of breast for tumor identification, and compare performance of experts and non-experts	Experts have committed less error in tumor identification than non-experts.	Alhalabi et al. (2005)
Surgery task: catheter Insertion in vessels	Whole-task Training		Motor coordination (position, orientation) & force control skills		Present a VR Catheter Insertion simulator	No experimental results on training have been provided but issues of realism of the haptic force feedback have been highlighted.	Zorcolo et al. (1999)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Surgery task: catheter insertion	Part-task Training (Simplification)		Force control skills	Concurrent KP (Active guidance)	Present a framework for training Minimal Invasive Surgery task in VR with haptic force feedback.	No experimental results have been provided.	Basdogan et al. (2004)
Surgery task: injection & dissection in endoscopic sinus surgery	Part-task Training (Simplification)	Repetitive-part	Motor coordination (position, orientation) & force control skills	Terminal KP	Explore the face and construct validity and the effectiveness of a VR training simulator for sinus surgery to transfer skills from VR to real world context. The VR simulator support training through 3 levels of complexity.	Face validity as the level of realism of virtual model was found. Construct validity as the ability to differentiate between several levels of expertise was reported. VR training alludes a positive transfer from VR to real world context.	Fried, M. P. et al. (2005)
Surgery task: intravenous catheterization	Whole-task Training		Motor coordination (position, orientation) & force control skills	Concurrent KR	Assess a VR training system for intravenous catheterization skills. They found that VR practice can be useful as a complement to RW practice (on plastic arm)	VR practice was found to be a useful complement to conventional training. However, the interaction within the system did not look realistic enough. A plastic arm as support would have been appreciable for the immersion.	Johannesson et al. (2010)
Surgery task: renal access procedure - catheter placement	Whole-task Training		Motor coordination (position, orientation)		Investigate the content validity of a VR training simulator for renal access training by comparing with conventional training technique on anesthetized porcine model.	In the overall, conventional training technique provides more realistic training conditions. However, VR training shows the advantage of several rehearsal considering several levels of difficulties	Mishra et al. (2010)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Surgery task: bone needle insertion, syringe positioning and injection in vertebra-plasty surgery	Whole-task Training		Motor coordination (position, orientation) & force control skills		Present a VR training system for bone needle insertion task in vertebra-plasty procedure.	No experimental results have been provided.	Chui et al. (2006)
Surgery task: bone-pin insertion	Whole-task Training		Force control skills	Terminal KR	Investigate to which degree training on bone pin placement task in VR is affected by varying stiffness models, and assess the effectiveness of such training to transfer force skills to the real world.	Augmented stiffness model led to similar performance than normal haptic force feedback. However, degraded force feedback led to worst performance.	Edmunds & Pai (2008)
Surgery task: bone drilling	Part-task Training (Simplification)	Repetitive-part	Force control skills	Concurrent KP & Terminal KR	Present a VR training system which propose a training framework to practice force skills for bone drilling procedure with a teaching mode with concurrent KP (force indicator, drilling velocity bar graph, drilling acceleration bar graph, acoustic force indicator) and KR (drilling end-position warning signal) and a simulator mode with KR (drilling end-position warning signal). The authors explored the effect of visual, acoustic KP and haptic force feedback on training performance.	Visual performance indicators are helpful but trainees tended to become easily dependent to apply correct force. Acoustic feedback did not have a dependence trend. Additional haptic DOF increase realism and provide a better understanding of the skill to perform.	Esen et al. (2004)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Surgery task: temporal bone drilling	Part-task Training (Simplification)		Force control skills	Concurrent KP (Active guidance)	Present and investigate the construct validity of a VR training simulator for bone surgery which enable evaluation and feedback performance information and assistance of learner using haptic playback mentoring	Expert surgeons should perform much better than novices. Construct validity of the VR training system has been found.	Morris et al. (2006)
Surgery task: ear bone drilling	Part-task Training (Simplification)		Force control skills	Concurrent KP	Compare the effectiveness of a VR bone drilling simulator with conventional training technique to transfer force skills required in ear surgery to real world context.	VR training was promising as it enabled participants to start out further on the learning curve.	Sewell et al. (2007)
Surgery task: bone drilling for reduction in oral surgery	Part-task Training (Simplification)	Repetitive-part	Motor coordination (position, orientation) & force control skills	Concurrent KR	Look at the effectiveness of a VR simulator for training bone reduction by drilling, to transfer skills to real world context. The training method proposed 3 three levels of difficulties (basic, advanced, examination).	Motor skills practiced on the VR simulator can be efficiently applied on cadaveric models.	Von Sternberg et al. (2007)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Surgery task: bone drilling	Part-task Training (Simplification)	Repetitive-part	Force control skills	Concurrent KP (KP + Active guidance)	Present a force skill VR training system based on online haptic collaboration with an experienced instructor for bone drilling task and investigate most appropriate assistance technique (verbal, passive & active guidance).	All methods speed up the acquisition of force skill, but the verbal method appeared to be the most effective. Passive haptic guidance was effective to reproduce accurately force pattern, but learning usually occurred passively. Active haptic guidance remained difficult to interpret and more practice was needed to get used to it.	Esen et al. (2008a, 2008b)
Surgery task: spine drilling and screw placement tasks in vertebra-plasty surgery	Part-task Training (Segmentation)		Force control skills	Concurrent KR	Explore the learning effect of a VR part-task training simulator for bone drilling task in vertebra-plasty procedure.	A significant learning effect was found.	Luciano et al. (2012)
Surgery task: grasping and placing gallstones in an bag, running the bowel, and clipping and cutting an artery	Part-task Training (Simplification & Segmentation)		Motor coordination (position, orientation) & force control skills		Compare the effectiveness of a part-task trainer laparoscopic simulator with conventional training technique and investigate the effectiveness to transfer surgical skills to a real world context.	In the overall, VR part-task training system enabled a significant transfer of surgical skills to real world context compared to conventional training technique.	Youngblood et al. (2005)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Surgery task: grasping, Electrocautery and cutting task	Part-task Training (Simplification)	Repetitive-part	Motor coordination (position, orientation)		Assess the effectiveness and aim to find the construct validity of a VR training simulator which proposed several levels of difficulties of a laparoscopic organ removal procedure.	The VR training system displayed construct validity as significant differences were found between all levels of expertise. VR training appeared particularly helpful at early learning stage.	Aggarwal et al. (2006)
Surgery task: Clipping and cutting in gallbladder, Clipping and cutting with two hands, dissection & Gallbladder separation	Part-task Training (Segmentation)	Part-whole	Motor coordination (position, orientation) & force control skills for 9 basic surgery skills		Investigate the construct validity of training curriculum implemented on a VR training system which aims the acquisition of technical skills for laparoscopic cholecystectomy through simplified and segmented part-task to whole-task training.	Construct validity as the ability to differentiate between several levels of expertise was found for most of technical skills. VR training led to significant learning effect for novices.	Aggarwal et al. (2009)
Surgery tasks (camera navigation, clipping, cutting, peg transfer, knot tying, and needle driving)	Part-task Training (Simplification & Segmentation)		Motor coordination (position, orientation) & force control skills from 6 essential surgery tasks	Terminal KR	Explore the construct validity of a VR system which support basic surgery skills training through task simplification (3 levels of complexity)	Significant differences in peg transfer and cutting tasks were found depending between expert and novice	Iwata et al. (2011)
Surgery task: laparoscopic rectal procedure - cutting task	Whole-task Training		Surgical skills		Present the development of a realistic VR simulator for training the performance of rectal surgery.	No experimental results have been provided.	Pan et al. (2011)

Task	Training Method	Integration method to whole-task	Practiced skills	Augmented Feedback	Study purpose	Conclusion	Authors
Surgery task: Prostate excision	Whole-task Training		Motor coordination (position, orientation) & force control skills		Present a VR simulator for training prostate surgery and conduct a complete validity study (face, content, construct, transfer to operation room).	Face validity was found as experts believed that VR training in the simulator could be profitable. Content validity was found as the simulation was realistic to mimic real task complexity. Construct validity of the system was found and a significant VR training effect allowed a successful transfer of surgical skills to real world conditions.	Kalltröm (2010)
Surgery task: suturing	Whole-task Training		Force control skills		Evaluate the value of haptic force feedback in a training a suturing task in VR	Significant performance and accuracy improvements in term of exerted forces on tissues and task completion time were reported	Moody et al. (2001)
Surgery task: suturing	Whole-task Training		Motor coordination (position, orientation) & force control skills		Present a VR training simulator for suturing task	No experimental results have been provided.	Webster et al. (2001)

Fundamental training methods applied to VR training have been found to efficiently support the acquisition of motor skills. On the one hand, whole-task training has been shown to enable the development of motor programs that lead to accurate performance of motor skills involved in dentistry (Suebnukarn et al., 2010; Rhienmora et al., 2011), assembly (Adams, J. R. et al., 2001; Oren et al., 2012) and surgical tasks (Moody et al., 2001; Johannesson et al., 2010; Kalltröm, 2010).

On the other hand, part-task training based on the segmentation of sequential motor skills (Section 2.3.2) has been commonly employed in surgical procedures and has been shown to be effective for motor learning (Youngblood et al., 2005; Aggarwal et al., 2009; Iwata et al., 2011, Luciano et al., 2012). However, to the best of the author's knowledge, few research studies have defined a full operative training procedure to support motor learning through part-whole integration method (Section 2.3.2). Only Aggarwal et al. (2009) have presented a training program in which segmented part-task components were integrated into a whole-target task.

Part-task training suggesting the simplification of tasks in the form of a reduction of coordination requirements by using physical assistance techniques or a modification of environment characteristics defining several levels of difficulty (Section 2.3.2) has been widely employed to support motor learning in calligraphy handwriting simulators (Solis et al., 2003; Wang, D. et al., 2006; Eid et al., 2007), assembly procedures (Bhatti et al., 2009), and surgery tasks such as palpation (Williams II et al., 2004a; Williams II et al., 2004b) and bone drilling operations (Aggarwal et al., 2006; Von Sternberg et al., 2007; Esen et al., 2008a; Esen et al., 2008b; Iwata et al., 2011). Nonetheless, in some particular cases, the reduction of coordination requirements has been shown to be not sufficient to support the development of concurrent motor skills such as motor coordination and force skills (Saga et al., 2005; Srimathveeravalli & Thenkurussi, 2005). Moreover, several research studies have defined training strategies which support motor learning throughout repetitive integration of part-task components (Section 2.3.3) in the form of additional coordination requirements and task difficulty increases towards whole-target tasks (Esen et al., 2004; Aggarwal et al., 2006; Eid et al., 2007; Von Sternberg et al., 2007; Bhatti et al., 2009).

On basis of the review of the available literature presented through Table 2, no references concerning part-task training inspired by the fractionation of simultaneous motor skills (Section 2.3.2) and progressive-part integration of those skills into a whole-target task (Section 2.3.3) have been found. Thus, the implementation of the progressive-part integration of fractionized motor skills into a whole-target task would be a valuable contribution to the field of VR training.

The VR training system presented in this thesis allows applying fundamental training methods such as part-task and whole-task training to the context of VR. Both training methods can be thus implemented in a training program which defines a complete training procedure. The effectiveness of part-task training inspired by fractionation and simplification techniques along with progressive-part integration, and whole-task training to support motor learning for fine grinding and polishing tasks will be evaluated through two experimental studies (Chapters 6 & 7).

3.3 KNOWLEDGE OF PERFORMANCE VS. KNOWLEDGE OF RESULTS

The effectiveness of augmented feedback in the form of Knowledge of Results (KR) and Knowledge of Performance (KP) (Section 2.4.2) in order to supplement intrinsic feedback with information which respectively indicate goal achievement and kinematic characteristics has been widely discussed (Todorov et al., 1997; Young et al., 2001; Mononen, 2007; Utley & Astill, 2008). However, the guidance hypothesis of frequently provided augmented feedback (Salmoni et al., 1984) and its trend to hamper the processing of intrinsic information feedback for the development of accurate motor programs has also been reported throughout VR training (Wierinck et al., 2005). Nonetheless, augmented feedback is considered as a prominent feature of motor learning throughout VR training (Johannesson et al., 2010; Gopher, 2012).

Many research studies have supported the development of complex motor skills in VR by providing KR and KP in a concurrent or terminal fashion. However, the identification of augmented feedback as KR or KP may be sometimes ambiguous depending on the training context. In single skill training, in which the task objective is achieved when performance of motor skill becomes accurate, the concepts of KR and KP may often merge. In contrast, in broader training contexts which implicated the performance of a complex task involving several motor skills, KR and KP are easily distinguishable.

On the one hand, concurrent KP has been often provided as active haptic guidance, a correcting force employed when the performance of motor coordination or force control skills tends to deviate from the reference of correctness (Section 3.1.2). On the other hand, concurrent KP has been often supplied in the form of a visual indication of motor skill accuracy with regards to a threshold of correctness. For instance, Solis et al. (2003) have employed visual concurrent KP using red and blue colours to inform in the course of VR training whether the shape of the calligraphy character being traced was correct or not. Balijepalli & Kesavadas (2003) have presented relevant force statistics such as normal force being exerted, maximum applied force, average force and target force during the performance of grinding operations. Sewell et al. (2007) have used a bar indicator to display the force being exerted on a virtual membrane with regards to a target force. Esen et al. (2004, 2008b) have proposed concurrent KP through a force indicator which informs whether the applied force is appropriate, too weak or too high. Moreover, Esen et al. (2004, 2008b) have also reinforced visual indication of force performance with drilling sound effects specific to each level of force. Wang, Y. et al. (2006, 2009) have employed a unique audio feedback to notify inclination errors when performing an arc welding task. Audio information to provide concurrent KP has been less frequently used as it has been often considered inefficient as, on the contrary to that proposed by Esen et al. (2004, 2008b), it rarely provides prescriptive information that enable error correction (Wang, Y. et al., 2006). Furthermore, according to Wang, Y. et al. (2006), it may result annoying when provided continuously.

In contrast to concurrent KP, terminal KP has been more rarely employed in VR training. Fried, M. P. et al. (2005) have developed an assessment technique that pointed out errors which have occurred during the prior training session. Rhienmora et al. (2011) have presented a VR simulator for training technical motor skills required in dental drilling procedures, which provided automatic terminal prescriptive KP that suggested applying more or less force during the next trial.

Concurrent KR as that type of augmented feedback which informs in real-time about the status of goal achievement and terminal KR that indicates goal achievement at the completion of the task have been both extensively employed to support motor learning throughout VR training. For example, Von Sternberg et al. (2007) and Luciano et al. (2012) have provided concurrent KR throughout VR practices of a bone drilling task in the form of additional viewpoints that inform about the progress of goal achievement through different perspectives. Johannesson et al. (2010) have emulated verbal comments that patients usually make during a painful intravenous catheterization task. Balijepalli & Kesavadas (2003) have highlighted the distribution of applied forces on a surface model during a grinding operation by using a colour coding which stated for the magnitude of those forces.

KR has been also often provided at the end of VR practices in the form of performance ratings which inform about goal achievement (Suebnukarn et al., 2010; Iwata et al., 2011, Rhienmora et al., 2011), pictorial information (Esen et al., 2004; Bhatti et al., 2009) and audio warning signals (Williams II et al., 2004b; Edmunds & Pai, 2008; Bhatti et al., 2009) to notify success or failure in goal achievement.

Although augmented feedback in the form of KP and KR has been broadly employed to support motor learning in VR training, the use of both types of feedback has been apparently more frequently associated to part-task training than whole-task training (Table 2). Effectively, part-task training has been commonly associated to concurrent KP in the form of active guidance technique (Gutiérrez et al., 2010; Lu et al., 2012) or visual notification of motor skill accuracy (Solis et al., 2003; Sewell et al., 2007; Esen et al., 2008b). However, terminal KP has been less frequently used in part-task training (Fried, M. P. et al., 2005). Moreover, concurrent KR (Balijepalli & Kesavadas, 2003; Von Sternberg et al., 2007; Luciano et al., 2012) and terminal KR (Esen et al., 2004; Williams et al., 2004b; Bhatti et al., 2009; Iwata et al., 2011) have been also broadly employed to support motor learning in part-task training. Nonetheless, when augmented feedback has been provided in whole-task training, it usually consisted of only KR (Edmunds & Pai, 2008; Suebnukarn et al., 2010; Johannesson et al., 2010; Rhienmora et al., 2011). Only Rhienmora et al. (2011) dared complementing terminal KR with terminal KP which provided prescriptive information in the form of recommendations for next performances.

In this thesis, it is presented a training toolkit which allows scheduling augmented feedback throughout part-task and whole-task training carried out on the VR training system (Section 5.1). Part-task training can be enhanced with:

1. Concurrent KP in the form of visual indications of angle and force skill accuracy with regards to a reference of correctness.
2. Concurrent KR as an indicator which displays remaining time for goal achievement.
3. Visual and audio terminal KR to inform about success or failure of task objectives.

Whole-task training can be enhanced with concurrent KR in the form of a colour map which uses a colour coding to depict task progress (Section 5.1.2.2). Moreover, terminal KR in the form of performance mean scores can be also provided.

3.4 VALIDITY OF TRANSFER

A VR training system, to be effective, must ensure the generalization of motor skills previously acquired through repetitive practices to similar experiences in the real world (Bossard et al., 2008). This is commonly presented as transfer of learning when it refers to the capacity of acquiring knowledge in a source context and generalizing that knowledge to a different context (Leberman et al., 2006), or transfer of training when it refers to the degree of retention and application of knowledge and skills from a training environment to a workplace environment (Bossard et al., 2008). However, transfer of learning and transfer of training are often used synonymously (Leberman et al., 2006). Transfer or learning is usually associated to educational fields while transfer of training is related to working contexts (Bossard et al., 2008). Thus, in this thesis, transfer of motor skills to real operating environments will be referred as transfer of training.

Transfer of training has been often determined by comparing task performance in the real world with that subsequent to VR training. Several research studies within those presented in Table 2, have shown that VR training enable the transfer of the trained motor skills to the real world. For instance, Von Sternberg et al. (2007) have shown that oral surgery skills trained on their VR training system could be effectively transferred to physical reality; Eid et al. (2007) have highlighted the effectiveness of their handwriting haptic-based training system to support motor learning of calligraphy characters and transfer to the performance in a real handwriting task; and Adams, J. R. et al. (2001) have demonstrated that VR training of an assembly task allows transferring motor skills to the performance of a real assembly task. Moreover, transfer of training can be quantified by comparing performance outcomes derived from real world training and VR training (Roscoe & Williges, 1980). Several research studies have given emphasis to transfer of training by making such comparison. However, none of these studies have dared quantifying the degree of transfer of training as suggested by Roscoe & Williges (1980). Sewell et al. (2007) have compared the effect of VR training on a precision drilling task commonly performed in bone surgery procedure with the conventional training technique usually conducted on egg shells. Their results suggested that VR training enables transferring the practiced force control skills to real world environment. However, for equivalent amount of training, task performance after VR training resulted lower than after conventional training. In contrast, Oren et al. (2012) have shown their VR training system enables transferring efficiently assembly skills to the performance of a real assembly task. Task performance with VR training was as good as that with real world training. Thus, the VR training presented by Oren et al. (2012) suggests an equivalent transfer of training than conventional training. Youngblood et al. (2005) have demonstrated that naïve participants trained on a VR part-task trainer performed better live surgical tasks than those who trained with conventional training methods. In that case, a high degree of transfer of training is suggested.

The issue of transfer of training with regards to the conditions that facilitate transfer of skills from a VR context to a real physical environment has been widely discussed (Rose et al., 2000; Hamblin, 2005; Bossard et al., 2008). The degree of fidelity of a VR training system to simulate a real target task is believed to be one of the factors which support effective transfer of training (Rose et al., 2000; Hamblin, 2005). Fidelity consists of the degree to which motor skills practised in a VR simulation accurately represents those motor skills in an equivalent situation in the real world (Hamblin, 2005). Transfer of training of a VR system has been proved high in conditions of high degree of fidelity, that is to say, in systems that provide realistic simulations featured by interaction paradigms that are close to those of the real physical task. Furthermore, high fidelity VR simulations emulate the consequences of those interactions in the way that they usually occur in real operating environments. Thus, VR simulations with a high degree of fidelity are able to simulate performance outcomes as in the real world. This means that those simulations enable discriminating between several levels of expertise. In contrast, transfer of training of a VR training system with a low degree of fidelity is believed to be rather weak (Rose et al., 2000).

Many research studies, as those proposed in Table 2, have investigated the fidelity of their VR training systems. For example, Martins et al. (2012) have explored the realism of a VR training system for forklift driving based on haptic interaction by comparing the suggested driving paradigm with that of the real world. Similarly, Mishra et al. (2010) have proposed to expert surgeons to compare the performance and the realism of a surgical task in a VR simulator with that usually performed while training in the real world. Nishino et al. (2011) have validated the fidelity of a handwriting simulation through subjective comparison between VR and real world task performance. Steinberg et al. (2007) and Kalltröm (2010) have respectively investigated the fidelity of a VR training system for dentistry and surgical tasks by assessing subjectively the realism of the suggested simulations. Moreover, as many other research studies (Fried, M. P. et al., 2005; Morris et al., 2006; Aggarwal et al., 2009; Iwata et al., 2011; Rhienmora et al., 2011), Kalltröm (2010) have also tested the fidelity of a VR training system by exploring the capability of the system to simulate performance outcomes corresponding to distinct levels of expertise. The study concluded that the simulation of performance outcomes appeared to be a realistic representation of the levels of expertise in the real world.

VR training systems have been used for the development of motor programs for accurate performance of complex manual tasks. However, to be of any use, VR training systems must also enable transferring those skills to the performance of a similar task conducted in the real world. For this reason, transfer of training can be considered as a criterion for the evaluation of the effectiveness of a VR training system. In this section, it has been shown that a high degree of fidelity contributes to the effective transfer of motor skills from virtual to real operational environments.

In this thesis, transfer of training of the suggested VR training system will be evaluated through two experimental studies presented in chapters 6 and 7. However, the evaluation of performance of fine grinding and polishing tasks in the real world is somehow complicated. Transfer of training will be thus discussed on the basis of the effectiveness of the system to train motor skills and to discriminate different levels of expertise. Moreover, subjective data concerning the fidelity of VR simulations will be also collected in order to assess the capability of the system to transfer to real operating environments.

3.5 CONCLUSION

This chapter has presented a literature review through which the application of fundamental training methods to the context of VR along with the provision of augmented feedback has been reviewed. First, the role of haptic force feedback to provide intrinsic and extrinsic information in order to support motor learning in VR has been discussed. Although some authors have pointed out that no clear consensus concerning the degree of realism of haptic force feedback to support motor learning in VR has been found, in general, the addition of haptics which allows simulating haptic intrinsic information similar to that in real operating environments, is believed to be profitable for the development of motor programs and thus for the learning of complex motor skills. Second, the current state of motor skill training in VR with regards to the application of fundamental training methods such as part-task and whole-task training has been reviewed. On the basis of the current literature review, it is believed that a training program composed of part-task training inspired by progressive-part integration of fractionized and simplified motor skills, along with whole-task training would be a valuable contribution to the field of motor skill training in VR. Third, emphasis was given to how concurrent and terminal augmented feedback has been employed throughout VR training. On the basis of previous studies, a relationship between the type of augmented feedback and training methods has been established. Finally, the validity of VR training systems to transfer motor skills from virtual to real operating environments has been reviewed. The capability of a VR training system to support transfer of training has been shown to be related to the degree of fidelity of that system.

This thesis presents a VR training system which aims to support the development of some of the motor skills that are relevant for the performance of fine grinding and polishing tasks (Chapter 4 & 5). Moreover, a training toolkit which enables building training programs is also proposed (Chapter 5). Training programs define the motor skill training carried out on the VR training system. They allow applying fundamental concepts such as training methods and augmented feedback to the context of VR.

A training program based on part-task training of angle and force skills broken down following a decomposition scheme and whole task training will be evaluated throughout the two experimental studies presented in this thesis (Chapters 6 & 7). To the best of the knowledge of the author, the effectiveness of the proposed part-task training in VR has not been reported so far. The training program will also enable managing concurrent and terminal augmented feedback throughout VR training. Moreover, the validity of transfer of the system will be also discussed later in this thesis (Chapter 8).

PART 3

TOOLS AND METHODS DEVELOPMENT

Chapter 4. Context Modeling & Requirement Analysis

In chapter 3, it has been shown that VR training enhanced with haptic force feedback which simulates realistic intrinsic information supports motor skill training for complex manual tasks. Among other things, VR allows part-task training of motor skills through practical exercises which cannot be performed the same way in the real world. Moreover, a fundamental advantage of VR training is the possibility to enhance motor learning with augmented feedback that often does not exist in conventional training.

This chapter sets the context for the development of a VR training system which aims to support the learning of a subset of motor skills involved in the performance of manual operations commonly conducted during maintenance campaigns in industrial facilities. This chapter starts by presenting the metallographic replica technique, a non destructive technique (NDT) for the inspection of industrial facilities (Section 4.1). The metallographic replica technique requires previous mechanical preparation of the surface of inspected materials. Material surface preparation encompasses fine grinding and polishing tasks for which specific training is needed. The way in which that training currently occurs along with the issues to transfer and provide feedback on movement characteristics and performance outcomes are presented according to the terminology defined in chapter 2 (Section 4.2). On the basis of these training issues, functional and requirement analyses have been conducted in order to design a VR training system which will be used to support motor learning for fine grinding and polishing operations (Section 4.3), and will be assessed through two experimental studies proposed later in thesis (Chapter 6 & 7).

4.1 THE METALLOGRAPHIC REPLICA TECHNIQUE

Engineering equipment in industrial plants is often subject to critical process conditions which result in damage to the integrity of equipment. Haribhakti (2010) have identified several process conditions that lead to the deterioration of the integrity of carbon steel and alloy steel materials. Equipment failures may strongly affect the safe and reliable development of manufacturing processes, and sometimes may have catastrophic consequences.

In order to ensure safety and reliable manufacturing processes, industrial plants frequently conduct maintenance campaigns during which inspections of operating components are carried out. NDT for inspection of industrial facilities are crucial for the assessment of the material integrity and the prevention of failure (Haribhakti, 2010). NDT consist of techniques of in-situ evaluation of materials that composed operating components, and enable early detection of defects (e.g. micro-structural degradation and mechanical damage as cracks, voids and carbides) (Gandy & Findlan, 1996; Sposito et al., 2010). Sposito et al. (2010) have proposed an exhaustive review of NDT for the detection of specific damage mechanisms. One of the most important NDT for the inspection of material microstructure is the metallographic replica technique (Delle Site et al., 2006; Haribhakti, 2010; Sposito et al., 2010).

The metallographic replica supports material life assessment and failure analysis in industrial facilities (Haribhakti, 2010). It consists of a sampling procedure that records the topography of a material as a negative relief on a plastic foil (ASTM E 1351 – 01, 2001). Once the replica of the microstructure of an inspected material is obtained, it is then analyzed off-site using precision monitoring tools (NT NDT 010, 1991; ASTM E 1351 – 01, 2001).

The key to obtaining an accurate evaluation of material integrity in industrial plants consists of two principles. First, the replica must give a representative picture of the damage suffered by the material (Gandy & Findlan, 1996; ASTM E 3 - 01, 2001). Therefore, the selection of the location where to proceed with the inspection of the material microstructure is crucial (Haribhakti, 2010). Second, the inspected material surface must be prepared in order to remove oxide scales and impurities and reveal the microstructure of a surface free of deformation, scratches and other defects previously to replication of the material surface and microstructure analysis (ASTM E 3 - 01, 2001).

This thesis looks at the development and the assessment of a VR training system to support motor learning for the performance of fine grinding and polishing tasks conducted for the preparation of material surface. Figure 7 shows the stages of the metallographic replica technique: location selection, material surface preparation, replication, replica mounting and microstructure analysis.

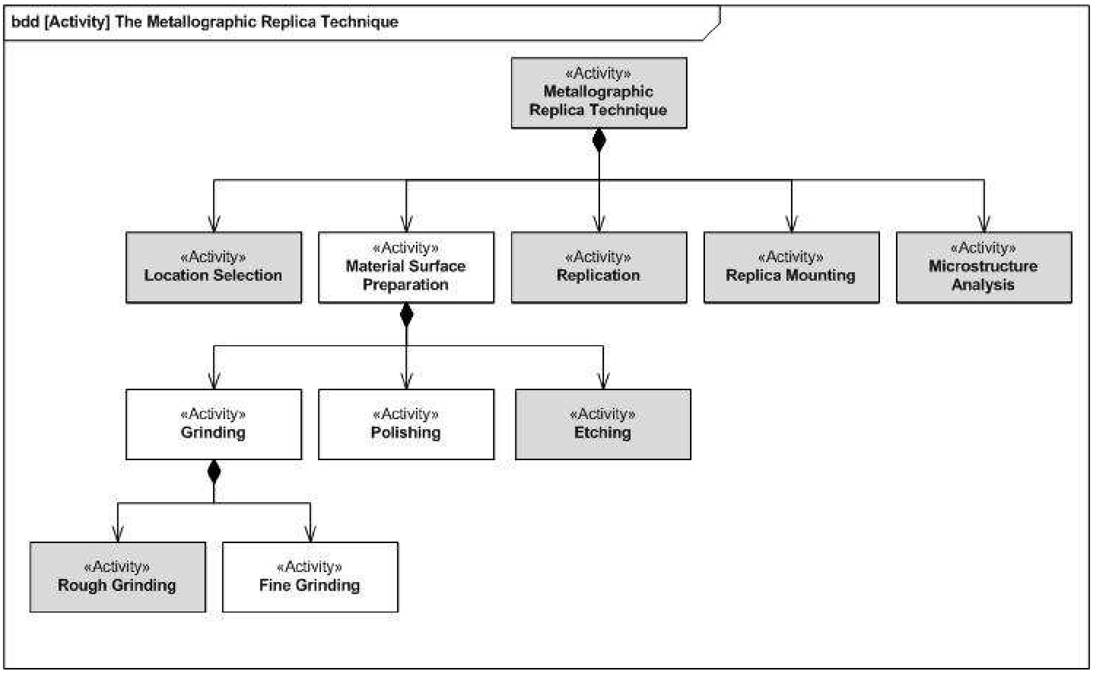

Figure 7. Stages of the metallographic replica technique with emphasis on fine grinding and polishing operations commonly carried out for material surface preparation (diagram resulting from discussions with two expert metallurgist from Tecnatom S.A.).

4.1.1 Location selection

Metallographic replica must be performed preferably in locations where a material microstructure is submitted to critical process conditions (Gandy & Findlan, 1996; ASTM E 3 - 01, 2001). For instance, in power plant facilities, expert metallurgists usually focus on operating components submitted to high temperature and pressure (Delle Sitte et al., 2006;

Joas, 2006) as valves (Figure 8.a), pumps, steam pipes, turbines (Figure 8.b). On all these components, expert metallurgists look carefully at welded seam and blades (Figure 8.b).

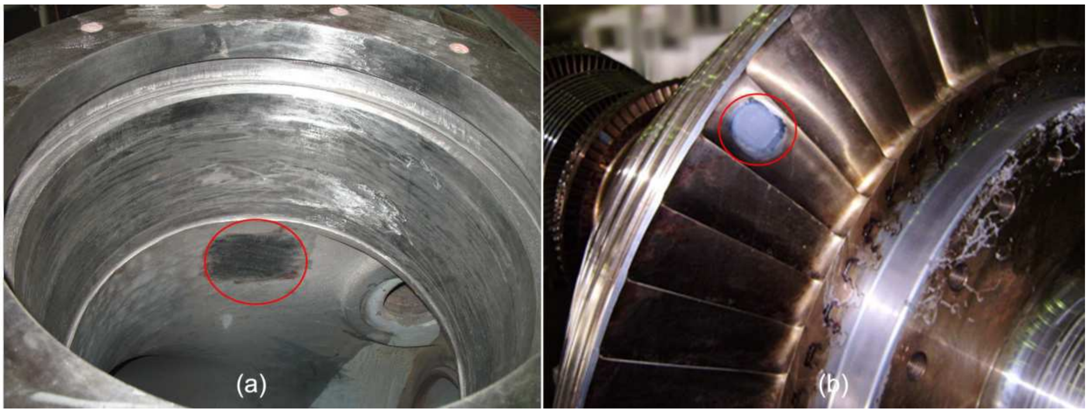

Figure 8. (a) Interior of an industrial valve and (b) a turbine blade on which metallographic replica tasks are commonly carried out.

The conditions of accessibility to these locations are often critical and therefore, material surface preparation tasks are often performed maintaining uncomfortable postures. For this reason, motor skills required in the performance of material surface preparation need to be trained in order to be carried out in any uncomfortable situation.

4.1.2 Material surface preparation

Before the replica extraction, the inspected material requires previous surface preparation in order to remove oxide scales and all imperfections that can alter its quality. Material surface preparation involves three steps: two mechanical tasks based on abrasive operations: grinding (Section 4.1.2.1) and polishing (Section 4.1.2.2); and a chemical treatment: the etching of the material surface (Section 4.1.2.3).

The VR training system proposed in this thesis aims to supplement conventional training on fine grinding and polishing tasks by using haptic force feedback to simulate the haptic intrinsic information perceived in real operating environments.

4.1.2.1 Grinding

Successive grinding operations aim to remove coarse coats and scales of oxide from the surface of the material being inspected. Expert metallurgists usually employ a collection of grinders mounted with abrasive accessories with different granularity.

When grinding, the granularity of the abrasive paper produces scratches on the surface of the material. Metallurgists perform the grinding maintaining the grinder with a constant orientation so scratches are produced in one direction. Usually, expert metallurgists generate only horizontal or vertical scratches on the plane of the metallographic replica area. However, in order to be valid for microstructure analysis, a replica must be scratch free. Therefore, subsequent grinding operations must be performed alternating the grinder orientation by 90º and reducing progressively the granularity of the abrasive accessory (NT NDT 010, 1991). These operations aim to remove the effects of previous grindings by producing thinner scratches with perpendicular direction (Figure 9).

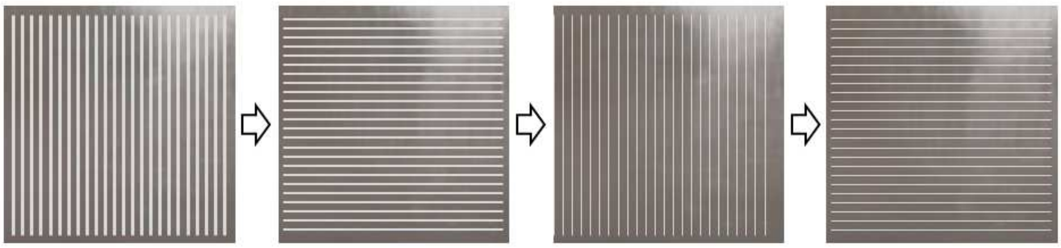

Figure 9. Sequence of grinding operations alternating the grinder orientation by 90º in order to remove scratches previously generated, with thinner scratches of perpendicular direction.

Grinding is a long lasting process as the duration of each operation increases by three compared to the previous one (NT NDT 010, 1991). Moreover, the performance of grinding must be accurate. Higher forces exerted on a surface can overheat and deteriorate the microstructure of the material, whereas lower forces may be ineffective to remove scratches generated during the previous operation. Thus, a controlled amount of force should be applied (NT NDT 010, 1991).

The ASTM standards (ASTM E 3 - 01, 2001) distinguish two stages of grinding operations in the mechanical preparation of a material surface: (1) rough and (2) fine grinding.

Rough grinding commonly referred as planar grinding, enables removing substantial amount of oxide from the material surface. Expert metallurgists use an angle grinder equipped with abrasive flap disc of rough grits (40, 60 & 80) (Figure 10.a) and then switch to an angle drill mounted with abrasive flap fan of thinner grits (120, 240, 320 & 400) (Figure 10.b).

Figure 10. (a) Angle grinder equipped with abrasive flap disc of rough grits and (b) angle drill mounted with abrasive flap fan to perform rough grinding operations.

Fine grinding enables removing residual oxide scales from the material surface. Metallurgists usually use a precision rotary tool with right angle attachment equipped with abrasive flap disc of thin grits (600, 800, 1000 & 1200) (Figure 11).

Figure 11. Precision rotary tool with right angle attachment equipped with abrasive flap disc to perform fine grinding operations.

4.1.2.2 Polishing

Polishing consists of smoothing down the surface of the material free of oxide scales, using a precision rotary tool with right angle attachment (Figure 11) equipped with a polishing cloth to spread uniformly a small quantity of diamond paste over the inspected area. Various grades of diamond paste are successively applied onto the material surface, starting from thicker (3 µm) to thinner (1 µm) grades (NT NDT 010, 1991).

Polishing is commonly referred to as mirror surfacing as the purpose of the task is to give a mirror-like finishing to the material surface (ASTM E 7 - 03, 2003). In other words, the inspected material surface must be as reflective as a mirror (Figure 12). The outcome of the polishing is usually checked using a torch lightening the material surface.

Figure 12. Mirror-like finishing of a material surface after a polishing task.

4.1.2.3 Etching

Etching consists of a controlled preferential attack on the freshly polished surface for the purpose of revealing structural details, as its microstructure. A controlled corrosion process is engaged (ASTM E 7 - 03, 2003). The process involves various highly corrosive chemical reagents resulting from the blends of alcohols and acid chemicals specific to the composition of materials. Expert metallurgists apply the chemical reagents on the material surface with a cotton piece (Figure 13). This manipulation is considered critical as the freshly polished surface can result easily scratched by cotton fibers.

Figure 13.The etching process

4.1.3 Remaining operations

Subsequent operations in the process of metallographic replica technique are less relevant in the context of this thesis. They consist of replication task, replica mounting task and microstructure analysis.

4.1.3.1 Replication

Replication consists of recording the topography of the material surface as a negative relief on a plastic foil (NT NDT 010, 1991; Gandy & Findlan, 1996; ASTM E 1351 – 01, 2001). A solvent composed of acetone is applied to the prepared material surface, and a plastic foil is delicately laid on the wet surface avoiding the air to remain between the film and the material (Figure 14).

The replication process

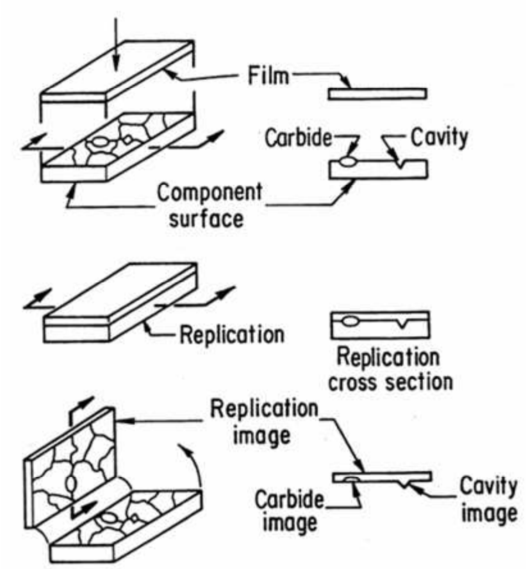

Figure 14. Schema of the replication process which records the topography of a material surface as a negative relief on a replica (Gandy & Findlan, 1996).

The plastic foil face in contact with the metal is partially dissolved by chemical reaction with the solvent. After the film has dried (30 to 60 seconds), the replica is pulled off from the surface using a piece of adhesive tape stuck on a corner on the back side used as languet. The replica is then mounted on a microscope slide for further analysis.

4.1.3.2 Replica mounting

Replica mounting consists of coating the replica with a light reflecting material in a vacuum chamber (NT NDT 010, 1991). Expert metallurgists usually coat the replica with a thin layer of gold because it yields optimum contrast during the microscope observation (ASTM E 1351 - 01).

4.1.3.3 Microstructure analysis

The microstructure analysis enables searching for damage (voids, cracks, carbides and deformation of material grain) of the integrity of the material (Figure 15). The microstructure analysis is traditionally performed using a light optical microscope with a range of magnification from 50 to 1000X, although sometimes when more resolution is needed, a scanning electron microscope (from 500 to 5000X) might be used (NT NDT 010, 1991).

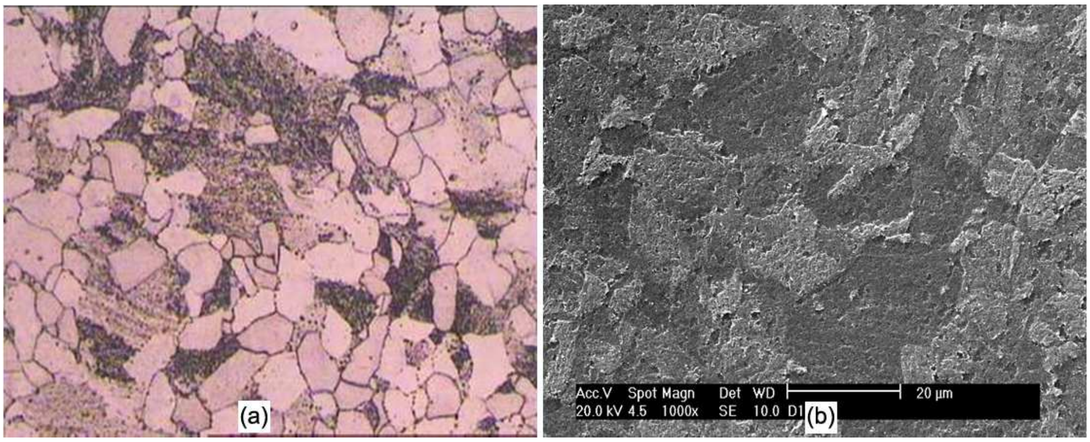

Figure 15. A metallographic replica correctly performed analyzed with (a) the light optical microscope and (b) the scanning electron microscope.

4.2 TRAINING TECHNIQUES AND ISSUES IN FINE GRINDING AND POLISHING

According to Hulsholf et al. (2005), the quality of a metallographic replica strongly depends on the accuracy of the material surface preparation tasks for which advanced skills are required. In the course of rough grinding operations, high forces exerted with the grinder or angle drill may lead to overheating and deforming the material surface (NT NDT 010, 1991), and low tool inclination may produce scratches with non-acceptable direction on the material surface. In the course of fine grinding, lower inclination of the flap disc also leads to the generation of scratches with inappropriate orientation. However, for fine grinding and polishing operations, higher forces exerted on a material surface may hinder the rotation of the tool disc. Thus, for the completion of these tasks, only a little amount of force has to be applied in order not to damage the material. Nonetheless, a too little amount of force exerted on the material surface may result in an ineffective performance. Finally, in the course of polishing tasks, a too pronounced tool inclination may lead to a non-uniform spreading of the diamond paste on the material surface. Therefore, motor skill training on such tasks is paramount to guarantee an efficient performance of the metallographic replica technique.

4.2.1 Current state of training

Training on grinding and polishing operations traditionally occurs under the supervision of an expert metallurgist who instructs trainees on movement characteristics by performing practical demonstrations and providing verbal guidelines. Afterwards, trainees practise each task that compounds the material surface preparation stage (Figure 7). Such training is considered as whole-task training (Section 2.3). In the course of the practice, the expert metallurgist sometimes provides concurrent Knowledge of Performance (KP) (Section 2.4.2) in the form of verbal feedback which aims to highlight movement errors. However, that feedback is somehow inaccurate (Section 4.2.2.2). Finally, after the completion of the practiced task, the expert metallurgist provides terminal Knowledge of Results (KR) (Section 2.4.2) to inform about performance outcomes at that stage of the material surface preparation. Figures 16 to 18 schematically[1] represent the workflow of the activities conducted during the conventional training on grinding and polishing tasks along with the interactions that occur between the expert metallurgist and the trainee.

[1] The proposed schematics consist of activity diagrams which are part of the Unified Modelling Language (Chonoles & Schardt, 2003).

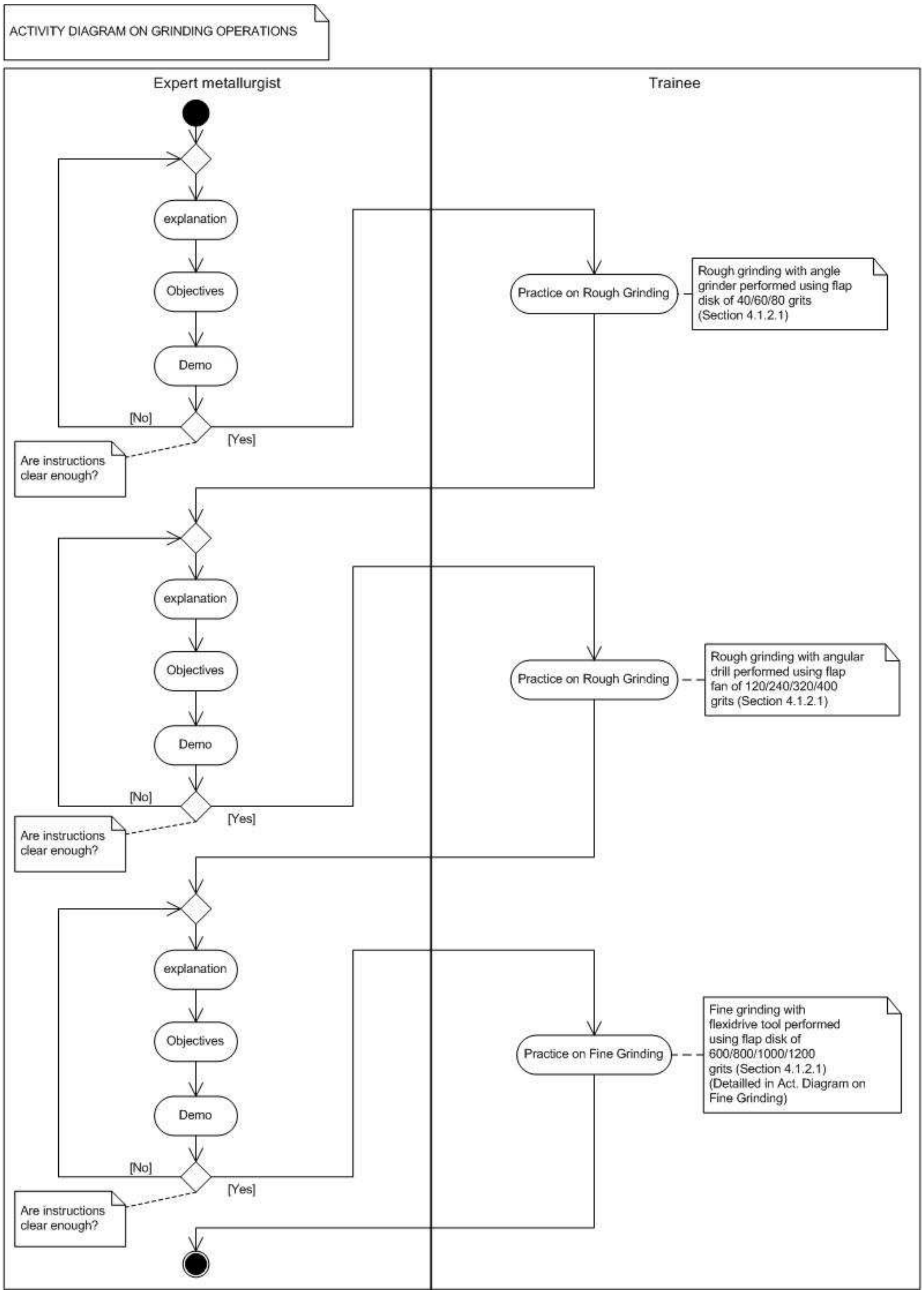

Figure 16. Activity diagram which depicts the workflow of activities between the expert metallurgist and the trainee during the training on grinding operations.

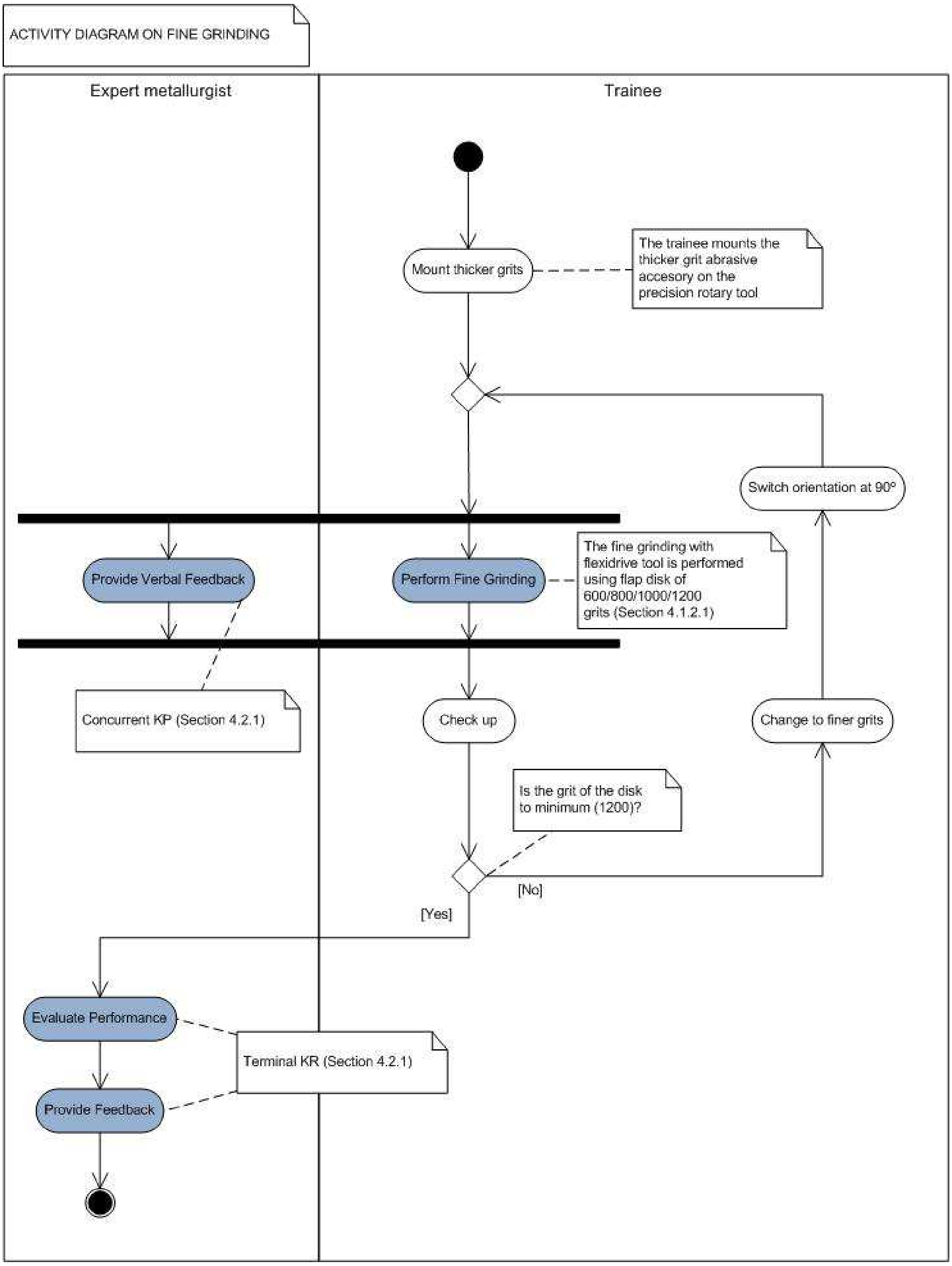

Figure 17. Workflow of activities conducted during conventional training on fine grinding operations. Highlighted activities related to task performance and information feedback are supplemented by the VR training system (Section 4.3).

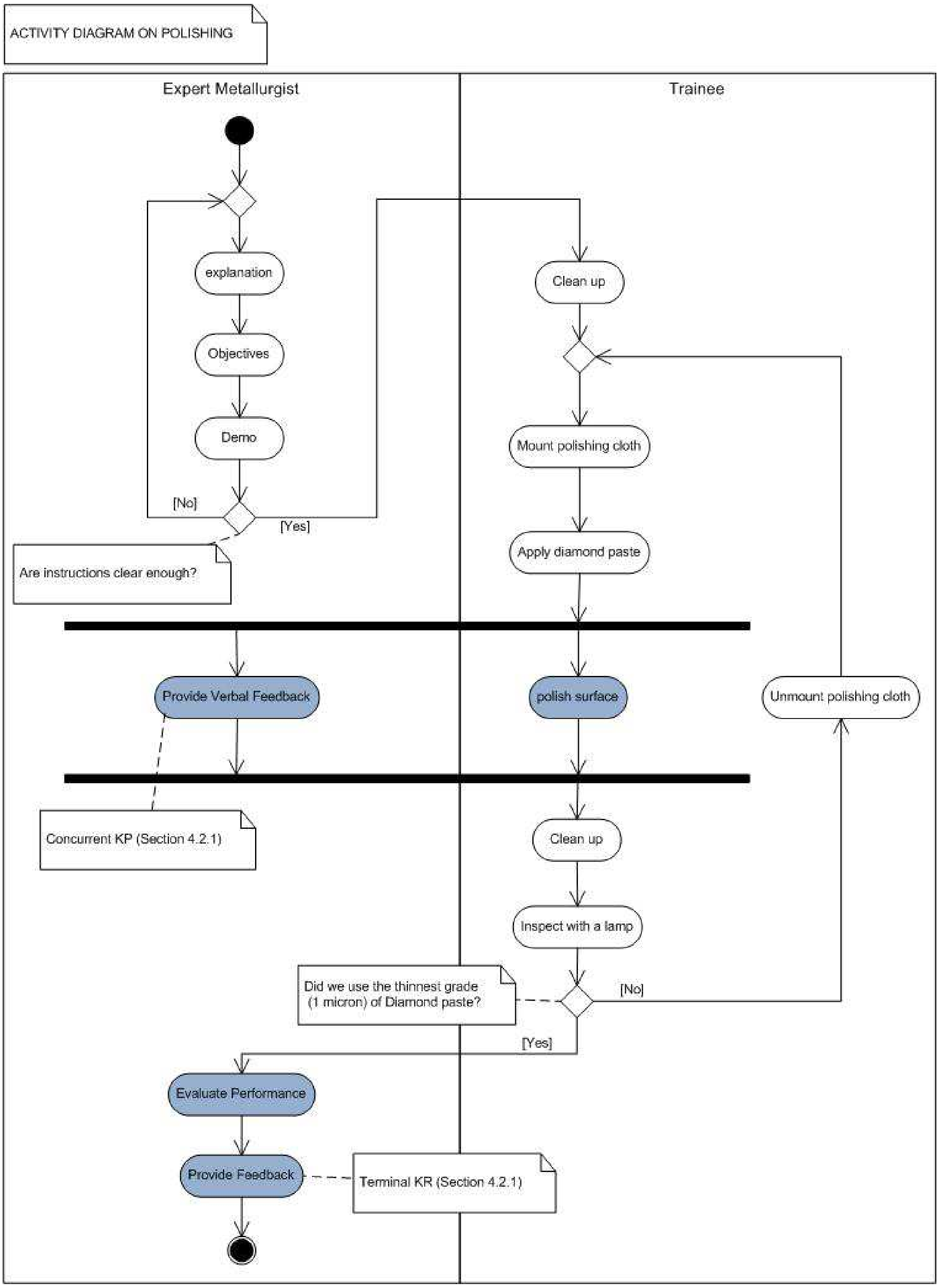

Figure 18. Workflow of activities conducted during conventional training on polishing operations. Highlighted activities related to task performance and information feedback are supplemented by the VR training system (Section 4.3).

The VR training system presented in this thesis initially aims to supplement conventional training on grinding and polishing operations through VR practice (Section 4.3). However, only those tasks that require the handling of power tools in which weight and generated forces can be simulated by a haptic device such as a Phantom Desktop device by Sensable Technologies (http://www.sensable.com/) will be considered. Thus, the proposed VR training will be limited to fine grinding and polishing operations for which a light precision rotary tool is used (Figure 11).

The activities that are proposed to be supplemented through VR training consist of the practice of both tasks along with the action of providing information feedback during and after that practice in order to support motor learning (Figures 17 & 18). The proposed VR training aims to solve the issues that arise in conventional training (Section 4.2.2). Thus, it should be performed previously to conventional training.

4.2.2 Issues of current training

Although conventional training occurs under the supervision of an expert metallurgist, the transfer of motor skills from expert to trainee remains troublesome due to difficulties to assess performance outcomes and provide accurate instructions on movement characteristics.

4.2.2.1 Assessment issues

The nature of fine grinding and polishing tasks prevents the expert metallurgist and the trainees to monitor in real-time the result of the interaction of the tool disc with the surface of the material. Performance outcomes cannot be checked until the disc has been taken off from the surface of the material. However, the assessment of polishing is even more problematic.

In the course of a polishing task, the diamond paste spread onto the inspected area impedes the performer to check the status of the mirror-like finishing of the material surface. Performance outcomes are only observable once the diamond paste has been wiped out at the end of the task. So, only terminal KR to inform whether task objectives have been achieved or not can be provided. The expert metallurgist is thus not able to provide concurrent KR to inform in real-time about the completion of task objectives. Nonetheless, during the performance of the task, advanced performers are able to evaluate the advancement of the polishing on the basis of the elapsed time, the exerted force and the applied angle on the material surface. This association between task performance and motor skill characteristics is developed throughout the associative stage of motor learning (Section 2.2.2.1). Therefore, performers at an early learning stage, for example at the cognitive stage of motor learning (Section 2.2.2.1), are not able to achieve such evaluation of performance.

4.2.2.2 Instruction accuracy issues

Previously to practice of fine grinding and polishing tasks, the expert metallurgist usually provides instructions related to movement characteristics in the form of verbal guidelines and demonstration. Moreover, in the course of the practice, the expert also provides concurrent KP in the form of verbal instructions to inform about the accuracy of angle and force applied on the material surface, through the precision rotary tool. The knowledge associated with the performance of angle and force skills for fine grinding and polishing tasks is tacit. This means that it is difficult to explain verbally. Thus, the transfer of motor skills from expert metallurgists to trainees is often weak and although there are no objective measures of accuracy, the concurrent feedback provided throughout practice does not enable refining accurately the force being applied and the inclination of the tool on the surface of the material (Poyade et al., 2012). Effectively, on the one hand, exerted forces and corresponding haptic sensations are not observable and therefore difficult to evaluate. Thus, it is difficult for trainees to find out what force to apply on the material surface and expert metallurgists to provide accurate feedback on force skill. On the other hand, previous verbal guidelines and demonstrations usually provide a good overview of the correct inclination of the tool for both tasks, but do not guarantee accurate refinements in the course of the practice. Moreover, the concurrent feedback provided throughout the practice often tends to be relatively inaccurate for angle refinements. So, inaccuracy is a common problem with the current training method. Training with inaccurate information feedback on angle and force skills is critical for the development of motor programs (Section 2.2.1) and effective performance of fine grinding and polishing tasks.

4.3 DESIGN OF A VR TRAINING SYSTEM

As mentioned previously, the implementation of fine grinding and polishing task training in a VR system enhanced with haptic interaction and augmented feedback is believed to improve the learning of motor skills required for the performance of both tasks. In this thesis, VR training system along with a training toolkit which enables building training programs to support motor learning for fine grinding and polishing tasks is proposed (Section 5.1). This training toolkit enables (1) part-task training (Section 5.1.1) on angle and force skills and (2) whole-task training (Section 5.1.2) on the performance of both tasks. Moreover, it also allows providing concurrent and terminal augmented feedback throughout both training methods.

The design of the VR training system has followed a methodology which proposes a functional analysis of the system, including a study of requirements, aiming to provide a description of what the system must do and how it must do it. The phases of functional analysis and requirement elicitation are part of a system engineering process (Figure 19) which collects and transforms customer needs and requirements in order to generate information specific to the design of the VR training system (DAU Press, 2001).

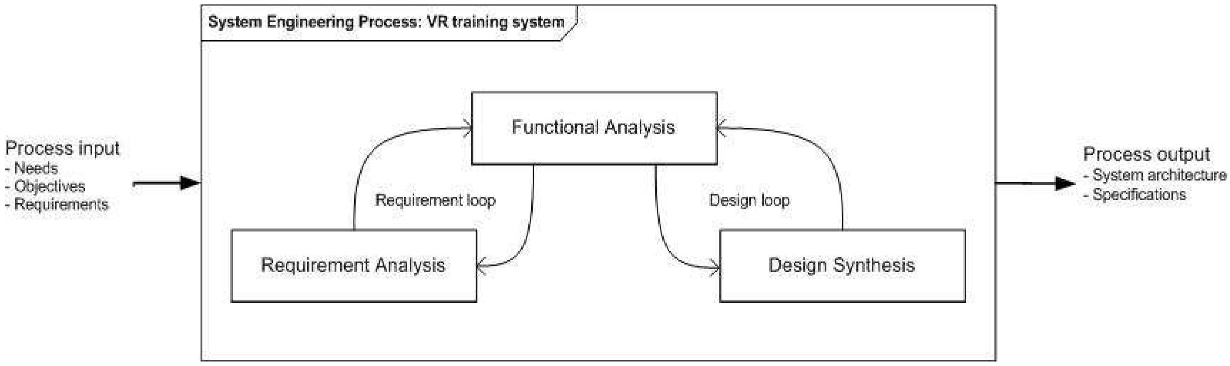

Figure 19. System engineering process which defined the methodology followed for the design of the VR training system (adapted from DAU Press, (2001)).

Section 4.3.1 describes the architecture of the proposed VR training system while the following sections focus on the requirements loop which extracts requirements for the design of that system. Section 4.3.2 details the steps of the functional analysis of the system, whereas section 4.3.3 presents the requirements that characterize the proposed VR training system. The resulting design is presented in chapter 5 and its effectiveness to support the development of motor programs for fine grinding and polishing tasks is evaluated in the experimental studies presented in chapters 6 and 7.

4.3.1 General architecture of the system

The VR training system is part of the ManuVAR platform (Krassi et al., 2010a), a system architecture that provides a technological and methodological framework to support manual work through the product lifecycle using VR and Augmented Reality (AR) technologies (Appendix C). Among other things, the ManuVAR platform enables: (1) supporting manual work training in industrial environments through VR simulations; (2) orchestrates the communication flow between all the connected elements and (3) manages the evaluation of performance throughout VR training.

The VR training system supports training of those motor skills that are relevant in fine grinding and polishing tasks. The VR training system also allows providing augmented feedback in the form of concurrent and terminal KR and KP throughout part-task and whole-task training (Poyade et al, 2011) (Figure 20).

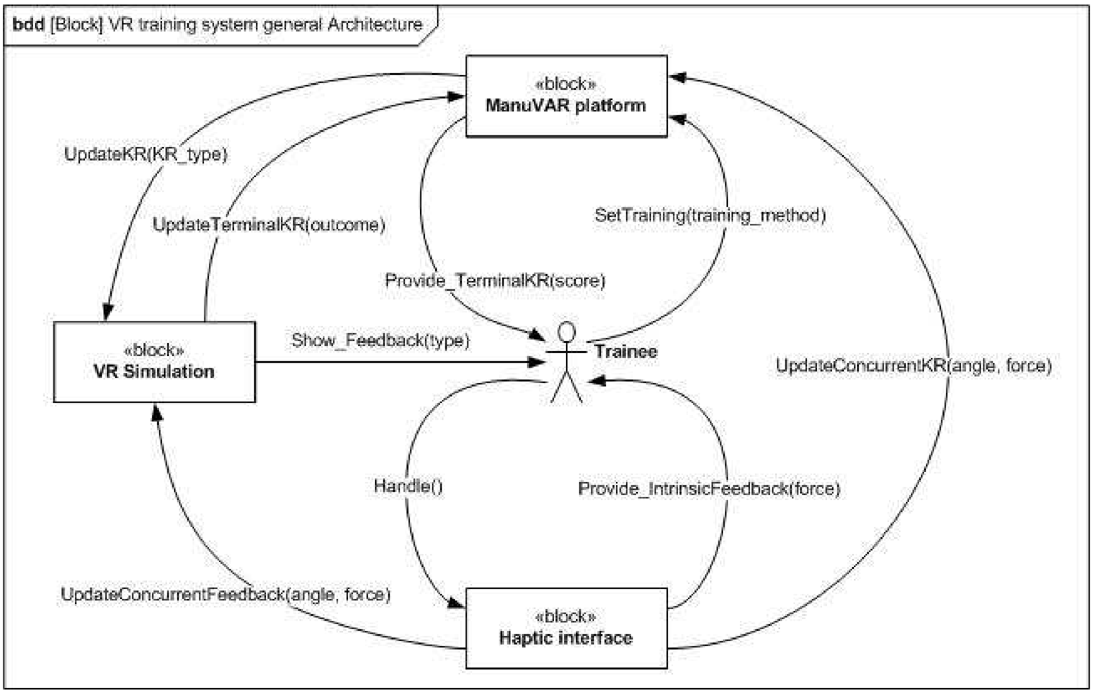

Figure 20. Block diagram of the general architecture of the VR training system which enable part-task and whole-task training and can provide concurrent and terminal augmented feedback; and a representation of the interaction between all the actors involved in the proposed VR training.

4.3.2 Functional analysis

The purpose of a functional analysis is to provide a coherent description of the functionalities of the VR training system. In other words, the functions that the VR training system must carry out (Section 4.3.2.1) and how it must be done (Section 4.3.2.2).

4.3.2.1 System Use Cases

The functionalities of the VR training system are depicted in the form of a use case diagram[2] (Figure 21). Each use case provides a description of a high level functionality of the system (Table 3) which satisfies one or several functional requirements (Section 4.3.3).

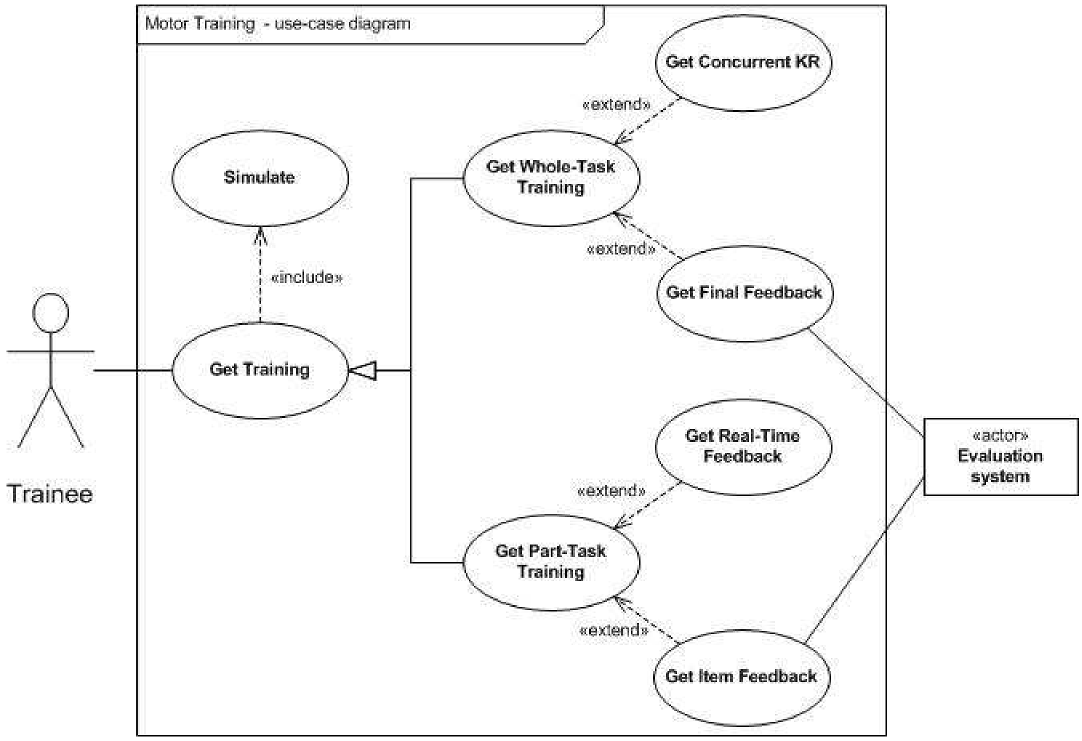

Figure 21. Use case diagram that describes the functionalities of the VR training system.

[2] Use case diagrams are part of the Unified Modelling Language (Chonoles & Schardt, 2003) and its extension for Systems Engineering, SysML (Friedenthal et al., 2008).

Table 3. Description of the functionalities of the VR training system.

Use-case name	Description	Pre-conditions	Narration	Post-conditions
Get training	This use case supports the proposed VR training. It allows the trainee to choose between two training methods to practice motor skills for the performance of fine grinding and polishing operations (Figure 22).	The trainee is logged in the ManuVAR platform and aims to train motor skills for the performance of fine grinding or polishing task.	The trainee is offered through the VR training system to train following two training methods: (1) part-task training method that proposes a set of training items in which angle and force skills required in fine grinding and polishing operations can be practised separately and progressively recombined in order to practise both skills simultaneously; and (2) whole-task training method in which fine grinding and polishing tasks can be practised in a simulated environment as they are usually performed in real operating environment. Both training methods can provide concurrent and terminal augmented feedback. The part-task training method can provide concurrent KP and KR throughout practice in order to respectively inform about motor skills characteristics and item objective achievement rate; and terminal KR to provide a final indication whether training objective has been achieved or not. The whole-task training method can provide concurrent and terminal KR in order to state for goal achievement during and after task practice. With both training methods, the trainee is immersed in a virtual environment which simulates the chosen task, and receives instructions concerning task objectives. The trainee handles a haptic device like a real precision rotary tool with right angle attachment would be hold (Figure 5). The trainee launches the virtual precision rotary tool to start the selected training.	Performance outcomes are collected in an evaluation system implemented on the ManuVAR platform so that expert metallurgists and trainees can assess performance outcomes (terminal KR) and learning curves for both tasks.

Use-case name	Description	Pre-conditions	Narration	Post-conditions
Simulate	This use case enables the simulation of fine grinding and polishing tasks in a virtual environment	The VR training system launches the virtual environment	The use case starts when the system loads all the components and set configuration parameters in the virtual environment. The system simulates the haptic sensations perceived in real operating environment by providing haptic force feedback. The system simulates the task to be trained.	
Get Part-Task Training	This use case enables part-task training of angle and force skills involved in fine grinding and polishing tasks (Figure 23).	The trainees has selected part-task training	The use case starts when the trainee launches the virtual precision rotary tool in order to proceed to part-task training. The trainee practises all the training items in which angle and force skills defined for the performance of the trained task can be practised separately and simultaneously. Concurrent KR and KP (use case: Get Real-Time Feedback) can be provided throughout those training items and terminal KR (use case: Get item Feedback) can be displayed after the completion of each item.	Performance outcomes are collected in an evaluation system implemented on the ManuVAR platform so that expert metallurgists and trainees can assess performance outcomes (terminal KR) and learning curves for both tasks.

Use-case name	Description	Pre-conditions	Narration	Post-conditions
Get Real-Time Feedback	This use case enables providing to the trainee real-time information feedback in the form of concurrent KP to inform about accuracy of trained motor skills, and concurrent KR to inform about remaining time before goal achievement during part-task training.	Concurrent KR and KP have been specified to appear throughout part-task training (Figure 24).	This use case starts when the trainee begins a training item which enables part-task practice of angle and/or force skills. The system provides real-time augmented feedback in the form of indicators that state for the values of the practiced motor skills (Figure 24). The system also provides real-time feedback in the form of a visual indicator that informs about the time spent on maintaining the practiced motor skills within the ranges of accuracy (Figure 24).	
Get item Feedback	This use case enables providing to the trainee terminal KR which informs whether the objective has been achieved or failed at the end of a training item (Figure 23).	Terminal KR has been specified to appear after training item completion in part-task training (Figure 23).	This use case starts when the trainee completes a training item in the process of part-task training. The system provides information about goal achievement in the form a visual indicator which states for successful or unsuccessful performance at the end of the training item (Figure 23).	

Use-case name	Description	Pre-conditions	Narration	Post-conditions
Get Whole-Task Training	This use case enables whole-task training on the performance of grinding and polishing tasks (Figure 25).	The trainee has selected whole-task training	The use case starts when the trainee launches the virtual precision rotary tool in order to proceed to whole-task training in a simulator application. Concurrent KR (use case: Get Concurrent KR) can be provided in the form of a colour map.	Performance outcomes are collected in an evaluation system implemented on the ManuVAR platform so that expert metallurgists and trainees can assess performance outcomes and learning curves for both tasks.
Get Concurrent KR	This use case enables providing to the trainee concurrent KR in the form of a colour map to inform about progression of goal achievement in the course of whole-task training.	Concurrent KR has been specified to appear throughout whole-task training (Figure 25).	The use case starts when the trainee begins whole-task training on the performance of fine grinding or polishing task. The system provides real-time information feedback on the performance of fine grinding or polishing task in the form of a colour map which used a colour scale to inform about the status of the completion of the practiced task on the material surface.	
Get Final Feedback	This use case enables providing to the trainee terminal KR to inform about for performance score.	Performance outcomes from whole-task training are collected in an evaluation system implemented on the ManuVAR platform	This use case starts when the trainee completes the whole-task training on the performance of fine grinding or polishing task. The system informs the trainee about the average task completion rate through the performance analyzer, an evaluation tool used by the ManuVAR platform for performance assessment.	

4.3.2.2 Main system scenarios

As mentioned previously, the VR training system aims to supplement conventional training on fine grinding and polishing tasks (Section 4.2.1). The conventional practice of both tasks is proposed to be supplemented with part-task and whole-task training in VR (Figure 22). The functionalities of the VR training system in terms of what activities are carried out during part-task and whole-task training and how a trainee interacts with the system are represented through several activity diagrams (Figures 23 to 25).

In contrast to conventional training (Section 4.2.1), VR training enables several task rehearsals following the part-task training method which enables separately practising each of the motor skills that are relevant for fine grinding and polishing tasks, and whole-task training. Moreover throughout VR training, a much more accurate concurrent augmented feedback can be provided when compared to that proposed in conventional training (Section 4.2.2). Moreover, that augmented feedback which consists of concurrent KR and KP and terminal KR, is based on an objective evaluation of performance.

The VR training system aims to carry novice trainees from the cognitive stage to a more advanced stage of motor learning such as the associative stage (Section 2.2.2.1). Thus, the VR training system intends to form advanced performers for whom motor learning throughout conventional training will not result as problematic as for novice performers (Section 4.2.2).

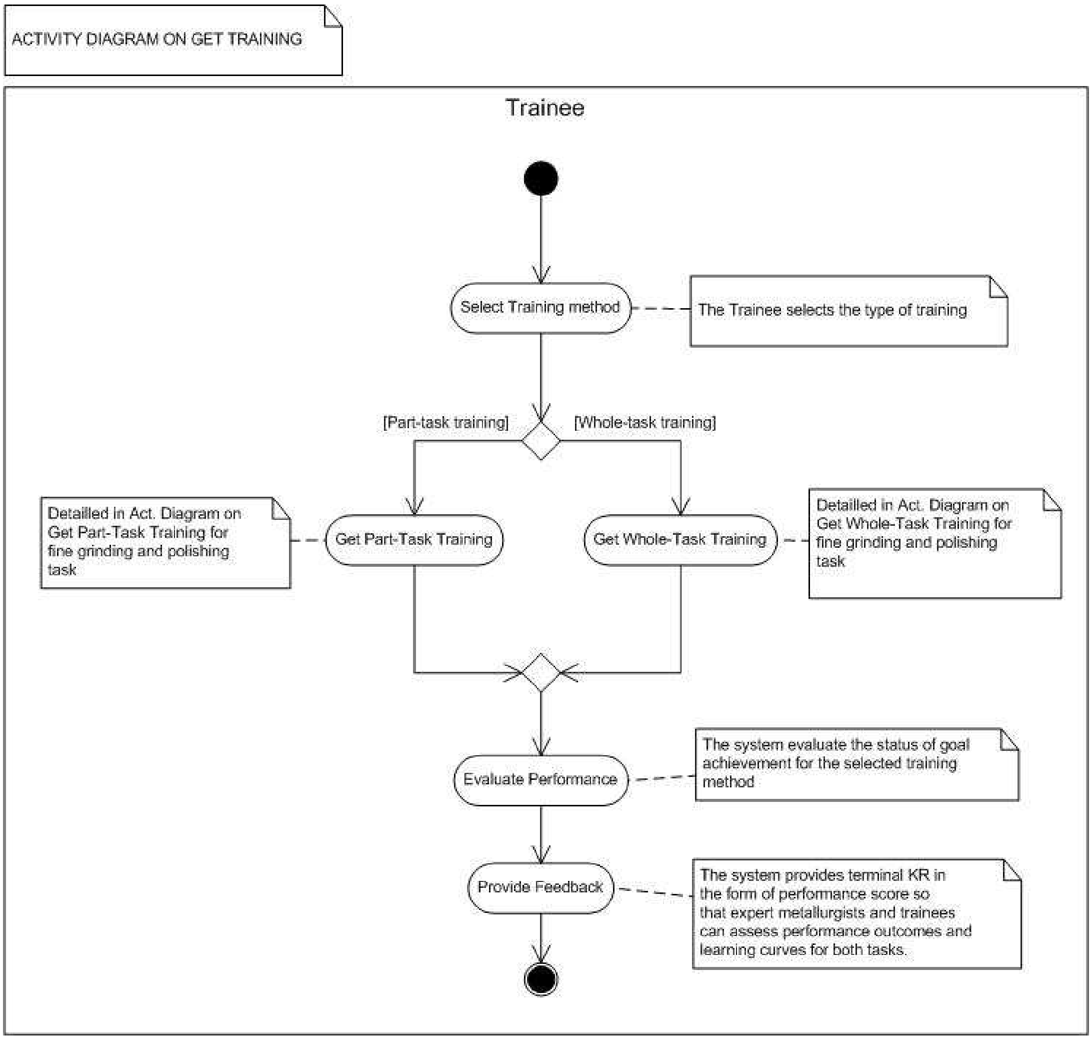

Figure 22. Activity diagram which represents the stepwise actions carried out during VR training. The trainee must first select the training method for the desired task. Secondly, the trainee practices the task in VR according to the selected training method. Finally, the trainee and the expert metallurgist receive augmented feedback in the form of performance score displayed in an evaluation system of the ManuVAR platform (Appendix C).

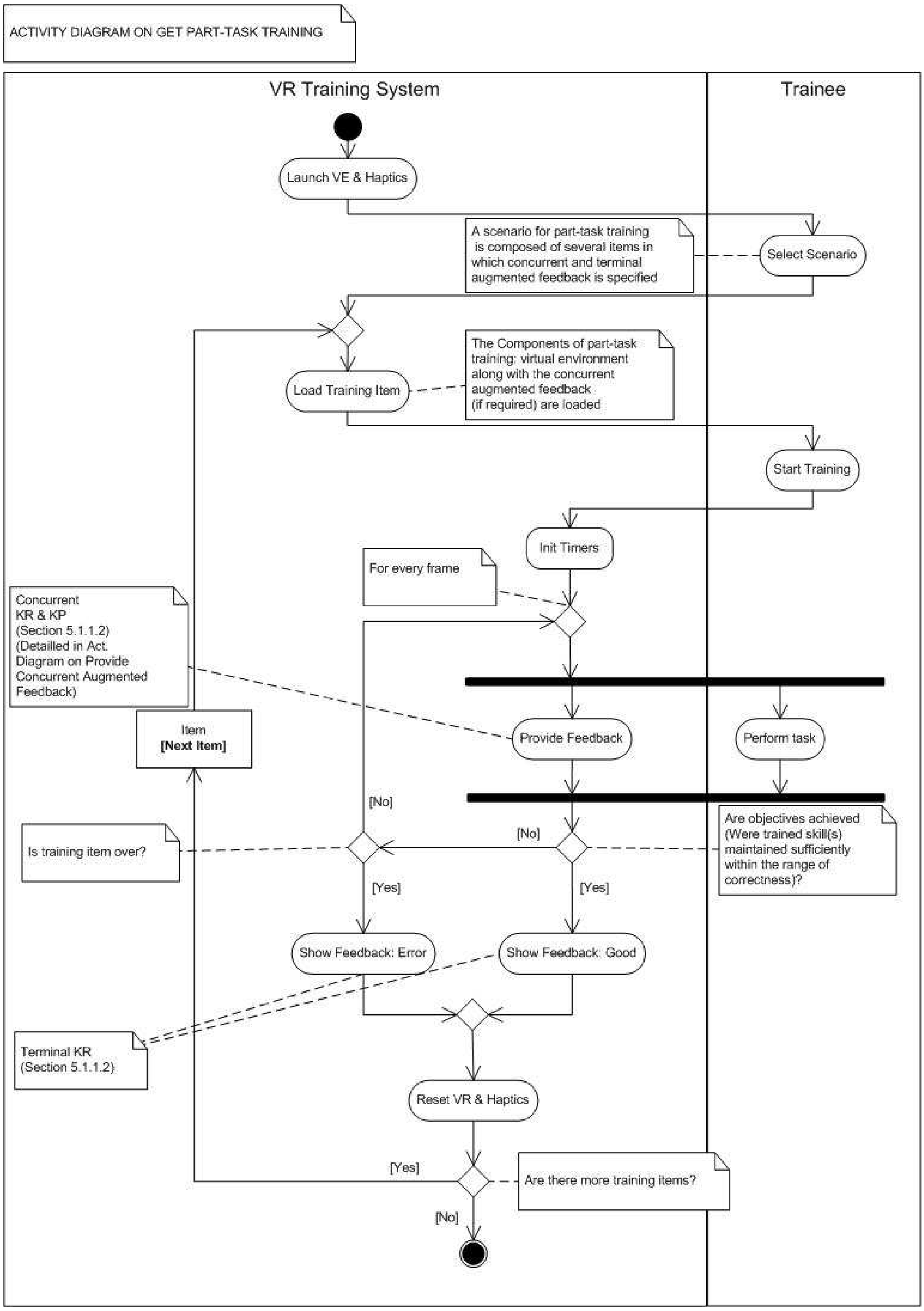

Figure 23. Activity diagram for the part-task training method.

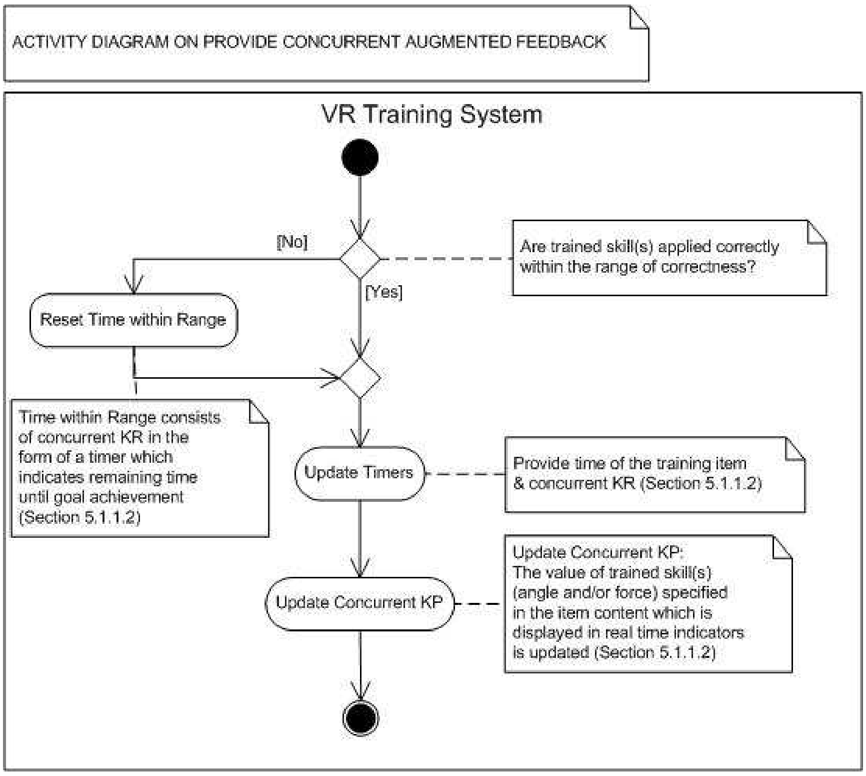

Figure 24. Activity diagram for providing concurrent augmented feedback in the form of KR and KP throughout part-task training.

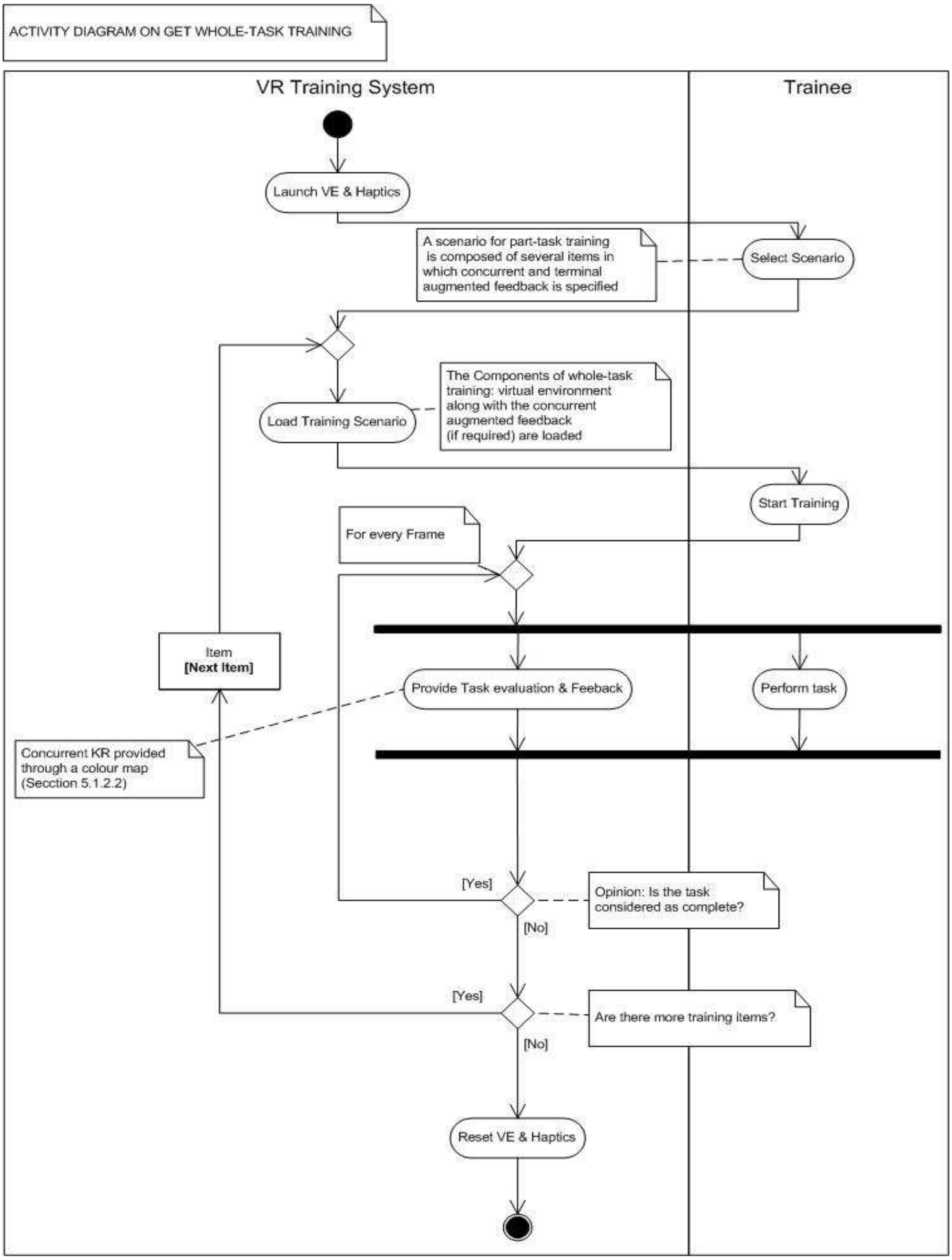

Figure 25. Activity diagram for the whole-task training method.

4.3.3 Requirement analysis

Interviews with two expert metallurgists and the rest of the professional team from Tecnatom S.A. enabled the capture of a series of customer requirements that specify their needs and what they expected from the VR training system. Customer requirements were translated into a set of functional requirements which define what the system must be able to achieve and how it must be achieved. Table 4 details the functional requirements of the VR training system and Figure 26 depicts the hierarchical relationships of those requirements associated to the system use cases (Figure 21) that satisfied them.

Table 4. Requirements of the proposed VR training system.

Id	Name	Description	Rationale	Verification	Related to
Req. 1	Simulate grinding	The system must be capable of simulating fine grinding operations.	The simulation of the task is required to perform training on independent motor skills and whole-task training.	A trainee performs the training task according to a parameterization specified by expert metallurgists.	Simulation (Req. 17)
Req. 2	Simulate polishing	The system must be capable of simulating polishing operations	The simulation of the task is required to perform training on independent motor skills and whole-task training	A trainee performs the training task according to a parameterization specified by expert metallurgists	Simulation (Req. 17)
Req. 4	Haptic feedback	The system must provide haptic feedback when performing on a material surface.	Haptic feedback is needed for an effective training on motor skills and performance of task.	Verified when its sons are verified.	Geometry (Req. 14)
Req. 5	Task feedback	The system must provide visual feedback of how the replica is being performed.		Verified when its sons are verified.	
Req. 7	Stereoscopic visualization	The system must present the virtual environment on a stereoscopic display.	Stereoscopic visualization is needed to perform the manual task as it enhances depth perception in the 3D environment.	The visualization element enables to stereoscopically visualize the virtual environment in 3D. The stereoscopic cues can be activated and deactivated.	Simulation (Req. 17)

Id	Name	Description	Rationale	Verification	Related to
Req. 8	POV tracking	The system must present the virtual environment according to the position of the trainee's point of view.	Movement parallax is needed to enhance the realism of the virtual environment.	The point of view of the trainee is tracked and the components of the virtual environment are reported to be static when the trainee moves.	Stereoscopic visualization (Req. 7)
Req. 11	Noise	The system must be capable of reproducing ambient noise.	The ambient noise would enable surrounding the trainee in an industrial facility that cannot be seen but heard.	The system reproduces the provided industrial noises.	Environment (Req. 31)
Req. 12	Light	The system must be capable of simulating several ambient light conditions.	Various illumination configurations can be setup in the system.	Different levels of environmental illumination are shown and expert metallurgists report about the realism.	Environment (Req. 31)
Req. 13	Dust	The system must be capable of simulating dust in the air.	The system should simulate various level of dust into the virtual environment to make difficult the performance of the task.	Different levels of environmental dust are presented and expert metallurgists report about the realism.	Environment (Req. 31)
Req. 14	Geometry	The system must be able to process the geometry of the virtual environment for the simulation of the task.	The system must simulate industrial equipments with arbitrary shape (i.e. complex pipe structures), place the metallographic replica area and simulate the haptic working conditions.	Verified when its sons are verified.	Simulation (Req. 17)

Id	**Name**	**Description**	**Rationale**	**Verification**	**Related to**
Req. 15	Components	The system must be able to represent arbitrary geometries in the virtual environment.	The system must simulate the industrial components with arbitrary shape (i.e. complex pipe structures).	Different components are attempted to be loaded in the virtual environment.	Geometry (Req. 14)
Req. 16	Inspected area	The system must be capable of simulating the inspected area.	The system must simulate the working area, being able to place the metallographic replica area on the component. The area must be a set of several sub-areas surrounded by rough oxide coat layer.	Several components are loaded and the metallographic replica area and rough oxide coat layer must be placed onto it.	Geometry (Req. 14)
Req. 17	Simulation	The system must be capable of simulating the performance of fine grinding and polishing operations on specified components.	The system enables performing grinding and polishing operations on specific components.	Verified when its sons are verified.	Simulation (Req. 17)
Req. 19	Blur	The system must be capable of blurring the visualization due to condensation on protective glasses.	The system must make difficult the performance of the task by simulating the condensation on the personal protective glasses.	Several levels of blur are shown and expert metallurgists report about the realism.	Environment (Req. 31)

Id	**Name**	**Description**	**Rationale**	**Verification**	**Related to**
Req. 25	Final Feedback	The system must provide the final outcome from the performance of the task.	The system must inform the trainee about performance rate at completing the task (Terminal KR). Performance rate consists of a percentage that states for the average completion of the task in the metallographic replica area.	The trainee completes the task and is informed about his/her performance rate through the performance analyzer.	Task feedback (Req. 5)
Req. 26	Training program	The system must support a training program.	The system must enable using a training program to support the development of complex motor skills for the performance of fine grinding and polishing operations.	Verified when its sons are verified.	
Req. 27	RT Feedback	The system must be capable of providing Real time feedback on motor skill performance.	The system must inform in real time the trainee about the correctness of the trained motor skills (concurrent KP & KR).	Trainee practice angle and force skills through a training session. In item 1, only RT feedback on angle is shown; in item 2, only RT feedback on force is shown; in item 3, both RT feedbacks are shown and in item 4 no RT feedback is displayed. (Chapter 6)	Task feedback (Req. 5)
Req. 29	Performance Feedback	The system must provide a real-time and natural feedback on the outcome of task performance.	The system must provide a real time performance feedback stating for the advancement of the task (concurrent KR). The feedback is provided in the form of a colour map laid onto the metallographic replica area. Moreover, the colour map can be also magnified and displayed in a lateral window.	Expert metallurgists perform the tasks and report for the realism of the provided feedback.	Task feedback (Req. 5)

Id	Name	Description	Rationale	Verification	Related to
Req. 31	Environment	The system must be capable of simulating the configuration of the virtual environment.	The simulation must be capable of simulating the environmental setup within the virtual environment.	The configuration is loaded in the virtual environment.	Simulation (Req. 17)
Req. 32	Skills training	The system must be capable of supporting part-task training of motor skills.	The system must enable training complex motor skills (angle and force) in an independent and concurrent manner (part-task training).	Verified when its sons are verified.	Training program (Req. 26)
Req. 37	Tool noise	The system must be capable of reproducing realistic sounds produced by the power tool operating.	The system must improve the realism of the performance of the task by reproducing the sounds generated by real power tool when operating on the material surface and when rotating freely.	The trainee reports about the changes of noises when the rotating wheel of the virtual power tool is in contact or not with the material surface.	Environment (Req. 31)
Req. 38	Vibration	The system must simulate the rotary vibrations of the power tool.	The system must enhance the realism of the performance by simulating vibrations resulting from the functioning of the power tool.	Expert metallurgists perform the tasks and report about the realism of the vibrations.	Haptic feedback (Req. 4)
Req. 39	Item Feedback	The System shall provide feedback at the end of each training item indicating to the trainee whether he/she has performed well or bad.	The system must state for the correct or incorrect performance of the motor skills training (Terminal KR).	Trainees perform the motor skill training and receive information concerning goal achievement after each training item (Green Tick for good performance and red cross for bad performance).	Task feedback (Req. 5)

Id	Name	Description	Rationale	Verification	Related to
Req. 40	Tangential force	The system must simulate tangential forces as a function of force and angle applied on the material surface.	The system must enhance the realism of task simulating the tangential forces resulting from the contact of the rotating wheel over the material surface.	Expert metallurgists perform the tasks and report about the realism of the tangential forces.	Haptic feedback (Req. 4)
Req. 41	Whole-task training	The system must be capable of providing whole-task training.	The system must provide training on the performance of fine grinding and polishing tasks as they are usually performed in real industrial contexts.	Trainees perform whole-task training for fine grinding and polishing operations. Their performance results improved by this training.	Training program (Req. 26)
Req. 42	Angle	The system must be capable of providing training on angle skill.	The system must enable training angle skill separately.	The trainee trains on tool inclination.	Skills training (Req. 32)
Req. 43	Force	The system must be capable of providing training on force skill.	The system must enable training force skill independently	The trainee trains on applying force on the material surface.	Skills training (Req. 32)
Req. 44	Tools	The system must be capable of simulating the geometry of power tool.	The system must simulate the geometry the Proxxon rotary tool with a right angle attachment equipped with a tool consumable.	The tool geometry can be load in the virtual environment and expert metallurgists report about the realism.	Geometry (Req. 14)

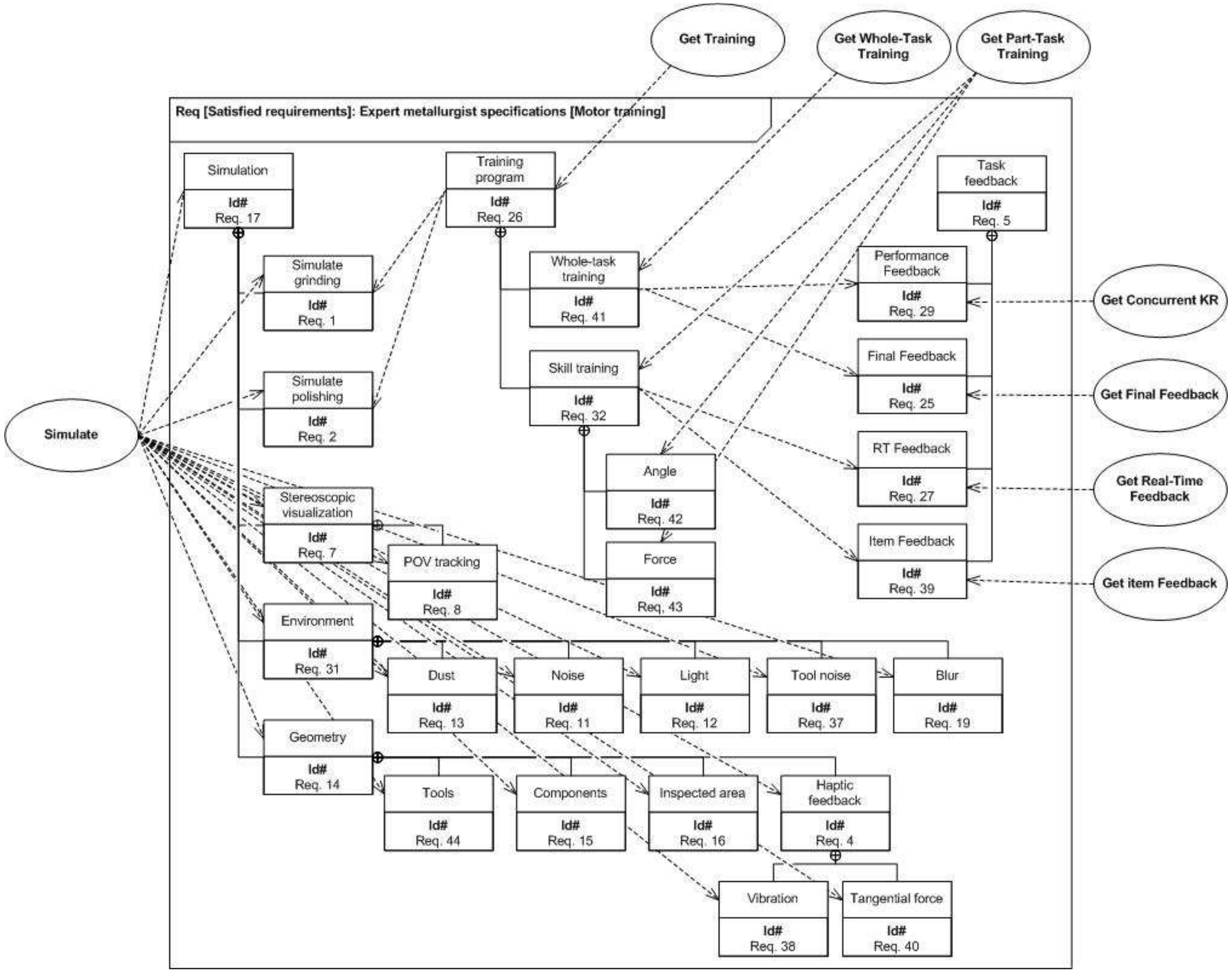

Figure 26. Hierarchical representation of functional requirements associated to VR training system use cases that satisfied them.

4.4 CONCLUSION

This chapter has presented the modeling of a VR training system which aims to support the development of motor programs for effective performance of fine grinding and polishing tasks. First, the metallographic replica technique during which fine grinding and polishing tasks are conducted to prepare the surface of the inspected materials was described. Second, the state of the current training for fine grinding and polishing operations was reviewed, and several issues in that training have been highlighted. Third, a detailed methodology which consists of functional and requirement analyses and aims to provide guidelines for the development of the VR training system has been presented.

Later in this thesis, the VR training system is presented along with a training toolkit that enables building training programs which allow practising those motor skills that are relevant for the performance of fine grinding and polishing tasks through part-task and whole-task training. The training toolkit also permits enhancing VR training with concurrent and terminal augmented feedback. The resulting design and development of the VR training system are presented in the chapter 5.

Chapter 5. Design of the Methods

In chapter 4, functional analysis was carried out for tasks involved in the metallographic replica technique as well as in conventional training procedures. Then, a requirement analysis was presented and a VR training system for supplementing that conventional training has been specified. These specifications are focused in a VR training system which aims to support the development of angle and force skills using haptic force feedback through part-task and whole-task training. This system also enables the provision of augmented feedback in the form of concurrent and terminal Knowledge of Results (KR) and Knowledge of Performance (KP) (Section 2.4.2) that are usually not available in real operating environments.

First, this chapter presents the resulting design of the VR training system. It proposes a training toolkit which enables building training programs to support the learning of angle and force skills through the VR training system (Section 5.1), along with the haptic simulation of operating conditions of the precision rotary tool employed in fine grinding and polishing tasks (Section 5.2). Then, the implementation of a model for the performance of both tasks in VR is described (Section 5.3) along with the methodology which has been followed to determine the values of the parameters of that model (Section 5.4).

5.1 TRAINING TOOLKIT

As mentioned previously, the training toolkit allows building training programs which enable applying fundamental training methods such as part-task and whole-task training to the context of VR (Sections 5.1.1 & 5.1.2) and allows providing augmented feedback throughout the training process. That augmented feedback consists of KR and KP. On the one hand, concurrent KR and KP, and terminal KR in the form of visual and audio indication can be scheduled throughout part-task training (Section 5.1.1.2). On the other hand, concurrent KR in the form of a colour map to inform in real-time about the status of task completion and terminal KR as performance scores can be both provided throughout whole-task training (Section 5.1.2.2). Figure 27 offers an overview of the functionalities supported by the VR training system and proposed by the training toolkit.

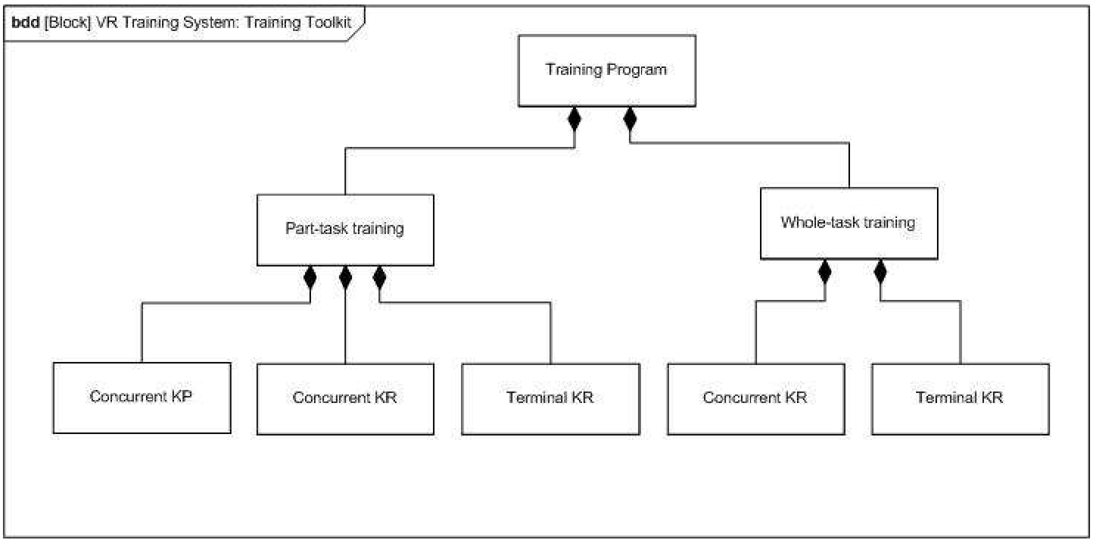

Figure 27. The VR training system enables carrying out the VR training suggested through a training program built with the training toolkit. Training programs encompass part-task and/or whole-task training throughout which augmented feedback can be provided.

Later in this thesis, the effectiveness of the VR training system to support the development of motor skills that are relevant in fine grinding and polishing tasks will be investigated (Chapters 6 & 7). To do so, a training program based on part-task training and whole-task training enhanced with concurrent and terminal augmented feedback will be specifically designed.

5.1.1 Part-task training method

Part-task training aims at the development of accurate fine motor skills such as angle and force skills for the performance of fine grinding and polishing tasks. Such discrete skills that are usually trained simultaneously in the real world, can be here broken down into several part-task components in order to be practised separately, and then progressively combined in order to build anew the whole-target task (Section 2.3.3). Moreover, concurrent and terminal augmented feedback can be provided in order to support motor learning.

5.1.1.1 Part-task training design

Part-task training proposes a set of training items through which angle and force skills can be practised. The sequence of those items is recommended to consider a design inspired by progressive-part practices of fractionized and simplified skills (Section 2.3.3). Thus, angle and force skills can be performed separately throughout first training items and then combined in order to be practised together.

In each training item, trainees are required to exert force and angle the virtual precision rotary tool on the surface of the inspected material within the metallographic replica area displayed in the virtual environment (Figure 28). Haptic interaction within the virtual environment is supported by a haptic device which mimics the operating conditions of a real precision rotary tool (Section 5.2). Trainees are requested to maintain the trained skill(s), within specific ranges, continuously for a prolonged period of time. Information about ranges for angle and force skills and the time during which the trained skill(s) must be maintained in range can be displayed in the form of graphical and textual instructions from the beginning of the item (Figure 28). Recommendations for threshold values of these ranges are made in section 5.4.2.

A right lateral panel provides support to display concurrent augmented feedback indicators (Figure 28). Concurrent KP and KR inform respectively about accuracy of the trained skill(s) and remaining time within range before the item goal is achieved (Section 5.1.1.2). The ranges for angle and force skills can be also notified in concurrent KP indicators.

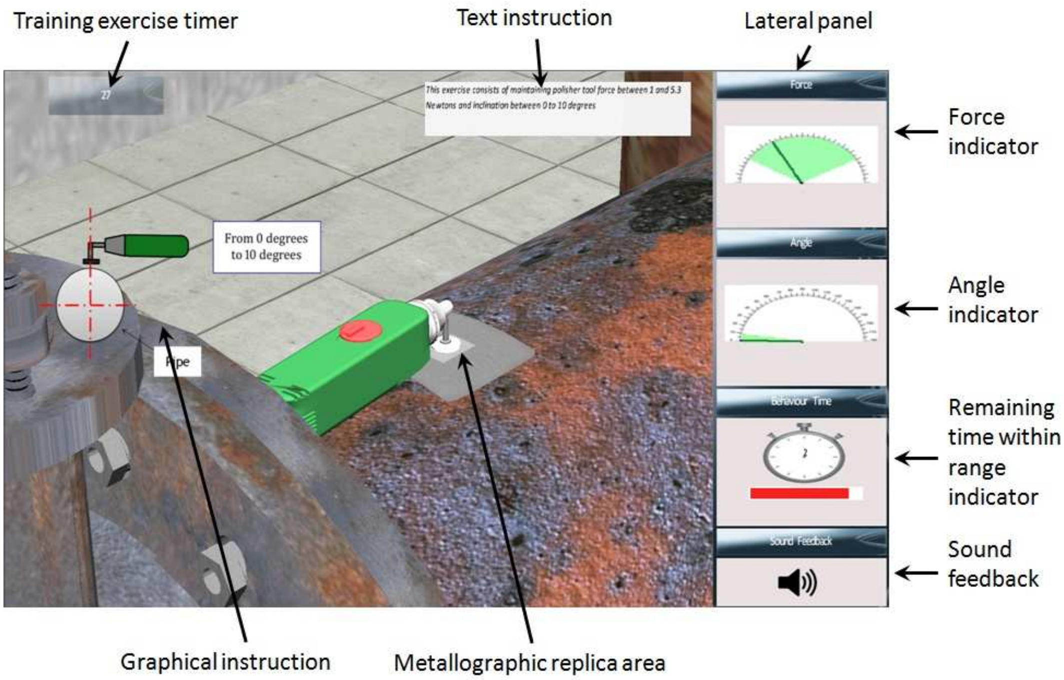

Figure 28. The part-task training interface

Part-task training aims to support motor learning throughout several rehearsals of training items. However, training items may often appear too challenging at an early stage of learning hindering the formation of motor programs for accurate performance of angle and force skills (Section 2.3.1). For this reason, it is recommended that the performance of training items is simplified at the early learning stage. That simplification consists of decreasing the level of difficulty by withdrawing the motion pattern usually carried out during the performance of fine grinding and polishing tasks in real operating environments. Thus, through several training items, angle and force skills can be practised while maintaining the virtual precision rotary tool in a fixed position. Nonetheless, the level of difficulty of items is recommended to be increased in order to make part-task training more challenging once the trainee's performance becomes more proficient. Therefore, angle and force skills are then suggested to be practised while attempting moving the virtual precision rotary tool across the metallographic replica area according to motion patterns usually carried out in real operating environments. Figure 29 details the proposed part-task training method with and without simplification of the motion pattern.

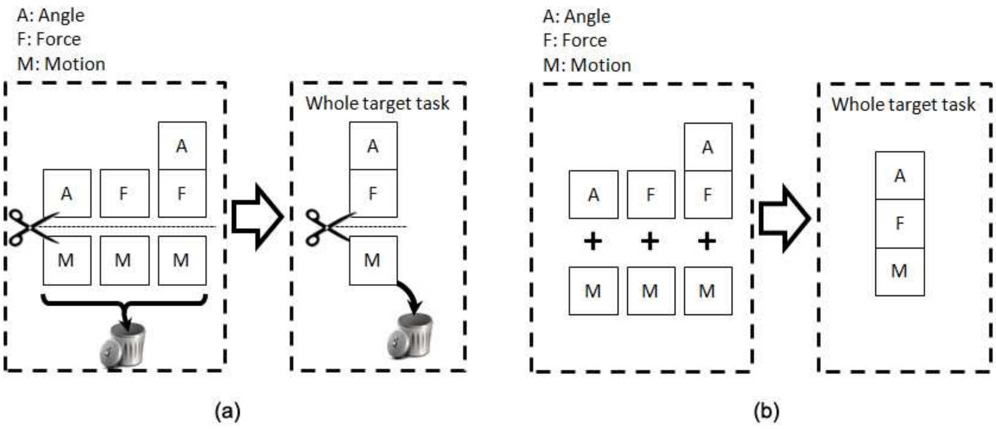

Figure 29. Part-task training method which consists of (a) a progressive-part practice of fractionized angle and force skills with motion pattern simplification; and (b) progressive-part practice of fractionized angle and force skills including motion pattern.

The effectiveness of part-task training to support motor learning has been investigated through the experimental study presented in chapter 6. Part task training consisted of progressive-part practice of fractionized angle and force skills through exercises composed of several training items. The motion pattern was simplified at the early learning stage and then integrated into the training design as shown in Figure 29.

5.1.1.2 Augmented feedback

The VR training system allows enhancing part-task training with concurrent KP and KR and terminal KR (Figure 27). As mentioned previously, concurrent KP and KR state respectively for the accuracy of the trained skill(s) and the status of the achievement of the item goal. Terminal KR indicates whether the item goal has been achieved or not. These types of augmented feedback can be scheduled throughout part-task training. Figure 30 presents a block diagram[3] which represents the settings of augmented feedback for part-task training.

[3] Block diagrams is part of the Unified Modelling Language (Chonoles & Schardt, 2003) and its extension for Systems Engineering, SysML (Friedenthal et al., 2008).

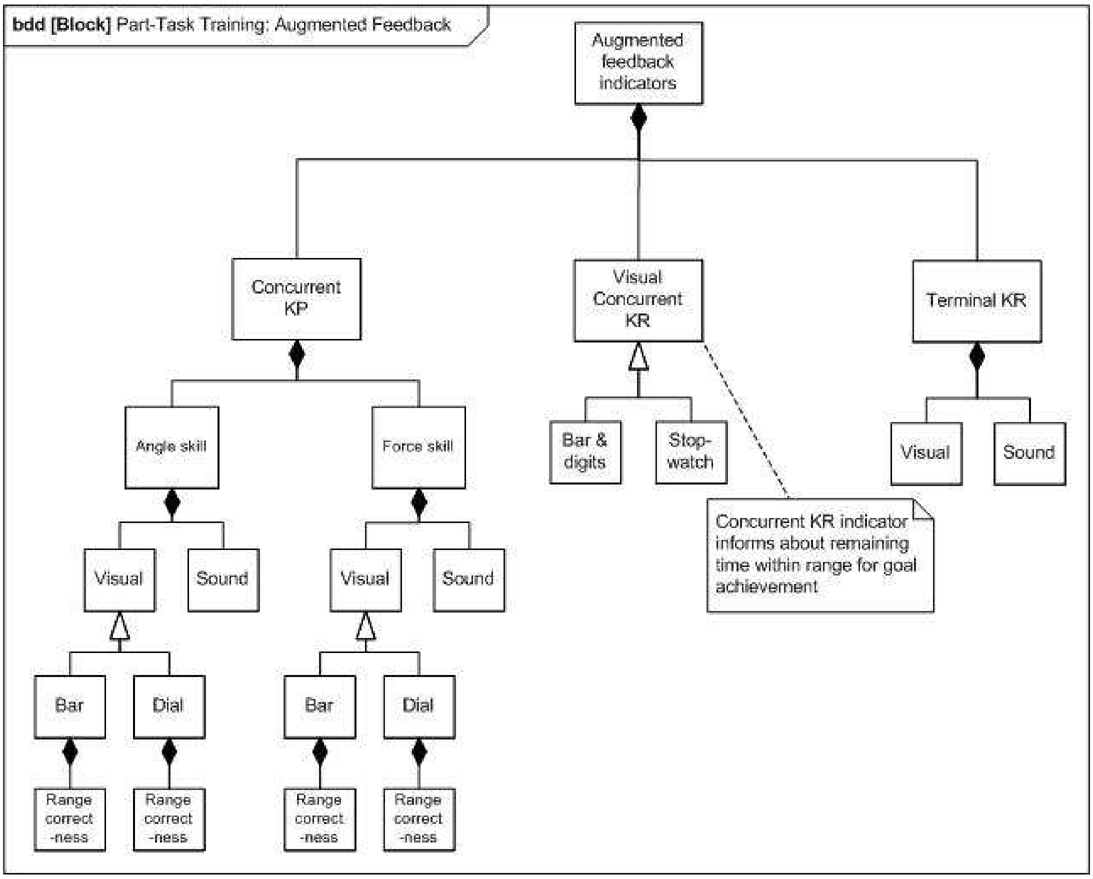

Figure 30. Configuration of augmented feedback indicators in part-task training[4].

As mentioned previously in section 5.1.1.1, concurrent KP and KR are displayed in a right lateral panel (Figure 28). Concurrent KP consists of (1) visual indicators which show in real-time the angle (Figures 31 & 32) and the force (Figures 33 & 34) being applied on the material surface through the haptic device and (2) a sound indicator that indicate instantaneously whether the trained skill(s) are within the required ranges (Figure 35). Visual indicators can be configured manually as a vertical bar (Figures 31 & 33) or a dial gauge (Figures 32 & 34) through a selection button located below the indicator. Moreover, these indicators can also display the ranges which refer to the targeted angle and force skills (Figures 31.b, 32.b, 33.b & 34.b). The range of a skill is bounded by two grey lines on a vertical bar indicator (Figures 31.b & 33.b) and marked as green area on a dial gauge (Figures

[4] SysML Glossary:

Generalization: defines an inheritance relationship between two block features

Composite aggregation: defines the property of a feature (i.e. the range of correctness is a property of the visual indicator of concurrent KP. The lack of indication of the range of correctness does not alter the functionality of the indicator).

32.b & 34.b). Audio KP can be activated and deactivated through a selection button located at the bottom of the right lateral (Figure 35). Figures 31 to 35 show the possible configuration of the concurrent KP presented in the right lateral panel.

Figure 31. Bar indicator for angle skill with (a) no reference of correctness to indicate targeted angle and with (b) two grey lines to mark the boundaries of the range for angle skill.

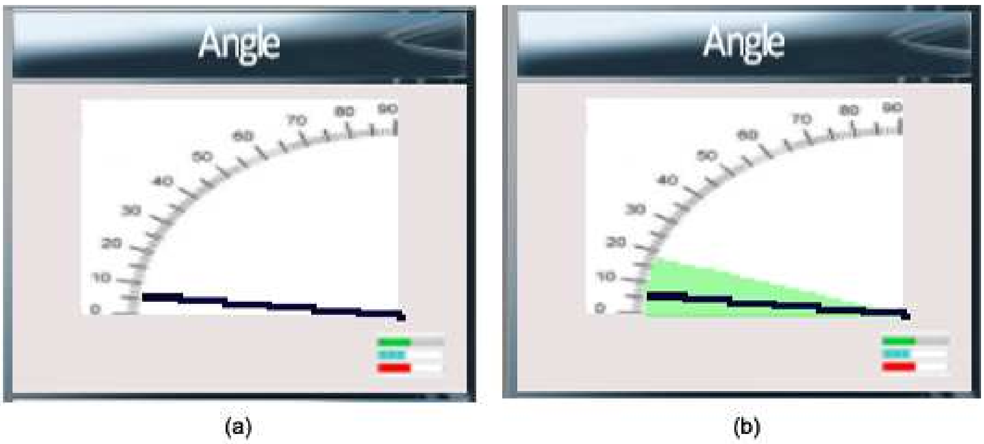

Figure 32. Dial indicator for angle skill with (a) no reference of correctness to indicate targeted angle and with (b) a green area to show the range for angle skill.

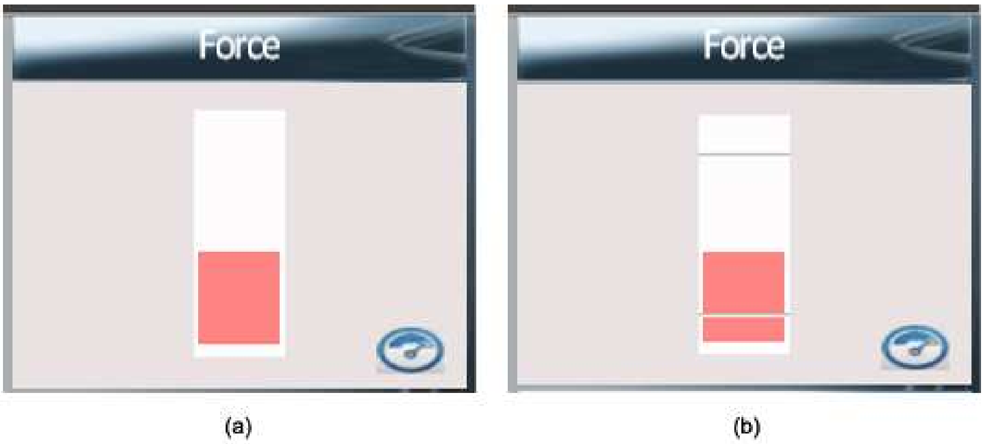

Figure 33. Bar indicator for force skill with (a) no reference of correctness to indicate targeted force and with (b) two grey lines to mark the boundaries of the range for force skill.

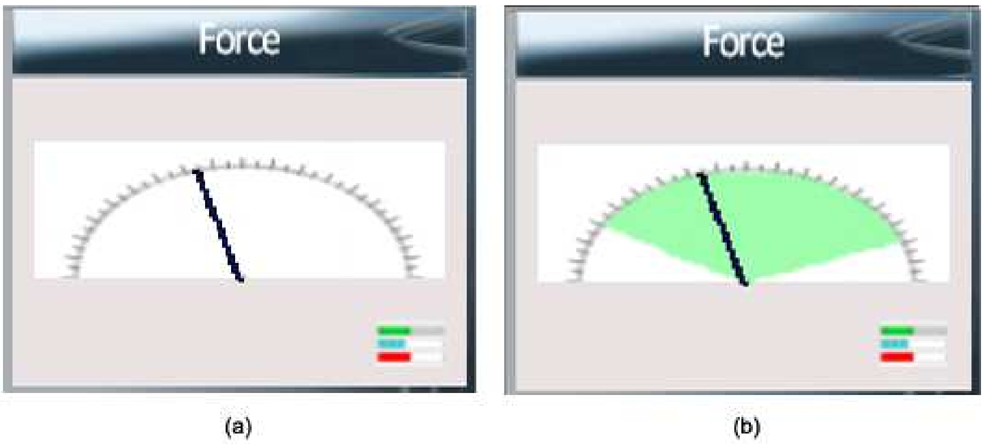

Figure 34. Dial indicator for force skill with (a) no reference of correctness to indicate targeted force and with (b) a green area to show the range for force skill.

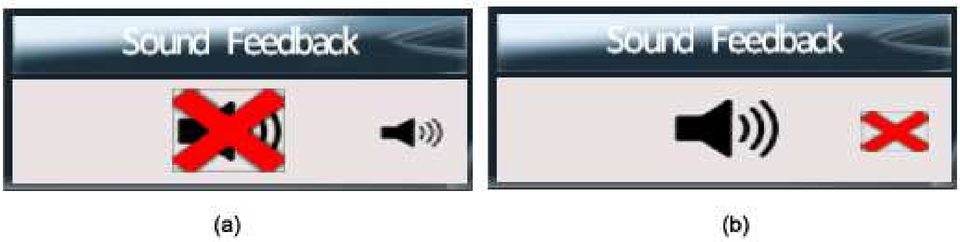

Figure 35. Sound indicator to inform in real time whether angle and/or force skills are within ranges: (a) deactivated and (b) activated.

The effectiveness of concurrent KP indicators to support the successful development of angle and force skills was investigated through a user evaluation test carried out by the Human Factors Research Group at the University of Nottingham (Langley et al., 2011). Visual concurrent KP indicators were found to result in significant performance improvements throughout VR training. However, no significant differences between the suggested configurations, bar or dial, were reported. Thus, all visual indicator configurations can be considered similarly effective for motor learning. However, no significant training effects were found for audio concurrent KP.

Throughout part-task training, information about the remaining time during which angle and force skills must be maintained within range is considered as Knowledge of Results (KR) which indicates in real-time the status of goal achievement. Thus, concurrent KR consists of a visual indication of the remaining time within range before the achievement of the item goal. That indicator is referred to as behaviour time (Figure 36) and represents a countdown until goal achievement. That countdown is activated when the trained skill(s) is placed within the desired range. As soon as the performance of the trained skill(s) becomes inaccurate, the countdown is reset. As with concurrent KP, concurrent KR indicator can be set manually as a progress bar along with a stopwatch (Figure 36.a), or a clock (Figure 36.b), through a selection button located below the indicator. The time displayed by the indicator when configured as a clock, (Figure 36.b) is relative. This means that the clock indicates the ratio of completion of the item goal rather than the time. A clock revolution means that the item goal has been achieved. The trainee has been thus able to maintain the trained skill(s) within the desired range for the targeted period of time.

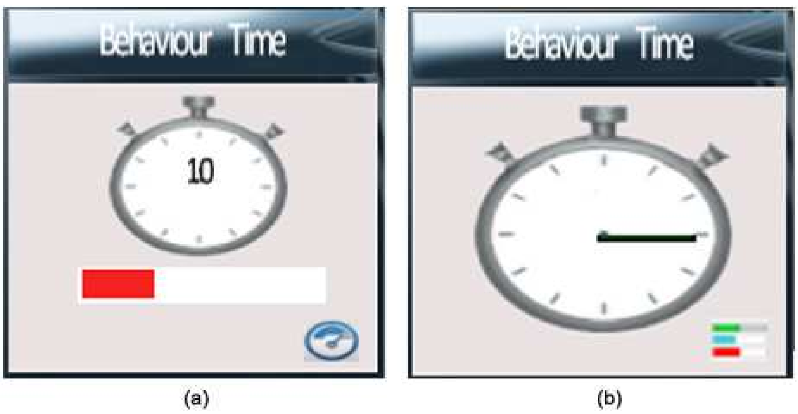

Figure 36. Indicator of the remaining time within range, in the form of (a) a progress bar along with a stopwatch and (b) a clock, to indicate the remaining time before goal achievement when the trained skill(s) are accurately performed.

The VR training system can also provide terminal KR after the completion of a training item. Terminal KR is referred as item feedback and indicates whether the item objective has been achieved or not. Terminal KR can be provided in the form of visual and/or auditory information that aim to positively or negatively reinforce the trainee's performance. When the item goal has been achieved, a green tick is displayed and/or a "*ding*" sound is reproduced (Figure 37.a). In contrast, when the item goal could not be achieved, a red cross is shown and/or an unpleasant "*buzz*" sound is played (Figure 37.b).

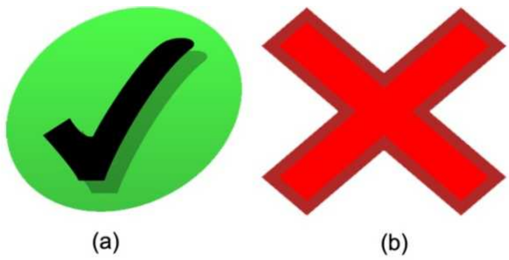

Figure 37. Visual terminal KR provided at completing a training item: (a) positive reinforcement and (b) negative reinforcement.

Despite augmented feedback in the form of KP and KR is considered as a prominent feature of motor learning throughout VR training, it has been demonstrated that when provided too frequently, it tends to hamper the processing of intrinsic information feedback for the formation of accurate motor programs (Section 2.4.2). The suggested part-task training should encourage trainees to rely on intrinsic feedback. To do so, augmented feedback should be scheduled throughout part-task training. At an early learning stage, if no augmented feedback is presented, part-task training may be particularly challenging. Thus, augmented feedback must be provided at that stage of motor learning. However, when the performance of the trained skill(s) becomes more proficient, part-task training enhanced with augmented feedback may be not challenging enough. Thus, trainees may not be encouraged to rely on their intrinsic sensations. For this reason, at more advanced stages of motor learning, augmented feedback should be withdrawn from part-task training. Thus, augmented feedback is recommended to be gradually withdrawn throughout part-task training in order to maintain the training challenging and ensure effective motor learning throughout all learning stages. Table 5 presents an example of the scheduling of augmented feedback throughout several items of part-task training.

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Table 5. Schedule of the augmented feedback throughout part-task training.

Items	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Trained Skill(s)	A	F	A&F	A	F	A&F	A	F	A&F	A	F	A&F	A	F	A&F	A	F	A&F
Concurrent KP: Angle & Force																		
Angle (bar/dial)	X_T		X_T	X_T		X_T												
Angle (Sound)	X		X				X		X									
Force (bar/dial)		X_T	X_T		X_T	X_T												
Force(Sound)		X	X					X	X									
Concurrent KR: Remaining time within range																		
Bar & Stopwatch/ Clock	X	X	X	X	X	X	X	X	X	X	X	X						
Terminal KR																		
Visual	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			
Sound	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			

A Angle
F Force
A&F Angle & Force

X_T Visual concurrent KP indicator displayed with the desired range which indicates the targeted skill

X Indicator shown with no range

The experimental study presented in chapter 6 investigated the effectiveness of the VR training system to support motor learning through part-task training. The suggested part-task training design consisted of several rehearsals of 4 items in which trainees were required to maintain angle and force skills within range, continuously for 15 seconds. In items 1, 2 and 3, angle, force, and angle and force were respectively trained and concurrent augmented feedback in the form of KR and KP was provided. In training item 4, angle and force skills were exercised simultaneously however concurrent KP indicators were withdrawn. After each item, terminal KR was provided in order to inform about whether the item goal has been achieved or not.

5.1.2 Whole-task training method

Whole-task training allows training on the performance of fine grinding and polishing tasks alike in real operating environments. Thus, whole-task training that is built upon angle and force skills acquired through previous part-task training (Section 5.1.1) enables applying the trained motor skills to the context of the performance of a whole task.

The VR training system aims to provide a realistic representation of fine grinding and polishing tasks by simulating the intrinsic information in a similar way as to how it is perceived in the real world. As in part-task training, a haptic device is used to interact within the virtual environment and mimic operating conditions of a real precision rotary tool (Section 5.2). Moreover, the VR training system allows supplementing intrinsic information with augmented feedback throughout the whole-task training. That augmented feedback consists of concurrent KR which is provided in the form of a colour map indicator that shows the performance outcome and enables visualizing task completion and therefore task progress over the time (Section 5.1.2.2). Finally, the VR training system can also provide terminal KR in the form of performance scores displayed in a module of the ManuVAR platform (Appendix C) in order to inform about achievement of the task objective.

5.1.2.1 Whole-task training design

The training toolkit enables configuring the whole-task training carried out on the VR training system. Several features are proposed by default. Those default features have been set heuristically by two expert metallurgists from Tecnatom S.A. However, these features can be adjusted in order to customize the whole-task training. Figure 38 presents a block diagram[5] which details the features that parameterize the whole-task training.

[5] Block diagrams is part of the Unified Modelling Language (Chonoles & Schardt, 2003) and its extension for Systems Engineering, SysML (Friedenthal et al., 2008).

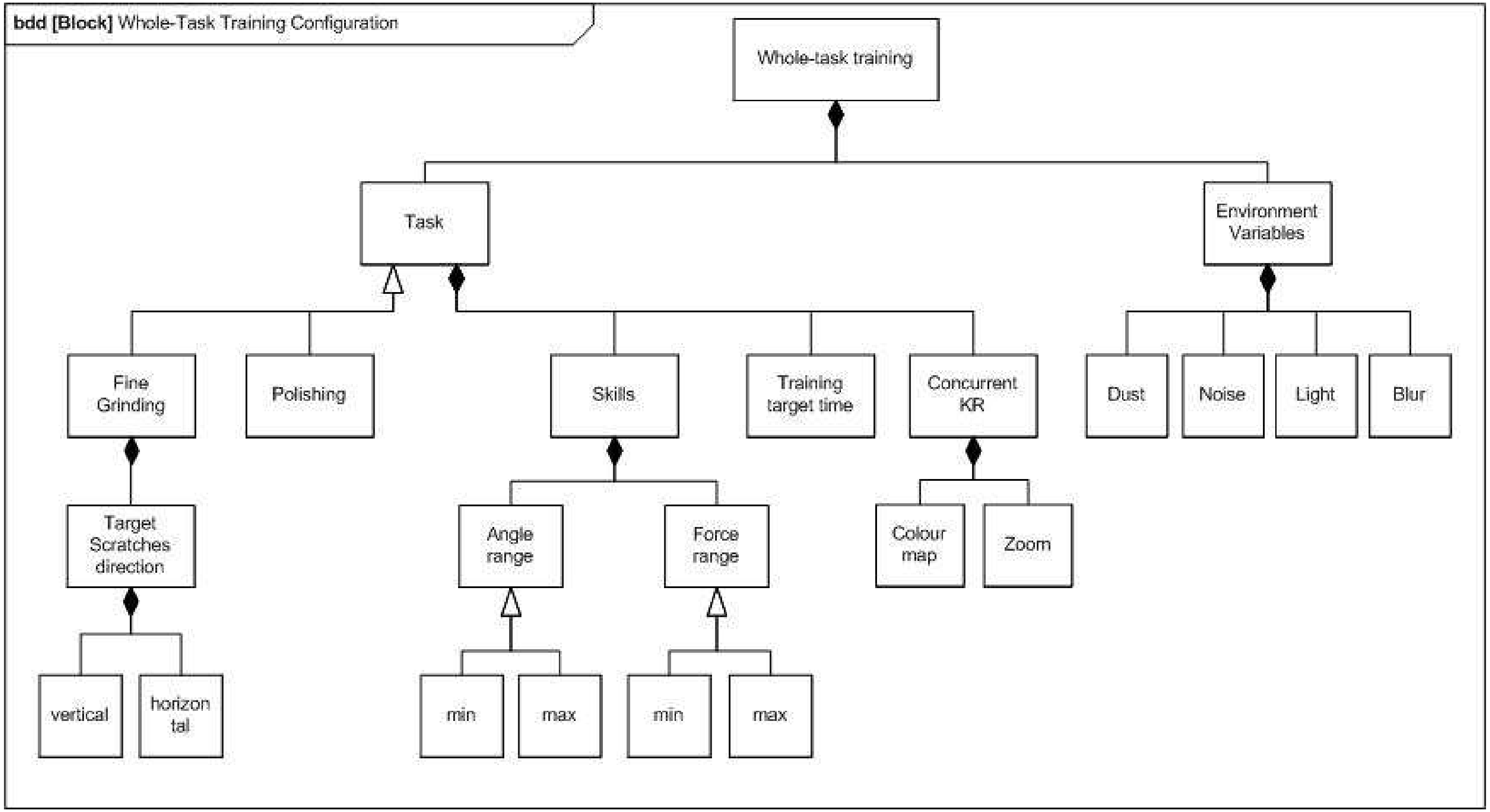

Figure 38. Features for the configuration of whole-task training.

The training toolkit allows setting the performance of the trained task along with ambient conditions of the virtual environment. Ambient conditions are listed below.

1. The blur level which sets the amount of steam accumulated on the protective glasses worn by the performer in the virtual environment.
2. The level of lighting of the virtual environment
3. The noise level which specifies the amount of ambient noise in the surroundings of the performer.
4. The dust level which defines the density of dust particles floating in the air.

The degree of each ambient condition is defined in the range [0,100].

The configuration of task performance is defined by the parameters expressed below:

1. The nature of the task to be trained which can be set either to fine grinding or to polishing.
2. The ranges for angle and force skills (recommendations for threshold values of these ranges for fine grinding and polishing tasks are made in section 5.4.2).
3. The target time to complete the whole-task training.
4. The concurrent KR which is provided in the form of a colour map that indicates the progression of the trained task (Section 5.1.2.2). That colour map can be displayed onto the metallographic replica area and/or magnified in a right lateral board in the virtual environment (Figure 39). The magnified view of the colour map enables visualizing in real-time the outcome of angle and force being applied with no need for the tool disc to be taken out from the surface of the material.

Figure 39. Whole-task training configured for a polishing task (angle range [0º, 10º], force range [1, 5N]; Target training time ≈ 3 min; Concurrent KR presented on the material surface and magnified on the right side).

5.1.2.2 *Colour map*

The colour map aims to inform about the status of the completion of the task being performed. The concept of colour map is inspired by thermal mapping which is an intuitive way to represent the spatial distribution of an attribute using colour coding. Thermal mapping has been extensively employed in the preventive and predictive inspection of industrial facilities (i.e. high voltage wiring and coil inspection) (Fluke Corp., 2009).

The colour map proposed throughout the whole-task training uses by default a gradual colour coding from red to green to indicate about the status of the task completion across the metallographic replica area. Red corresponds to 0% of task completion, bright green represents 100% of task completion, and shades of orange and yellow are used to show intermediate levels of task completion (Figure 40).

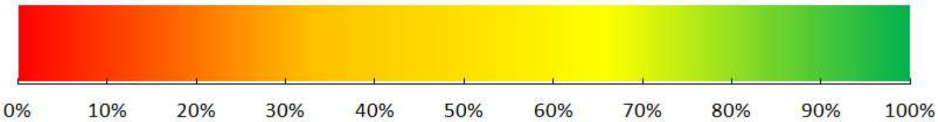

Figure 40. Default colour coding used in the colour map to indicate task progress across the metallographic replica area.

An alternative colour coding can be set for colour-blind people. Instead of using a gradual colour scale from red to green, the colour map can use a gradual colour coding of white for 0% of task completion, and black for 100% of task completion, with shades of grey for intermediate levels of task completion (Figure 41). Colour map can be switched from one colour coding to the other by pressing the key “G” on the keyboard.

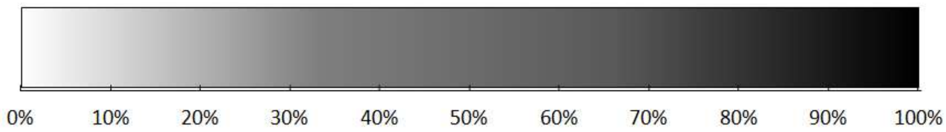

Figure 41. Alternative colour coding used in the colour map to indicate task progress across the metallographic replica area (adapted for colour-blind people).

In the virtual environment in which whole-task training is carried out, the colour map consist of a 64 ×64 pixel texture mapped on the working area on the material surface. That working area is squared (W: 70 × H: 70 mm) and encompasses the metallographic replica area (W: 30 × H: 45 mm) in which fine grinding and polishing operations must be achieved (Section 4.1.2). Figure 42 shows the working area that encompasses the metallographic replica area in which the trained task must be performed.

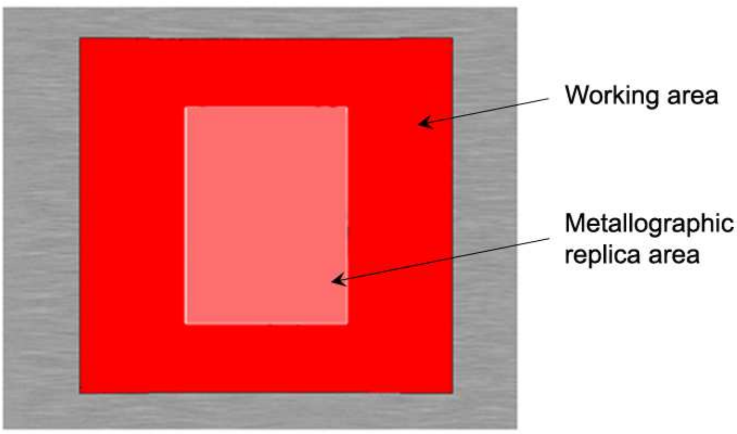

Figure 42. Colour map set on the material surface.

5.1.2.3 Modelling of task performance

Each pixel from the colour map texture is associated to an element of the matrix $A_{64\times 64}(n)$:

$$A(n) = \begin{bmatrix} a_{1,1}(n) & \cdots & a_{1,64}(n) \\ \vdots & \ddots & \vdots \\ a_{64,1}(n) & \cdots & a_{64,64}(n) \end{bmatrix}$$

The colour of a pixel indicates the status of the task completion in that pixel in accordance with the colour coding presented in section 5.1.2.2. The colour of a pixel is determined by the percentage of task completion stored in the corresponding element of $A_{64\times 64}(n)$. Those percentages values are included between 0% and 100%.

Percentages of task completion stored in elements of $A_{64\times 64}(n)$ are updated when the corresponding pixels on the colour map texture are covered by the disc of the virtual precision rotary tool when operating. Depending on the exerted force and applied angle on the material surface, the tool disc can be completely or partially in contact with the surface of the material. On the one hand, when the tool disc is completely in contact with the material surface, the interaction is represented on the colour map as a circular area (Figure 43.a) in which percentages of task completion corresponding to covered pixels are updated. On the other hand, when the tool disc is partially in contact with the material surface, the interaction is represented on the colour map as a circular segment area (Figure 43.b & c) in which percentages of task completion corresponding to covered pixels are updated. The contact model of the tool disc on the material surface for fine grinding and polishing tasks has been captured from a performance carried out in the real world by the two expert metallurgists from Tecnatom S.A. The methodology followed for the definition of the model of contact of the tool disc on the material surface is described in section 5.4.1.

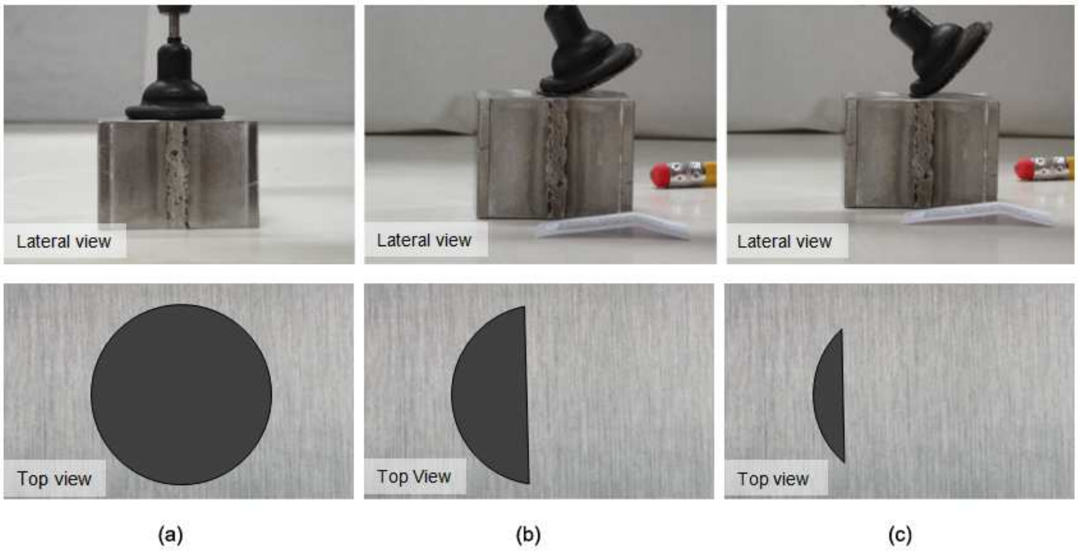

Figure 43. Tool disc when being pressed and inclined so it is (a) completely in contact with the material surface, and (b & c) partially in contact with the material surface.

However, depending on the nature of the trained task, the tool disc interacts differently with the material surface. The interaction is thus depicted distinctly on the colour map texture and percentages of task completion corresponding to covered pixels are updated distinctly for fine grinding and polishing tasks.

The performance of fine grinding generates scratches on the material surface (Section 4.1.2.1). As described previously, a fine grinding task aims for the generation of scratches in a unique direction on the material surface. Appropriate scratches are either horizontal or vertical with regards to the orientation of the metallographic replica area. Thus, two kinds of circular sector on the surface of the abrasive accessory that equipped the tool disc can be defined. In each type of sector, scratches are assumed to be generated in a unique direction.

In the first type of sector, scratches are generated with the desired direction. These sectors are referred as S_+ and are defined by a central angle θ which has been heuristically set to 80º (Figure 44). In the second type of sector, the direction of generated scratches is inappropriate. These sectors are referred as S_- (Figure 44). In sectors S_+, percentages of task completion stored in elements of $A_{64\times64}(n)$ which correspond to colour map pixels being covered are positively updated. Thus, in accordance with the colour coding described in section 5.1.2.2, fine grinding is shown to be closer to the completion in those pixels. In contrast, in sectors S_-, percentages of task completion corresponding to covered pixels are negatively updated. In the case those pixels have been previously correctly grinded, which means covered by one of the sectors S_+ defined on the surface of the abrasive accessory, the task completion in those pixels is shown to recede.

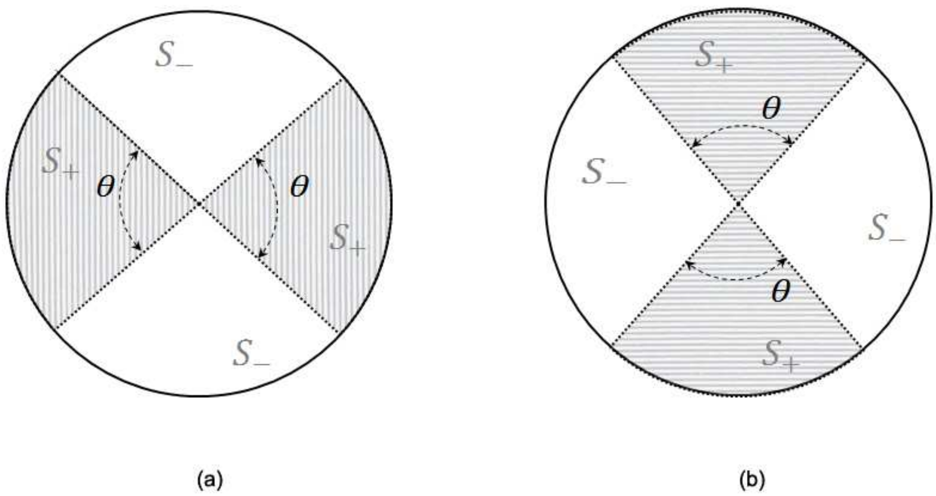

Figure 44. Circular sectors S_+in which scratches are generated with the appropriate direction, (a) vertically and (b) horizontally; and S_- in which generated scratches are considered to be inappropriate.

As described in section 4.1.2.2, the performance of polishing aims to spread uniformly diamond paste over the surface of the metallographic replica area. The interaction resulting from the partial or complete contact of the tool disk with the material surface is uniform. Thus, percentages of task completion corresponding to covered pixels are always positively updated. In the case of the polishing, the area of contact is referred as S_+ and no area S_- is defined.

The model for updating percentages of task completion stored in elements of $A_{64\times64}(n)$ for both tasks can be thus expressed as below (*Eq. 1*).

$$\left.\begin{matrix}\forall\, i \in [1{,}64]\\ \forall\, j \in [1{,}64]\end{matrix}\right\} \Rightarrow a_{i,j}(n) = a_{i,j}(n-1) + b(\mathrm{n}) \mid a_{i,j}(n) \in \ [0{,}1] \qquad \textit{Eq. 1}$$

Where $b(t)$ is thus expressed as below (*Eq. 2*):

$$b(\mathrm{n}) = \begin{cases} 0 \ \Leftrightarrow \begin{cases}(i,j) \notin \ S_+ \\ (i,j) \notin \ S_-\end{cases} \\ \Delta(n) \Leftrightarrow \ (i,j) \in S_+ \\ -\Delta(n) \Leftrightarrow \ (i,j) \in S_- \end{cases} \qquad \textit{Eq. 2}$$

Where $\Delta(n)$ corresponds to the update of the percentage of task completion between two graphical frames.

5.2 HAPTIC RENDERING

Haptic interaction is used to simulate the haptic intrinsic feedback in a similar way to that perceived in real operating environments. The haptic device allows handling the haptic stylus as if it were a real precision rotary tool (Figures 45 & 46). In this thesis, haptic devices from the Sensable Technologies Phantom product line are used to support the haptic interaction throughout the suggested part-task and whole-task training (Section 5.1). A Phantom Omni (Appendix A) was used in the experimental study presented in chapter 6, whereas a Phantom Desktop (Appendix A) has been employed in the validation process described in chapter 7. Figures 45 and 46 show:

1. The appropriate handling of the stylus of both haptic devices in the scope of the experimental studies conducted for fine grinding and polishing tasks.
2. The mapping of the virtual precision rotary tool on both haptic devices with the accessory attachment sitting at 90º at the tip of the stylus.

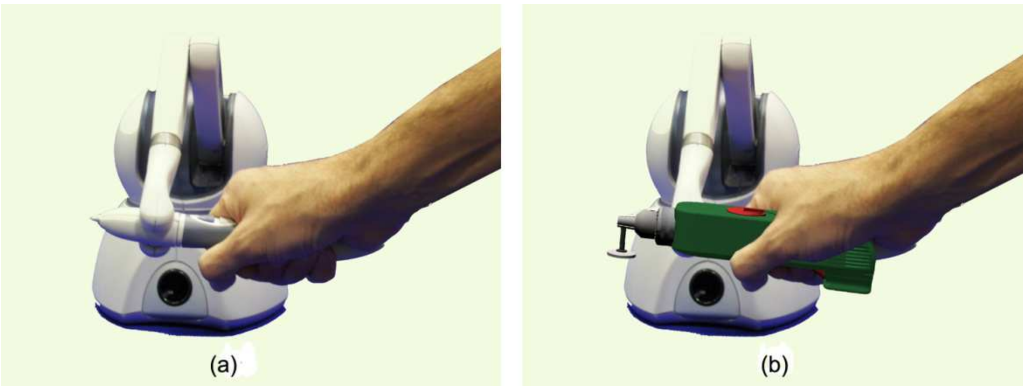

Figure 45. Handling of a Phantom Omni as proposed in chapter 6, and mapping of the virtual precision rotary tool on the stylus of the haptic device (The body of the power tool in figure b. has been added with an image editing software).

Figure 46. Handling of a Phantom Desktop as proposed in chapter 7, and mapping of the virtual precision rotary tool on the stylus of the haptic device (The body of the power tool in figure b. has been added with an image editing software).

The haptic rendering is supported by the Sensable OpenHaptics 3.0 Haptic Device API (HDAPI) and High Level API (HLAPI) designed to work with punctual inter-actuators from haptic devices from the Sensable Technologies product line (Appendix A). The haptic rendering engine enables rendering custom force effects at 1 KHz rate. Thus, the haptic device enables simulating:

1. The weight of a precision rotary tool.
2. The contact with geometries (Section 5.2.1).
3. The operating conditions of the tool such as rotary vibrations (Section 5.2.2) and a tangential force resulting from the contact of the rotating tool disc on the material surface (Section 5.2.3).

All force models were heuristically parameterized by the two expert metallurgists proposed by Tecnatom S.A.

5.2.1 Estimated applied force model

The estimated applied force $\overrightarrow{F_A}$ is defined as a function of the depth of penetration x of the punctual inter-actuator of the haptic device in the geometry and its velocity v, considering the components of stiffness k and damping d of the material (*Eq. 3*).

$$\overrightarrow{F_A} = -(k \cdot x - d \cdot v) \cdot \frac{\vec{N}}{\|\vec{N}\|} \qquad Eq.3$$

Where $\vec{N}$ is the normal vector at contact point with the geometry (Figure 47).

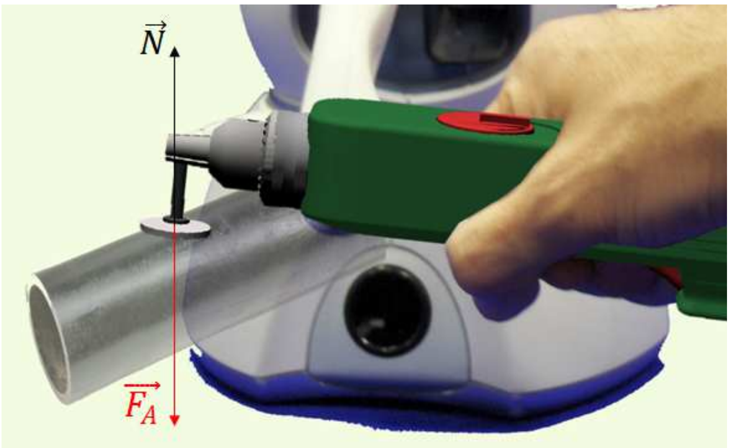

Figure 47. Representation of the estimated applied force $\overrightarrow{F_A}$ on the material surface as a function of $\vec{N}$, the normal force at contact point.

The magnitude of the estimated applied force $\overrightarrow{F_A}$ can be visualized in real-time through the force indicator proposed throughout part-task training (Section 5.1.1.2). However, the magnitude of the $\overrightarrow{F_A}$ which is based on the depth of penetration of the punctual inter-actuator of the haptic device in the geometry (*Eq. 3*), may sometimes differ from the force exerted through the haptic device. Effectively, not all haptic devices are able to render forces up to a certain level. For instance, the Phantom Omni used in the experimental study presented in chapter 6, is only able to render forces up to 3.3N (Appendix A). Beyond this level of force, the virtual stiffness of the object being contacted decreases, becoming a natural limit for the force applied. However, according to Schmidt (1975), motor skills can be generalized (Section 2.2.1.2). Thus, this discrepancy is believed to be not problematic in the extent that the human perceptual system can fill this gap.

5.2.2 Rotary vibrations

Rotary vibrations consist of those vibrations generated by the rotation of the engine rotor of the precision rotary tool, around the axis of rotation defined by the *z* local axis of the haptic device which is described by the vector $\overrightarrow{Dir}$ (Figure 48).

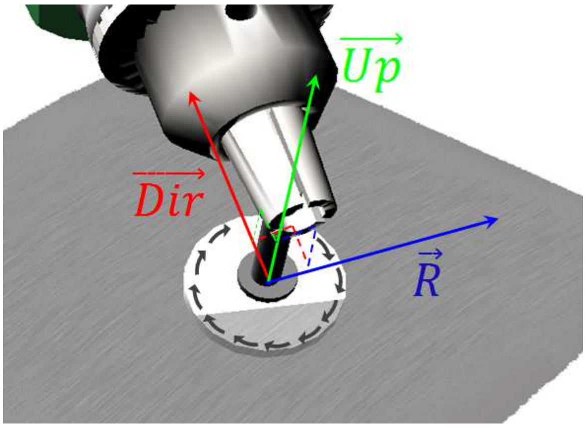

Figure 48. Local axes of the haptic device mapped on the virtual precision rotary tool.

The proposed model of rotary vibrations consists of an oscillating system defined by the vector $\overrightarrow{F_V}$ which direction varies in time. The vector $\overrightarrow{F_V}$ is parameterized with the magnitude m and the angular frequency ω of vibrations as in the equation below (*Eq. 4*):

$$\overrightarrow{F_V} = m \cdot \left(\hat{R} \cdot \cos \omega t + \widehat{Up} \cdot \sin \omega t\right) \qquad \textit{Eq. 4}$$

$\vec{R}$ and $\overrightarrow{Up}$ are respectively the vectors on the x and y local axes of the haptic device (Figure 48) and $\hat{R} = \frac{\vec{R}}{\|\vec{R}\|}$, $\widehat{Up} = \frac{\overrightarrow{Up}}{\|\overrightarrow{Up}\|}$. The angular frequency ω is expressed as $\omega = 2\pi \cdot f_V$, and m and f_V have been respectively heuristically set to $0.4\ N/m$ and $40\ Hz$.

5.2.3 Tangential forces

The haptic device enables simulating the tangential force resulting from the contact of the rotating tool disc with the surface of the material. The tangential force $\overrightarrow{F_T}$ defines a motion which is parallel to the material surface (Figure 49) and is a function of the estimated applied force $\overrightarrow{F_A}$ on the material surface (Section 5.2.1).

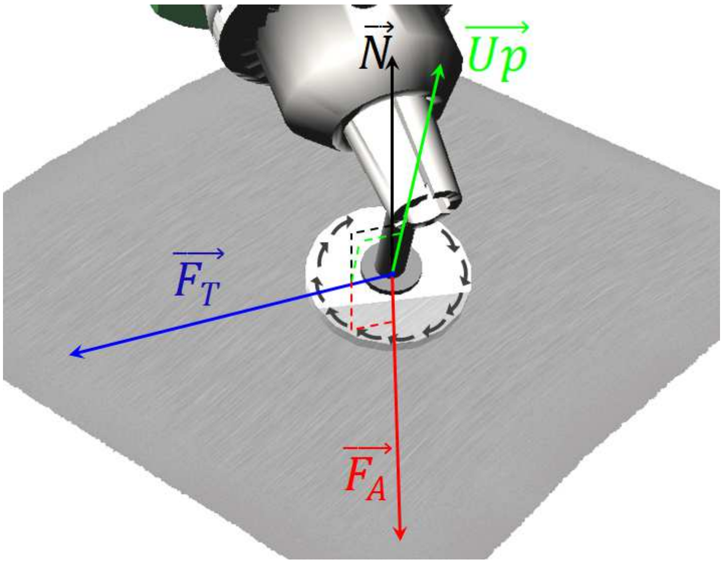

Figure 49. Modeling of the tangential force $\overrightarrow{F_T}$ as a function of the estimated applied force $\overrightarrow{F_A}$ and therefore of the normal vector $\vec{N}$ at the contact point, and the vector $\overrightarrow{Up}$ on the y local axis of the haptic device.

The tangential force $\overrightarrow{F_T}$ consists of the cross product of the estimated applied force $\overrightarrow{F_A}$ (Section 5.2.1) with the vector $\overrightarrow{Up}$ (Figure 49). Therefore, the tangential force $\overrightarrow{F_T}$ can be expressed as a function of the normal force $\vec{N}$ at contact point with the material surface (Figure 49), the depth of penetration x of the punctual inter-actuator of the haptic device in the geometry and its velocity v considering the components of stiffness k and damping d of the material (*Eq. 5*).

$$\overrightarrow{F_T} = (k \cdot x - d.v) \cdot \left(\frac{\vec{N} \times \overrightarrow{Up}}{\|\vec{N} \times \overrightarrow{Up}\|}\right) \qquad \textit{Eq. 5}$$

Where $k = 0.6\ N/m$, $d = 0.4\ N/m\,.s^{-1}$.

The motion of the tool disc on the material surface and therefore that induced by the tangential force as described in *Eq. 5*, is constrained by the friction between the tool disc and the material surface. Friction encompasses static friction and kinematic friction. Static friction describes how resistive is the material surface to motion as that induced by the tangential force when no motion has been engaged. Dynamic friction describes how resistive is the material surface to motion once a motion has been engaged. Both frictions offer resistance to the motion of the tool disc on the material surface. The magnitude of each friction force can be expressed as F_f such as $F_f = \mu_x \cdot N$, where μ_x is the coefficient of friction of the surface of the material for each type of friction. For static and kinematic friction forces, their respective coefficients of friction have been heuristically set to $\mu_s = 0.2$ and $\mu_k = 0.1$.

5.3 INTERACTION MODEL

Section 5.1.2.3 describes the functioning of the colour map to indicate the status of task completion across the metallographic replica area, and inform about task progress throughout the performance of the trained task. This section describes the modelling of the interaction between the tool disc and the material surface so that task completion can be represented on the colour map.

The representation of that interaction on the colour map texture is based on the projection of the points that compose the tool disc in the three-dimensional space onto the bi-dimensional UV coordinate system set in the texture image (Heckbert, 1989).

As mentioned previously in section 5.1.2.3, the tool disc can be (1) completely or (2) partially in contact with the material surface. When the contact is complete, the interaction is represented on the colour map as a circular area, whereas when it is partial, the interaction is drawn as a circular segment area. In both cases, the representation of contact is a function of the radius r of the tool disc. However, in order to enable the mapping of such interaction on the colour map, the radius r must be normalized to range in [0,1]. The normalized length r_{uv} is calculated as $r_{uv} = {r}/{\mathrm{W}}$ where W is the side size of the square working area (Figure 42).

The normalized length r_{uv} is later used to determine the conditions that colour map pixels must satisfy in order to be considered as covered when the tool disc is in complete (Section 5.3.1) or in partial (Section 5.3.2) contact with the material surface.

5.3.1 Complete contact model

The projection of the centre of the tool disc in the three-dimensional space, into the UV coordinate system set in the colour map texture is referred as O_{uv} and is expressed in UV coordinates as (u_0, v_o).

Each pixel of the colour map texture is assigned a unique UV coordinate. From now on, pixels of the colour map will be identified as their corresponding elements in $A_{64\times64}(n)$. Thus, pixels referred as $a_{i,j}$, with $i \in [1,64]$ and $j \in [1,64]$, are assigned UV coordinates expressed as $(u_{a_{i,j}}, v_{a_{i,j}})$. Thus, pixels covered by the tool disc completely in contact with the material surface satisfy the condition presented below (*Eq. 6*).

$$\left.\begin{matrix} \forall\, i \in [1{,}64] \\ \forall\, j \in [1{,}64] \end{matrix}\right\} \Rightarrow \left(u_{a_{i,j}} - u_0\right)^2 + \left(v_{a_{i,j}} - v_o\right)^2 \leq r_{uv}^{\ 2} \qquad Eq.\ 6$$

5.3.2 Partial contact model

Partial contact of the tool disc on the material surface is drawn as a circular segment area on the colour map. That circular segment area is centered in O_{uv}, and is enclosed between a circular arc which is centered in the edge point E'_{uv}, and the secant line (L) that intersects perpendicularly with the diameter line of the projection of the tool disc shape in the point H_{uv} (Figure 50). The slope of the secant line (L) is determined by applying the rotation matrix $R\begin{pmatrix} \cos\frac{\pi}{2} & -\sin\frac{\pi}{2} \\ \sin\frac{\pi}{2} & \cos\frac{\pi}{2} \end{pmatrix}$ to the vector $\overrightarrow{O_{uv}\,E'_{uv}}$.

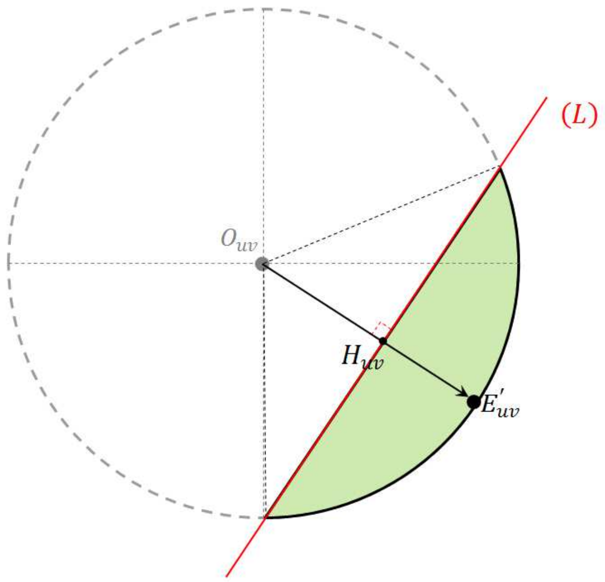

Figure 50. Representation of partial contact of the tool disc with the material surface on the colour map.

The edge point E'_{uv} on the colour map is the bi-dimensional representation of the point E which is the point of the tool disc in the three-dimensional space that deeper penetrates into the material (Figure 51).

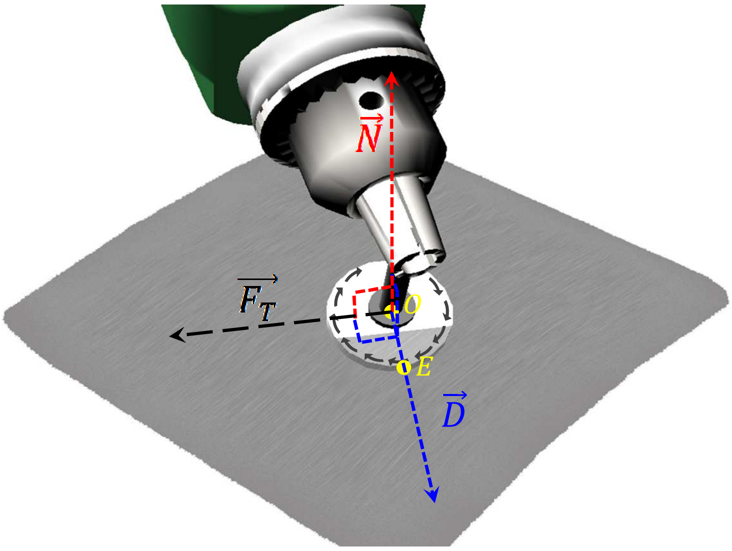

Figure 51. Determination of the point E on the tool disc.

The point E can be obtained from the vector $\overrightarrow{OE}$ such as $\overrightarrow{OE} = r \cdot \widehat{D}$ with the normalized vector $\widehat{D} = \frac{\vec{F_T} \times \vec{N}}{\|\vec{F_T} \times \vec{N}\|}$.

The normal projection of E on the colour map is the point E_{uv} that allows forming the vector $\overrightarrow{O_{uv}E_{uv}}$ which magnitude varies as a function of the inclination α of the virtual precision rotary tool with regards to $\vec{N}$ at contact point (Figure 52).

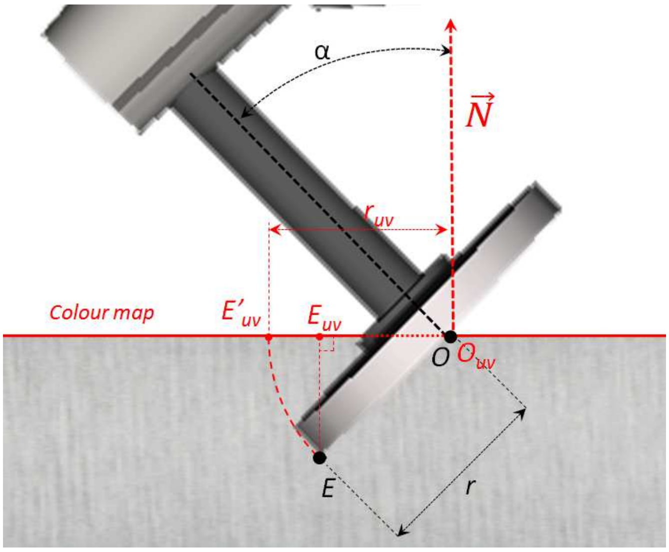

Figure 52. Normal projection of the point E on the colour map as E_{uv} and representation of the point E on the colour map as the edge point E'_{uv}.

The edge point E'_{uv} as the representation of the point E on the colour map can be expressed as below:

$$\overrightarrow{O_{uv}E'_{uv}} = r_{uv} \times \frac{\overrightarrow{O_{uv}E_{uv}}}{\|\overrightarrow{O_{uv}E_{uv}}\|}$$

*W*here r_{uv} is the normalized length of the radius of the tool disc on the colour map.

The intersection point H_{uv} (Figure 50) is a function of the degree of contact of the tool disc on the material surface. The vector $\overrightarrow{H_{uv}\,E'_{uv}}$ determines the height of the circular segment area in contact with the material surface (Figure 50). The model of contact of the tool disc on the material surface is defined as a function of the exerted force and applied angle on the precision rotary tool. It has been determined heuristically by the two expert metallurgists from Tecnatom S.A. and it is expressed as the ratio δ of the diameter of the tool disc in contact with the surface material (Section 5.4.1). Thus, the vector $\overrightarrow{H_{uv}\,E'_{uv}}$ can be expressed as:

$$\overrightarrow{H_{uv}E_{uv}} = 2 \cdot \delta \cdot r_{uv} \cdot \frac{\overrightarrow{O_{uv}E'_{uv}}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|}$$

Hence, when the contact is partial, percentages of task completion are updated for those pixels which satisfy the condition presented in *Eq. 6* (Section 5.3.1) and one of the conditions described in the following cases (Figures 53 to 55).

Conditions

$$\frac{\overrightarrow{O_{uv}E_{uv}^{'}} \cdot \vec{v}}{\left\| \overrightarrow{O_{uv}E_{uv}^{'}} \right\| \cdot \|\vec{v}\|} > 0 \wedge \frac{\overrightarrow{O_{uv}E_{uv}^{'}} \cdot \vec{u}}{\left\| \overrightarrow{O_{uv}E_{uv}^{'}} \right\| \cdot \|\vec{u}\|} > 0$$

$$\frac{\overrightarrow{O_{uv}E_{uv}^{'}} \cdot \vec{v}}{\left\| \overrightarrow{O_{uv}E_{uv}^{'}} \right\| \cdot \|\vec{v}\|} > 0 \wedge \frac{\overrightarrow{O_{uv}E_{uv}^{'}} \cdot \vec{u}}{\left\| \overrightarrow{O_{uv}E_{uv}^{'}} \right\| \cdot \|\vec{u}\|} < 0$$

$$\frac{\overrightarrow{O_{uv}E_{uv}^{'}} \cdot \vec{v}}{\left\| \overrightarrow{O_{uv}E_{uv}^{'}} \right\| \cdot \|\vec{v}\|} > 0 \wedge \frac{\overrightarrow{O_{uv}E_{uv}^{'}} \cdot \vec{u}}{\left\| \overrightarrow{O_{uv}E_{uv}^{'}} \right\| \cdot \|\vec{u}\|} = 0$$

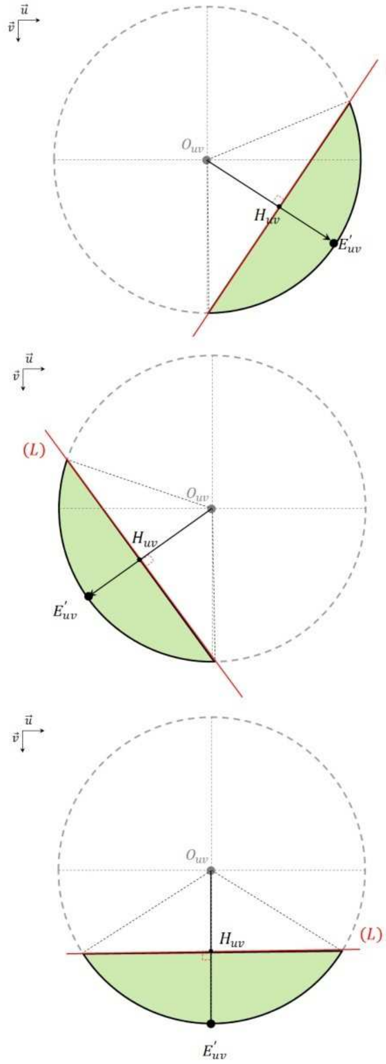

Figure 53. Case 1: representation of the circular segment area on the colour map. Percentages of task completion corresponding to pixels enclosed in that circular segment area are updated.

Conditions

$$\frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{v}\|} < 0 \ \wedge \ \frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{u}\|} > 0$$

$$\frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{v}\|} < 0 \ \wedge \ \frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{u}\|} < 0$$

$$\frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{v}\|} < 0 \ \wedge \ \frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{u}\|} = 0$$

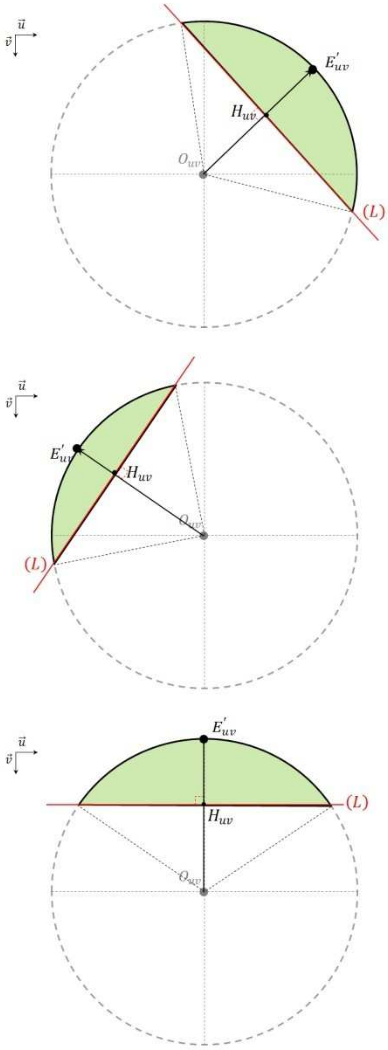

Figure 54. Case 2: representation of the circular segment area on the colour map. Percentages of task completion corresponding to pixels enclosed in that circular segment area are updated.

<u>Conditions</u>

$$\frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{v}\|} = 0 \wedge \frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{u}\|} = 1$$

$$\frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{v}\|} = 0 \wedge \frac{\overrightarrow{O_{uv}E'_{uv}} \cdot \vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\| \cdot \|\vec{u}\|} = -1$$

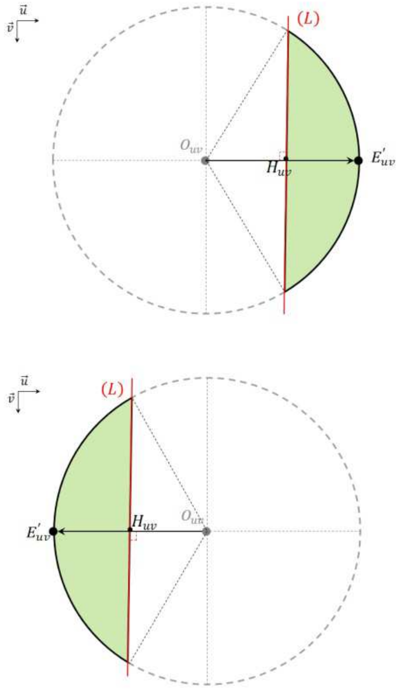

Figure 55. Case 3: representation of the circular segment area on the colour map. Percentages of task completion corresponding to pixels enclosed in that circular segment area are updated.

Those cases (Figures 53 to 55) can be expressed as a function of the UV coordinates of pixels $(u_{a_{i,j}}, v_{a_{i,j}})_{i\in[1,64],j\in[1,64]}$ with regards to the affine equation of the secant line (L) which is defined by the slope a and the y-intercept b of the secant line (L) in the UV coordinates system. Those cases are presented below ($Eq.$ *7* to *9*).

Case 1 (Figure 53):

$$\left.\begin{array}{l}\forall\, i \in [1,64] \\ \forall\, j \in [1,64]\end{array}\right\} \Rightarrow \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{v}\|} > 0 \;\wedge\; \begin{cases} if\ \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{u}\|} = 0 \;\Rightarrow\; v_{a_{i,j}} \geq b \\ if\ \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{u}\|} \neq 0 \;\Rightarrow v_{a_{i,j}} \geq a \cdot\, u_{a_{i,j}} + b \end{cases} \qquad Eq.\ 7$$

Case 2 (Figure 54):

$$\left.\begin{array}{l}\forall\, i \in [1,64] \\ \forall\, j \in [1,64]\end{array}\right\} \Rightarrow \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{v}\|} < 0 \;\wedge\; \begin{cases} if\ \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{u}\|} = 0 \;\Rightarrow\; v_{a_{i,j}} \leq b \\ if\ \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{u}\|} \neq 0 \;\Rightarrow v_{a_{i,j}} \leq a \cdot\, u_{a_{i,j}} + b \end{cases} \qquad Eq.\ 8$$

Case 3 (Figure 55):

$$\left.\begin{array}{l}\forall\, i \in [1,64] \\ \forall\, j \in [1,64]\end{array}\right\} \Rightarrow \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{v}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{v}\|} = 0 \;\wedge\; \begin{cases} if\ \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{u}\|} = 1 \Rightarrow u_{a_{i,j}} \geq \mathrm{n}_{\mathrm{n}\in[0,1]} \\ if\ \frac{\overrightarrow{O_{uv}E'_{uv}}\cdot\vec{u}}{\left\|\overrightarrow{O_{uv}E'_{uv}}\right\|\cdot\|\vec{u}\|} = -1 \Rightarrow u_{a_{i,j}} \leq \mathrm{n}_{\mathrm{n}\in[0,1]} \end{cases} \qquad \text{E}q.\ 9$$

5.3.3 Representation of the interaction of the abrasive accessory

As mentioned previously in section 5.1.2.3, depending on the nature of the task, the abrasive accessory that equipped the tool disc interacts differently with the material surface.

The performance objective of fine grinding is to generate scratches in a unique direction on the material surface: horizontal or vertical direction with regards to the orientation of the metallographic replica area. Two kinds of circular sector on the surface of the abrasive accessory disc have been defined (Figure 44). Sectors S_+ generate scratches with the desired direction whereas sectors S_- generate inappropriate scratches. Thus, as detailed in *Eq. 2*, percentages of task completion stored in elements of $A_{64\times 64}(n)$ corresponding to colour map pixels covered by the tool disc are updated differently whether pixels are enclosed in sectors S_+ or S_-. The orientation of those sectors varies as a function of the desired direction of generated scratches (Figure 56).

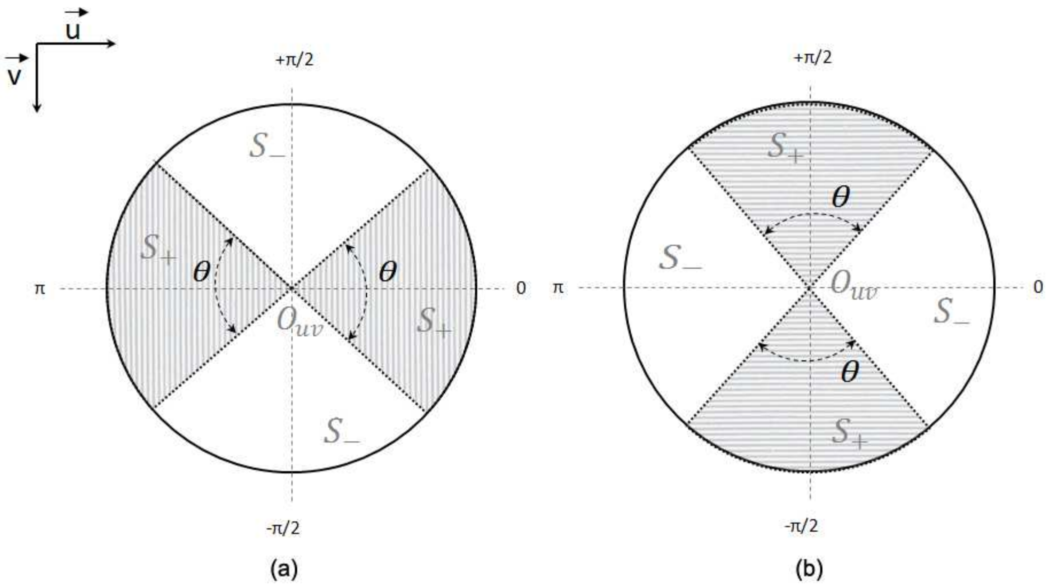

Figure 56. Circular sector areas S_+ in which scratches are generated in the desired direction: (a) vertical and (b) horizontal. Sectors S_+ are defined by a central angle θ which has been heuristically set to 80º (Section 5.1.2.3).

The type of sector in which covered pixels, expressed as $a_{i,j}$ with $i \in [1,64]$ and $j \in [1,64]$, are located, can be expressed as a function of the angle λ formed by the vector $\overrightarrow{O_{uv}a_{i,j}}$ and the horizontal vector $\vec{u}$ of the UV coordinate system such as:

$$\left.\begin{matrix} \forall\, i \in [1,64] \\ \forall\, j \in [1,64] \end{matrix}\right\} \Rightarrow \lambda = \cos^{-1} \frac{\overrightarrow{O_{uv}a_{i,j}}.\vec{u}}{\|\overrightarrow{O_{uv}a_{i,j}}\|.\|\vec{u}\|}$$

Thus, the condition for covered pixels $a_{i,j}$ to be located in a sector S_+ can be thus expressed as below:

$$\left.\begin{matrix} \forall\, i \in [1,64] \\ \forall\, j \in [1,64] \end{matrix}\right\} \Rightarrow a_{i,j} \in S_+ \Leftrightarrow |\cos\lambda| \geq \cos\left(\frac{\theta}{2}\right) \vee |\sin\lambda| \geq \sin\left(\frac{\pi}{2} - \frac{\theta}{2}\right)$$

Otherwise, those covered pixels are located in S_-.

As mentioned in section 5.1.2.3, In the course of a polishing task, the interaction between the surface of the tool disc in contact with the material surface is uniform. All colour map pixels being covered by the abrasive accessory are assumed to be located in an area with similar properties as sectors S_+ defined for fine grinding task. Thus, percentage of task completion corresponding to covered pixels which satisfy the condition presented in *Eq. 6* (Section 5.3.1) and one of the conditions presented in *Eq. 7* to *9* (Section 5.3.2) are positively updated following the model presented in *Eq. 1* and *2* (Section 5.1.2.3).

5.4 ESTIMATION OF THE VALUE OF PARAMETERS

The development of the VR training system as proposed in this thesis in order to train angle and force skills through part-task training (Section 5.1.1) and practise the performance of fine grinding and polishing tasks through whole-task training (Section 5.1.2) has required the heuristic determination of a series of parameters. The resulting values enable the definition of the model of contact of the tool disc on the material surface (Section 5.4.1) and the ranges for angle and force skills for the suggested tasks (Section 5.4.2). The determination of these values aims to enable realistic simulations of both tasks in VR. The two expert metallurgists from Tecnatom S.A. have been involved in the procurement of these values.

5.4.1 Definition of the model of contact of the tool disc

This section aims to define the model of contact of the tool disc on a material surface for both fine grinding and polishing tasks. The obtaining of such model of contact has followed a heuristic method which resulted in the determination of the ratio δ of the diameter of the tool disc in contact with the material surface. As mentioned previously in section 5.3.2, that ratio is a function of the force exerted and the inclination of the precision rotary tool on the material surface and is expressed in the form of a percentage.

The two expert metallurgists have captured the tool disk in contact with a material surface while attempting several tool inclinations and forces. Those exerted forces were assumed to be close to those defined later for the range for force skill for both tasks (Section 5.4.2.1). Resulting captures are presented through a series of images shown in Table 6.

The ratio δ has been measured directly on the images of captures. Resulting measurements which enable the definition of the contact model of the tool disk on the material surface are shown in Table 7. Figure 57 offers a graphical representation of the contact model.

Table 6. Heuristic method for the determination of the contact model of the tool disc on a material surface considering several forces and tool inclinations.

	Minimum Force	Maximum Force
Angle: 0 º		
Angle: ≈ 5 º		
Angle: ≈ 10 º		
Angle: ≈ 15 º		
Angle: ≈ 30 º		

	Minimum Force	Maximum Force
Angle: ≈ 45 º		
Angle: ≈ 60 º		

Table 7. Definition of the contact model in the form of a percentage which states for the ratio δ of the diameter of the tool disc in contact with the material surface.

	Force Min.	Force Max.
Angle: ≈ 0º	δ = 100 %	δ = 100 %
Angle: ≈ 5º	δ ≈ 25%	δ ≈ 65 %
Angle: ≈ 10º	δ ≈ 19 %	δ ≈ 63 %
Angle: ≈ 15º	δ ≈ 15 %	δ ≈ 33 %
Angle: ≈ 30º	δ ≈ 9 %	δ ≈ 27 %
Angle: ≈ 45º	δ ≈ 7 %	δ ≈ 22 %
Angle: ≈ 60º	δ ≈ 4 %	δ ≈ 15 %
Angle: ≥ 90º	δ = 0%	δ = 0 %

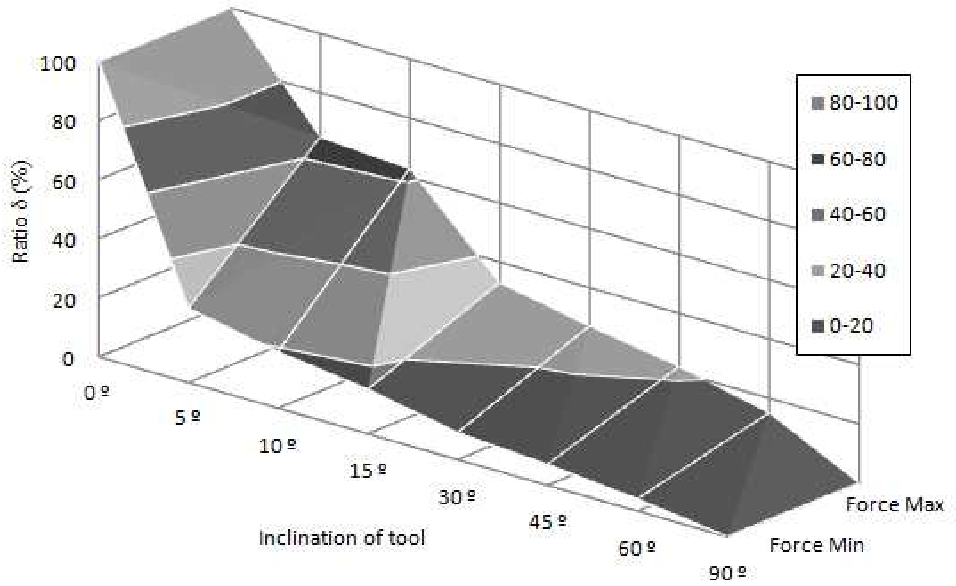

Figure 57. Graphical representation of the contact model.

5.4.2 Definition of ranges for force and angle skills

A trial session which involved the two expert metallurgists from Tecnatom S.A. was carried out at the University of Malaga in order to collect force and angle data related to the performance of fine grinding and polishing tasks. The purpose of this trial session was to determine heuristically the threshold values that bound the ranges for force and angle skills considered for the training of both tasks.

Expert metallurgists were standing at about one meter in front of a wide screen (W: 2400 x H: 1800 mm) on which was monoscopically displayed a 3D virtual environment. That virtual environment simulated an industrial pump component located in an industrial plant and a virtual precision rotary tool with right angle attachment controlled in position and orientation by a haptic device (Figure 58).

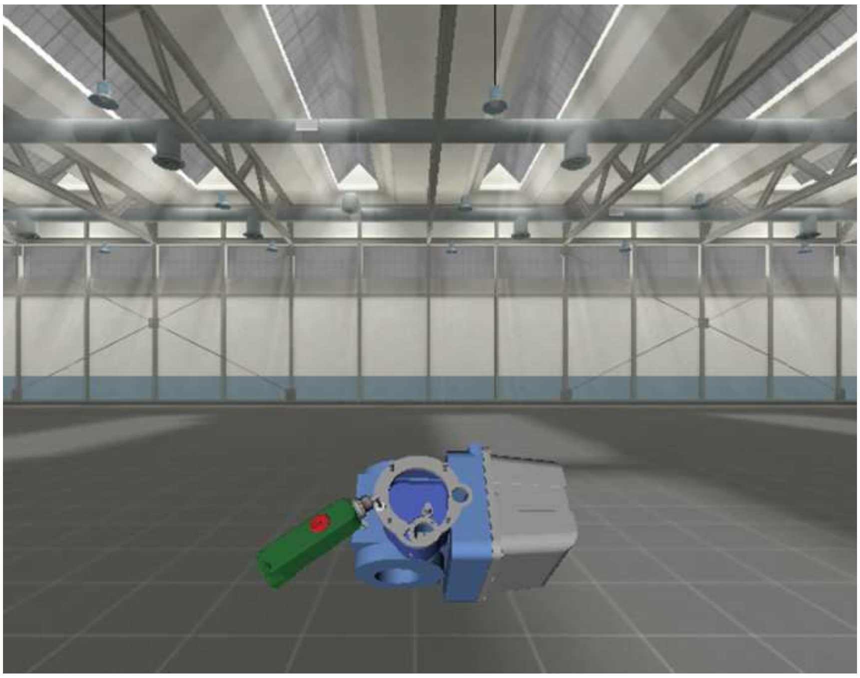

Figure 58. Virtual environment in which the trial session occurred.

Throughout the trial session, expert metallurgists were required to manipulate the virtual precision rotary tool on the surface of a gasket inclined of 45º on the horizontal axis, mounted on the frontal face of the pump component (Figure 58). A Phantom Desktop haptic device from Sensable Technologies was used for the collection of force and angle data. The haptic device model employed in the trial session was similar to the one owned by Tecnatom S.A and used in the experimental study presented in chapter 7. The haptic device was able to render up to 7.9 N onto 3 Degrees of Freedom (DOF) (Appendix A). Expert metallurgists were required to handle the haptic device as if it were a real precision rotary tool (Figure 46). The haptic device mimicked the operating conditions of a real precision rotary tool by simulating the weight of the tool which has been set heuristically and validated by expert metallurgists, rotary vibrations (Section 5.2.2) and tangential forces caused by the rotation of the tool disc on the material surface (Section 5.2.3).

5.4.2.1 Force for fine grinding and polishing tasks

Expert metallurgists were required to exert the (1) minimum, (2) maximum and (3) optimum forces they could apply during the performance of fine grinding and polishing tasks in real operating environments. Forces were exerted perpendicularly to the gasket surface.

Force measurements were performed at 100 Hz rate and data were collected once the virtual precision rotary tool was launched. Measures were averaged aiming to determine overall threshold values for the minimum and maximum boundaries of the range of force for both tasks (Table 8).

Table 8. Average exerted forces with a Phantom Desktop haptic device

	Minimum Force	Maximum Force	Optimum Force
Force Value	$F_{min} \geq 1\ N$	$5\ N \leq F_{max}\ \leq 6\ N$	$F_{opt} \cong 3\ N$

In each trial, the two expert metallurgists applied relatively similar amount of forces. The values of the boundaries suggested for the range for force skill consists of recommendations made on the basis of the heuristic determination from the part of both experts. Chapters 6 and 7 present two experimental studies for which the range has been respectively set to [1N, 5.3N] and [1N, 5N].

5.4.2.2 Angle for Fine grinding task

As explained previously in section 4.1.2.1, the fine grinding task aims to the generation of scratches in a unique direction on the material surface. Two types of circular sectors on the surface of the abrasive accessory have been defined (Section 5.1.2.3). In sectors S_+, scratches are generated in the desired direction, vertical or horizontal depending on the requirement of the task. In contrast, in sectors S_-, generated scratches are inappropriate.

The determination of the range for angle skill for a fine grinding task consists of defining the optimum contact area so that all scratches are generated only with the desired direction. That contact area consists of a circular segment area S_{opt} as a cut-off of a sector S_+ defined by its height h (Figure 59). The height h enables defining the optimum ratio δ_{opt} of the diameter of the tool disc in contact with the material surface. That ratio δ_{opt} can be expressed such as $\delta_{opt}\ = {h}/{(2 \cdot r)}$ with $h\ = r\left(1 - \cos\frac{\theta}{2}\right)$ and the radius r of tool disk.

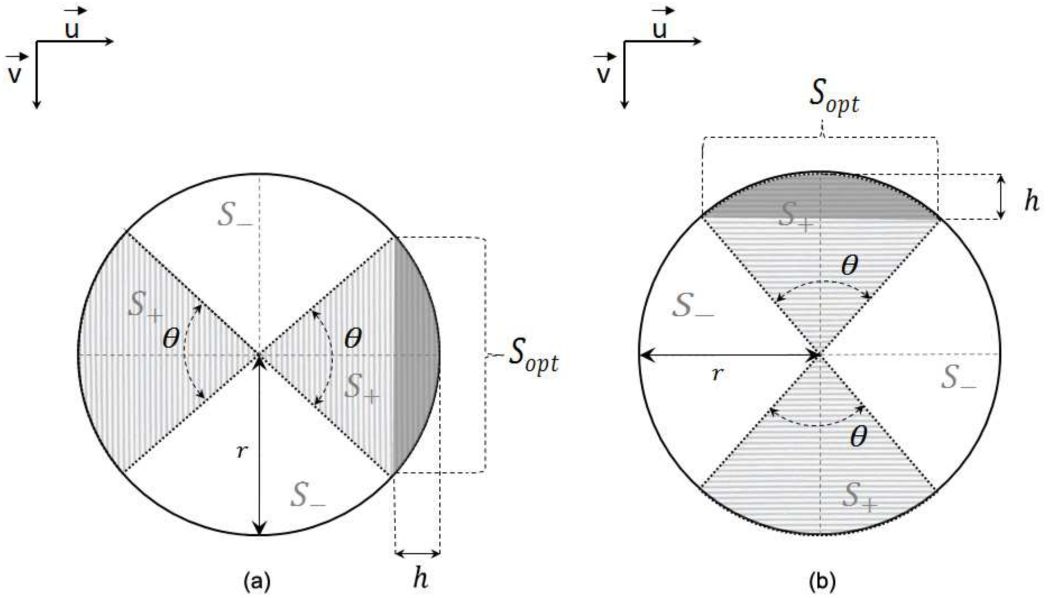

Figure 59. Definition of the optimum contact area so that all scratches are generated with the desired direction: (a) vertical and (b) horizontal with regards to the orientation of the metallographic replica area.

To the extent that the central angle θ of sectors S_+ has been set heuristically to θ = 80º (Section 5.1.2.3), and the radius r of the tool disk has been measured as r = 13.5 mm, the optimum ratio is calculated to be $\delta_{opt} \approx 0.117$. This means that the height of the circular segment area S_{opt} corresponds to 11.7% of the diameter of the tool disc.

By reporting that value on the contact model presented in section 5.4.1, the range for angle skill for fine grinding task is bounded in [≥25º, 90º] when the exerted force approaches the lower limit of the range of force (Section 5.4.2.1), and in [≥65º, 90º] when the exerted force is within the threshold that define the upper limit of the range of force (Section 5.4.2.1).

Chapter 7 presents an experimental study which proposes among others, part-task and whole-task training of angle skill for a fine grinding task. The range for angle skill has been set to [75º, 90º].

5.4.2.3 Angle for polishing task

Considering the nature of the interaction of the tool disc on a material surface during polishing operations (Section 5.1.2.3), the inclination of the precision rotary tool is not really relevant for the quality of the polishing. However, the two expert metallurgists from Tecnatom S.A. were required to determine heuristically the boundaries of the ranges in which the performance of angle skill during a polishing task is considered to be efficient along with an optimal tool inclination for a comfortable task performance. Those threshold values were determined from angle data collected at 100 Hz rate once the virtual precision rotary tool was launched and operating on the inclined gasket of the pump component. Table 9 presents the average values of the recommended thresholds of the angle skill for a polishing task.

Table 9. Average applied angle on the surface of the inclined gasket.

	Minimum Angle	Maximum Angle	Comfortable Angle
Angle value	≅ 0º	≅ 15º	≅ 5º

On the basis of these results, part-task and whole-task training for polishing tasks are recommended to be configured with a range for angle skill bounded from 0º to up to 15º. However, training with angle boundaries which overpass the maximum recommended value is not critical for the performance of the task.

In the experimental studies presented in chapters 6 and 7, the range for angle skill for a polishing task has been respectively set to [0º, 10º] and [0º, 20º].

5.5 CONCLUSION

In this chapter, the resulting development of the VR training system inherent to functional and requirement analyses carried out in chapter 4 has been presented. A training toolkit which enables building training programs based on fundamental training methods such as part-task and whole-task training carried out on the VR training system has been proposed. Moreover, part-task and whole-task training can be enhanced with augmented feedback in the form of concurrent and terminal KP and KR. Several configurations for augmented feedback indicators are presented.

The suggested VR training occurs in realistic virtual environments which simulate haptic intrinsic information like that perceived during the performance of fine grinding and polishing tasks in real operating environments.

Furthermore, this chapter has emphasized on the provision of concurrent KR during whole-task training through a colour map indicator. Such augmented feedback aims to inform in real-time about the status of task completion and therefore task progress over the time. The implementation of the representation of task performance through the colour map has been presented along with the methodology followed for the determination of the parameters that are relevant for that development.

The following chapters propose two experimental studies which among other things, aim to assess the effectiveness of the VR training system to support motor learning of angle and force skills for fine grinding and polishing tasks.

PART 4

EVALUATION FRAMEWORK

Chapter 6. Experimental study 1

6.1 INTRODUCTION

As it was described in chapter 4, the metallographic replica is an in-situ non-destructive inspection technique which enables recording the microstructure of a material surface as a negative relief on a plastic foil (ASTM E 1351 – 01, 2001). The metallographic replica technique requires previous material surface preparation that encompasses among other things, several polishing operations for which specific tool inclination and force need to be accurately applied (ASTM E 3 - 01, 2001). Thus, training those motor skills is paramount to guarantee an efficient performance of the task.

It has been also mentioned in chapter 4 that conventional training usually occurs under the supervision of an expert metallurgist who assists the trainee's performance by providing concurrent Knowledge of Performance (KP) (Section 2.4.2) in the form of verbal guidelines. However, that verbal concurrent KP is often insufficient to support the transfer of tacit knowledge such as angle and force skills from the expert to the trainee. Moreover, the nature of the polishing task impedes the expert metallurgist and the trainee to monitor in real-time the performance outcome on the material surface. The expert metallurgist can only provide terminal Knowledge of Results (KR) (Section 2.4.2) on the basis of final performance outcomes.

This chapter presents an experimental study which investigates the effectiveness of the VR training system presented in chapters 4 and 5, to support the training of angle and force skills for a polishing task. The proposed training is enhanced with concurrent and terminal augmented feedback provided through a set of visual and audio indicators.

The experimental study presented in this chapter has been submitted as a journal paper in the following publication:

Poyade, M., Molina-Tanco, L., Reyes-Lecuona, A., Langley, A., D'Cruz, M., Sharples, S. (2013). Experimental evaluation of haptic-based part-task training for motor skill learning in industrial maintenance operations. *IEEE Transaction on Haptics* (Pending on acceptance).

6.1.1 Development of motor skills

In general, the development of motor skills to efficiently perform a polishing task as required in the metallographic replica technique is a long process during which trainees practice to progressively gain in efficacy. Fitts & Posner (1968) proposed that the development of motor skills occurs through a hierarchical model composed of three stages: cognitive, associative, and autonomous (Section 2.2.2.1). At the early stage of learning, motor skills are awkward and usually require a considerable amount of cognitive load, but progressively gain in proficiency and gradually merge into the next stage until motor skills become automatized.

In many occasions, motor skills are too complex, and practising only the whole-task may be ineffective for training purposes (Schmidt & Wrisberg, 2008). Thus, part-task training which consists of breaking down motor skills into simple part-task components appears as an alternative to the training of complex motor skills through whole-task practice (Teague et al., 1994; Utley & Astill, 2008; Browne et al., 2009; Coker, 2009).

As presented in chapter 2, Wightman & Lintern (1985) (reported in Roessingh et al., 2002) have defined three techniques to break down motor skills into part-task components:

1. The segmentation which consists in separating serial skills into parts according to spatial or temporal considerations.
2. The fractionation which consists in separating skills that are usually executed simultaneously during the task.
3. The simplification which consists in acting on some characteristics of the task to decrease the level of difficulty and therefore ease the performance.

Part-task training of motor skills that are performed simultaneously during a polishing task is difficult to achieve through conventional training. Nonetheless, it is believed that VR training supports the fractionation of and the progressive integration of those motor skills in order to be practised separately and concurrently.

6.1.2 VR and haptic training

As it has been already discussed in chapter 3, haptic and VR technologies have been successfully employed for training motor coordination and force skills (Esen et al., 2004; Tholey et al. 2005; Morris et al., 2007; Wagner et al., 2007; Esen et al., 2008a; Martin et al., 2012; Zhou et al. , 2012). The importance of haptic force feedback for training motor skills involved in healthcare activities has been demonstrated (Morris et al., 2006; Steinberg et al., 2007; Sternberg et al., 2007; Suebnukarn et al., 2010; for review see Coles et al., 2011; Rhienmora et al., 2011). Moreover, VR training systems enhanced with haptic force feedback have also been employed to support the training of technical motor skills involved in industrial procedures (Balijepalli & Kesavadas, 2003; Wang, Y. et al., 2006; Abate et al., 2009; He & Chen, 2006; Wang, Y. et al., 2009; Sung et al., 2011). However, the validity of those VR training systems has been investigated so far.

VR allows enhancing the training experience with augmented information feedback that is often not available in real world contexts (Todorov et al., 1997; Esen et al., 2004; Gopher, 2012). Moreover, fundamental training methods such as part-task and whole-task training have been successfully applied to the context of VR training (Aggarwal et al., 2006; Eid et al., 2007; Sternberg et al., 2007; Aggarwal et al., 2009; Suebnukarn et al., 2010; Iwata et al., 2011, Rhienmora et al., 2011; Luciano et al., 2012; Oren et al., 2012), offering the possibility of repetitive and safe tasking in realistic virtual environments (Bossard et al., 2008; Johanesson et al., 2010; Mishra et al., 2010; Pan et al., 2011; Bhatti et al., 2012). However, to the best of the knowledge of the author, the effectiveness of part-task training inspired by the fractionation of simultaneous motor skills applied to VR training has not been reported so far. Thus, an experimental study investigating the effectiveness of such VR training would be a valuable contribution to the field of motor skill training in VR.

6.1.3 Hypothesis and rationale

This experimental study aims to assess the effectiveness of the VR training system presented in chapter 5, which enables part-task training to support the successful development of angle and force skills for the performance of a polishing task. Part-task training is inspired by the progressive integration of fractionized and simplified motor skills into a whole-target task (Section 2.3). So far, the effectiveness of this type of VR training method has not been evaluated.

In this thesis, it is believed that a VR training system able to provide such training would enable supplementing the conventional training on polishing tasks to the extent that:

1. Such VR training would allow the trainee to progress towards a more advanced stage of motor learning than previously possible using conventional training.
2. More accurate information on performance and results in the form of visual concurrent KP and KR can be provided in order to improve the transfer of tacit knowledge to the trainee.

In order to evaluate the effectiveness of the VR training system to support the training of angle and force skills required in a polishing task, two hypotheses have been formulated:

1. Part-task training is effective in improving trainees' proficiency in angling the virtual precision rotary tool and exerting the correct force on the material surface.
2. Part-task training allows to efficiently transfer trained motor skills to the performance of whole-target task such as a polishing task simulated in a virtual environment.

6.2 METHODS

6.2.1 Participants

Thirty students and members of staff from the University of Nottingham, 14 males and 16 females aged from 18 to 65 (M =30.21, SD = 2.85 years), were recruited for this study. The participants had no previous experience manipulating haptic devices and power tools. All participants but one were right handed, and did not report any arm or wrist disability and uncorrected visual impairments.

Participants were asked to fill a prior consent form in which they were informed about the purpose of the study, their rights as participants and publication policies (Appendix D). Participation was voluntary and rewarded with a £10 voucher ticket per hour.

6.2.2 Apparatus

The experimental setup consisted of the VR training system supported by the ManuVAR platform (Krassi et al., 2010a) which has a flexible architecture that allows running the components of the training system on several networked computers to enhance performance (Appendix C). For this experiment, the system was distributed across 3 workstations with identical technical characteristics (Intel Core Duo CPU 3GHz with 3.18G RAM). PC 1 ran a haptic server designed for the ManuVAR platform to support the haptic rendering of geometries and force effects at a rate of 1 KHz using the Sensable OpenHaptics Haptic Device API (HDAPI) and High Level API (HLAPI). A PHANToM Omni by Sensable Technologies (http://www.sensable.com), a punctual inter-actuator able to sense position and orientation on 6 DOF input and render forces up to 3.3 N onto 3 DOF output within a delimited workspace (up to 160 W x 120 H x 70 D mm), was used as haptic interface (Appendix A). In order to prevent the haptic interface from warming up when it was used for a prolonged period of time, the haptic device was swapped with a similar one at the beginning of the experiment for each participant. PC 2 displayed a virtual environment on a 2D Panasonic LCD monitor (W: 850 x H: 450 mm) with a 1920 x 1080 pixels screen resolution. The virtual environment was rendered by the 3DVia Virtools 5.0 VR Player at a 60 Hz refresh rate. PC 3 ran support tasks such as managing user profile, launching applications, loading lesson definition files and orchestrating communication among all components (Poyade et al., 2011). In addition, a laptop was used to display instructions to participants.

Participants sat at about one meter in front of the 2D LCD monitor with their line of sight targeting to the centre of the screen. They were facing the haptic device placed in the centre of LCD monitor width (Figure 60).

Figure 60. The haptic device was located in front of the monitor and instructions were displayed on a laptop placed on the left of the participant.

Participants interacted in the virtual environment using a virtual precision rotary tool simulated by the haptic device. Participants were shown how the virtual tool was mapped on the haptic device and were asked to handle it as if it were a real portable power tool (Figure 61). The haptic device simulated the weight of the tool, the force resulting from the contact with surfaces, and the operating conditions of a precision rotary tool (Section 5.2).

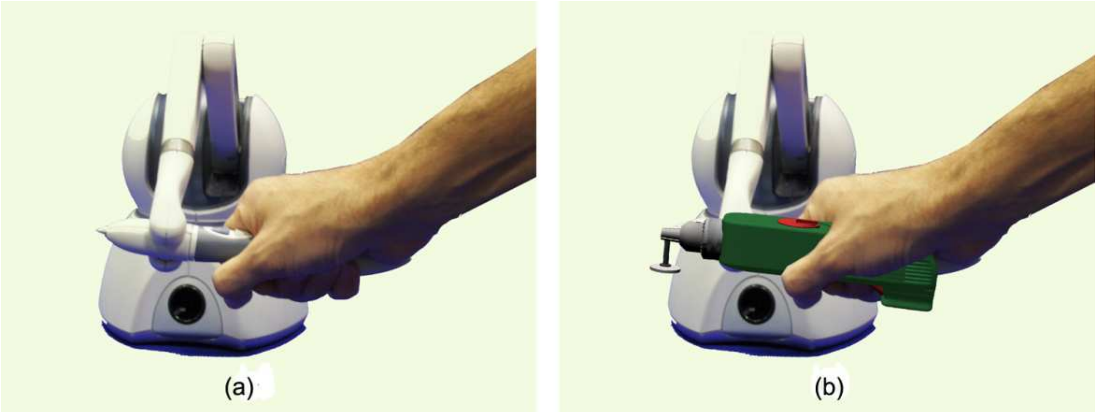

Figure 61. Handling of the haptic device and mapping of the virtual precision rotary tool on the device. The stylus represented the body of the virtual tool with the accessory attachment sitting at a 90° angle from the end of the stylus (This figure has been manipulated with an image editing software).

The virtual environment consisted of a 3 x 4.5 cm metallographic replica area on the upper side of a pipe located in an industrial plant. The virtual environment presented general stationary regulatory conditions (Section 2.1.5). Environmental noise recorded from the performance of the task in the real industrial facilities during maintenance process was played to increase the realism of the virtual environment. Moreover, sounds produced by a real precision rotary tool operating on a material surface were also recorded and implemented to enhance the realism of the simulation of the polishing task.

A training toolkit which enables building training programs to apply fundamental training methods such as part-task and whole-task training to the context of VR has been proposed in section 5.1. In this experimental study, the training program consisted only of part-task training. However, the effectiveness of part-task training to support motor learning and transfer trained motor skills to the performance of a polishing task was assessed through a single trial of whole-task training.

Part-task training was inspired by progressive-part practices which enabled training on maintaining angle and force skills separately and simultaneously within range for a prolonged period of time. As described in section 5.1.1.2, a set of dial indicators was displayed in a panel located on the right side of the monitor so it did not interfere with the visualization of the virtual environment (Figure 62). Those indicators provided concurrent KP on applied angle and theoretical exerted force applied on the material surface[6]. Furthermore, a stopwatch and a progression bar provided concurrent KR on the status of goal achievement. Concurrent KR informed about the remaining time during which participants should keep maintaining the trained motor skill(s) within range in order to achieve the goal of the training. The effectiveness of these indicators to train motor skills with regards to their design was assessed in a user evaluation test carried out by the Human Factors Research Group at the University of Nottingham (Langley et al., 2012).

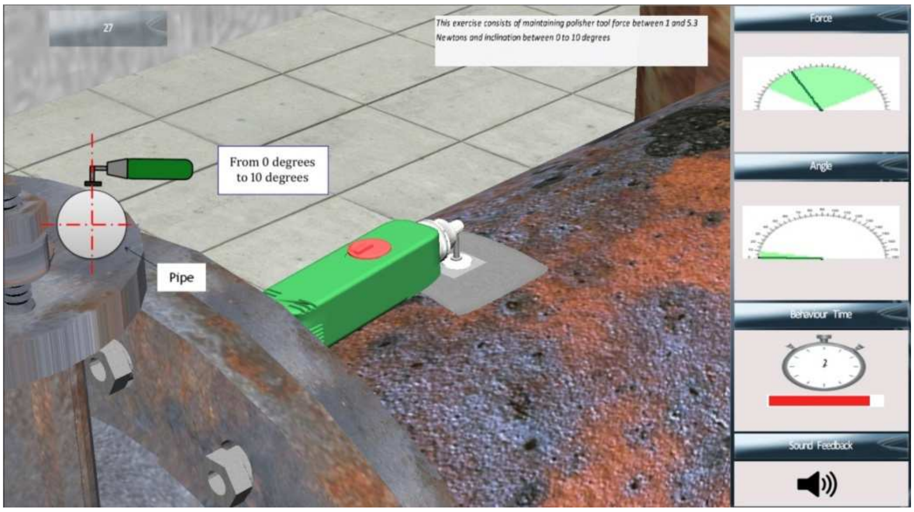

Figure 62. Part-task training enabled training angle and force skills separately and simultaneously in a virtual environment. Concurrent augmented feedback was provided through a set of indicators located in a side panel.

As mentioned previously, the effect of part-task training on motor learning for the performance of a polishing task was assessed through a single trial of whole-task training. The trial allowed performing the polishing task as it is usually carried out in a real operating environment. However, concurrent KR was provided in the form of a colour map indicator located on the surface of the material, which provided information about the completion of the polishing across the metallographic replica area (Figure 63). The colour map uses a gradual colour coding from red to green to depict the advancement of the task across the area (Section 5.1.2.2). Red corresponds to 0% of task completion, bright green represents 100% of task completion, and shades of orange and yellow are used to show intermediate levels of

[6] The theoretical exerted force consists of the magnitude of the applied force on the material surface based on the penetration of the haptic device in the geometry (Section 5.2.1).

task completion. This colour map was also replicated and magnified in a window located on the lower right corner of the monitor (Figure 63).

Figure 63. A trial of whole-task training supported the evaluation of the performance of a whole polishing task in a virtual environment. A colour map displayed on the area being polished enabled monitoring in real-time the advancement of the task. That colour map was also magnified and displayed in a panel located on the right lower corner of the monitor.

6.2.3 Design and procedure

The study used a between-group design to test the effect of motor skill training on the performance of a polishing task. Participants were randomly distributed into three groups of 10 members. The condition of motor skill training was the independent variable. Three training condition levels were proposed: Full Training condition (FT), Haptic familiarization Training condition (HT) and Control Training condition (CT). Each group was assigned to a unique training condition.

Each training condition included a period of familiarization with haptic interaction and a practice step (Table 10). After those steps, all participants performed an evaluation step carried out through a trial of whole-task training. During the evaluation step, the effect of the training condition on the performance of a polishing task was assessed.

Table 10. Training conditions assigned to groups

Groups	Familiarization step	Practice step	Evaluation step
FT	Performed	Performed	Performed
HT	Performed	Video	Performed
CT	Video	Video	Performed

Before each step, all participants received textual, verbal and graphical instructions (Appendix D). These explained the purpose of each step, the configuration of the virtual environment, the meaning of the visual feedback displayed on the monitor and the functioning of the virtual precision rotary tool, with an emphasis on the simulated forces and the handling of the haptic device.

In the FT group, the participants performed the familiarization and the practice steps. In the familiarization step, participants manipulated the virtual tool following a series of exercises presented through the instructions. A first exercise consisted of moving the virtual tool clockwise and anti-clockwise towards each corner of the area to be polished. A second exercise consisted of moving the virtual tool across the area. Both exercises were repeated when the virtual precision rotary tool was switched on so that participants could feel the generated forces that emulated the functioning of the tool. The familiarization step aimed to help participants in understanding the mapping of the workspace of the haptic device in the virtual environment.

Once the familiarization step was complete, participants from the FT group performed the practice step which consisted of part-task training on angle and force skills. Participants were previously instructed about the ranges for angle and force skills required for the performance of a polishing task which were respectively set to 0º to10º, and 1 N to 5.3 N[7].

[7] These ranges were estimated asking the two expert metallurgists from Tecnatom S.A. to perform the task in the laboratory at the University of Malaga using a Phantom Desktop (Section 5.4.2). However, in the case of the maximum boundary of the range of correctness of force skill (5.3 N), it was not possible to provide such contact force feedback in this experimental study because the haptic device used here, a Phantom Omni, was only able to render forces up to 3.3 N. Beyond this level of force, the virtual stiffness of the object being contacted decreases, becoming a natural limit for the force to be applied by participants. Nevertheless, this is not a problem for the internal validity of the experiment, as this limit was consistent between the practice step and the evaluation step.

The design of the proposed part-task training was previously refined in a pilot experiment which involved 4 PhD students from the Human Factors Research Group at the University of Nottingham. The resulting design consisted of 10 exercises.

In exercises 1 to 5, participants were required to maintain the virtual tool in a fixed position. In exercises 6, 7 and 8, participants were required to perform respectively circular (Figure 64.a), forward to backward (Figure 64.b) and left to right (Figure 64.c) motions across the surface area. In exercises 9 and 10, participants were asked to repeat the motion with which they felt more confident. After each exercise, participants rested for at least three minutes maintaining their wrist and forearm in a neutral position resting on the table. Nonetheless, they were free to prolong their resting as long as they felt necessary.

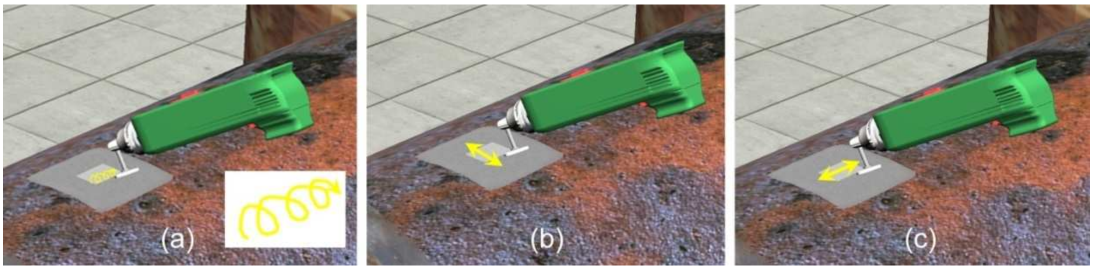

Figure 64. During the practice step, all participants were presented three trajectories: (a) circular, (b) forward to backward and (c) left to right. In exercises 6 to 10, FT were required to practice angle and force skills moving the virtual polishing tool across the metallographic replica area according to these trajectories.

Each exercise was composed of 4 items of 60 seconds each in which participants attempted to maintain angle and force skills within the specified ranges continuously for 15 seconds. After completing an item, participants were provided with augmented feedback in the form of visual and audio terminal KR (Section 5.1.1.2) which informed whether they had succeeded or failed at achieving this goal (Table 11).

Table 11. Design of the part-task training and schedule of the augmented feedback throughout part-task training items for each of the 10 exercises.

Items	1	2	3	4
Trained Skill(s)	A	F	A&F	A&F
Concurrent KP: Angle & Force				
Angle (dial)	X_T		X_T	
Angle (Sound)				
Force (dial)		X_T	X_T	
Force(Sound)				
Concurrent KR: Remaining time within range				
Bar & Stopwatch	X	X	X	X
Terminal KR				
Visual	X	X	X	X
Sound	X	X	X	X

A Angle
F Force
A&F Angle & Force

X_T Concurrent KP indicator shown with range which indicates the threshold values of the target skill

X Indicator shown but range is hidden

For item 1, participants were asked to maintain the inclination of the virtual precision rotary tool within a given range. A dial indicator was displayed to show whether the angle was within the range or not (Table 11). For item 2, participants were required to apply force on the surface area. This time they had to apply a force within a given range (Table 11). A different dial indicator was displayed to show whether the force was within range. For item 3 participants were asked to simultaneously maintain the angle and the applied force within their respective ranges. Both dial indicators were displayed to angle and force (Table 11). In both dial indicators presented in these last items, the ranges for angle and force skills were marked as a green area (Figure 62). For item 4, participants were asked again to maintain angle and force within range, but this time no dial indicators were displayed (Table 11).

In the HT group, participants physically performed the initial familiarization step, but not the practice step. Therefore, they were aware of the mapping between the haptic device and visual/haptic system responses, but had not been specifically trained in the performance of angle and force skills required in the polishing task. Instead, this group watched a video of a screen recording of the part-task training performed by an expert user and received verbal explanations. The expert user was not shown on the video in order to prevent participants from mimicking motor skills by observation (Heyes & Foster, 2002).

The CT group physically performed neither the familiarization nor the practice steps. Instead they watched two videos. This condition was included to allow the isolation of the impact of the familiarization exercises and the training activity on performance. The first video which substituted the familiarization step staged an expert user performing the familiarization exercises. Thus, any possible learning effect was discarded from the performance of the familiarization step. While watching the video, participants of the CT group received verbal explanations of the haptic sensations perceived by the expert. The second video which substituted the practice step was the same video watched by participants of the HT group.

Finally, all groups were instructed to perform the evaluation step. During three minutes, participants attempted to complete the polishing across the metallographic replica area by applying trained skills and moving the virtual precision rotary tool according to the motions proposed to them through the practice step. Colour map indicators were displayed to monitor the progression of the polishing task. However, no indicators showed whether angle and force skills were or not within range.

Afterwards, participants were interviewed and were required to rate a series of items and give their impression through a questionnaire (Appendix D).

The total duration of the experiment was approximately of two hours for the participants of the FT group and one hour for those of other groups.

6.2.4 Data Analysis

Six dependent variables were measured. The first three referred to performance measures which were related to the completion of the polishing task across the metallographic replica area. Completion was first computed as a value between 0 and 100% for each pixel of the colour map and stored in a 64×64 completion matrix (Section 5.1.2.3): (1) the “Task Completion” was the average of the values stored in the completion matrix; (2)

the “Half-completion Area” was the percentage of area where the polishing was completed at more than 50%; (3) the “Full-completion Area” as the percentage of the area for which the polishing was completed at more than 80%. The other three dependent variables were related to the accuracy of angle and force skills:(4) the angle error time, (5) the force error time and (6) the total error time which respectively measured the total elapsed time when applied angle, force and either angle or force were maintained out of the range defined for the polishing task.

At the end of the experiment, participants were required to rate a series of items related to their experience during the performance of the polishing task, and give their impression. Subjective data were collected in the form of a questionnaire through a series of closed-ended questions and raw textual data (Appendix D). A typical 5-level Likert-scale was used for ratings.

In all, there were 33 questions arranged by themes: one item of perception of performance, one item of perception of accuracy, two items of easiness of the task, two items of easiness of interaction, two items of fatigue, three items of perception of the effectiveness of training, five items of perception of realism, six items of quality of feedback and 11 items of presence.

6.3 RESULTS

Measures of performance showed that participants of the FT group achieved higher means in comparison with non trained participants of HT and CT (Figure 65). A One-Way analysis of variance (ANOVA) was performed using SPSS statistical analysis software package release version 19.0.0., to test the effect of the training condition on the performance of a polishing task. Statistical significance was established at $p < 0.05$. The ANOVA reported significant differences between groups. The effect of the training condition was statistically significant for the task completion measures ($F(2,27) = 33.47$, $p < 0.001$), the half-completion area ($F(2,27) = 39.23$, $p < 0.001$) and the full-completion area ($F(2,27) = 34.90$, $p < 0.001$).

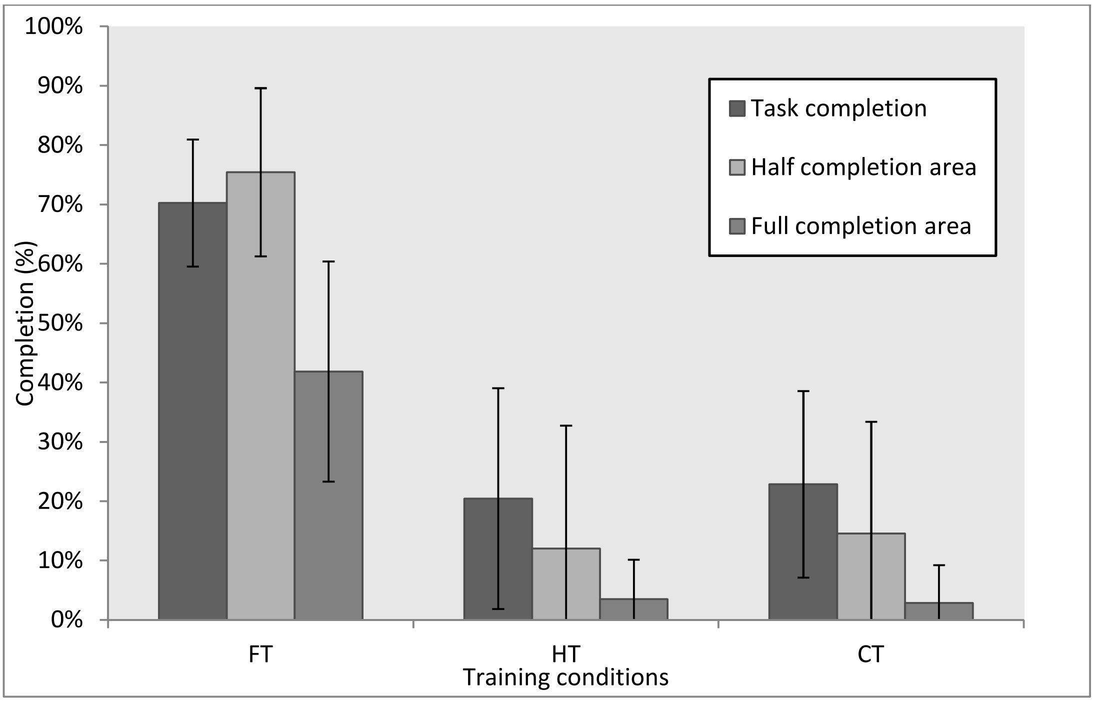

Figure 65. Mean performance results along with the standard deviation (error bars) for each training condition.

A Tukey´s HSD Post Hoc Test indicated that trained participants of the FT group performed significantly better than those from HT and CT who were not trained on angle and force skills (Table 12). Moreover, the analysis did not report any significant differences of performance between participants of HT and CT groups.

Table 12. Multiple comparison of training conditions performance means

	Task completion	Half completion area	Full completion area
FT vs. HT	$p < 0.001$	$p < 0.001$	$p < 0.001$
HT vs. CT	$p = 0.935$	$p = 0.949$	$p = 0.933$
CT vs. FT	$p < 0.001$	$p < 0.001$	$p < 0.001$

Note. Significant level at $p < 0.05$.

Results obtained from error time measures suggested that trained participants of the FT group were more capable of maintaining applied angle and force within range compared to non trained participants from HT and CT (Figure 66).

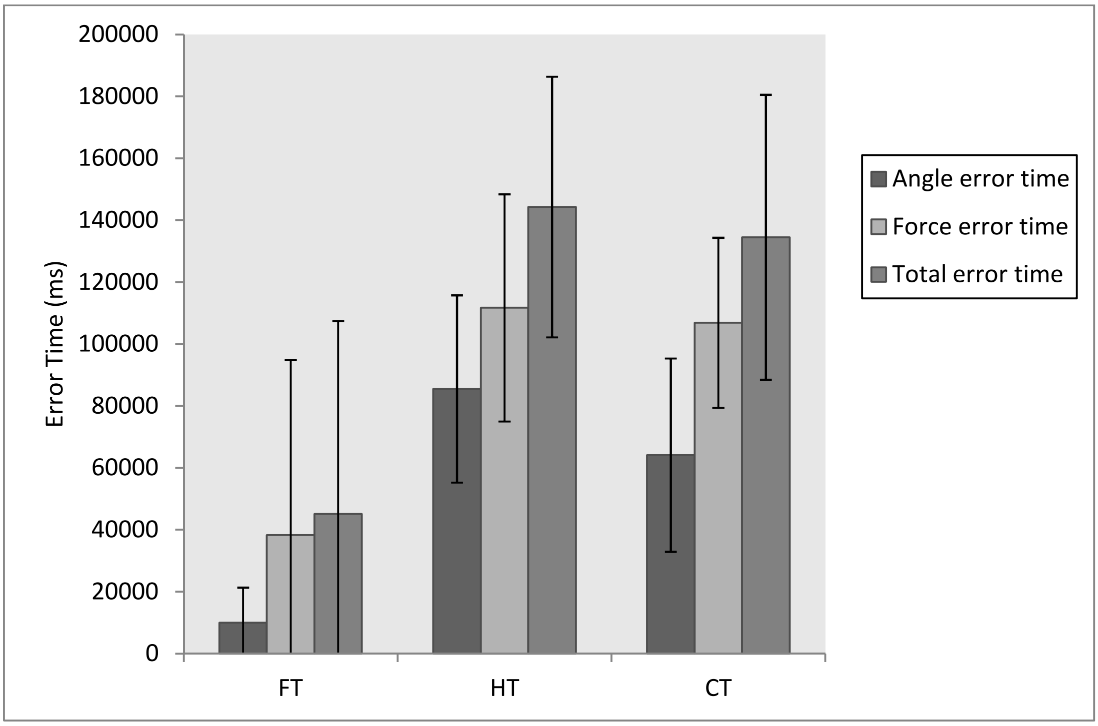

Figure 66. Means error time differences between training conditions.

A one-way ANOVA analysis highlighted a significant effect of training conditions on angle error time ($F(2,27) = 6.29$, $p = 0.006$), force error time ($F(2,27) = 12.54$, $p < 0.001$) and total error time ($F(2,27) = 23.28$, $p < 0.001$). A Tukey´s HSD Post Hoc analysis indicated significant or marginally significant differences between trained participants of the FT group and non trained participants from HT and CT groups (Table 13). Although a significant difference in angle error time was reported between participants from FT group and those from HT, there was only a marginally significant difference between FT and CT and no significant difference between HT and CT. Participants of the CT group appeared slightly more accurate at maintaining angle within range than those from HT. However, participants of the FT group appeared significantly more accurate to exert forces than those from HT and CT. No significant difference was found between non trained participants from HT and CT groups.

Table 13. Multiple comparison of training conditions error times

	Angle error time	Force error time	Total error time
FT vs. HT	$p = 0.005$	$p < 0.001$	$p < 0.001$
HT vs. CT	$p = 0.599$	$p = 0.949$	$p = 0.815$
CT vs. FT	$p = 0.051$	$p < 0.001$	$p < 0.001$

Note. Significant level at $p < 0.05$.

Subjective data collected through the questionnaire consisted of rated items arranged by themes, and comments. For each group, ratings of items were averaged per theme in order to provide a mean score in accordance with the Likert scale (Table 14). The ratings suggested that participants of the FT group found the task and the interaction paradigm to be easier compared to those from groups HT and CT. They also reported that they felt their performance to be more effective and accurate, and had a better opinion concerning the effectiveness of the training they received. However, participants from CT group also reported, to a lesser extent, satisfaction about the training condition they were assigned. In general, participants of the CT group tended to provide higher ratings compared to those of participants from HT. Moreover, all participants felt relatively involved in the virtual environment for the performance of the task, and have a positive opinion concerning the realism of the simulation and the quality of the provided feedback.

Table 14. Descriptive (means and standard deviation[8]) of the averaged ratings for themes.

	Easiness of task	Easiness of Interaction	Perception of performance	Perception of accuracy	Fatigue	Perception of realism	Presence	Perception of training	Quality of feedback
	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD	M ± SD
FT (N = 10)	3.7 ± 0.6	4.25 ± 0.4	3.9 ± 0.7	3.7 ± 0.8	3.8 ± 0.9	3.8 ± 0.8	3.9 ± 0.5	4.6 ± 0.4	4.25 ± 0.6
HT (N = 10)	2.6 ± 1.15	3.15 ± 0.9	2.4 ± 1.3	2.8 ± 1.23	3.6 ± 0.8	3.7 ± 0.5	3.5 ± 0.5	3.3 ± 0.7	4.02 ± 0.5
CT (N = 10)	3.25 ± 1	3.7 ± 0.7	2.8 ± 1.13	3 ± 0.9	3.9 ± 1.2	3.7 ± 0.5	3.8 ± 0.4	4.03 ± 1	4.4 ± 0.6
All (N = 30)	3.2 ± 1	3.7 ± 0.8	3 ± 1.22	3.2 ± 1.05	3.8 ± 0.9	3.7 ± 0.6	3.7 ± 0.5	4 ± 0.9	4.22 ± 0.6

Likert Scale quote: 1- denoting strongly disagree, 2 - disagree, 3 - neutral, 4 - agree, and 5 - strongly agree

[8] The criterion used to represent means and standard deviation data were as follow:

Data are rounded to one decimal point, unless that decimal is 1 or whether being a 2, the following is less than 5. In such cases means and standard deviation data are rounded to two decimal points. This approach will be followed onwards to express means and standard deviation data.

Table 15. Statistics analysis (Kruskal–Wallis H-test) to test the significance of comparison of data mean ranks from all groups.

Kruskal-Wallis Test	Chi-Square	df	Asymp. Sig.
Easiness of the end task	4,521	2	0,104
Easiness of the haptic Interaction	10,805	2	0,005
Perception of performance	7,757	2	0,021
Perception of accuracy	3,953	2	0,139
Fatigue	0,454	2	0,797
Perception of realism	0,129	2	0,938
Presence	3,237	2	0,198
Perception of training	13,383	2	0,001
Quality of feedback	2,480	2	0,289

Mean scores for each group were compared in a Kruskal–Wallis H-test, with $p < 0.05$ considered to indicate the statistical significance (Table 15). Significant differences were found between groups in the ratings of items related to the easiness of the interaction (H(2) = 10.805, p = 0.005), the perception of task performance (H(2) =7.757, p = 0.021) and the perception of the effectiveness of the training (H(2) = 13.383, p = 0.001). A post-hoc all-pairwise comparison Kruskal-Wallis One-Way ANOVA (k-Samples) conducted on statistically significant results reported significant differences between participants from groups FT and HT (easiness of the haptic interaction, p = 0.003; perception of performance, p = 0.024, and perception of the effectiveness of training, p = 0.001). However, no statistically significant difference was found between groups FT and CT, and neither between HT and CT.

After the experiment, participants were strongly encouraged to provide comments related to their experience. The collected data were analyzed with a Theme-Based Content Analysis (TBCA) (Neale & Nichols, 2001), a methodology that aims to enhance the qualitative evaluation of interactive technologies and enables reporting opinions presented in the form of raw textual data in a consistent way (Appendix E).

Almost all participants found the instructions and the colour map useful to understand what was asked and what was happening during the polishing task. However, couple of participants admitted some slight confusion to correlate the magnified colour map to the metallographic replica area. Moreover, participants considered the VR simulation to be quite realistic but the modelling of force to be a bit weak.

Many participants commented the complexity of the task and their lack of accuracy. For instance, five participants from FT group, seven from HT and seven from CT reported some troubles and sometimes feeling confused applying the correct force on the surface of the material, while only two from HT and four from CT found difficult applying the correct angle. However, none of the participants from FT group mentioned the complexity of maintaining the angle within range.

Although the proposed part-task training was long lasting, only three participants of the FT group reported to feel fatigue in the course of the experiment and four participants recognized that it was effective to support the motor learning and thus improve the task performance. Two other participants from FT group also highlighted that receiving more practice would have been appreciable in order to improve the performance of angle and force skills. However, many participants from other groups, eight from HT and four from CT, considered that the training condition to which they were assigned was not sufficient to accurately perform the polishing task, and previous physical practice would have been necessary. Moreover, several participants from CT group underlined the complexity of converting the information presented in the videos into accurate motor skills.

6.4 DISCUSSION

In this experimental study, the effect of part-task training on the development of angle and force skills for the performance of a polishing task simulated in a virtual environment has been investigated. The design of the proposed part-task training has been refined during a pilot experiment. The resulting design was inspired by progressive-part practices of fractionized and simplified skills enhanced with concurrent and terminal augmented feedback. Moreover, a haptic device enabled simulating intrinsic information like that perceived in real operating environments.

Three training conditions were tested. FT provided familiarization with the haptic interaction and enabled practicing independently and simultaneously angle and force skills required for the performance of a polishing task. HT provided only familiarization with the haptic manipulation. The training consisted in watching a video of the part-task training performed by an expert. CT watched videos of the familiarization and the practice performed by an expert.

The results showed that participants of the FT group were significantly more proficient performing the polishing task than those from HT and CT. This suggests that the proposed part-task training supports motor learning and enables novice participants to progress to a more advanced stage of learning such as the associative stage (Section 2.2.2.1). However, the significance of the measure of angle error time between participants from CT and FT groups is controversial. Effectively, results surprisingly reported a marginally significant difference between both groups. In contrast, as it was expected, a significant difference between participants from FT and HT groups and no significant difference between those from HT and CT were found. Thus, these findings highlight an issue in the design of the training condition assigned to participants of the CT group. More investigation would be needed to determine the nature of this issue.

These findings enable discarding any significant learning effect due to the manipulation of the haptic device during the familiarization step, suggesting that motor learning occurred only through the practice step. The two experimental hypotheses are thus verified:

1. The part-task training proposed throughout the practice step enhances motor learning which led to the successful development of angle and force skills.
2. Motor skills trained through part-task training can be transferred to the performance of a whole polishing task simulated in a virtual environment.

The experimental results concur with those of Morris et al. (2007), which stated that the effectiveness of training with augmented feedback provided through visual and haptic cues enhanced learning of complex motor skills such as force skills. However, the complexity of the polishing task is far from that of the task proposed by Morris et al. (2007). Effectively, in this experimental study, the correct force consists of a force exerted within a specific range, whereas in the study of Morris et al. (2007), the correct force varied along a passively guided trajectory. However, the complexity of the polishing task was high to the extent that the stability of applied angle and force tended to be altered by changing tangential forces generated by the haptic device while moving across the metallographic replica area. Moreover, on the basis of the findings of Balijepalli and Kesavadas (2006), it is assumed that the curvature of the surface perceived while moving across the area also has a significant effect on the stability of applied forces. Thus, the polishing task presented an increased degree of complexity to the extent that participants were required to pro-actively perform several motor skills simultaneously:

1. Angling correctly the virtual precision rotary tool.
2. Applying forces within a specific range
3. Moving the virtual tool within the metallographic replica area.
4. Attempting to reproduce one of the three motion models across the area.

Augmented feedback was provided in the form of visual concurrent KR and KP in order to enhance motor learning throughout part-task training. However, in accordance with Esen et al. (2004), concurrent KP was sometimes withdrawn in order to prevent trainees to only rely on it for the estimation of the correctness of trained motor skills. Alike in the proposed part-task training, Esen et al. (2004) used such augmented feedback to provide performance information on applied forces while training a bone drilling operation. They have demonstrated that force skills could be learnt using that source of information.

In more recent studies, Esen et al. (2008a, 2008b) proposed an online haptic interaction paradigm which was used to provide the haptic sensation perceived by a trainee to an experienced instructor. Thus, the system enabled the experienced instructor to interfere with the performance of the force skill. In their studies, they have shown that training assisted by verbal instructions based on visual and haptic observation was generally more effective to enhance the learning of force skills than other assisted training modes. However, Todorov et al. (1997) have demonstrated that training of tacit motor knowledge resulted to be more effective with visual augmented feedback when compared to verbal guidelines provided by an experienced instructor. Alike angle and force skills involved in the performance of the polishing task, motor skills trained by Todorov et al. (1997) could be hardly refined with accuracy through verbal instructions. Therefore, the augmented feedback scheduled throughout the part-task training suggested in this experimental study appeared to be superior for accurate skills adjustments compared to verbal guidelines usually provided by an expert metallurgist during conventional training.

6.5 CONCLUSION

In this chapter, the effectiveness of part-task training inspired by progressive-part practices of fractionized and simplified skills, enhanced with haptic force feedback and augmented feedback, has been assessed. Experimental results suggest that part-task training was an effective method to train angle and force skills for the performance of a whole polishing task simulated in a virtual environment.

In the following chapter, the effectiveness of the VR training system to train on fine grinding and polishing tasks is investigated. VR training of angle and force skills for both tasks is proposed through a training program composed of:

1. Part-task training of angle and force skills inspired by progressive-part practices, enhanced with augmented feedback and haptic force feedback, as proposed in this experimental study.
2. Whole-tasks training which enables practicing fine grinding and polishing tasks as in real operating environments.

Chapter 7. Experimental Study 2

7.1 INTRODUCTION

As explained in chapter 4, conventional training on fine grinding and polishing tasks in the context of the metallographic replica technique has issues (Section 4.2.2). However, on the basis of outcomes of the experimental study 1 presented in chapter 6, the application of training methods such as part-task and whole-task training in VR enhanced with haptic force feedback is believed to enable the development of angle and force skills required in both tasks.

As detailed in Section 3.2, whole-task training in VR has been found to effectively support the performance of motor skills involved in complex manual operations (Suebnukarn et al., 2010; Johanesson et al., 2010; Rhienmora et al., 2011; Oren et al., 2012). Similarly, previous research has highlighted the effectiveness of part-task training in VR to support motor learning (Esen et al., 2004; Aggarwal et al., 2006; Eid et al., 2007; Sternberg et al., 2007; Esen et al., 2008a; Esen et al., 2008b; Aggarwal et al., 2009; Iwata et al., 2011; Luciano et al., 2012). However, to the best of the knowledge of the author, conclusions concerning the effectiveness of part-task training procedures based on the fractionation of concurrent motor skills are still missing. Moreover, many of the works previously mentioned have proposed full operative training procedures through which part-task components were gradually integrated into a whole-target task (Esen et al., 2004; Aggarwal et al., 2006; Eid et al., 2007; Sternberg et al., 2007; Aggarwal et al., 2009). Nevertheless, part-task and whole-task training have been rarely associated in a common training framework to support the development and the performance of motor skills in the context of a whole-task as did Aggarwal et al. (2009).

This chapter presents an experimental study which was carried out over three days during the demonstration phase of the ManuVAR project (Appendix C) at Tecnatom S.A. facilities. Two expert metallurgists participated in the experimental study during the first day and six non-expert workers during the following two days.

This experimental study consists of two experiments which investigate the effectiveness of part-task and whole-task training to support motor learning. Chapter 6 has presented an experimental study which has already highlighted that part-task training enables the successful development of angle and force skills for the performance of a polishing task in a virtual environment. However, in this chapter, the first experiment explores whether the part-task training of those fine motor skills that are required in a polishing task can be also extended to a fine grinding task for which a different range of the angle skill is defined (Section 7.2). In the second experiment, the effectiveness of whole-task training is investigated along with the capability of VR simulations to provide a realistic representation of the performance of fine grinding and polishing tasks (Section 7.3).

Part of the experiment 2 presented in this chapter has been accepted for publication in the following paper:

Poyade, M., Molina-Tanco, L., Reyes-Lecuona, A., Langley, A., D'Cruz, M., Frutos, E., & Flores., S. (2012, October). Validation of a haptic virtual reality simulation in the context of industrial maintenance. *Proceedings of the Joint VR Conference of euroVR (JVRC 2012) and EGVE*, Madrid, Spain.

7.2 EXPERIMENT 1: PART-TASK TRAINING

As mentioned previously, on the basis of outcomes of the experimental study presented in chapter 6, this experiment investigates the effectiveness of part-task training inspired by the fractionation of concurrent motor skills and enhanced with augmented feedback, to support motor learning for fine grinding and polishing tasks. The first hypothesis formulated in chapter 6 was tested in this experiment for both tasks: Part-task training is effective in improving the proficiency of trainees in applying angle and force skills for fine grinding and polishing tasks.

7.2.1 Methods

7.2.1.1 Participants

Six trainees (1 female and 5 males) aged from 30 to 55 took part in the experiment. All trainees were non-expert workers from Tecnatom S.A. One declared that he/she was skilled in performing the metallographic replica technique, the other four had little knowledge and another one was a complete novice. However, all trainees received previous procedural training through which they acquired theoretical knowledge about the metallographic replica technique (Appendix C). They were also familiar with the manipulation of power tools but they had no previous experience with VR technology and haptic device handling.

All trainees filled in a consent form before the procedural training and were informed about the purpose of the experimental study and publication policies (Appendix D). Trainees reported no arm or wrist disabilities and only one trainee (trainee 3) reported colour blindness as uncorrected visual impairment.

7.2.1.2 Apparatus

The VR system ran on the ManuVAR platform distributed on two workstations (Appendix C). PC 1 supported the ManuVAR technological elements in charge of the management of the platform (Poyade et al., 2011) and a haptic server especially designed for ManuVAR. A Phantom Desktop, a haptic device able to render a maximum force of 7.9 N on 3 DOF, enabled interacting within the virtual environment (Appendix A). PC 2 displayed the virtual environment in which part-task training was carried out, on a 3D screen (W: 1500 x H: 1200 mm) with a resolution of 1280 x 960 pixels. The 3DVia Virtools VR player rendered the virtual environment at a refresh rate of 60Hz. The virtual environment was visualized through a pair of passive stereoscopic glasses equipped with a set of infrared light reflective markers which were tracked by 6 infrared cameras from Natural Point Optitrack in order to estimate the point of view of the performer (Appendix B). A separate laptop located in an adjoining room was used to display the instructions.

Trainees stood at about 1 m in front of the 3D screen (Figure 67). The haptic device was placed in front of them and elevated so the haptic workspace physically matched with the manipulation workspace in the virtual environment.

Figure 67. A worker performs a part-task training session, attempting to apply angle and force within specific ranges.

Trainees were asked to handle the haptic device as if it were a real portable power tool. The stylus represented the body of the virtual power tool with the rotating wheel attachment sitting at a 90° angle from the end of the stylus (Figure 68).

Figure 68. Mapping of the virtual precision rotary tool on the Phantom Desktop stylus (This figure has been manipulated with an image editing software).

The virtual environment consisted of a 3 x 4.5 cm metallographic replica area located on the lateral of a pipe in an industrial plant (Figure 69).

A set of performance indicators, displayed in a lateral panel (Figure 69), provided concurrent augmented feedback in the form of Knowledge of Performance (KP) and Knowledge of Results (KR) to inform respectively about motor skill accuracy and goal achievement (Section 2.4.2). KP indicators consisted of a dial and bar gauge that respectively showed the value of angle and force being applied. For both skills, indicators also displayed the threshold values which referred to the boundaries of the target ranges. Moreover, KR was displayed in the form of a clock which indicated the remaining time during which the trained skills should be maintained within thresholds in order to achieve the goal of the training item. As mentioned in Section 5.1.1.2, the effectiveness of those indicators to support motor learning has been previously discussed in an experimental study carried out at the University of Nottingham (Langley et al., 2012).

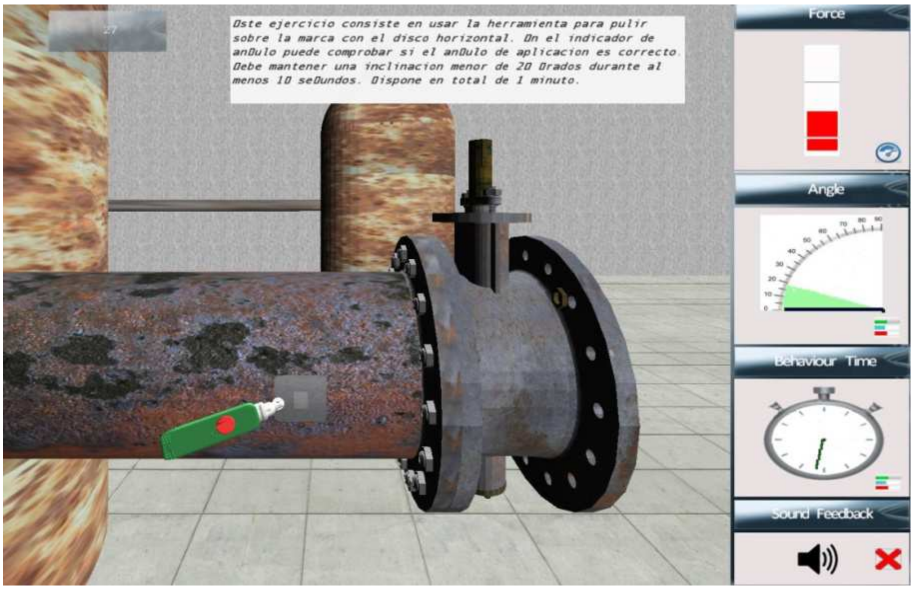

Figure 69. Virtual environment in which part-task training took place along with the lateral panel in which concurrent augmented feedback was provided.

Moreover, as in the experimental study presented in chapter 6, recorded environmental noise and sounds from a real precision rotary tool with its rotating wheel in contact with a material, or when rotating freely, were rendered in order to enhance the realism of the simulation.

7.2.1.3 Design and Procedure

The experimental procedure followed a within-subject design. The performance of participants was compared before and after part-task training. The procedure to follow consisted of:

1. A pre-evaluation.
2. Two part-task training exercises[9].
3. A post evaluation.

Before starting, trainees were assigned a unique identification number and were randomly distributed in two groups: One group performed part-task training related to a fine grinding task and the other to a polishing task. Previously to the experiment, trainees were verbally and textually informed about the purpose of the experiment and the procedure they were required to follow (Appendix D). They were also given a description of the virtual environment and instructed about the visual augmented feedback they would receive throughout part-task training.

The pre-evaluation was composed of six items of one minute each in which trainees attempted to maintain angle and force skills for 10 seconds within specific ranges for the task to which they were assigned. Ranges had been discussed and set heuristically by the two expert metallurgists from Tecnatom S.A. For the fine grinding task, the ranges for angle and force were respectively set to 75º to 90º and 1N to 5N, whereas for the polishing task, the ranges were 0º to 20º and 1N to 5N. No visual feedback on the performance of angle and force skills (concurrent KP) was provided while performing the pre-evaluation.

Each part-task training exercise was composed of a sequence of four training items of 60 seconds, inspired by progressive-part practices (Section 2.3.3). In each item, trainees attempted to maintain angle and force skills separately or jointly within ranges for 10 seconds. In items 1 and 2, participants were required to maintain respectively angle and force within the specified ranges. Visual indication of angle in item 1 and force in item 2 were provided so that trainees could refine the practised skills (Table 16). In item 3, angle and

[9] Due to restrictions on the availability of workers to perform the experiment, part-task training was shortened to two training exercises.

force skills were combined in order to be practised together (Table 16). Trainees tried to maintain both skills concurrently within the required ranges using the visual aid provided by angle and force indicators (Figure 69). In item 4, trainees attempted the same as proposed in item 3 but KP indicators were withdrawn (Table 16). Thus, trainees were encouraged to perform based on the motor knowledge acquired throughout previous items. After each item, trainees were provided terminal KR as a positive or negative hint in the form of a green tick or a red cross that stated for goal achievement (Section 5.1.1.2). Between each exercise, each trainee was required to rest in an adjoining room while another trainee from the other group performed the equivalent exercise.

Table 16. Design of the part-task training and provision of the augmented feedback in each training item.

Items	1	2	3	4
Trained Skill(s)	A	F	A&F	A&F
Concurrent KP: Angle & Force				
Angle (dial)	X_T		X_T	
Angle (Sound)				
Force (bar)		X_T	X_T	
Force(Sound)				
Concurrent KR: Remaining time within range				
Clock	X	X	X	X
Terminal KR				
Visual	X	X	X	X
Sound	X	X	X	X

A Angle
F Force
A&F Angle & Force

X_T Concurrent KP indicator shown with range which indicates the threshold values of the target skill

X Indicator shown but range is hidden

After the two training exercises, participants performed the post-evaluation which was designed as the pre-evaluation.

At the end of the experimental study, participants were interviewed and were required to rate their training and give their impression through a questionnaire (Appendix D).

7.2.1.4 Data analysis

Two measurements were carried out for all participants during the pre and post evaluations in order to be compared. The collected data consisted in:

1. Measures of effectiveness of part-task training to support learning of angle and force skills revealed by the number of successfully completed items for each participant.
2. Measures of efficiency expressed by the average completion time of items for each participant.

At the end of the experimental study, trainees were invited to give their impression and rate their training. Subjective data were collected in the form of a questionnaire through a series of open and closed-ended questions (Appendix D). A typical 5-level Likert-scale was used for ratings assigned to closed-ended questions.

7.2.2 Results

Considering that the number of participants was too small to perform a statistical analysis, experimental results are presented for each trainee.

Measures of effectiveness of part-task training suggested that all trainees were able to achieve the six items proposed during the post-evaluation for both tasks (Figure 70.a & b). However, only one participant (trainee 4) from the group assigned to the polishing task succeeded in achieving the six items proposed during the pre-evaluation (Figure 70.b).

Measures of efficiency showed that trainees were more efficient in completing the six items during the post-evaluation compared to those of the pre-evaluation (Figure 71.a & b). Although it is not possible to claim without statistical analysis, these findings point out that, participants became more accurate at maintaining angle and force skills within the specified ranges after motor skill training. Thus, part-task training enabled trainees to become more proficient performing motor skills required in both tasks.

Moreover, trainees provided high ratings of part-task training with the statements that tasks were easy to complete and indicators of angle and force were helpful in performing the items scored near to the maximum (Table 17). None of the participants reported any physical discomfort and found difficult to use the haptic device to interact within the virtual environment although one trainee mentioned that more time would have been necessary to get familiarized with the interface.

The trainees also positively rated the visual quality of the virtual environment displayed on the 3D screen and found that it did not impact on their performance. However, they commented that the quality of graphics could still be improved in order to bring more realism to the virtual environment, and the size and the workspace of the virtual precision rotary tool could be refined to fit with more realistic dimensions (Appendix F).

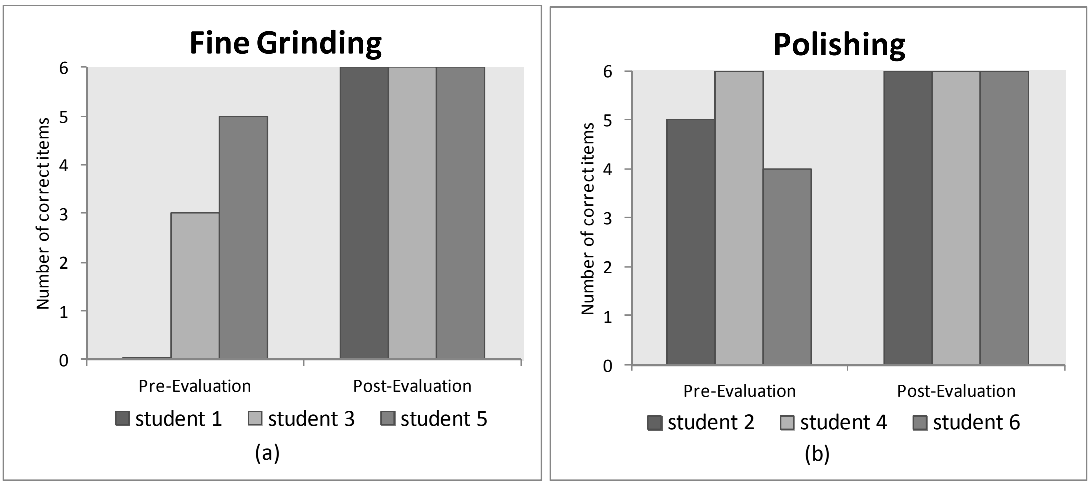

Figure 70. Comparison of performance of trainees before and after part-task training on angle and force skills for (a) fine grinding and (b) polishing tasks.

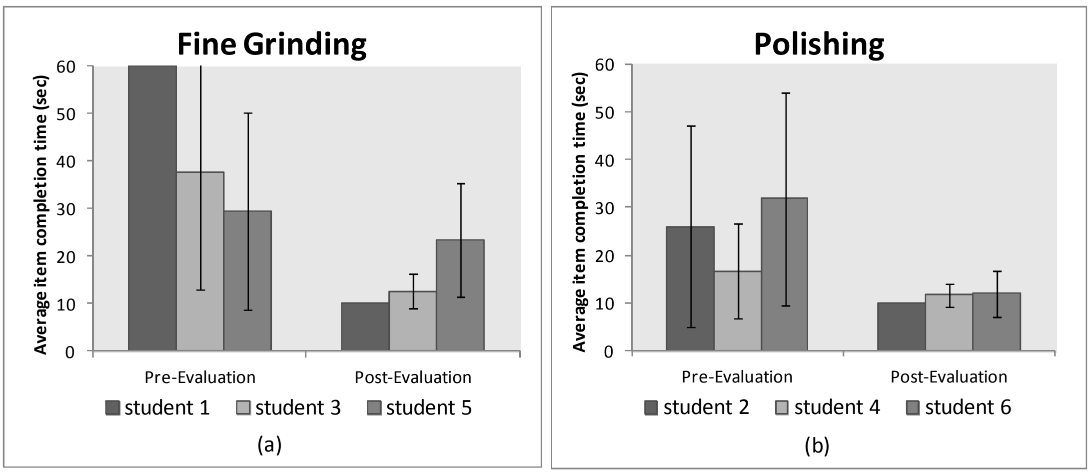

Figure 71. Comparison of the average completion time of items before and after practice of angle and force skills for (a) fine grinding and (b) polishing tasks.

Table 17. Mean scores and ranges given by trainees after part-task training.

Nº	Statements	Mean	Range (N = 6)
1	I found it easy to do the task	4.17	4-5
2	I found the force feedback helpful to perform my task	4.7	3-5
3	I found the angle feedback helpful to perform my task	4.7	3-5
4	The system provided adequate feedback to show the time that has passed during the task	4.3	3-5
5	I found it easy to learn how to use the haptic device	4.3	4-5
6	It was easy to use the haptic device	4.5	4-5
7	Virtual representations of objects moved in a natural way	4	3-5
8	I liked the way that the motor skills training application[10] was realized	4.17	3-5
9	I did not experience any physical discomfort during the task	4.8	4-5

Likert Scale quote: 1- denoting strongly disagree, 2 - disagree, 3 - neutral, 4 - agree, and 5 - strongly agree

7.2.3 Discussion

These findings suggest that the proposed part-task training, even when performed during a short time, enabled the successful development of angle and force skills according to the requirements for fine grinding and polishing tasks. These findings are actually in agreement with those presented in chapter 6 for the polishing task. Thus, the initial hypothesis addressed in chapter 6 has been thus newly verified for the polishing task. Moreover, in this experiment, the effectiveness of part-task training has also been demonstrated for a fine grinding task for which the range for angle skill was different. Although the verification of the initial hypothesis for a fine grinding task cannot be claimed as in chapter 6 due to the lack of experimental results, with regards to the results obtained in this experiment and considering the principle of generalization of motor programs (Section

[10] In the context of the ManuVAR demonstration phase, the VR training system supporting part-task training was referred as motor skill training application.

2.2.1.2) presented by Schmidt (1975), it is highly probable the initial hypothesis to be also true in the case of a fine grinding task.

From Figure 71, it can be noticed that participants appeared to be more efficient maintaining motor skills within the specified ranges in the case of the polishing task. This suggests that motor skills required for polishing were easier to apply when compared to those of a fine grinding task. One possible explanation would be that the estimation of correct angle for polishing was more intuitive. However, more investigation is needed to explore this.

These findings also suggest that the proposed scheduling of concurrent augmented feedback (KP and KR) provided throughout training exercises was effective to support motor learning. Effectively, once angle and force indicators were withdrawn, as in the post evaluation items, the performance of those motor skills did not worsen. Thus, augmented feedback provided in the form of concurrent KP gradually withdrawn throughout part-task training and concurrent KR always provided did not have any guidance effect as described by Salmoni et al. (1984), Schmidt & Wrisberg (2008) and Ranganathan & Newell (2009). Moreover, as discussed in chapter 6, these experimental results are in concurrence with Esen et al. (2004), Morris et al. (2007) and Esen et al. (2008a, 2008b) to the extent that the suggested training enhanced with such augmented feedback enabled learning complex forces. However, as far as it has been investigated, no experimental data concerning the learning of the angle skill in virtual environments have been found. Thus, these experimental results allow filling this gap demonstrating that VR training can also support the development of angle skills within distinct ranges.

7.3 EXPERIMENT 2: WHOLE-TASK TRAINING

In the context of the ManuVAR project, this experiment investigates the effectiveness of whole-task training to support performance improvements for fine grinding and polishing tasks. Moreover, this experiment also explores whether task simulations proposed through the whole-task training provide a realistic representation of the reality to the extent that the simulation of task performance allows discriminating between the level of expertise of expert metallurgists and non-expert workers.

In this experiment, two hypotheses have been thus formulated:

1. Whole-task training consists of an effective training for the performance of fine grinding and polishing tasks.
2. Task simulations proposed through the whole-task training provide a realistic representation of task performance to the extent that levels of expertise acquired in real operating environments can be sucessfully applied to the context of VR training.

7.3.1 Methods

7.3.1.1 Participants

The six trainees involved in the experiment 1 (Section 7.2) were invited to participate in this experiment. Moreover, two expert metallurgists (2 males) aged 31 and 35 also took also part in the experiment. Expert metallurgists had several years of experience manipulating power tools in the context of the mechanical preparation of material surface required in the metallographic replica technique, and had very little experience with haptic device handling in virtual environments. Expert metallurgists did not report any arm or wrist disabilities, and uncorrected visual impairment.

7.3.1.2 Apparatus

The experimental setup described for the experiment 1 (Section 7.2.1.2) was reused in this experiment but PC 2 displayed the virtual environment in which whole-task training occurred.

As in experiment 1, participants stood at about 1 m in front of the 3D screen and handled the haptic device placed in front of them as if it were a real portable power tool (Figure 72).

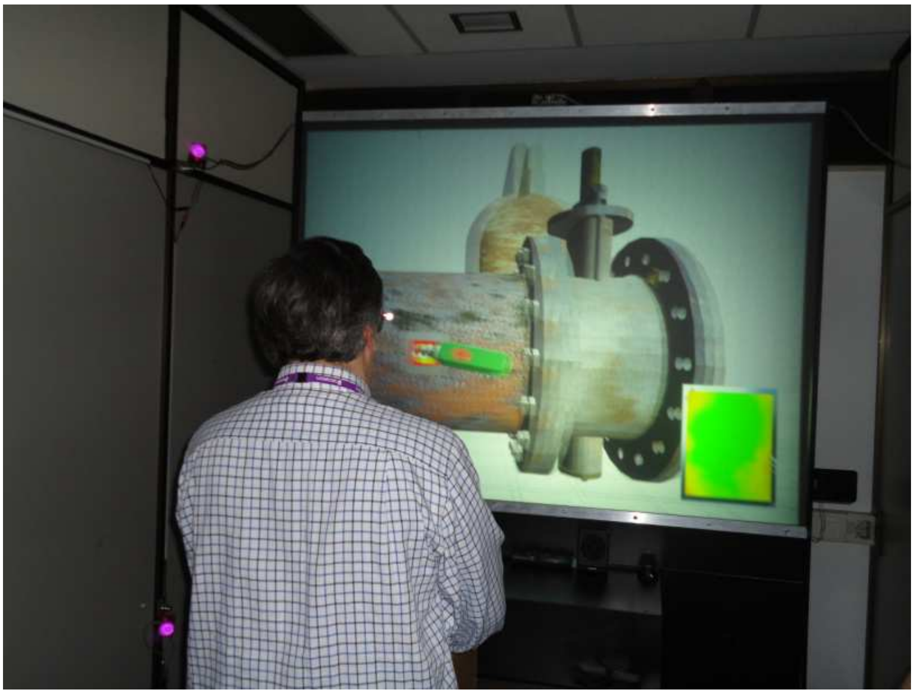

Figure 72. A trainee performs a whole-task training session, using the colour map on the metallographic replica area along with the magnification represented in the lateral window.

The virtual environment was also similar to that of experiment 1 (Figure 69). However, for the whole-task training, there was no lateral panel to provide concurrent augmented feedback on the performance of the trained motor skills. Instead a colour map indicator laid on the metallographic replica area provided concurrent KR. As it has been presented in Section 5.1.2.2, the colour map used a colour coding (from red to green) to inform about the completion of the task on the metallographic replica area (Figure 73). The colour map was also magnified and shown in a lateral window located on the right lower corner of the monitor (Figure 73).

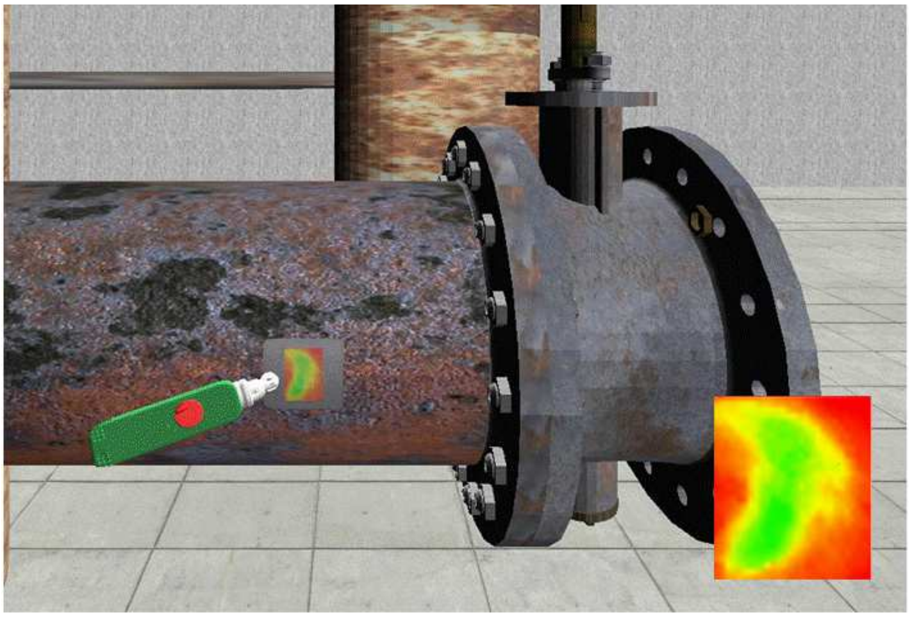

Figure 73. Virtual environment in which whole-task training took place.

7.3.1.3 Procedure

The experimental procedure consisted of a within-subject design. The distribution of trainees into two groups was maintained as in experiment 1. Expert metallurgists repeated the training procedure for each task, as described below for trainees.

Before starting, all trainees received verbal and textual instructions about the purpose of the task and were explained how to interpret the information provided by the colour map (appendix D). Then, trainees performed a pre-evaluation step composed of two items of 3 minutes:

1. A familiarization item during which they were asked to perform the task they were assigned, using the visual aid provided by the colour map indicators.
2. A pre-evaluation item during which they performed the task without visual feedback.

Trainees practised the whole-task through two training items of 3 minutes[11]. For each item, colour map indicators were displayed on demand continuously for 10 seconds. Between each item, the trainee rested in an adjoining room while another trainee from the other group performed the equivalent item.

[11] As for part-task training, due to restrictions on the availability of workers to perform the experiment, whole-task training was shortened to two training items.

Finally, trainees were evaluated through a post-evaluation item which consisted of performing the whole-task during 3 minutes with no colour map. Afterwards, trainees were interviewed. As in experiment 1, they were required to rate the training and give their impression through a questionnaire (Appendix D).

7.3.1.4 Data analysis

Measurements were carried out during the pre and post-evaluation items. The collected data provided three measures of performance expressed in the form of percentages which stated for distinct levels of task completion[12]:

1. The "Task Completion" was the average of the values stored in the matrix.
2. The "Half-completion Area" was the percentage of area where the task was completed at least at 50%.
3. The "Full-completion Area" as the percentage of the area for which the task was completed at more than 80%.

As in experiment 1, participants were invited to share their opinion and rate the training through a questionnaire composed of open and closed-ended questions (Appendix D). A typical 5-level Likert-scale was used for ratings assigning the following statements to closed-ended questions.

7.3.2 Results

As in experiment 1, the statistical analysis of results could not be conducted, thus experimental results are here presented for each participants.

Measures of performance showed the effect of whole-task training on task completion, half-completion area and full-completion area for fine grinding and the polishing tasks (Figure 74). Overall, the findings highlight the general trend of improvement of performance after whole-task training. Although, improvements were slight in the case of the fine grinding task, the performance of trainees generally tended to improve. However, trainee 1 was not as successful in performing the fine grinding task during the post-evaluation as

[12] These were obtained from the processing of the data stored in the elements of the matrix $A_{64\times 64}(n)$ corresponding to the percentages of task completeness in the pixels of the colour map (Section 5.1.2.3).

he/she was during the pre-evaluation (Figure 74.a, c & e), and all participants but one (trainee 2) performed the polishing task better after whole-task training (Figure 74.b, d, & f). Moreover, measures collected during the pre-evaluation item revealed that expert metallurgists were able to complete both tasks achieving higher performance rates than trainees (Figure 75). This suggests that simulations proposed through the whole-task training provided a realistic representation of task performance enabling differentiating between expert and non-expert workers.

All participants were mostly positive about the whole-task training although, one trainee (trainee 6) disagreed with the statements concerning the easiness of the task and the understanding of what was happening during the task. This trainee stated that he/she had experienced difficulties on correctly applying force on the material surface.

All participants found the user interface very intuitive, the colour map to be helpful even if one trainee (trainee 3) reported to be colour-blind, and appreciated the simulation of the virtual environment and haptic sensations (Table 18). Trainees reported that the simulation" *fits the reality of the work*" and expert metallurgists highlighted the realism of the simulated tool and the effectiveness of the whole-task training because it enabled to put a performer in the context of the mechanical preparation tasks required in the metallographic replica technique (Appendix F).

Moreover, as in experiment 1, participants positively rated the visual quality of the virtual environment displayed on the 3D monitor while performing the whole-task training and found that it did not impact on their performance. As well, comments concerning graphics quality, the size and the workspace of the virtual power tool reported in experiment 1 could be also applied to this experiment.

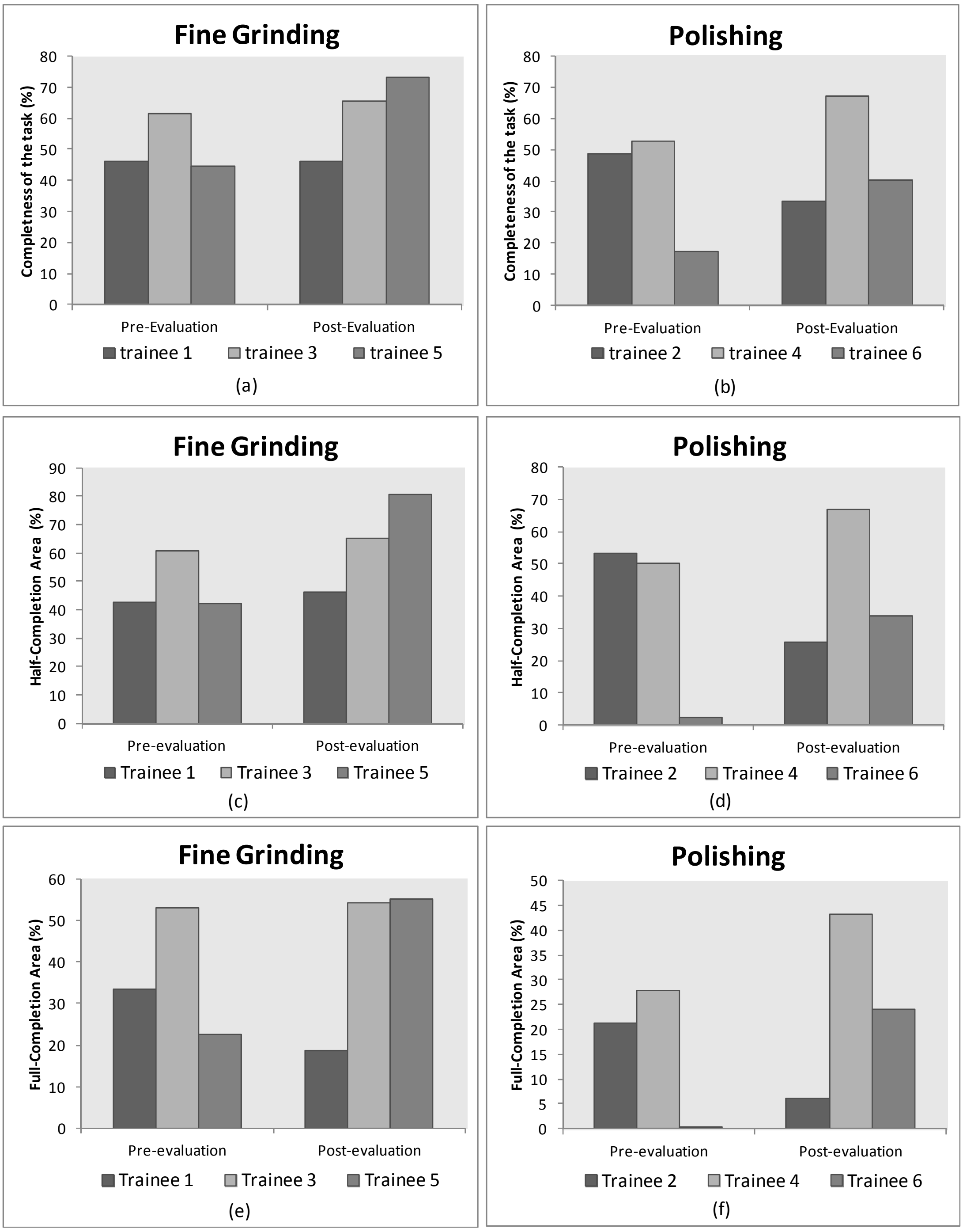

Figure 74. Measures of performance for all trainees before and after whole-task training: Completion of (a) the fine grinding task and (b) the polishing task; Half-completion area for (c) the fine grinding task and (d) the polishing task; Full-completion area for (e) the fine grinding task and (f) the polishing task.

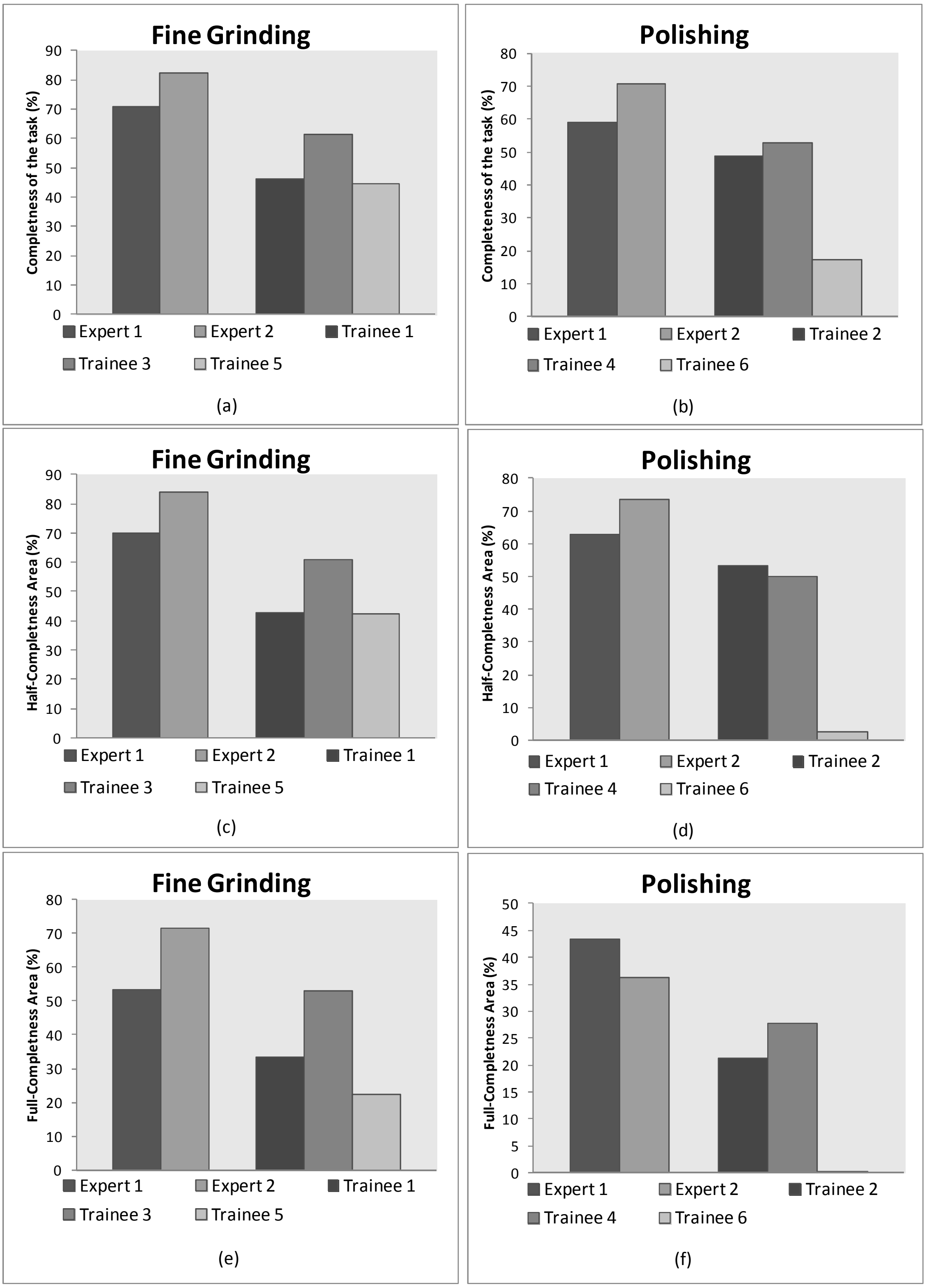

Figure 75. During the pre-evaluation, expert metallurgists were more efficient than trainees, performing (a, c, e) the fine grinding task and (b, d, f) the polishing task.

Table 18. Mean scores and ranges given by the expert metallurgists and trainees after performing on the training simulator

		Experts (N = 2)		Trainees (N = 6)	
Nº	Statements	Mean	Range	Mean	Range
1	I found it easy to do the task	4.5	4-5	3.7	2-5
2	The user interface seemed intuitive to use	5	5	4.5	4-5
3	I understood what was happening during the task	5	5	4	2-5
4	I found the colour map helpful to perform my task	5	5	4.8	4-5
5	Virtual representations of objects moved in a natural way	4.5	4-5	4.3	3-5
6	I liked the way the simulation application[13] was represented	5	5	4	3-5
7	I did not experience any physical discomfort during the task	4.5	4-5	4.17	4-5
8	It was easy to use the haptic device	4.5	4-5	4.7	4-5

Likert Scale quote: 1- denoting strongly disagree, 2 - disagree, 3 - neutral, 4 - agree, and 5 - strongly agree

7.3.3 Discussion

Performance of trainees was first compared before and after training in order to highlight improvements subsequent to whole-task practice. In the overall, experimental results suggest that performance of trainees tended to improve after whole-task training, even though in some cases, improvements were slight. However, the performance of one trainee (trainee 2) was less efficient after whole-task training. That trainee later provided an explanation for his/her low performance rate commenting that throughout the post-evaluation item, "*you don't know where you are performing so it is not easy to do it*", "*I didn't know how it was working it was blind work*". Moreover, even though it has not been reported in comments, the trainee stated that he/she felt tired prior to the experimental study. Nonetheless, these comments could also suggest the guidance effect of the augmented

[13] In the context of the ManuVAR demonstration phase, the VR training system supporting whole-task training was referred as simulation application.

feedback as described by Salmoni et al. (1984), Wierinck et al. (2005), Schmidt & Wrisberg, (2008) and Ranganathan & Newell (2009). However, more investigation would be needed in order to verify the guidance hypothesis of the colour map indicator.

The colour map indicator received high ratings from all participants and positive comments were provided such as "*The colour map is useful, you can check the work you are performing and how you perform it*" and "*…it shows the point in which you have to polish*". However, as mentioned in section 7.2.1.1, one of the trainees (trainee 3) has reported colour blindness as uncorrected visual impairment. The interpretation of the augmented information provided through the colour map indicator was somehow problematic as the trainee was not able to distinguish some of the colour nuances. In order to enable that trainee to refer to the colour map indicator throughout the whole-task training, he/she was indicated how colours changed. Nonetheless, such visual impairment did not seem to affect that much task performance when compared to other trainees from the same group. However, a colour map using a grey colour coding has been later developed for colour blind people. This colour map has been presented in section 5.1.2.2.

In the overall, experimental results enable verifying the hypothesis addressed on the effectiveness of whole-task training to support task performance improvements. However, due to restrictions to run the whole experimental study, whole-task training has been drastically shortened and most probably, task performance improvements would have resulted more outstanding after more intensive training. In that sense, experimental results would concur with findings of Suebnukarn et al. (2010) who have showed that multiple rehearsals of whole-task training led to significant improvements of task performance. However, in that case, a wider sample of trainees would also be necessary in order to allow running a statistical analysis of quantitative data.

Performance of trainees before whole-task training was also compared to that of expert metallurgists in order to investigate whether VR simulations provided realistic representations of task performance enabling discriminating between different levels of expertise. Experimental results show that expert metallurgists were able to achieve higher performance than trainees. In that sense, task simulations enabled applying the levels of expertise acquired in real operating environments to the context of whole-task training in VR. Thus, simulations proposed in whole-task training consisted of realistic representations of both tasks performance. The second hypothesis formulated in this experiment has been therefore verified. These findings agree with with those obtained through similar research studies carried out on nowadays successfully validated whole-task training simulators for surgical & dentistry tasks (Kalltröm, 2010; Rhienmora et al., 2011). However, in order to confirm the trend of whole-task training simulations to allow discriminating between several levels of expertise, a statistical analysis of performance means involving a wider sample of participants with different levels of expertise such as novice, intermediary, advanced and expert would be necessary.

Similarly to Rhienmora et al. (2011), participants have also demonstrated a high degree of acceptance of the realism of task simulations proposed through the whole-task training. Effectively, positive comments concerning the realism of simulations have been provided by expert metallurgists *"… it makes you feel that you are performing the real metallographic replica*", "*The environment is very good*" and trainees "*…it fits the reality of the work", "...very similar to performing the real task*" (Appendix F). Expert metallurgists also notified about the realism of the simulated power tool as "*It feels like holding the real tool along with the vibration and sound*", which is in unison with the belief of Abate et al. (2009) that the addition of haptics contributes in increasing the realism of the interaction.

7.4 CONCLUSION

In this chapter, the effectiveness of the VR training system has been investigated. A training program has been suggested in order to allow training those motor skills that are relevant in the performance of fine grinding and polishing tasks on the VR training system. That training program consisted of two fundamental training methods:

1. Part-task training inspired by the fractionation of angle and force skills usually performed simultaneously throughout fine grinding and polishing tasks, which enabled practicing those skills separately and then jointly.
2. Whole-task training which consisted of a holistic approach to the performance of fine grinding and polishing tasks.

Part-task training offered the opportunity to isolate each motor skill in order to be practice independently and jointly previously to whole-task training. In contrast, whole-task training did not allow focusing on the development of a particular motor skill but rather enabled practicing fine grinding and polishing tasks as in real operating environments. In that extent, part-task training was complementary to whole-task training.

Two experiments have been carried in order to evaluate the effectiveness of each training method to support motor learning. Moreover, the realism of the representation of task performance provided through whole-task training has been investigated in term of how well simulations enabled discriminating between several levels of expertise reported in real operating environments.

In experiments 1 and 2, the effectiveness of part-task and whole-task training to support the development motor skills required in fine grinding and polishing tasks has been respectively established by comparing the performance of trainees before and after training. Moreover, in experiment 2, task performance of trainees was compared to that of two expert metallurgists, resulting in a clear differential of performance between both levels of expertise. Thus, simulations proposed through the whole-task training consisted of a realistic representation of the reality enabling applying levels of experience acquired in real operating environments to the context of VR training. However, more investigation involving a wider sample of participants offering a larger panel of levels of expertise is needed to confirm that trend.

PART 5 CONCLUSION OF THE THESIS

Chapter 8. Discussion and Conclusion

Traditional training of the fine motor skills required for fine grinding and polishing tasks in the metallographic replica technique consists of whole-task training and occurs under the supervision of an instructor. These motor skills are tacit knowledge which is complex to transfer verbally. Motor learning is hampered by performance assessment issues (Section 4.2.2.1) and inaccurate instructions (Section 4.2.2.2). Hence, conventional training often remains complicated, exhausting and discouraging.

Fundamental training methods such as part-task and whole-task training are believed to facilitate motor learning (Section 2.3). These training methods have been employed to successfully train fine motor skills that are relevant in clinical (Johnson et al., 2008; De Visser et al., 2011; Kolozsvari et al., 2011; Klein et al., 2012), educational (Klapp et al., 1998; Clawson et al., 2001) and industrial (So et al., 2012) activities. However, part-task training based on the fractionation of concurrent motor skills, such as angle and force skills required in fine grinding and polishing tasks, may be hard to achieve in the real world. Moreover, the implementation of this training method in the real world would not resolve the issues which arise in conventional training (Section 3.2).

On many occasions, training of complex industrial manual tasks in VR has been considered to be superior to conventional training, as it enables solving issues which usually arise in real operating environments (Mujber et al., 2004; Lee et al., 2010). Moreover, VR technologies such as haptic force feedback devices are believed to enable realistic interaction within virtual environments (Abate et al, 2009; Dalto et al., 2010).Thus, the implementation of a haptic-based training system which allows part-task and whole-task training in VR, and also enables providing augmented feedback is believed to be effective for fixing those issues that arise in conventional training. Motor learning would be thus enhanced.

This thesis introduces a VR training system enhanced with haptic force feedback, which aims to support the development of motor programs (Section 2.2.1) for the accurate performance of fine grinding and polishing tasks. This training system enables applying fundamental training methods in VR and allows the provision of augmented feedback throughout the training process (Chapters 4 & 5). The effectiveness of the system to support development of fine motor skills and transfer those skills to real operating environments has been investigated through two experimental studies (Chapters 6 & 7).

In this chapter, the objectives of this thesis are addressed in the form of a discussion. The design of the suggested training and its effectiveness are argued with regards to the findings of other research studies in section 8.1. The objectives addressed by the experimental outcomes are discussed in section 8.2. Finally, the discussion presents the limitations of the VR training system and experimental studies in section 8.3, making recommendations for further research sequels in section 8.4.

8.1 VR TRAINING

This thesis has also proposed a training toolkit which allows building training programs that enable specifying the training to be carried out on the VR training system. A training program enables defining the training methods such as part-task and whole-task training, to be followed during the VR training (Section 8.1.1). Moreover, augmented feedback in the form of concurrent and terminal Knowledge of Results (KR) and Knowledge of Performance (KP) (Section 2.4.2) can be provided for a more effective motor skill training (Section 8.1.2). As well, haptic force feedback was used to simulate haptic intrinsic information in VR alike that perceived in real operating environments (Section 8.1.3).

8.1.1 Training methods

Part-task and whole-task training methods have been widely proposed to support motor learning through VR training (Basdogan et al., 2004; Morris et al., 2006; Abate et al., 2009; Wang, Y. et al., 2009; Gutiérrez et al., 2010; Suebnukarn et al., 2010; Iwata et al., 2011; Nishino et al., 2011; Rhienmora et al., 2011; Sung et al., 2011). A review of the current state of the art of the application of those fundamental training methods to the context of VR training has been proposed in section 3.2.

8.1.1.1 Part-task training

The part-task training suggested in this thesis was inspired by the progressive-part integration of fractioned practices of angle and force skills which are performed simultaneously in fine grinding and polishing tasks (Section 5.1.1). Despite the fact that part-task training has been frequently proposed to support motor learning in VR on the basis of the segmentation of sequential motor skills (Youngblood et al., 2005; Aggarwal et al., 2009; Iwata et al., 2011, Luciano et al., 2012) and the simplification of task performance (Solis et al., 2003; Williams II et al., 2004a; Williams II et al., 2004b; Aggarwal et al., 2006; Wang, D. et al., 2006; Esen et al., 2008a; Esen et al., 2008b; Iwata et al., 2011), to the best of the knowledge of the author, the suggested part-task training has not been implemented so far. Therefore, this is considered to be an original approach for training concurrent motor skills in VR. Moreover, in concurrence with other works (Esen et al., 2004; Aggarwal et al., 2006; Eid et al., 2007; Von Sternberg et al., 2007; Bhatti et al., 2009), it was also suggested to include a gradual increase of the degree of complexity of motor coordination requirements through the addition of a motion pattern in order to bring part-task practices closer to the performance of the whole-target task. On the basis of findings of Saga et al. (2005) and Srimathveeravalli & Thenkurussi (2005) which have highlighted the complexity of performing force and motion skills simultaneously at an early learning stage, the suggested part-task training aimed to facilitate the successful development of the force skill at an early learning stage. Quantitative results from experimental studies presented in chapters 6 and 7 suggest that this kind of part-task training was effective to learn angle and force skills for fine grinding and polishing tasks. However, it is difficult to compare these experimental results with findings of other research studies considering that no similar examples were found. Nonetheless, a comparison can be drawn with those studies which have highlighted the effectiveness of part-task training based on segmentation and simplification methods. Experimental results presented in this thesis are consistent with their findings. The effectiveness of part-task training was also supported by the positive feedback provided by participants throughout both experimental studies. As some participants stated, "…*training was good and my performance continued to improve*", "...*I feel it very useful to maintain force, angle and trajectory…*" and "*With the training, my sense and capability of doing the task are improved*".

8.1.1.2 Whole-task training

The whole-task training evaluated in this thesis consisted of an holistic approach of the conventional training on fine grinding and polishing tasks. In concurrence with several research studies (Moody et al., 2001; Johanesson et al., 2010; Kallträm, 2010; Suebnukarn et al., 2010; Rhienmora et al., 2011; Oren et al., 2012), whole-task training has been shown to be effective to support motor skill training. Moreover, expert and non-expert workers gave very positive feedback: "*I liked the simulator*[14]", "*I liked the training on the simulator*", "…*I liked the learning method, it was very similar to performing the real task*". However, in accordance with Utley & Astill (2008) and Coker (2009), the suggested whole-task training which involved several concurrent motor skills is believed to be too challenging at an early learning stage. Thus, previous development of motor skills through part-task training, as proposed in experimental studies 1 and 2 (Chapters 6 & 7), may be useful to guarantee successful whole-task training.

8.1.2 Augmented Feedback

Augmented feedback in the form of KP and KR is believed to be particularly beneficial to enhance learning experiences (Schmidt & Wrisberg, 2008; Utley & Astill, 2008). For this reason, it has been widely employed to support motor learning throughout VR training (Section 3.3). However, as noted in section 3.3, both KP and KR have been regularly associated with part-task training, whereas KR alone has been frequently provided in whole-task training. In contrast, KP has been rarely employed in whole-task training. A possible explanation would be that whole-task training in VR aims to support task practice as in the real world, where the focus is on task performance, rather than on the execution of each independent motor skill.

[14] In the context of the demonstration phase of the ManuVAR project, the term "*simulator*" referred to whole-task training.

8.1.2.1 Knowledge of performance

The training toolkit enables managing the provision of concurrent KP throughout part-task training. Concurrent KP was delivered through real-time visual and audio indicators, which provided feedback about angle and force skill accuracy with regards to a reference of correctness. The effectiveness of concurrent KP throughout part-task training was evaluated separately in a user evaluation test carried out by the Human Factors Research Group at the University of Nottingham (Langley et al., 2011). The results showed that performance improvements of participants who received visual concurrent KP throughout part-task training were significantly better when compared to those of participants who had no feedback. However, no significant differences were reported between participants who received concurrent KP in the form of audio information and those who had no audio feedback (Langley et al., 2011). Therefore, in concurrence with Wang, Y. et al. (2006), these results suggest that descriptive audio information giving concurrent KP is not always effective to improve task performance. For this reason, audio concurrent KP was not added to the design of part-task training in experimental studies 1 and 2 (Chapters 6 & 7).

In both experimental studies, visual indication of accuracy of angle and force skills throughout part-task training consisted of dial gauges and vertical bars on which the desired range for the corresponding skill was indicated (Section 5.1.1.2). Several research studies have provided similar concepts of visual notification of motor skill accuracy with regards to an indication of the target skill (Balijepalli & Kesavadas, 2003; Solis et al., 2003; Esen et al., 2004; Sewell et al., 2007; Esen et al., 2008b).

Participants from both experimental studies considered those indicators to be "…*good to learn the right angle and force*", "…*good for training*", "…*it is easier to understand how much to press*", "… *helpful for orientation*", and suitable as they indicated "…*where the angle and force should be….*". However, the guidance effect of such augmented feedback has been suggested once: "*…with feedback it was ok, but without feedback it was hard…*". Esen et al. (2004) and Wierinck et al. (2005) considered that the dominance of visual cues while training led to a loss of concentration on the haptic intrinsic feedback and therefore hampered motor learning. For this reason, concurrent KP was scheduled throughout part-task training in order to encourage participants to rely on their haptic intrinsic feedback. The resulting scheduling has shown to be effective to support motor learning and participants provided positive testimonies concerning its effectiveness as "*This is a good practice combined with the unseen displays…*".

The VR training system did not allow providing terminal KP throughout part-task training, and neither concurrent nor terminal KP in whole-task training.

8.1.2.2 Knowledge of results

The VR training system allowed providing concurrent KR in order to assist performance throughout part-task and whole-task training. In the context of this thesis, concurrent KR is given through an alternative representation of task performance which aims to provide real-time information feedback about the status of goal achievement. Concurrent KR has been frequently provided in part-task (Balijepalli & Kesavadas, 2003; Von Sternberg et al., 2007; Luciano et al., 2012) and whole-task training (Johanesson et al., 2010).

In this thesis, concurrent KR in whole-task training was provided through a colour map indicator which depicted the status of task completion across the metallographic replica area and aimed to inform about task progress over the time. Such augmented information was appreciated by participants from both experimental studies to the extent that "*The colour map helps me to understand what I should do with the task, which area should be covered, and how to maximize the coverage area*", "*…it shows the point in which you have to polish*" and "*The colour map is useful, you can check the work you are performing and how you perform it*". However, as for concurrent KP in part-task training (Section 8.1.2.1), the guidance trend of that kind of augmented feedback has been suggested by novice participants from experimental study 1 (Chapter 6): "*... I let the colour screen be the guiding device*" and "*... The colour was what mattered most and helped me to put a less strong and more efficient force (judging from the colour) towards the end*". In order to prevent the guidance effect of concurrent KP in experimental study 2 (Chapter 7), the colour map was thus displayed on-demand, making training more challenging. Overall, the on-request concurrent KR throughout whole-task training did not hamper motor learning. However, some negative comments provided by non-expert workers, such as "*…you don't know where you are performing, so it is not easy to do it*" and "*I didn't know how it was working, it was blind work. In contrast, in the real world you can see what you are doing...*", tend to confirm the findings of (Rodriguez et al., 2010) which suggested that on-demand augmented feedback might not have the expected effect on the development of motor programs.

Concurrent KR has also been provided throughout part-task training, in the manner of a real time indicator that provided information about the remaining time for goal achievement during the performance of training items. Similar augmented information was provided by

Balijepalli & Kesavadas, 2003 in order to support motor skill performance throughout part-task training. However, although concurrent KR was provided continuously throughout part-task training, motor learning was apparently not affected as suggested by Wierinck et al. (2005). Nonetheless, more investigation on the effect of the suggested concurrent KR in part-task training would be needed.

Terminal KR informs about goal achievement once the training has been completed. Terminal KR provided in the form of visual and/or audio information has been frequently used in part-task training (Esen et al., 2004; Williams et al., 2004b; Bhatti et al., 2009; Iwata et al., 2011) and whole-task training (Edmunds & Pai, 2008; Suebnukarn et al., 2010; Rhienmora et al., 2011). In the part-task training presented in this thesis, terminal KR consisted of visual and audio information which indicated whether the item objective has been achieved or not (Section 5.1.1.2). For whole-task training, terminal KR was not provided to participants. However, the VR training system allows providing terminal KR in the form of performance scores displayed by an evaluation system implemented on the ManuVAR platform (Appendix C). Thus, expert metallurgists and trainees can assess performance outcomes and learning curves for both tasks.

The effect of terminal KR on motor learning has not been investigated in depth in this thesis. Thus, on the basis of experimental results, it can only be said that terminal KR provided after each items of part-task training did not seem to hamper motor learning.

8.1.3 Haptic interaction

The VR training system was enhanced with haptic force feedback to support the successful development of angle and force skills. Haptic force feedback allows simulating the haptic intrinsic feedback perceived in the real world. This has been demonstrated to be profitable for motor learning in VR training (Moody et al., 2001; Wagner et al., 2007) and more particularly for the development of force skills (Panait et al., 2009). Moreover, the effectiveness of motor skill training in VR has been shown to be closely related to the realism of the haptic interaction (Moody et al., 2001; Zhang et al., 2009; De Visser et al., 2011; Zhou et al., 2012).

The haptic interaction suggested in this thesis enables manipulating a virtual precision rotary tool, feeling its weight and the contact with hard metallic surfaces (Section 5.2). Similar to Morris et al. (2006), the haptic interaction also includes the simulation of the operating conditions of the virtual tool in the form of rotary vibrations and a tangential force expressed as a function of the exerted force on the material surface (Section 5.2). Moreover, Steinberg et al. (2007) and Rhienmora et al. (2011) have highlighted the effectiveness of haptic interfaces to simulate contacts with hard surfaces. Thus, in this thesis, the implementation of the suggested haptic interaction is believed to be profitable for the development of angle and force skills required in fine grinding and polishing tasks.

Although the evaluation of the haptic interaction was not the focus of this thesis, expert metallurgists provided encouraging comments concerning the haptic sensations of the virtual tool as "*...it feels like holding the real tool, with vibrations and sounds*".

8.2 EVALUATION FRAMEWORK

Two experimental studies have been presented in this thesis. Their purpose was to evaluate the effectiveness of the VR training system to support motor learning through part-task and whole-task training, in order to establish the external validity of the system.

Two initial hypotheses concerning the validity of the VR training system were presented in Chapter 1:

1. <u>Hypothesis 1:</u> The implementation of fundamental training methods such as part-task and whole-task training in the context of VR training, along with the provision of augmented feedback, is valid for training the fine motor skills that are required in fine grinding and polishing tasks.
2. <u>Hypothesis 2:</u> The suggested VR training enables transferring the trained motor skills to real operating environments.

8.2.1 Validity of training

Hypothesis 1 was verified through four experimental hypotheses which were addressed by the experimental studies 1 and 2:

> <u>Experimental hypothesis 1:</u> Part-task training is effective in improving the trainees proficiency performing angle and force skills with regards to the requirements of the target task.
>
> This hypothesis was addressed throughout both experimental studies. In the experimental study 1 presented in chapter 6, performance of angle and force skills required in a polishing task resulted to be significantly improved

when participants went through part-task training. Novices became thus more proficient throughout part-task training enabling their knowledge on angle and force skills to progress toward a more advanced stage of motor learning. In experimental study 2 presented in chapter 7, this hypothesis was also addressed for a fine grinding task. However, despite the study had an insufficient number of participants to allow performing a statistical analysis of the results, the pattern of results does seem to indicate that part-task training effectively supports motor learning for both tasks.

Participants from both experimental studies provided positive comments such as "*User performance is improved compared to the beginning of the task*" which indicated that part-task training was perceived as an effective way of learning, as mentioned in section 8.1.1.1. These results suggest that part-task training was effective for the development of motor programs that support accurate performance of fine motor skills such as angle and force skills required in both tasks.

<u>Experimental hypothesis 2:</u> Motor skills trained through part-task training can be transferred to the performance of a whole-target task simulated in a virtual environment.

In experimental study 1, it was shown that motor skills trained through part-task training can be successfully transferred to the performance of a whole polishing task simulated in a virtual environment. Even though, to the best of the knowledge of the author, the effectiveness of the suggested part-task training has not been reported yet through the literature, the capability of other types of part-task training to transfer motor skills to the performance of a whole-target task in VR has already been highlighted through several research studies (Aggarwal et al., 2006; Aggarwal et al., 2009;Nishino et al., 2011). To that extent, the effectiveness of the suggested part-task training is consistent with that reported in these studies.

In experimental study 1, results suggest a causal relationship between part-task training and effective performance of the polishing task, claiming thus for the *internal validity* of the training. The internal validity refers to the principle of cause to effect between the independent variable controlled in the experimental study and experimental outcomes (dependent variables). To that extent, the part-task training presented in this thesis was the cause for novice trainees to efficiently perform the whole-target task.

In this thesis, this hypothesis has been verified only in the context of the polishing task proposed in experimental study 1. Thus, the internal validity of the training was achieved only for that task. However, on the basis of results presented in experimental study 2, the internal validity can be also claimed for a fine grinding task.

The transfer of motor skills from part-task training to fine grinding and polishing task performance was not investigated in experimental study 2. However, motor skills trained through part-task training were subsequently applied to whole-task training The trained motor skills were thus transferred to the performance of a whole-target task. Quantitative evaluation shows that the transfer of the trained motor skills to whole-target task performance was equal or even superior in the case of fine grinding when compared to that of polishing. Thus, on the basis of outcomes from the experimental study 1, these results point out at the internal validity of part-task training for a fine grinding task.

<u>Experimental hypothesis 3:</u> Whole-task training leads to a more efficient performance of fine grinding and polishing tasks.

Although the training procedure followed in experimental study 2 was shortened in order to adapt to the duration of the demonstration phase of the ManuVAR project and the availability of participants, experimental results suggest that task performance tended to improve after whole-task training. These findings are consistent with those presented in other research studies (Moody et al., 2001; Fried, M. P. et al., 2005; Suebnukarn et al., 2010; Oren et al., 2012). However, in this thesis, it is believed that performance improvements would have been better after a more intensive whole-task training. Indeed much previous research has highlighted how task performance is considerably improved through multiple rehersals of VR training (Esen et al., 2004; Fried, M. P. et al., 2005; Esen et al., 2008b; Suebnukarn et al., 2010).

Experimental hypothesis 4: VR simulations are realistic representations of industrial processes to the extent that the level of expertise in real operating environments can be applied to the context of VR training. Thus, the VR training system allows discriminating between different levels of expertise.

In experimental study 2, the performance of non-expert workers during the pre-evaluation of whole-task training was compared with that of the two expert metallurgists proposed by Tecnatom S.A. Experimental results revealed that performance scores derived from the performance of fine grinding and polishing tasks were higher for expert metallurgists than for non-expert workers. This suggests that the level of expertise acquired in real operating environments could be successfully applied to the performance of both tasks in whole-task training in VR. Thus, the VR training system is valid for training to the extent that it provides a realistic representation of performance outcomes for both tasks allowing discriminating between expert and non-expert workers. This hypothesis has been therefore verified.

Many research studies, and not only those which have investigated the effectiveness of whole-task training, have made a similar comparison between different levels of expertise in order to determine to which degree their VR training systems were effective to simulate realistic processes (Alhalabi et al., 2005; Fried, M. P. et al., 2005; Aggarwal et al., 2006;Morris et al., 2006; Aggarwal et al., 2009; Bajka et al., 2009; Kalltröm, 2010; Iwata et al., 2011; Rhienmora et al. 2011). This has been commonly referred to as *construct validity* (Morris et al., 2006; Bajka et al., 2009; Kalltröm, 2010; Iwata et al., 2011).

Construct validity refers to the degree to which VR simulations reflect what has been measured, in this case, task performance of participants in whole-task training on the basis of the level of expertise in the real world. Experimental results provide evidence of the construct validity of simulations to identify expert and non-expert performers based on performance scores. These findings are thus in concurrence with those studies which have established the construct validity of VR training systems based on whole-task practice (Alhalabi et al., 2005; Kalltröm, 2010; Rhienmora et al. 2011).

8.2.2 Validity of transfer

Hypothesis 2 has been verified on the basis of the internal validity of the training along with the construct validity of simulations proposed through whole-task training, allowing thus to suggest the external validity of the training proposed by the VR training system (Figure 76). As described in the introduction of this thesis (Chapter 1), the external validity of the system refers to its ability to effectively train motor skills which can be transferred to real operating environments. Thus, it is assumed that if the system enables training motor skills in a specific context which consists of an accurate representation of the reality, the system allows transferring those skills to the real world.

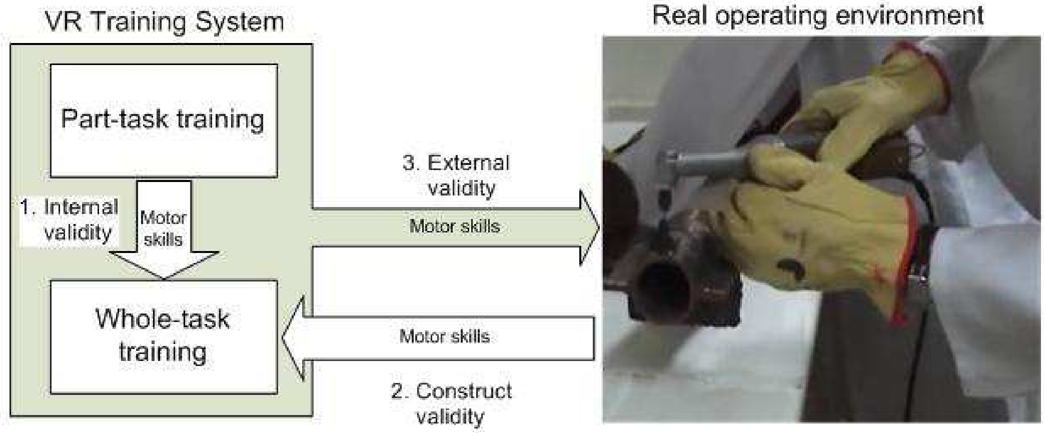

Figure 76. External validity of the VR training based on the internal validity of the training and construct validity of simulations proposed throughout whole-task training.

On the one hand, the internal validity of the training is a proof of the effectiveness of part-task training to train and transfer motor skills to the performance of a whole-target task in VR. However, those motor skills are not equivalent to those performed in real operating environments to the extent that suggested part-task training does not allow focusing on task performance. For this reason, whole-task training is required in order to enable bringing motor skill training closer to reality. On the other hand, the construct validity of simulations proposed through whole-task training suggests that the VR training system provides an accurate representation of the reality.

Hence, although the effectiveness of the VR training system to transfer motor skills to real operating environments has not been directly explored as in Eid et al. (2007), Sewell et al. (2007), Von Sternberg et al. (2007) or Oren et al. (2012), the capability of the system to train and transfer motor skills to a realistic performance of a whole-target task in a virtual environment pointed out at the external validity of that system to transfer those motor skills to real operating environments.

In experimental study 2, expert and non-expert participants provided comments which enabled exploring qualitatively the external validity of the training to the extent that they opined about how the suggested training supported motor learning and how it could improve the current training (Appendix F). These comments indicate that the external validity of the training is coherent with that evaluated objectively.

On the one hand, expert metallurgists have highlighted the potential of the VR training system to train motor skills commenting that "*The potential is very good*", "*…it is a good way to learn how to perform the steps*", "*…good to learn the right angle and force*" and "*…useful to understand some points that we can teach to the students*". On the other hand, non-expert workers considered the training to be "*…quite useful for learning…*" highlighting that it enabled the successful development of motor skills as " *It trains you in adapting correct angle and force which drives you to the correct behaviour…*" and "*User performance is improved compared to the beginning of the task*". Moreover, non-experts workers were of the opinion that the suggested training was "*…more accurate…*" "*…very precise…*", and "*…easy to learn...*", when compared to conventional training: "*It is more complicated to learn in the lab*".

Furthermore, all participants agreed on the complementary relationship of VR training and conventional training mentioning that "*…it could be combined with the conventional training*", "*…both training in VR and real word are complementary*", "*VR training and physical training are complementary*", "*It's good using VR as a complement to real world training*", "*VR training is complementary to real world training…*","*…it would be good to combine VR training and real world training*" and "*After the training received, it might be more efficient to combine with the real world training*", to the extent that the suggested training allowed to "*…cover some points that the traditional training cannot*". Finally, VR training was perceived "*As an introduction…*", because "*…it provides background and knowledge to real world training*" and "*…you can use as a background before the real world training*" allowing to "*…save you some time in the lab*".

Opinions concerning the capability of the suggested system to train motor skills and transfer those skills to conventional training suggest the external validity of the VR training system. Moreover, the external validity evaluated subjectively is reinforced with statements which indicated the fidelity of simulations proposed throughout whole-task training. Effectively as mentioned in section 3.4, a high degree of fidelity is believed to be an important factor which supports the transfer of motor skills from virtual to real operational environments also known as transfer of training. In experimental study 2, expert and non-expert workers provided comments which suggested the fidelity of simulations as "*...it makes you feel that you are performing the real metallographic replica*", "*...close to the real situation you can think that it is like holding the real tool...", "The environment is very good*", "*...it fits to the reality of the work*" and "*...very similar to performing the real task*". Nonetheless, some of the non-expert workers who performed the fine grinding task also commented the lack of fidelity of whole-task training simulations when the colour map was withdrawn: "*It is annoying when performing the last task, in contrast when you are performing in the real world you do have a visual idea about how you are doing*", and "*… the lack of feedback is annoying because in the real world they can see the metal changing*". These comments are encouraging to the extent that they confirm the fidelity of the representation of task performance outcome on the colour map. However, in the course of a polishing task in real operating environments, performance outcome on the material surface is not observable (Section 4.2.2.1). Thus, in the case of a polishing task, the colour map provided an additional assistance to the realization of the task, supposedly lessening the degree of fidelity of the simulation. Nevertheless, in this thesis, it is believed that lowering the degree of fidelity of simulations providing additional assistance is profitable to support the transfer of motor skills to real operating environments at early stage of learning. This is contrary to those studies which have argued that higher degree of fidelity support higher transfer of training (Section 3.4).

8.3 LIMITATIONS OF THE STUDY

In this thesis, a VR training system which aimed to support motor learning for fine grinding and polishing tasks has been designed and developed (Chapters 4 & 5). The effectiveness of training through that system has been explored in chapters 6 and 7. This section reviews the limitations in the design, development, and evaluation of the system.

8.3.1 Design and development of the VR training system

The VR training system allowed simulating the performance of fine grinding and polishing tasks within virtual environments (Section 5.1.2.3). However, the graphical realism of simulations can be questioned (Section 8.3.1.1). Those simulations relied upon an interaction model (Section 5.3) which has been heuristically defined by the two expert metallurgists from Tecnatom S.A. (Section 5.4). Nonetheless, that model presented some incongruence which is discussed here (Section 8.3.1.3).

Finally, the suggested VR training was enhanced with haptic force feedback which allowed interacting within virtual environments. A haptic device enabled manipulating a virtual precision rotary tool and allowed emulating the operating conditions of a real tool (Section 5.2). However, the realism of the force generated when the tool disc contacted a surface assumed a simplification of the haptic paradigm which is also discussed here (Section 8.3.1.3).

8.3.1.1 Task simulation

The lack of graphical realism of VR simulations is one limitation of this work. Although graphical realism has not been extensively reported as a critical issue, it was commented upon several times in both experimental studies. Two participants from experimental study 1 said that that the virtual environment was a "*…poor environment*" and that it could be improved (Appendix E). Similarly, some participants from experimental study 2 pointed out that the virtual environment was graphically poor, suggesting that "*graphics need to evolve to a better quality…*" (Appendix F). Moreover, the perception of contact through visual cues has been reported to be sometimes confusing:"*…it was complicated to see where I was touching*" and "*I had some doubts if I was touching or not touching the pipe*".

Some of the factors that may contribute to a perception of poor graphics quality include: poor lighting conditions, absence of shadow cues within the virtual environment and the lack of simulation of deformable objects such as the tool disc when being pressed on a material surface. Furthermore, the absence of stereoscopic visualization and point of view tracking in experimental study 1 (Chapter 6) is believed to lower the realism of virtual environments (Deering, 1993).

8.3.1.2 Parameterization of the interaction model

The interaction model encompasses the model of contact of the tool disc on the material surface along with the ranges for angle and force skills specific to fine grinding and polishing tasks. The parameterization of the model has followed a heuristic methodology (Section 5.4). The resulting interaction model was subjective and therefore questionable.

The model of contact of the tool disc on the material surface has been determined in the form of a ratio on the basis of measurements performed on a series of images. Each image showed the tool disc contacting with the material surface when specific angle and force were applied on the tool (Section 5.4.1). The measurements consisted of visually estimating the ratio of the diameter of the tool disc in contact with the material surface. Thus, a degree of uncertainty in measurements can be logically assumed. Moreover, the exactitude of exerted forces and applied angles announced by expert metallurgists for each image is relative. Applied angles were approximated. Similarly, expert metallurgists supposedly exerted controlled forces on the tool, but those forces were not measured. Thus, the accuracy of exerted forces could not be guaranteed. This could be a possible explanation for a noticeable incongruence of the model of contact when the exerted force was supposedly close to the permitted maximum exertable force and the inclination of the tool about 10º (Section 5.4.1).

The definition of ranges for motor skills was performed throughout a unique trial session during which angle and force data related to the performance of fine grinding and polishing tasks were collected (Section 5.4.2). During this trial session, expert metallurgists were required to operate on a specific surface with a virtual precision rotary tool controlled in position and orientation by a Phantom Desktop haptic device (Appendix A).

The process followed for the definition of ranges for both skills can be considered as a limitation of the research study in the extend that:

1. One of the experimental studies (Chapter 6) was conducted using a different haptic device through which haptic sensations were most probably perceived distinctly (Section 8.3.2.2).
2. The surfaces on which the evaluation of the VR training system was carried out (Chapters 6 & 7), were oriented differently compared to that of the trial session. Thus, angle and force data collected during the trial session could be argued to be specific to that case.

8.3.1.3 Haptic interaction

Realistic simulation of forces resulting from the contact of the virtual tool on the material surface is complex. In the real world, the tool disc contacts the material surface in multiple points. However, in the simulations, that contact was rather different. The haptic interfaces employed in this study consisted of punctual inter-actuators (Appendix A). The contact model proposed by default by the manufacturer consists of a one point-based contact. Therefore, contact was only perceived in a point located in the centre of the tool disc.

Such contact was considered to be sufficient to train angle and force skills. Nonetheless, there was a discrepancy between what could be seen and what could be felt. Effectively, although the tool disc collided with the material surface, contact could not be felt until half of the disc had penetrated the material surface. Thus, the collision of a point located at the edge of the disc with the material surface did not generate any haptic response.

Visualization and haptics are considered to be very important components of VR simulations as each of these cues complements each other (Steinberg et al., 2007). The discrepancy between visual and haptic cues has been reported as a lack of realism of the haptic interaction in experimental study 1. Several participants reported that “*It was hard to see why I did not touch the pipe/ make contact with it, especially as it felt I was touching it*” suggesting that the contact of the tool disc on the material surface was somehow confusing (Appendix E). Nonetheless, most of those participants were not familiarized to the haptic interaction. Similar comments have been made in experimental study 2: “*…it was complicated to see where I was touching*” and “*I had some doubts if I was touching or not touching the pipe*” (Appendix F).

8.3.2 Evaluation of the VR training system

The validity of a VR training system has been verified through two experimental studies in which the effectiveness of a training program to support motor learning has been evaluated (Chapters 6 & 7).

This thesis has proposed a training toolkit which enables building training programs. However, the effectiveness of a single training program has been tested and findings have been generalized to the VR training system.

This section proposes a critical analysis of the experimental studies presented in this thesis and points out at the limitations of experimental methods.

8.3.2.1 Participants Sampling

One limitation for both experimental studies was the sampling of participants. In experimental study 1, an a-priory G-power analysis for ANOVA designs (Faul et al., 2007) has predicted a minimum sample size of 30 participants (using $\alpha = 0.05$ as a standard of accuracy). All participants were staff and students at the University of Nottingham. They were all recruited on the basis of their availability and willingness at the time of the study. This sampling method consists of convenience sampling, a non probability sampling technique (Gravetter & Forzano, 2011). Convenience sampling is probably used more than any other sampling methods because it consists of an easier, non-expensive and quick sampling process. However, convenience sampling is usually considered as a weak form of sampling as it does not guarantee the representativeness of the sample. In the experimental study 2, participants were few technical workers and the two expert metallurgists proposed by Tecnatom S.A. The small amount of participants was critical as it did not enable conducting a statistical analysis of experimental data (Section 8.3.2.1). Such few participants could be argued to be unrepresentative of the metallurgist worker population.

8.3.2.2 Experimental setup

The distinct experimental setups which have been used in both experimental studies could be a limitation to the conclusion drawn for the validity of the VR training system.

First, visualization setups were different in experimental studies 1 and 2. In experimental study 1, simulations could only be visualized monoscopically and participants' point of view was not tracked. This last point has been reported as an issue by one of the participants of the study: *"...the angle of view onto the display when standing was not good*". In contrast, in the experimental study 2, participants could visualize virtual environments stereoscopically with their point of view being tracked.

Secondly, as mentioned in section 8.3.1.2, different haptic interfaces were employed throughout this work. Force effects specific to the haptic interaction proposed by the VR training system such as the weight of the virtual precision rotary tool, effects of contact, rotary vibrations and tangential forces (Section 5.2) were configured by the two expert metallurgists of Tecnatom S.A. with a Phantom Desktop haptic device. In experimental study 2 (Chapter 7), the haptic device was similar to that employed by the two expert metallurgists for the configuration of force effects. Therefore, force effects could be perceived as they were configured. However, in experimental study 1 (Chapter 6), a different haptic device was employed: a Phantom Omni which was the only device available at the study site. The Phantom Omni haptic device is not as advanced and accurate as the Phantom Desktop device (Appendix A). Thus, force effects may have been perceived differently when compared with those defined by the expert metallurgists. Moreover, the effect of VR training on force skills could be argued to be limited by the technical capability of the Phantom Omni haptic device to render high forces (Appendix A).

8.3.2.3 Experimental design

In this research, fine motor skills have been practised in order to support motor learning. Those skills also aimed to be transferred to the performance of a whole-target task simulated in a virtual environment and to real operating environments. A first limitation of experimental designs was that motor learning was immediately assessed after VR training. Thus, it could be argued that experimental studies only demonstrated the effectiveness of the VR training system to support short-term motor learning. Different training procedures would have been required to investigate long-term motor learning (Yang et al., 2008).

Other limitations consist of the training designs suggested in both experimental studies. In experimental study 1, part-task training has been designed according to outcomes of a pilot study which involved few participants. Nonetheless, the representativeness of those participants could be discussed to the extent that some of the participants of experimental study 1 who received part-task training questioned the resulting training design and suggested alternative design features such as "*…training longer time, training sessions of 15sec were too short*" and "*....to improve upon accuracy, there could have been smaller session after each task to focus on improving small things such as maintaining the correct force or how to improve on keeping the angle constant*". Moreover, several participants reported fatigue after completing part-task training. These findings suggested that the part-task training design was not optimal. However, it was sufficient to demonstrate the principles underlying to the suggested training.

Moreover, the scheduling of the concurrent augmented feedback throughout part-task training could also be considered to be weak when compared to that proposed in other research studies (Rodriguez et al., 2010).

In experimental study 2, training procedures proposed for part-task and whole-task training were limited by the availability of the participants and the duration of the demonstration phase of the ManuVAR project (Appendix C). Both types of training were therefore drastically shortened to a few rehearsals. On the one hand, part-task training led to satisfactory results. On the other hand, the amount of whole-task training was apparently not sufficient to support meaningful improvements in the performance of fine grinding and polishing tasks. However, it was sufficient for the evaluation of the construct validity of simulations.

Concurrent augmented feedback has shown to be positive for motor skill training. However, the effectiveness of the method of provision of that augmented feedback during whole-task training can be discussed. For instance, Rodriguez et al., (2010) highlighted that augmented feedback was more effective when provided automatically as a function of trainee's performance.

Moreover, the colour map adapted to colour blind people (Section 5.1.2.2) was not implemented at that time. So, the colour blind participant was provided the default colour map. This is controversial to the extent that the participant was not able to distinguish a specific range of colour.

Another limitation was that the effectiveness of the VR training system to transfer motor skills to a real operating environment could not be directly explored but was rather suggested through the internal validity of the training and the construct validity of whole-task training simulations. The lack of technical resources impeded to evaluate transfer of training in a real operating environment.

8.3.2.4 Data analysis

In the experimental study 2 (chapter 7), the collected quantitative data could not be statistically analyzed because of the limited number of participants involved in the study (Section 8.3.2.1).

8.4 RECOMMENDATIONS FOR FUTURE STUDIES

More developments are needed to improve the VR training system in order to support motor learning (Section 8.4.1). In addition, more studies are required in order to further investigate the development of fine motor skills for the performance of fine grinding and polishing tasks and the transfer of those skills to real operating environments (Section 8.4.2).

8.4.1 Recommendations for further developments

Further implementations in the VR training system should focus on improving the realism of simulations. The realism of virtual environments could result strongly enhanced by more realistic audio cues, for example by using binaural sounds (Katz & Picinali, 2011), improved graphical realism including lighting conditions along with object shadow casted on surfaces (Nikolic, 2007) and the representation of object deformation such as that of the tool disc when being pressed on the material surface.

However, the optimization of interaction model must be considered as a priority. The model of contact of the tool disc on the material surface needs to be more accurately defined in order to enable even more realistic simulations. During the definition of the model of contact, applied angle and exerted force must be accurately controlled. For instance, the exerted force could be measured with a force sensor as in Sewell et al. (2007), in order to be adjusted at the correct value before image capture.

The haptic interaction needs to be investigated more in depth. The contact of the tool disc with a material surface could be improved. It should not be limited to a unique point. As in real task performance, performers should be able to perceive contact through the whole surface of the tool disc. A virtual disc which simulates the tool disc could be used as haptic cursor instead of the default contact point. To do so, the development of the haptic interaction will most probably require migrating completely towards low level programmable interfaces such as HDAPI (http://www.sensable.com).

8.4.2 Recommendations for further research

Further research aiming to investigate the validity of the VR training system should consider a larger sample of participants with similar characteristics as those involved in experimental study 2. The participants should be a sample of the technical worker population able to perform the metallographic replica technique. Furthermore, participants could be distributed into several sub-groups as a function of their level of expertise. Thereby, the effectiveness of the VR training system to support motor learning could be tested at several stages of learning so the construct validity of the whole system could be more clearly established. Many research studies have investigated the capability of VR training systems to make the distinction between several levels of expertise (Fried, M. P. et al., 2005; Wagner et al., 2007; Aggarwal et al., 2009; Iwata et al., 2011). The most appropriate sampling technique corresponding to the proposed model would consist in a stratified sampling technique (Gravetter & Forzano, 2011). However, gathering a population of technical workers of various levels of expertise from which a large sample of participants could be extracted may be hard to achieve. Therefore, future studies could maintain similar sampling techniques as those employed in this work, but must attempt to increase participants sample size in order to proceed to statistical analysis of experimental data.

Further experimental studies should also avoid the limitations of experimental designs presented in this discussion (Section 8.3.2.3) in order to better establish the validity of the VR training system. A preliminary study should be carried out to explore most appropriate designs for part-task and whole-task training. Moreover, the scheduling of augmented feedback must be investigated in order to optimize the development of accurate motor programs through both training methods. Furthermore, the findings of a preliminary study would consist of a useful guideline for the design of effective training programs.

Further experimental studies should investigate the validity of the VR training system to support short-term and long-term learning by proposing different training procedures similar to those suggested by Mononen, 2007 and Yang et al., 2008. As well, transfer of training from virtual to real operating environments could be attempted to be quantified following the method proposed by Roscoe & Williges (1980). However, to do so, task performance should be objectively assessed in real operating environments.

8.5 SUMMARY

This thesis has presented and evaluated a VR training system which aimed to train a set of fine motor skills that are required in the fine grinding and polishing tasks carried out during the metallographic replica technique. Two experimental studies have been performed in order to investigate whether the VR training system is valid for training motor skills in the suggested context and transferring those skills to real operating environments.

The validity of the VR training system to train motor skills has been established on the basis of the internal and the construct validity of the system. On the one hand, the internal validity of the system has been achieved showing the capability of the system to enable the successful development of the trained motor skills throughout part-task training procedure and to transfer those skills to the performance of a whole-target task in a virtual environment. On the other hand, the construct validity of the system has been highlighted demonstrating that the system is able to provide an accurate representation of the reality through whole-task training, enabling thus discriminating between several levels of expertise.

The external validity of the VR training system to support transfer of training has been established on the basis of the internal and the construct validity of the system and strengthened by the analysis of subjective data collected throughout both experimental studies.

Although the suggested VR training system has shown to be effective for training the fine motor skills that are required in the performance of fine grinding and polishing tasks, more developments and investigation are needed in order to improve the functionalities of the system and quantify transfer of training.

APPENDICES

Appendix A. Technical Specifications of Haptic Devices

Haptic technology enables real-time three-dimensional proprioceptive interaction within virtual environments (McLaughlin et al., 2002). Haptic interaction relies on force sensory information provided by a haptic device, which contributes in enhancing the way users interact within virtual environments (Mark et al., 1996).

In the research presented in this thesis, two haptic interfaces from the Phantom product line (Massie & Salisbury, 1994) of Sensable Technologies (http://www.sensable.com/) have been employed: the Phantom Desktop and Omni which are two affordable solutions for the haptic interaction in virtual environments (Figure 77). The Phantom devices consist of punctual inter-actuators which in their default version use a stylus handle attached to an end-effector (Hayward et al., 2004). These interfaces are impedance devices (Hannaford & Okamura, 2008) which sense the position of the end effector controlled by the operator on 6 DOF input and generate forces in order to constraint the motion on 3DOF output. The Phantom Desktop is more accurate and can render higher forces than the Phantom Omni.

Table 19 provides a comparison of the technical specificities of both haptic devices.

Figure 77. (a) Phantom Desktop device and (b) Phantom Omni device from Sensable Technologies.

Sensable Technologies also proposes software solutions for haptic interaction such as the Software Development Kit (SDK) OpenHaptics® toolkit.

The OpenHaptics® Toolkit (currently at the version 3.0) has been used for the implementation of the haptic interaction presented in this thesis. It consists of a C++/Open GL-based library which supports the haptic rendering through multi-thread programming. Basically, the OpenHaptics Toolkit enables executing at high frequency the sensing of the position of the end effector of the haptic device used to calculate the generated forces. Such execution runs on a servo loop thread at a minimum of ~1 KHz.

The OpenHaptics® Toolkit presents a three-layer architecture: Haptic Device API (HDAPI), High Level API (HLAPI) and QuickHaptics API. The implementation of the suggested haptic interaction consists of HDAPI and HLAPI-based programming which provides low-level and high-level access to the haptic device driver. The HDAPI enables direct rendering of forces effects and allows the implementation of customized force effect such as those to simulate the operating conditions of the portable power tool (Section 5.2). The HLAPI is built upon HDAPI. It offers several commands to setup the rendering of common force effects such as stiffness, damping, friction, dynamic friction, viscosity and many more. Moreover, HLAPI provides three pre-implemented threads: The client thread (~30 Hz) which supports the rendering of haptic objects; the collision thread (~100 Hz) which supports the collision detection and the servo loop thread (~1 KHz) which handles the sensing of the position of the haptic device and enables rendering force effects.

Table 19. Technical specifications of Phantom Desktop and Omni devices.

Model	PHANTOM Desktop Device	PHANTOM Omni Device
Force feedback workspace	> 160 W x 120 H x 120 D mm	> 160 W x 120 H x 70 D mm
Range of motion	Hand movement pivoting at wrist	Hand movement pivoting at wrist
Nominal position resolution	> 1100 dpi ~ 0.023 mm	> 450 dpi ~ 0.055 mm
Backdrive friction	< 0.23 oz (0.06 N)	< 1 oz (0.26 N)
Maximum exertable force at nominal (orthogonal arms) position	1.8 lbf. (7.9 N)	0.75 lbf. (3.3 N)
Continuous exertable force (24 hrs.)	0.4 lbf. (1.75 N)	> 0.2 lbf. (0.88 N)
Stiffness	X axis > 10.8 lb/in (1.86 N/mm) Y axis > 13.6 lb/in (2.35 N/mm) Z axis > 8.6 lb/in (1.48 N/mm)	X axis > 7.3 lb/in (1.26 N/mm) Y axis > 13.4 lb/in (2.31 N/mm) Z axis > 5.9 lb/in (1.02 N/mm)
Inertia (apparent mass at tip)	~ 0.101 lbm. (45 g)	~ 0.101 lbm. (45 g)
Force feedback	x, y, z	
Position sensing	x, y, z (digital encoders)	
[Stylus gimbal]	[Pitch, roll, yaw (± 3% linearity potentiometers)]	
Interface	Parallel port and FireWire® option	IEEE-1394 FireWire® port
Supported platforms	Intel or AMD-based PCs	Intel or AMD-based PCs
Application Programming Interface	OpenHaptics® Toolkit	

Source: http://www.sensable.com/documents/documents/STI_Jan2009_DesktopOmniComparison_print.pdf.

Appendix B.
Visualization and Tracking Technology

In the specific case of manipulation in virtual environments, the perception of depth is a decisive factor. This section aims to provide background knowledge to the reader concerning visualization mechanisms that support the perception of depth (Section B.1) and display technologies used in the experimental study 2 (Chapter 7) which enabled perceiving depth in virtual environments (Section B.2).

B.1 PERCEPTION OF DEPTH

The perception of depth in virtual environments results from the computation of a series of information cues by the human visual system which enables building a three-dimensional mental model of the virtual scene. Some of these cues provide binocular and oculomotor (Section B.1.1), and motion parallax-related information (Section B.1.2) which are respectively supplied through stereoscopic display (Section B.2.1) and point of view tracking (Section B.2.2).

B.1.1 Binocular & oculomotor cues

The human visual system is able to perform complex tasks such as simultaneously processing two visual stimuli received from both eyes and generating a three-dimensional mental model. This mechanism is known as stereopsis and it refers to the visual system capacity of computing coherently two monocular signals in order to create a three-dimensional representation of an environment. Stereopsis has demonstrated to plays an important role in the perception of depth in the near and mid-fields (Nagata, 1993) as in virtual environments (Poyade et al., 2009).

Stereopsis depends on binocular and oculomotor depth cues (Pfautz. 2002). Binocular depth cues refer to the depth sensation perceived by means of the processing of the slightly different retinal images of both eyes, resulting from the human eyes horizontal separation. It is commonly assumed that human eyes separation known as the average interocular distance is about 6,3cm (Dodgson, 2004). Oculomotor depth cues comprise the sight accommodation and convergence processes (Pfautz. 2002).

In stereoscopically displayed virtual environments, binocular depth cues are supplied by providing to each eye, its corresponding point of view. Eyes accommodation in oculomotor depth cues is usually neglected (Pfautz. 2002) and convergence is naturally performed at the viewing distance. Figure 78 shows how depth is perceived in virtual environments on the basis of the mechanisms encompassed in the stereopsis.

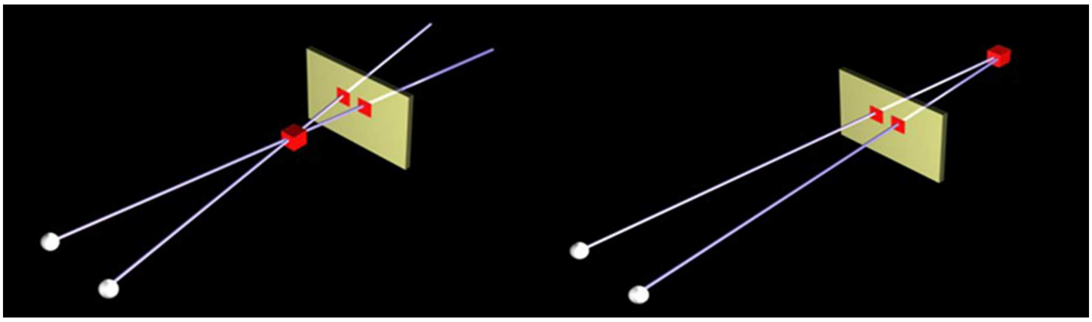

Figure 78. Perceived depth in front of and behind the display panel as a function of the representation of binocular cues and eyes convergence.

B.1.2 Motion parallax cues

Motion parallax cues provide depth information obtained from the relative displacement between objects located at different depth, subsequently to movements of the point of observation (Wanger et al., 1992).

B.2 DISPLAY TECHNOLOGIES

In experimental study 2, virtual environments were displayed stereoscopically and the point of view of participants was tracked which enabled providing additional depth information.

B.2.1 Stereoscopic display

Many research studies have demonstrated the advantages of using stereoscopic visualization in virtual environments (Kim et al. 1987; Rosenberg. 1993; Bouguila et al. 2000; Alexander et al. 2003). Stereoscopy provides a noteworthy improvement of depth perception in a very realistic way (Holliman. 2006), intensifying perception of surfaces and materials (Pfautz. 2002), but also, facilitating spatial localization and navigation. Stereoscopic visualization has shown to enhance accuracy throughout manipulation tasks in virtual environments (Kim et al. 1987).

Binocular depth cues (Section B.1.1) were supplied by a polarized 3D system composed of two projectors which superposed the two stereopsis viewpoints on the screen through circular polarization filters of opposite dextrorotation[15].

Virtual environments could be visualized through a pair of glasses equipped with circular polarized filters mounted in reverse. Each glasses crystal enabled filtering light with a particular type of circular polarization: clock-wise or anti-clock-wise (Figure 79). Such polarization allows head inclination without disturbing the perception of the virtual environment.

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[15] Definition from Merriam-Webster (http://www.merriam-webster.com):
dextrorotation: right-handed or clockwise rotation-used of the plane of polarization of light

Figure 79. Polarization of light on each glass crystal.

B.2.2 Point of view tracking

The tracking of the point of view enables providing addition depth cues through motion parallax-related information (Section B.1.2). The tracking of participants point of view in the experimental study 2 (Chapter 7) was supported by the Optitrack Tracking Tool from Natural Point (http://www.naturalpoint.com). Optitrack Tracking Tool consists of a software package which enables tracking infrared light reflective markers in position and orientation on 6 DOF. Tracking of a marker is performed with set of infrared light emitted cameras that are synchronized between each other (Figure 80).

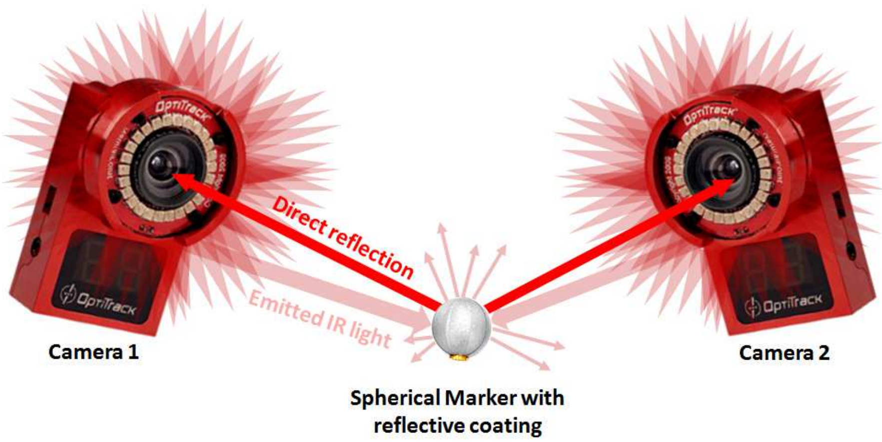


Figure 80. Example of tracking of a marker using two IR light emitted cameras

Cameras are arranged so their viewing frustum overlaps and define a capture volume within the tracked area (Figures 81 & 82). In the experimental study 2 (Chapter 7), 6 Optitrack V100:R2 tracking cameras were employed for tracking the point the view of the performer. Technical specifications of the Optitrack V100:R2 Camera can be found at the manufacturer website (http://www.naturalpoint.com/optitrack/products/v100-r2/specs.html).

By default, the Optitrack V100:R2 is equipped with a lens which has a horizontal angle of view about 46º. Figure 82 presents a possible arrangement of cameras around the tracked area.

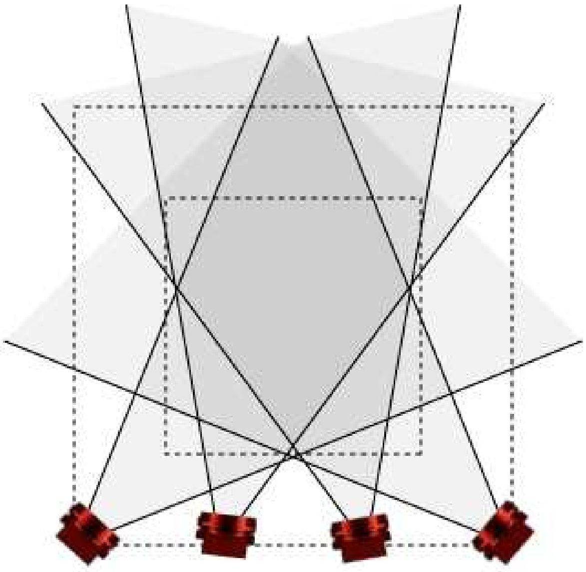


Figure 81. Volume capture composed by 4 cameras (http://www.naturalpoint.com).

Figure 82. An Optitrack V100:R2 Camera in a 12 camera setup mounted on stands (http://www.naturalpoint.com).

In the experimental study 2 (Chapter 7), four infrared light reflective markers were clustered on a pair of passive stereoscopic glasses (Section B.2.1) in order to form a unique set of markers that was recognized by the system (Figure 83).

Figure 83. Passive stereoscopic glasses equipped with a set of infrared light reflective markers that form a unique rigid body for the tracking of the point of view.

The Optitrack Tracking Tool enables streaming tracking data in real-time over a network in order to be used in other applications such as a VR visualization interface, for instance the 3DVia Virtools 5.0 VR Player. Tracking data streaming is ensured by the industry standard Virtual-Reality Peripheral Network (VRPN) which consists of a set of classes that define a server/client architecture which provides a network-transparent interface between applications and VR interfaces such as tracking devices (Taylor II et al., 2001).

In the experimental study 2 (Chapter 7), the Optitrack Tracking Tool provides a VRPN server which enabled streaming tracking data in real-time to the 3DVia Virtools 5.0 VR Player. A VRPN client for tracking service is implemented by default in the 3DVia Virtools platform. Thus, the viewing camera in virtual environments proposed in the study could be updated according to the participant's point of view.

Appendix C. ManuVAR

C.1 THE MANUVAR PROJECT

ManuVAR (Manual work support throughout system lifecycle by exploiting Virtual and Augmented Reality) is a Seventh Framework European project that ran from 2009 through 2012 and involved 18 partners across 8 countries (http://www.manuvar.eu/). ManuVAR aimed to demonstrate that virtual and augmented reality technology (VR/AR) to support high value high knowledge manual work throughout the product lifecycle is an opportunity to improve the competitiveness of EU industries (Krassi et al., 2010a, Krassi et al., 2010b, Krassi et al., 2010c). ManuVAR proposed the development of an innovative technological and methodological framework which aimed to support high value high knowledge manual work throughout the whole product lifecycle.

Five working groups (clusters), in which a strong collaboration between industrial and research partners was established, have consolidated several industrial use cases for which high value high knowledge manual work-related issues needed to be resolved. These industrial use cases presented a homogeneous distribution across the product lifecycle (Figure 84) in various fields of activity such as:

1. Cluster 1: Satellite assembly - VR/AR assisted procedure compliance in aerospace component assembly clean rooms.
2. Cluster 2: Assembly line and Small and Medium Enterprise (SME) - Low cost VR systems for improving assembly lines in SMEs.
3. Cluster 3: Remote maintenance - VR/AR-enhanced remote online maintenance support in the railway sector.
4. Cluster 4: Power plants - The Metallographic Replica: Use of VR for improving training on nondestructive inspection technique.
5. Cluster 5: Heavy machinery - VR/AR in large machine assembly and maintenance.

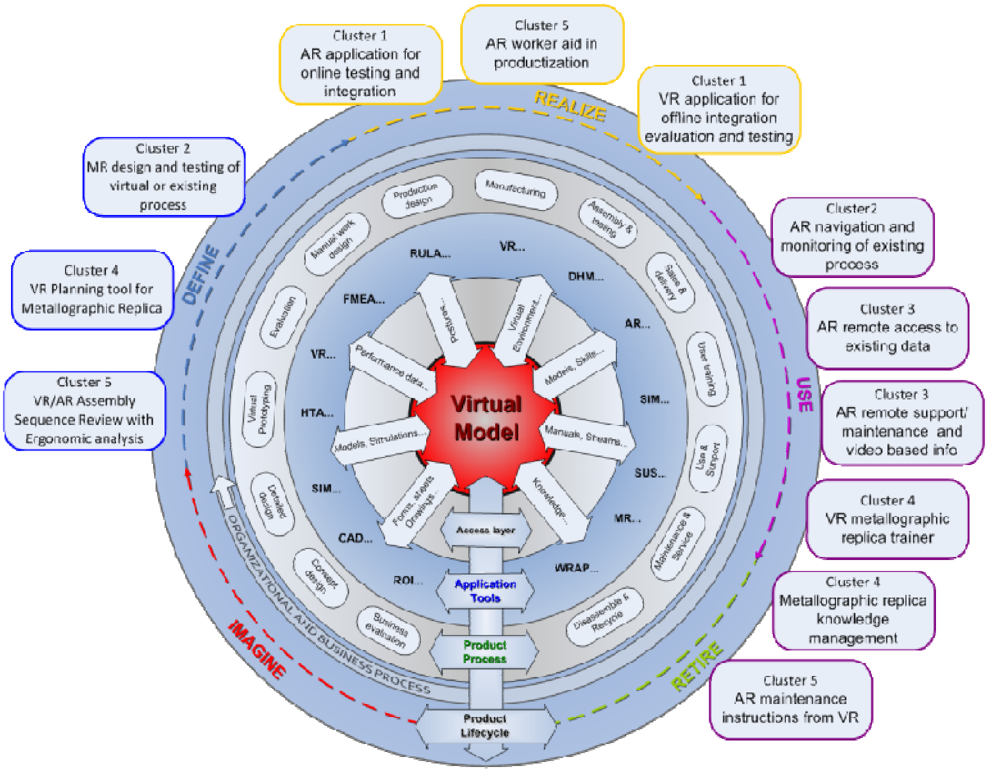


Figure 84. Distribution of industrial cases across the ManuVAR product lifecycle management model (PLM) with the product lifecycle located on the external layer (Courtesy of ManuVAR consortium).

Several industrial use cases were prioritized in order to define a sample of cases to be implemented which demonstrated that the ManuVAR platform can effectively support manual work across the product life cycle. Those industrial use cases with higher degree of priority for each cluster are detailed below:

1. Cluster 1: VR application for off line integration and testing.
2. Cluster 2: MR design and testing of existing or virtual production processes
3. Cluster 3: AR Remote Support/Maintenance and video-based information.
4. Cluster 4: VR metallographic replica trainer.
5. Cluster 5: VR assembly sequence review with ergonomic analysis.

The work presented in this thesis supports the industrial use case "*VR metallographic replica trainer*" (Figure 84) which was consolidated by the cluster 4 composed of Tecnatom S.A. and University of Malaga in collaboration with the Association for the Advancement of Radical Behavior Analysis (AARBA) and the Human Factors Research Group from the University of Nottingham. This industrial use case pointed out at the limitations of the conventional training of the metallographic replica technique. It aimed among other things, at the implementation of motor skill training on the ManuVAR platform for fine grinding and polishing tasks in order to enable solving transfer and assessment issues of the conventional training.

C.2 THE MANUVAR ARCHITECTURE

The architecture of the ManuVAR platform is modular. It proposes a set of generic components organized in a series of layers (Figure 84). The first component is the Virtual Model (VM) which is considered as the core of the ManuVAR architecture. The VM provides semantic references of information stored in one or various PLM repositories (Figure 85). It enables linking all actors (workers, tools, products) to a semantic aggregation of information in the form of models, processes, and simulations that describe the system in evolution throughout the product lifecycle (Krassi et al., 2010c).

The second component is the Application Tool (AT) which gathers a set of elements which consist of interchangeable methodological and technological solutions and provides specifically designed services in order to solve high value high knowledge manual work-related issues in one or several industrial use cases (Figure 85). AT orchestrates the communications between all technological components connected to the ManuVAR platform. AT accesses to the VM with a set of application independent functions provided by the access layer (Krassi et al., 2010b, Krassi et al., 2010c).

Throughout the ManuVAR project, six ATs were developed. Four ATs provided dedicated services to the high value high knowledge manual work presented in prioritized industrial uses (Section C.1) whereas two others support ManuVAR platform management-related services. These ATs are detailed below:

1. Delivery of work instructions - (real-time) On-site support of integration/assembly and/or maintenance which aims to improve high value high knowledge manual work by providing support to workers based on instructional techniques in virtual environment models, and remote communication between operators and experts expert.
2. Ergonomics evaluation: (real-time) - Ergonomics analysis and workplace design which aims to improve workplace design giving emphasis to ergonomic issues to which operators may be confronted.
3. Task planning and analysis - aims to improve working procedure description, design and validation using virtual or mixed reality environments.
4. Training - Training and performance evaluation which aims to improve high value high knowledge manual work proposing procedural and motor skill training based on performance evaluation and appropriate information feedback to the user(s).
5. VM database editing tool which supports the offline editing of the VM.
6. Platform services which is part of each instance of the ManuVAR platform and supports the User Specific Logic (USL) which consists of platform management-related services such as authentication procedure and accessibility to information referenced in the VM.

A third component of the ManuVAR architecture is the User Specific logic (USL) which performs a series of service operations that enable the use of the ManuVAR components to support high value high knowledge manual work in a specific industrial use case. Service operations consist of:

1. User authentication management.
2. Management of ATs for a specific industrial use case (one or several ATs can be required).
3. Management of the workflow for the specific user activity. The USL offers a Graphical User Interface (GUI) which enables a user to interact with the system components.

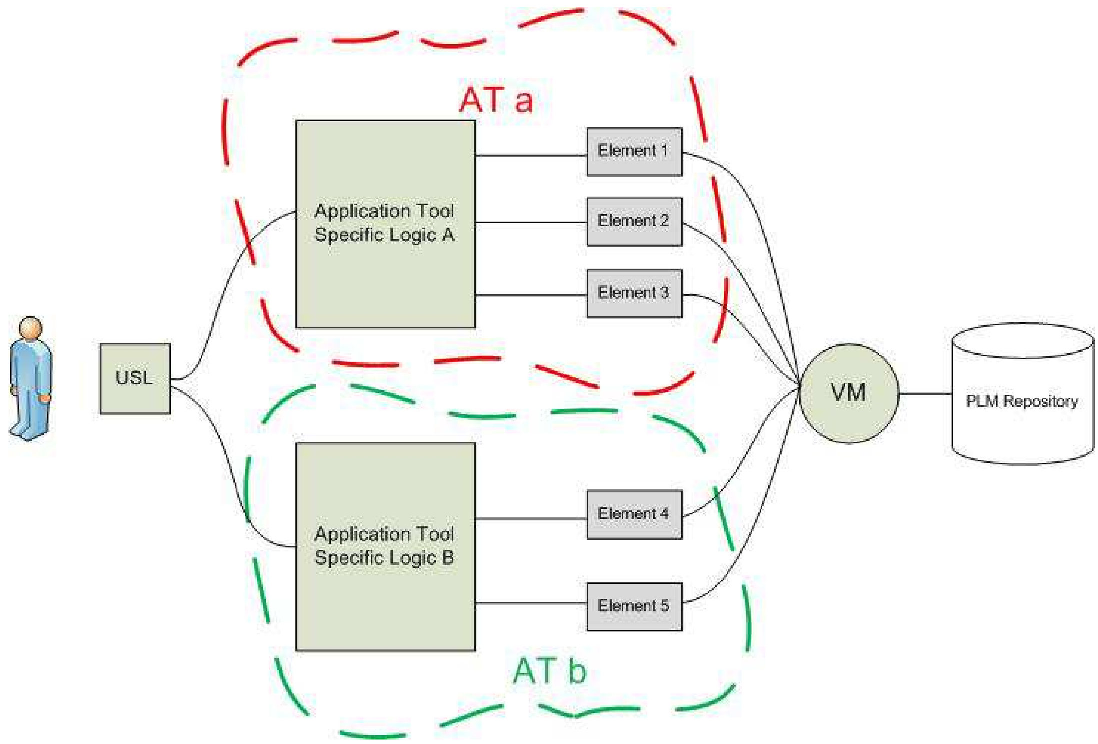


Figure 85. The ManuVAR components for a specific industrial use case (Courtesy of ManuVAR consortium).

C.3 APPLICATION TOOL - TRAINING

The work presented in this thesis has required the implementation of motor skill training on the ManuVAR platform. The AT providing training and performance evaluation services has been employed in order to provide a technological and methodological solutions to the issues that arise throughout the training of the metallographic replica technique traditionally carried out. As mentioned previously, that AT proposes a set of technological and methodological elements which enable procedural training on the metallographic replica technique and motor skill training on fine grinding and polishing tasks (Table 20).

Table 20. Methodological and technological elements proposed by the AT in order to support procedural and motor skill training in the context of the metallographic replica technique.

Procedural training	
Methods	Technologies
Precision Teaching	Visualization element (version 2D) Lesson Runner (including Performance Analyzer)
Motor skill training	
Methods	Technologies
Part-task training	Visualization element (version 3D) Lesson Runner (including Performance Analyzer) Haptic server
Whole-task training	Visualization element (version 3D) Lesson Runner (including Performance Analyzer) Haptic server

The effectiveness of the suggested procedural and motor skill training is based on performance evaluation and the provision of feedback to the user(s). The AT performs mathematical calculations to support performance evaluation throughout both procedural and motor skill training (Sections C.3.1 & C.3.2), and handles communication between technological components (Section C.3.3).

C.3.1 Procedural training

Procedural training is based on the Precision Teaching which consists of "*basing educational decisions on changes in continuous self-monitored performance frequencies displayed on standard celeration charts*" (Lindsley, 1992). Procedural training is performed through a 2D Graphical User Interface (GUI) displayed by the visualization element (Figure 86).

Figure 86.The GUI for the procedural training in the ManuVAR platform (the trainee is required to click on the picture which shows the tool and the abrasive accessory required to remove the oxide scale during a rough grinding task).

A training session is composed of a set of training items. In each item, the trainee is given a limit of time to answer a multiple choice question by selecting the most plausible pictorial response or by writing it. Questions can be related to the performance of one of the steps of the metallographic replica technique, performance outcome evaluation and material surface preparation. The elapsed time during a training item is indicated by a progression bar located on the right side of the GUI (Figure 86).

After the completion of each item, augmented feedback in the form of terminal Knowledge of results (KR) (Section 2.4.2) is provided in order to inform the trainee about the correctness of the answer. Moreover, the instructor can monitor the performance of a trainee over the time through the performance analyzer, a module embedded in the Lesson Runner Application (Section C.3.3.1). This module shows a chart which displays the behaviour fluency (i.e., performance and frequency of training sessions calculated as right answers per minute) (Poyade et al., 2011).

C.3.2 Motor skill training

The AT supports motor skill training through two fundamental methods: part-task and whole task training (Chapter 5). Part-task training focuses on the development of angle and force skills whereas whole-task training enables exercising the performance of whole fine grinding and polishing tasks. This thesis explores the effectiveness of those training methods to support motor learning through two experimental studies (Chapters 6 & 7).

Both training methods are implemented in 3D virtual environments which can be displayed monoscopically and stereoscopically by the visualization element (Section C.3.3.3). Moreover, the point of view of the trainee can be tracked by using optical tracking technology in order to provide additional depth cues (Appendix B). Motor skill training is carried out through a haptic device which enables simulating the operating conditions of a real precision rotary tool (Section 5.2). The angle and force being exerted are sensed by a haptic server specifically designed for the ManuVAR platform (Section C.3.3.2) in order to enable the AT to perform the mathematical calculations which support performance evaluation. Performance evaluation outcomes can be displayed through concurrent and terminal augmented feedback (Sections 5.1.1.2 & 5.1.2.2).

C.3.2.1 Part-task training

As explained in chapter 5, part-task training enables fractioning the performance of fine grinding or polishing into several part-task components which can be practiced separately and jointly throughout a series of training items. While the trainee goes through a training item, the AT computes the status of the achievement of the item goal on the basis of the accuracy of the trained skill(s). After the completion of an item, the AT estimates how well the task has been performed and terminal augmented feedback can be provided on this basis. Moreover, as in the procedural training, the instructor can monitor the performance of part-training of a trainee over the time through the performance analyzer (Section C.3.3.1).

C.3.2.2 Whole-Task Training

Whole-task training consists of a holistic approach of fine grinding and polishing tasks. The trainee has to perform the trained task as in the real world. After the completion of the task, the AT computes performance outcomes at every single point on the metallographic replica area enabling the performance analyzer (Section C.3.3.1) to provide a final score stating for the degree of completeness of the task.

C.3.3 Technological elements for motor skill training

C.3.3.1 Lesson Runner and Performance Analyzer

The Lesson Runner is an application which enables loading a training lesson, a XML template-based file. Each lesson is composed of a series of items that define the content of training items in procedural and motor skill training.

The performance analyzer is a module embedded in the Lesson Runner. As said previously, it shows a final chart which displays the accuracy of a trainee to complete procedural and motor skill training items once the training is complete (Poyade et al., 2011). The chart enables comparing the trainee´s performance outcomes over the time. For the procedural training, performance outcome is presented in the form of right answers per minute whereas for motor skill training, it is expressed as a performance score which indicates the ratio of completion of training items.

C.3.3.2 Haptic Server

The haptic server supports the haptic interaction within virtual environments, through a haptic interface from the Sensable Technologies product line (Appendix A). The haptic server provides in real-time force feedback-based information to the AT in order to perform mathematical calculations which support performance evaluation for motor skill training. A description of a preliminary development of haptic server has been presented by Cuevas-Rodriguez at al. (2012).

C.3.3.3 Visualization element

The Visualization element enables displaying 3D virtual environments in which motor skills training occurs. The graphical rendering is performed by the 3DVia Virtools 5.0 VR Player (http://www.3ds.com/products/3dvia/3dvia-virtools/) at a 60 Hz refresh rate. In the experimental study 1 (Chapter 6), virtual environments were displayed on a 2D Panasonic LCD monitor (W: 850 x H: 450 mm) with a 1920 x 1080 pixels screen resolution. In the experimental study 2 (Chapter 7), virtual environments were displayed on a 3D screen (W: 1500 x H: 1200 mm) with a resolution of 1280 x 960 pixels. Moreover, the trainee’s point of view was tracked using optical tracking technology implemented on a VRPN tracking server connected to the visualization element (Appendix B).

C.3.4 Topology of experimental setup

This section shows how the ManuVAR platform has been used in the experimental studies presented in this thesis. Technological elements were distributed across several networked computers. Figures 87 and 88 respectively show the experiment setup for experimental studies 1 (Chapter 6) and 2 (Chapter 7).

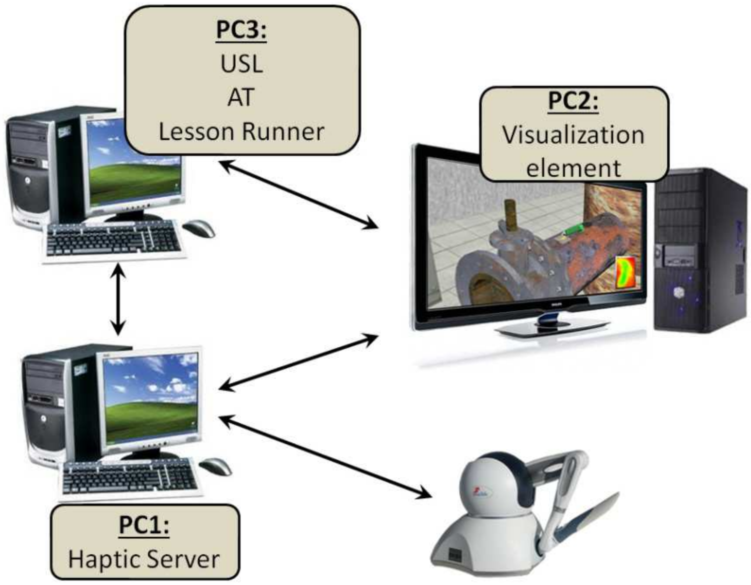


Figure 87. Setup of the experimental study 1(Chapter 6).

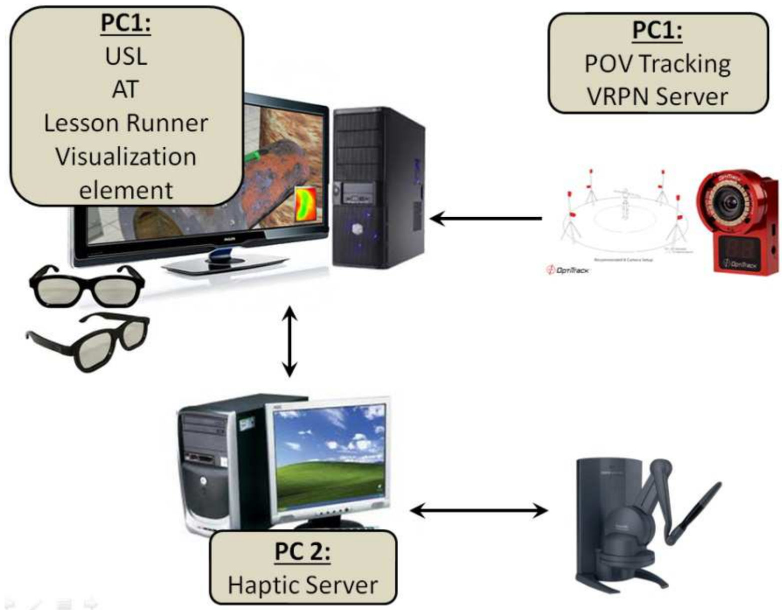


Figure 88. Setup of the experimental study 2(Chapter 7).

Appendix D.
Experimental Documentation

D.1 EXPERIMENTAL STUDY 1

D.1.1 Consent form and payment form

ManuVAR *Confidential* Participant ID

Consent Form

Investigation of real-time feedback when using a haptic device

The ManuVAR project is a three year collaborative study that investigates improving the human factors issues related to manual tasks using virtual reality (VR) and augmented reality (AR). This study covers one part of the project aimed at improving training available to manual workers. **The experiment should take no longer than 2 hours.**

The aim of the experiment is to investigate how training motor-skills using Virtual Reality (VR) technologies and a PHANTOM Omni haptic device (SensAble Technologies Inc. 2003-2009) enhances performance of polishing task performed as part of the metallographic replica process, a non-destructive industrial facilities inspection technique.

The experiment involves using a haptic device to manipulate a virtual polishing tool to complete a training task and then an end task. In addition, during the experiment you will complete a number of questionnaires.

All information collected will be **strictly confidential and anonymous** and stored on a secured system with hardcopies kept in a locked desk. The data will be identified by numbers.

Your participation in this study is very much appreciated. Please remember your participation is voluntary and you may ask questions or withdraw at any time.

Please read the statement below and if in agreement sign and date.

I confirm that I have voluntary agreed to take part in the study. I have read and understood the above explanation and have been given the opportunity to ask questions about the study. I authorise the investigator to disclose the results of my participation while I remain anonymous. I understand that I am free to withdraw from the study at any time.

Please print your name:	Date:
Signature:	

ManuVAR *Confidential* Participant ID

PAYMENT

Thank you for participating in this experiment. Your time and effort is greatly appreciated.

Please sign below to confirm the following details:

I have received the £10/hour high street voucher(s) for taking part in the study

Signed (participant)……………………………………………………….

Date ……………………………………………………………………………….

Investigator ………………………………………………………………….

Database Information
If you would like to be contacted about participating in any further studies run by the Human Factors Research Group (HFRG) you can be added our participant database. Please provide the following details listed below or supply Anne Floyde or Kirstie Dane with these details (Tel. 0115 9514040) and sign below

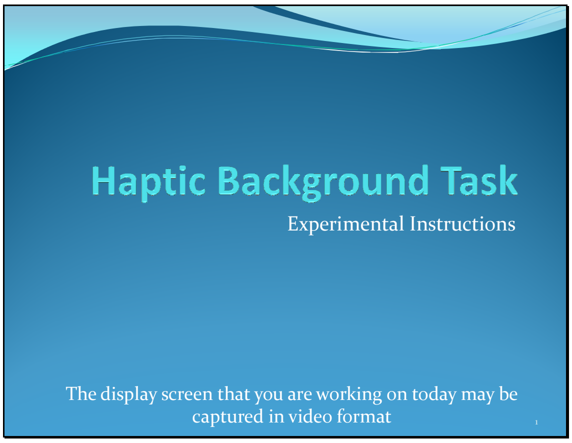
Name
Contact email
Contact number

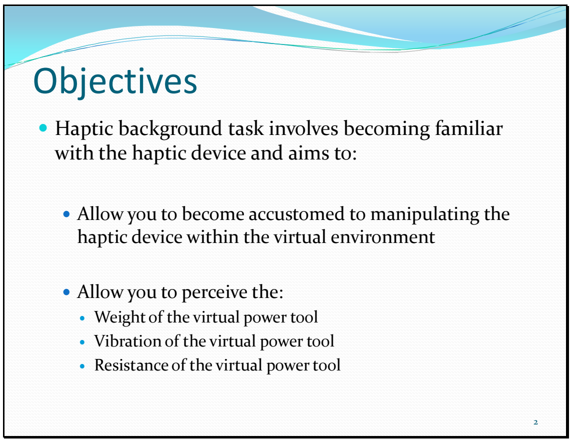
I am willing for the information above to be held on the participant database to be used in further studies

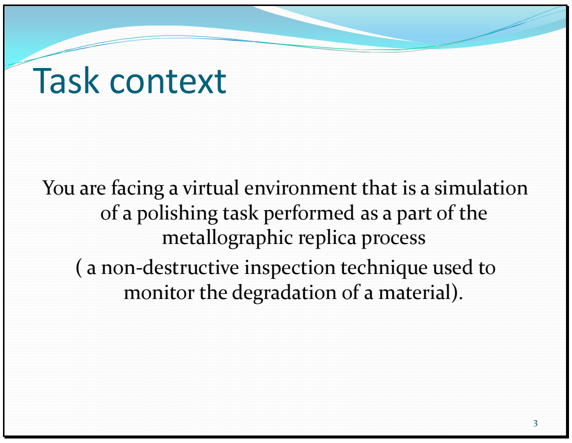
D.1.2 Instructions

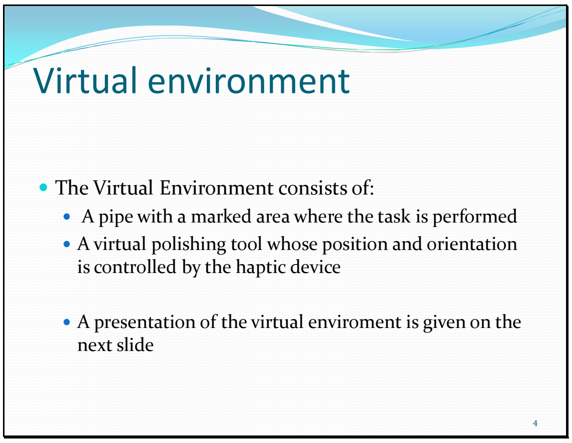
Instructions were displayed in presentation slides. The following sections present the instructions provided for the haptic familiarization, the practice and the evaluation step.

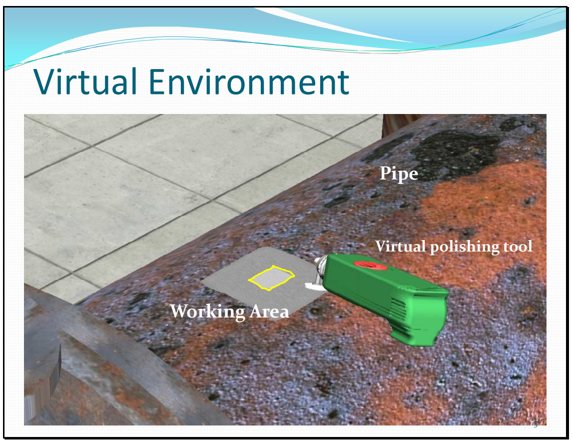
D.1.2.1 Haptic familiarization step

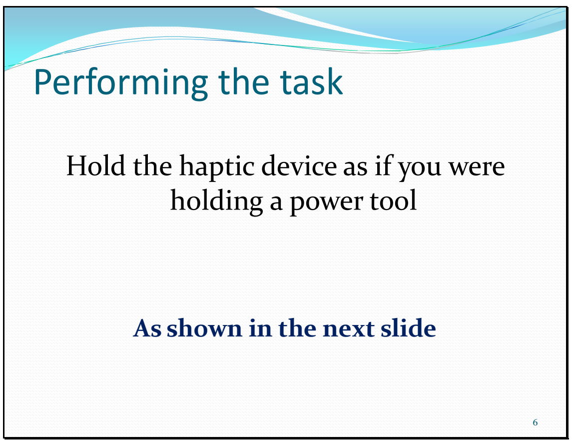












Haptic Device

7

Haptic Device

'the stylus represents the polishing tool body with the polishing attachment sitting at a 90° angle from the end of the stylus'.

8

Performing the task

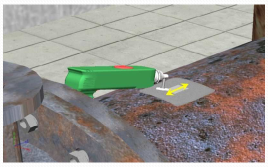
- Remember that you can repeat each exercise until you feel confident enough handling the haptic device
- Please complete each exercise in the virtual environment before switching to next slides

9

Ex. 1.

Remember that you can repeat each exercise until you feel confident enough handling the haptic device.

- Move the polishing tool up and down, left to right on the marked area as in the pictures below
- When you feel you have completed the exercise move on to the next slide

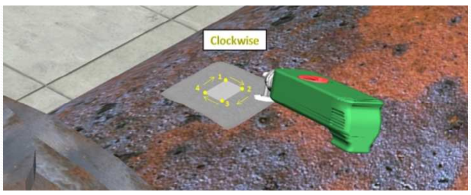


10

Ex. 2.1

Remember that you can repeat each exercise until you feel confident enough handling the haptic device.

- Place the tool disk onto each corner of the marked area for approximately 5 seconds as shown below
- When you feel you have completed the exercise move on to the next slide

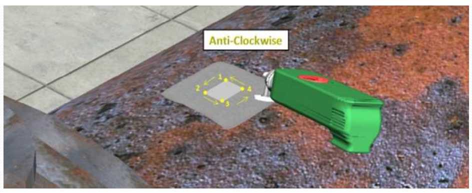


11

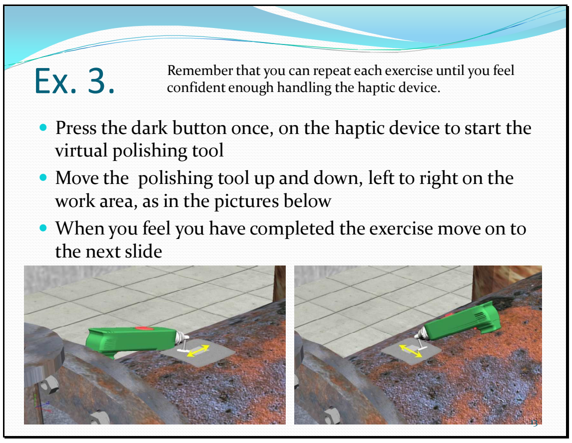
Ex. 2.2

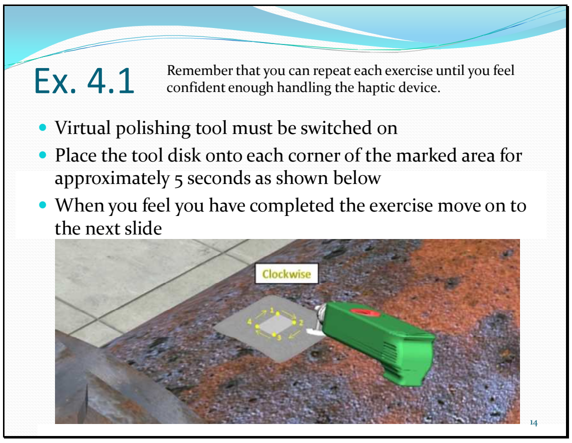
Remember that you can repeat each exercise until you feel confident enough handling the haptic device.

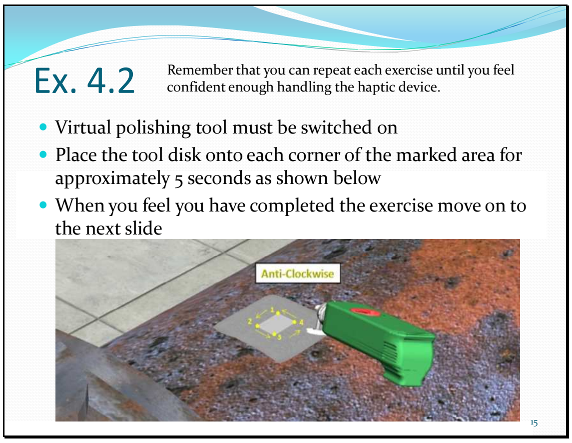
- Place the tool disk onto each corner of the marked area for approximately 5 seconds as shown below
- When you feel you have completed the exercise move on to the next slide



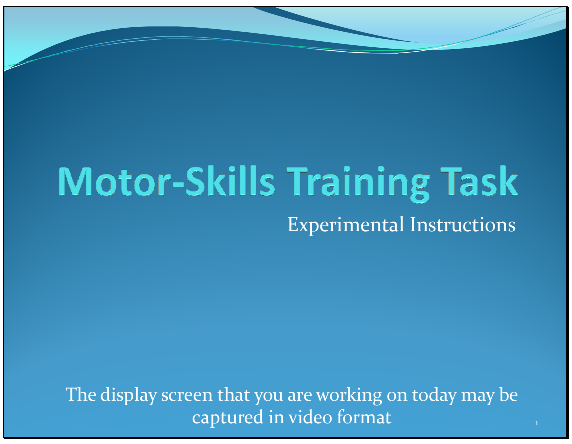
12

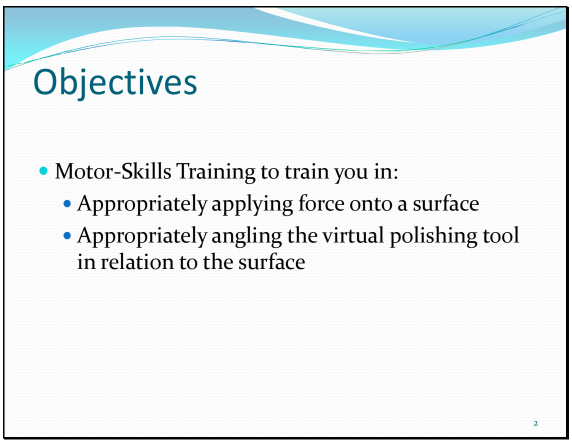






D.1.2.1 *Practice step*





Context

- You are facing the training application that consists of:
  - A simulation of a polishing task
  - A side panel that enables you to monitor in real-time your task performance

3

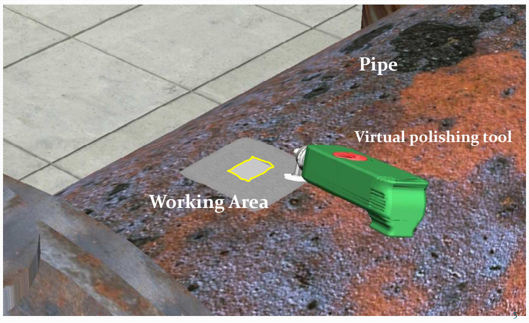
Virtual environment

- The Virtual Environment consists of:
  - A pipe with a marked area where the task is performed
  - A virtual polishing tool whose position and orientation is controlled by the haptic device

As shown in the next slide

4

Virtual Environment



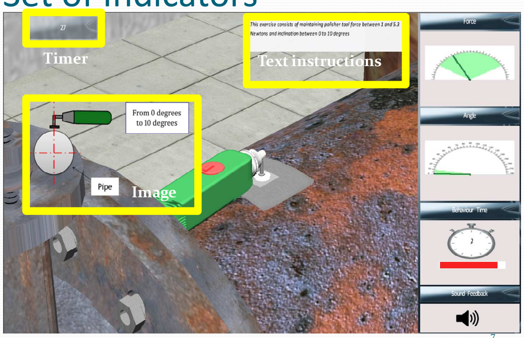
Virtual environment

- Also a set of indicators which include:
  - A timer that displays the duration of the task
  - An illustration that gives you the optimum behaviour
  - A overlaid written instructions explaining the task that you are expected to perform

As shown in the next slide

6

Set of Indicators



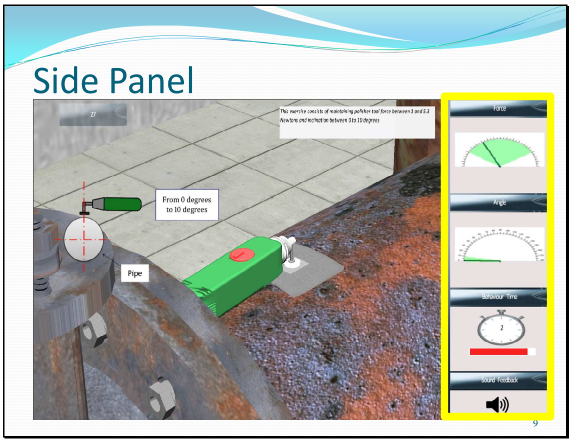
7

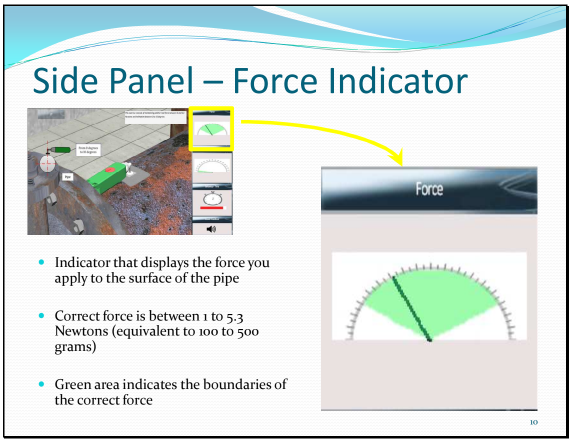
Virtual environment

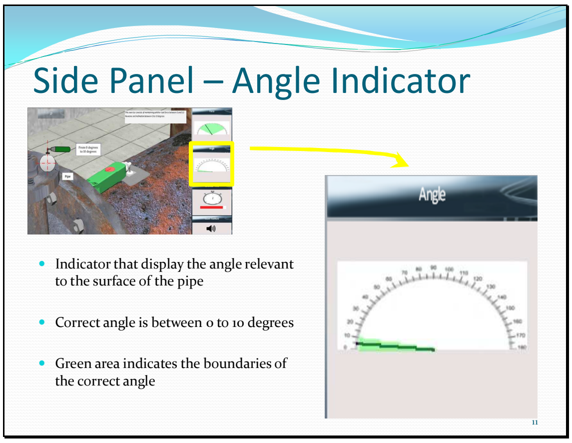
- The side panel which consists of:
  - Indicators representing force and angle
  - Timer representing behaviour time as the accumulated time in which you have exerted the right amount of force and/or placed the tool at the right angle

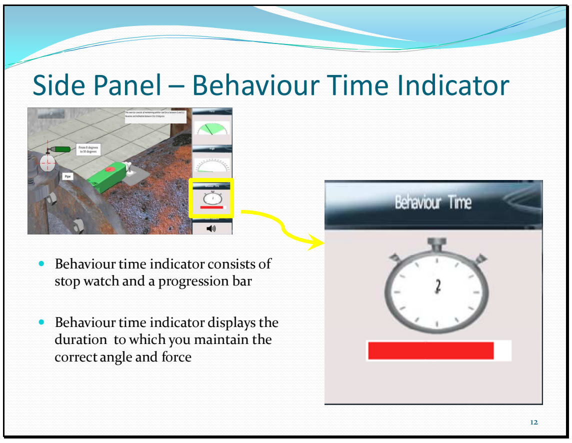
As shown in the next slide

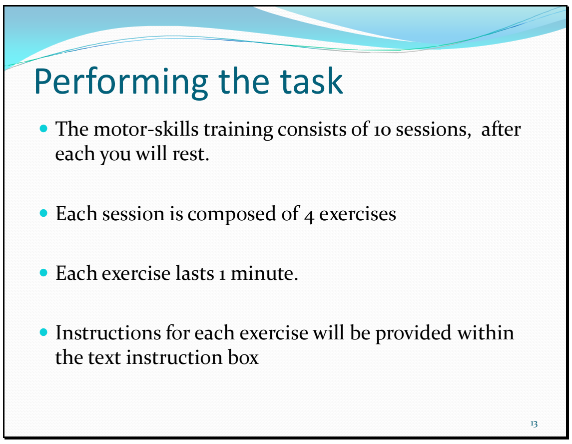
8

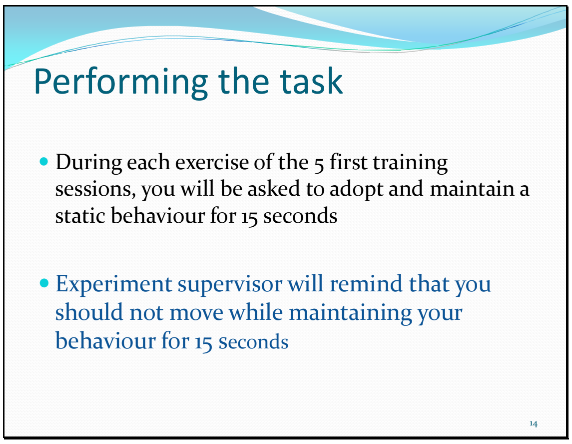

Side Panel
From 0 degrees
to 10 degrees
Pipe
Force
Angle
Behaviour Time
Sound Feedback
9


Side Panel – Force Indicator
Force
Indicator that displays the force you apply to the surface of the pipe
Correct force is between 1 to 5.3 Newtons (equivalent to 100 to 500 grams)
Green area indicates the boundaries of the correct force
10


Side Panel – Angle Indicator
Angle
Indicator that display the angle relevant to the surface of the pipe
Correct angle is between 0 to 10 degrees
Green area indicates the boundaries of the correct angle
11


Side Panel – Behaviour Time Indicator
Behaviour Time
Behaviour time indicator consists of stop watch and a progression bar
Behaviour time indicator displays the duration to which you maintain the correct angle and force
12


Performing the task
The motor-skills training consists of 10 sessions, after each you will rest.
Each session is composed of 4 exercises
Each exercise lasts 1 minute.
Instructions for each exercise will be provided within the text instruction box
13


Performing the task
During each exercise of the 5 first training sessions, you will be asked to adopt and maintain a static behaviour for 15 seconds
Experiment supervisor will remind that you should not move while maintaining your behaviour for 15 seconds
14

Performing the task

- During each exercise of the 5 last training sessions, you will be asked to adopt and maintain a dynamic behaviour for 15 seconds
- Experimenter will demonstrate a movement following a specific trajectory while maintaining your behaviour for 15 seconds

15

Performing the task

- In exercise 1, you will be asked to angle the polishing tool between 0 to 10 degrees and maintain your behaviour for 15 seconds
- In exercise 2, you will be asked to apply a force between 1 N to 5.3 Newtons and maintain your behaviour for 15 seconds
- In exercise 3, you will be asked to apply a force between 1 N to 5.3 Newtons and angle the polishing tool between 0 to 10 degrees and maintain your behaviour for 15 seconds
- In exercise 4, you will be asked to apply a force between 1 N to 5.3 Newtons and angle the polishing tool between 0 to 10 degrees and maintain your behaviour for 15 seconds

16

Performing the task

- In exercises 1, 2 and 3, You can use the side panel to refine your angle and force
- In exercise 4, none of the force and angle indicators will be visible, so it is important you to remember your behaviour from previous exercises

17

Performing the task

Hold the haptic device as if you were holding a power tool

As shown in the next slide

18

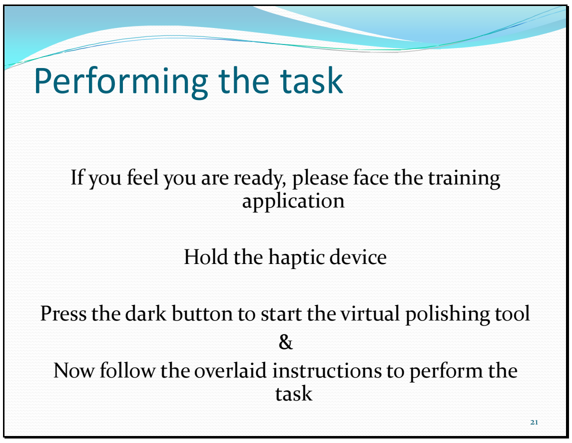
Haptic Device

19

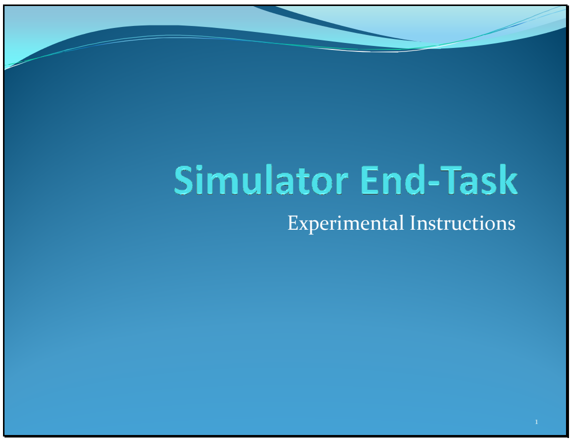
Haptic Device

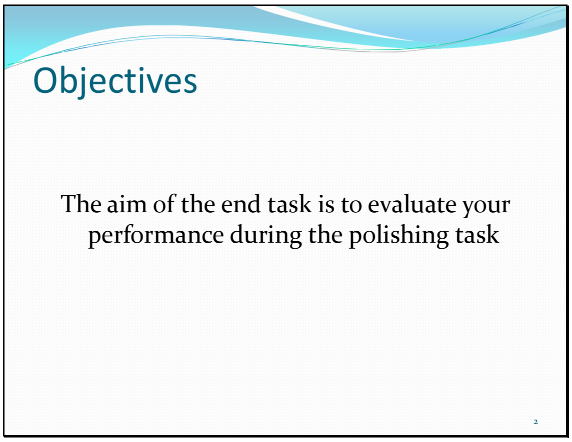
'the stylus represents the polishing tool body with the polishing attachment sitting at a 90° angle from the end of the stylus'.

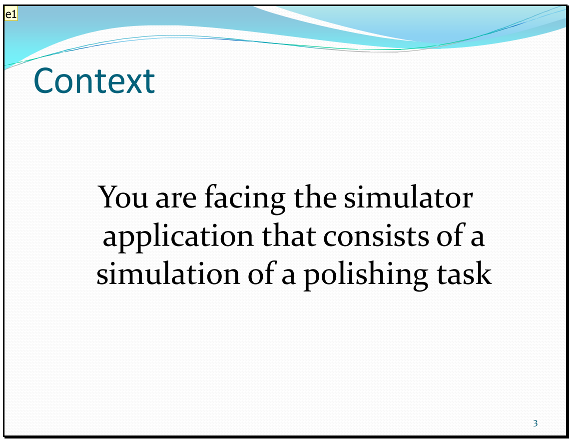
20

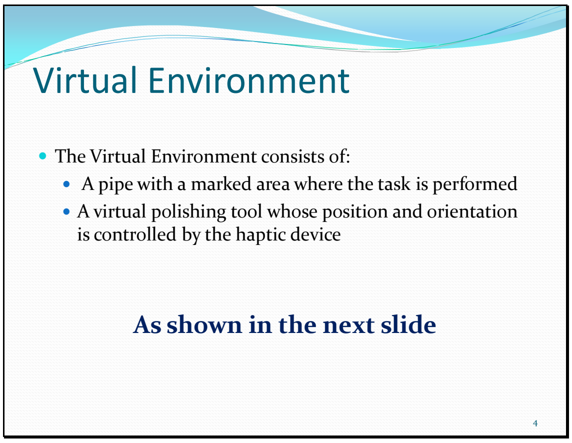


D.1.2.3 Evaluation step

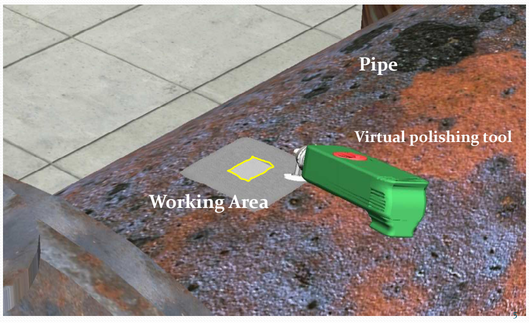








Virtual Environment



Virtual Environment

- The Virtual Environment also consists of two colour map indicators:
  - On the working area
  - On the lower right corner of the monitor

As shown in the next slide

6

Colour Maps

7

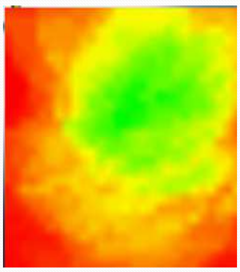
Colour Maps

- Each colour map displays the progression of your task performance
- It shows:
  - Where you have polished
  - How well you have polished
  - with the changing colours :
    - **Red** means not polished
    - **Orange** means not polished enough
    - **Yellow** means not polished enough
    - **Green** means satisfactorily polished

As shown in the next slide

8

Colour Maps



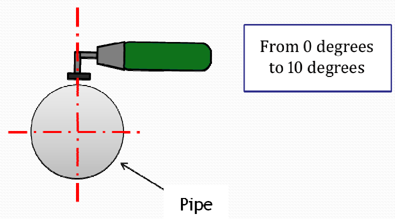
The changing colours represent:

- Red; not polished
- Orange; not polished enough
- Yellow ; not polished enough
- Green; satisfactorily polished

9

Performing the task

- To accurately perform the task, the disk of the virtual polisher should be completely flat onto the surface of the pipe so that the angle equals o degrees



10

Performing the task

- Your performance is depicted on the colour map
- Optimum performance means the full colour map appears in **green**

Performing the task

Hold the haptic device as if you were holding a power tool

As shown in the next slide

Haptic Device

Haptic Device

'the stylus represents the polishing tool body with the polishing attachment sitting at a 90° angle from the end of the stylus'.

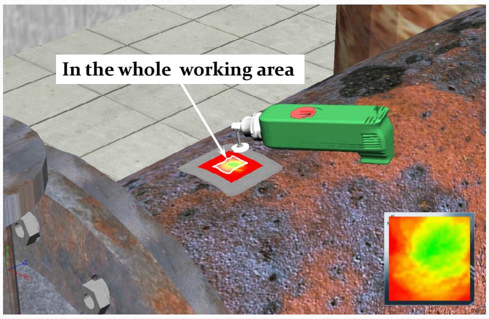
Performing the task

If you feel you are ready, please face the simulator display

Hold the haptic device

Press the dark button to start the virtual polishing tool
&
perform the polishing task in the whole working area

Performing the task



D.1.3 Questionnaire

ManuVAR *Confidential* Participant ID ☐

Pre-screener

Name: ………………………………………………………………………………………………………

1) Do you have normal vision? ☐ Yes ☐ No

If no, how is your vision corrected? ☐ Glasses ☐ Contact lenses ☐ Not corrected

2) Are you colour blind? ☐ Yes ☐ No

3) Do you have any other visual impairment? ☐ Yes ☐ No
If yes, please give details ………………………………………………………………………………

4) Do you regard yourself as susceptible to motion sickness?

☐ Not at all ☐ Slightly ☐ Moderately ☐ Very much so

5) Are you presently in your normal state of health? ☐ Yes ☐ No
If no, please give details ………………………………………………………………………………

6) Do you have any of the following medical conditions?:

Migraine	☐ Yes	☐ No
Recurring headache	☐ Yes	☐ No
Back pain or back problems	☐ Yes	☐ No
Neck or shoulder strain	☐ Yes	☐ No
Wrist or arm pain	☐ Yes	☐ No
Heart condition	☐ Yes	☐ No
Asthmatic or respiratory disorder	☐ Yes	☐ No
Epilepsy (photosensitive or other)	☐ Yes	☐ No
Problems with depth perception	☐ Yes	☐ No
Other serious injury or illness	☐ Yes	☐ No

If yes, please give details ………………………………………………………………………………

ManuVAR *Confidential* Participant ID ☐

Participant demographics

1) Age: ☐ under 25 ☐ 25-34 ☐ 35-44 ☐ 45-54 ☐ 55-65 ☐ over 65

2) Gender: ☐ Male ☐ Female

3) What is your occupation

…………………………………………………………………………………………

4) Have you any experience of computer sciences? ☐ Yes ☐ Some ☐ No

5) Have you previous experience of playing video games? ☐ Yes ☐ Some ☐ No

6) Have you previous experience of using virtual environments? ☐ Yes ☐ Some ☐ No

7) Have you any experience using a haptic device? ☐ Yes ☐ Some ☐ No

8) Have you previous experience of handling power tools? ☐ Yes ☐ Some ☐ No

ManuVAR   Confidential   Participant ID

Section 1: **Pre Symptom Checklist**

*Please circle below if any of the following symptoms apply to you **right now***

1. General discomfort	**None**	**Slight**	**Moderate**	**Severe**
2. Fatigue	**None**	**Slight**	**Moderate**	**Severe**
3. Boredom	**None**	**Slight**	**Moderate**	**Severe**
4. Drowsiness	**None**	**Slight**	**Moderate**	**Severe**
5. Headache	**None**	**Slight**	**Moderate**	**Severe**
6. Eyestrain	**None**	**Slight**	**Moderate**	**Severe**
7. Difficulty focusing	**None**	**Slight**	**Moderate**	**Severe**
8. Salivation increased	**None**	**Slight**	**Moderate**	**Severe**
9. Salivation decreased	**None**	**Slight**	**Moderate**	**Severe**
10. Sweating	**None**	**Slight**	**Moderate**	**Severe**
11. Nausea	**None**	**Slight**	**Moderate**	**Severe**
12. Difficulty concentrating	**None**	**Slight**	**Moderate**	**Severe**

13. Mental depression	**No**	**Yes**
14. “Fullness of the head”	**No**	**Yes**
15. Blurred vision	**No**	**Yes**
16. Dizziness eyes open	**No**	**Yes**
17. Dizziness eyes closed	**No**	**Yes**
18. Vertigo	**No**	**Yes**
19. Visual flashbacks	**No**	**Yes**
20. Faintness	**No**	**Yes**
21. Aware of breathing	**No**	**Yes**
22. Stomach awareness	**No**	**Yes**
23. Loss of appetite	**No**	**Yes**
24. Increase of appetite	**No**	**Yes**
25. Desire to move bowels	**No**	**Yes**
26. Confusion	**No**	**Yes**
27. Burping	**No**	**Yes**
28. Vomiting	**No**	**Yes**
29. Exhilaration	**No**	**Yes**
30. Other symptoms	**No**	**Yes**

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Section 2: **Short Symptom Checklist (to be filled after each step)**

You should complete this questionnaire every 5 minutes as instructed by the experimenter

0 1 2 3 4 5 6 7 8 9 10

No symptom at all — Unbearable level of symptom

Please write down the number from the scale above corresponding to the level at which you are experiencing the following symptoms right now in the first column below:

		Start	HB	Part 1	Part 2	Part 3	Part 4
1	Headache						
2	Eyestrain						
3	Blurred vision						
4	Dizziness (eyes open)						
5	Dizziness (eyes closed)						
6	Sickness						
7	Physical fatigue						
8	Mental fatigue						

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		Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
1	Headache						
2	Eyestrain						
3	Blurred vision						
4	Dizziness (eyes open)						
5	Dizziness (eyes closed)						
6	Sickness						
7	Physical fatigue						
8	Mental fatigue						

	End-task performance	Task 1
1	Headache	
2	Eyestrain	
3	Blurred vision	
4	Dizziness (eyes open)	
5	Dizziness (eyes closed)	
6	Sickness	
7	Physical fatigue	
8	Mental fatigue	

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Section 3: **Haptic Background Questionnaire**

3.1. User Feedback: Haptic background Task

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1. I found it easy to do the task					
2. I found easy to handle haptic device					
3. I feel confident in handling the haptic device simulating the virtual polishing tool					
4. I do not feel mentally fatigued					
5. I do not feel physically fatigued					

Please provide any further comments below

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Section 4: **Motor-Skills Training Questionnaire**

User Feedback: Motor-Skills training (to be repeated after each training session)

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1. I found it easy to do the task					
2. I found easy to handle haptic device					
3. I found it easy to apply force					
4. I found it easy to keep within the force threshold					
5. I found it easy to angle the polishing tool					
6. I found it easy to keep within the angle threshold					
7. I found it easy to maintain the expected behaviour during the required time (5 or 15 seconds)					
8. I feel satisfied with my performance in this training session					
9. I feel I performed the task accurately					
10. I do not feel mentally fatigued					
11. I do not feel physically fatigued					

Please provide any further comments below

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Section 5: **End-Task Questionnaire**

User Feedback: end-task Performance

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1. I found it easy to do the task					
2. I found easy to handle haptic device					
3. I found it easy to maintain the expected behaviour during the required time during the task					
4. I feel satisfied with my performance					
5. I feel I performed the task accurately					
6. I do not feel mentally fatigued					
7. I do not feel physically fatigued					

Please provide any further comments below

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Section 6: **Post Symptom Checklist**

Please circle below if any of the following symptoms apply to you ***right now***

1. General discomfort	**None**	**Slight**	**Moderate**	**Severe**
2. Fatigue	**None**	**Slight**	**Moderate**	**Severe**
3. Boredom	**None**	**Slight**	**Moderate**	**Severe**
4. Drowsiness	**None**	**Slight**	**Moderate**	**Severe**
5. Headache	**None**	**Slight**	**Moderate**	**Severe**
6. Eyestrain	**None**	**Slight**	**Moderate**	**Severe**
7. Difficulty focusing	**None**	**Slight**	**Moderate**	**Severe**
8. Salivation increased	**None**	**Slight**	**Moderate**	**Severe**
9. Salivation decreased	**None**	**Slight**	**Moderate**	**Severe**
10. Sweating	**None**	**Slight**	**Moderate**	**Severe**
11. Nausea	**None**	**Slight**	**Moderate**	**Severe**
12. Difficulty concentrating	**None**	**Slight**	**Moderate**	**Severe**

13. Mental depression	**No**	**Yes**
14. "Fullness of the head"	**No**	**Yes**
15. Blurred vision	**No**	**Yes**
16. Dizziness eyes open	**No**	**Yes**
17. Dizziness eyes closed	**No**	**Yes**
18. Vertigo	**No**	**Yes**
19. Visual flashbacks	**No**	**Yes**
20. Faintness	**No**	**Yes**
21. Aware of breathing	**No**	**Yes**
22. Stomach awareness	**No**	**Yes**
23. Loss of appetite	**No**	**Yes**
24. Increase of appetite	**No**	**Yes**
25. Desire to move bowels	**No**	**Yes**
26. Confusion	**No**	**Yes**
27. Burping	**No**	**Yes**
28. Vomiting	**No**	**Yes**
29. Exhilaration	**No**	**Yes**
30. Other symptoms	**No**	**Yes**

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Section 7: Final evaluation questionnaire

(to be performed after the end-task simulation)

7.1 Visual display and interface design

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1. I found the virtual environment to be realistic					
2. I found the screen was not cluttered with unnecessary information					
3. The visual quality of the display did not impact on my performance					
4. I found the colour map easy to understand					
5. I found the side colour map practical to evaluate the advancement of my performance					
6. I found the colour map located onto the material practical to evaluate the advancement of my performance					
7. I found it easy to correlate the colour map with a location on the material surface					

Please provide any further comments below

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Participant ID

7.2 Haptic device

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1. I found it easy to manipulate the haptic device					
2. I found the force simulation of polishing tool realistic					
3. I found the weight of the virtual polishing tool realistic					
4. I found the vibration of the polishing tool realistic					
5. I found the simulation of the contact with surface realistic					

Please provide any further comments below

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7.3 Virtual Environment and Presence

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1. I felt completely involved with the virtual representation					
2. I was able to control the events in the system					
3. I was always aware of the displays and the control devices					
4. I was able to anticipate what would happen next in response to my actions in the system					
5. The system reacted to my actions in a way that I expected					
6. I found that the input devices distracted me from the virtual representation					
7. The visual display quality did not interfere or distract me from performing tasks using the system					
8. The haptic feedback quality did not interfere or distract me from performing tasks using the system					
9. The visual quality of the virtual representation increased my sense of feeling that I was actually “seeing” the virtual object					
10. The haptic quality of the virtual representation increased my sense of feeling that I was actually “feeling” the virtual object					
11. Whilst performing tasks with the virtual object I found myself distracted by other aspects of the system					

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7.4 Evaluation of training

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1) The instructions I received were sufficient to help me to understand how to perform the task					

Please explain your answer

2) The training I received was sufficient to help me to accurately perform the task					

Please explain your answer

3) The training I received was effective to help me to accurately perform the task					

Please explain your answer

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Participant ID

Please provide any further comments below

D.2 EXPERIMENTAL STUDY 2

D.2.1 Consent form

Page **1 of 2**

ManuVAR

Participant ID:

Consent Form Group B

ManuVAR Demonstration

The ManuVAR project is a three year collaborative study that investigates improving the human factors issues related to manual tasks using virtual reality (VR) and augmented reality (AR).

As a participant you will have an introduction to the technology and a specific task. You will have the opportunity to interact with the system and to ask questions. Your actions will be observed and you will be interviewed. In addition you will be asked to complete some questionnaires during the study.

The study will be recorded using video and audio and the data will be identified by numbers and it will be stored on the internal system accessible by all members of the ManuVAR consortium.

Your participation in this study is very much appreciated. Please remember your participation is voluntary and you may withdraw at any time.

Please read the statement below and if in agreement sign and date.

I confirm that I have voluntary agreed to take part in the study. I have read and understood the above explanation and have been given the opportunity to ask questions about the study. I understand that I am free to withdraw from the study at any time.

☐ **I permit my name to be used in association with my responses within the ManuVAR consortium.** It means information can be used to clarify the meaning of responses by providing information on its source, but only within ManuVAR. It is important, for example, in case of technical and business impact feedback analysis. The anonymous results can be published in the form that makes it impossible to reveal respondent's identity following ManuVAR standard publication procedure.

☐ **I permit my name to be used in association with my responses in publications.** It means information can be used as a testimonial or a public reference to the ManuVAR project. Before publishing in accordance with the standard ManuVAR publication procedure, you will be informed on the exact quote and context in which it will be published.

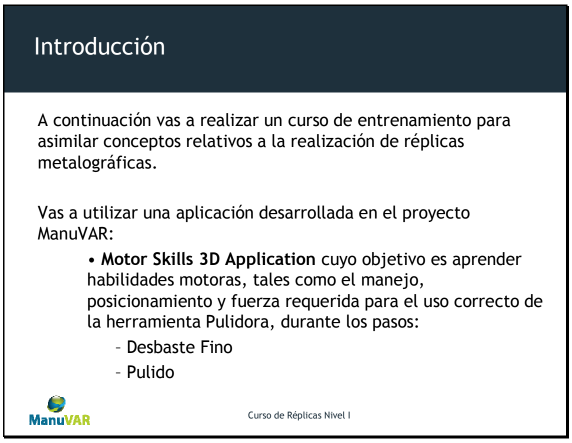
☐ **I do not permit my name to be associated with my responses but I allow the data to be used anonymously.** It means information will be identified only with numbers. The anonymous results can be published in the form that makes it impossible to reveal respondent's identity following ManuVAR standard publication procedure.

Please print your name:	Date:
Signature:	

D.2.2 Instructions

Instructions were displayed in presentation slides. The following sections present the instructions provided for part-task and whole-task training.

D.2.2.1 Part-task training



Motor Skills Application

Esta aplicación consiste en la realización de una serie de ejercicios para aprender el manejo de la herramienta Pulidora portatil durante los pasos de Desbaste fino y Pulido.

El entorno virtual consiste en:

- Una tubería con un área marcada en gris que representa la zona de trabajo donde se va a realizar la réplica.
- Una herramienta virtual que simula a la Pulidora portatil cuya posición y orientación es controlada por el dispositivo háptico.

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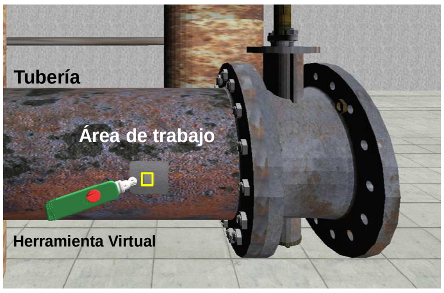
Motor Skills App: Entorno Virtual



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Motor Skills App: Indicadores

En la pantalla podrás ver un panel lateral con unos indicadores para ayudarte durante la ejecución:

- **Fuerza** (en Newton) que representa la presión que estás ejerciendo sobre la superficie utilizando el dispositivo háptico.
- **Ángulo** (en grados) que representa la orientación del disco de la herramienta respecto de la superficie de la tubería.
- **Cronómetro que indica el tiempo restante (en segundos)** durante el cual tiene que mantener determinada posición y/o fuerza con la herramienta.

Y además:

- **Timer** (en segundos) que representa la duración total del ejercicio.
- **Instrucciones** en el cuadro superior que es la descripción del ejercicio a realizar.

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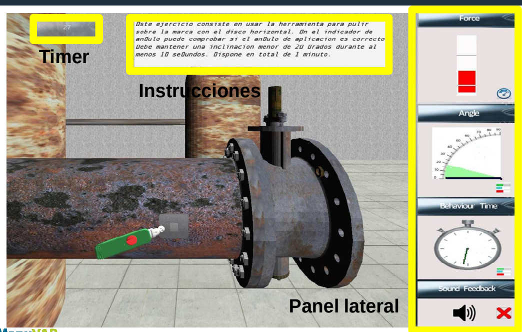
Motor Skills App: Indicadores



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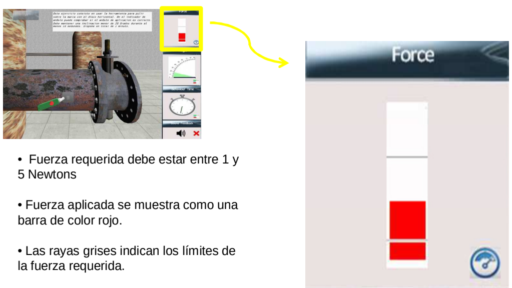
Motor Skills App: Indicador de Fuerza



- Fuerza requerida debe estar entre 1 y 5 Newtons
- Fuerza aplicada se muestra como una barra de color rojo.
- Las rayas grises indican los límites de la fuerza requerida.

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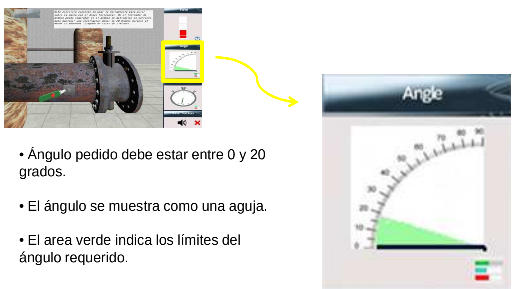
Motor Skills App: Indicador de ángulo



- Ángulo pedido debe estar entre 0 y 20 grados.
- El ángulo se muestra como una aguja.
- El area verde indica los límites del ángulo requerido.

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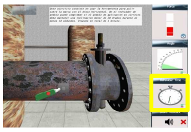
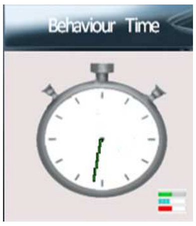
Motor Skills App: Indicador de tiempo



- Se representa como un cronómetro.
- El indicador representa el tiempo restante durante el cual debes mantener el comportamiento correcto.



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Motor Skills App: Realización de la tarea

- La tarea consiste en el entrenamiento de los diferentes conceptos necesarios en la realización de la réplica metalográfica.
- El entrenamiento se realizara en pareja, aunque alternativamente, de forma que solo un alumno este en la sala de realidad virtual haciendo los ejercicios.
- Cada alumno se entrenará en una tarea de la réplica metalográfica, Desbaste Fino o Pulido.

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Motor Skills App: Realización de la tarea

- Antes de empezar el entrenamiento, vas a realizar un examen para evaluar tu nivel en la tarea que te fue asignada (desbaste fino o pulido).
- Al finalizar el entrenamiento realizarás también un examen para evaluar tu nivel.
- Cada examen consiste en una serie 6 ejercicios de una duración máxima de 1 minuto durante los cuales se te pedirá mantener ángulos y fuerzas específicos durante 10 segundos.

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Motor Skills App: Realización de la tarea

- El entrenamiento consiste en un tipo de lección para cada tarea.
- Lección de Desbaste Fino:
  - Límites de Ángulo [60º-85º]
  - Límites de Fuerza [1N-5N]
- Lección de Pulido:
  - Límites de Ángulo [0º-20º]
  - Límites de Fuerza [1N-5N]

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Motor Skills App: Realización de la tarea

- Cada lección está formada por 4 ejercicios. Cada ejercicio dura como máximo 1 minuto.
- Después de cada lección, irás a descansar. El siguiente alumno entrará a realizar su lección.
- Las instrucciones de cada ejercicio se muestran en el cuadro de texto superior.
- Durante el ejercicio, se te pedirá que adoptes y mantengas durante 10 segundos una determinada posición y fuerza con la herramienta.
- Además, esta posición y fuerza deben mantenerse de forma dinámica, siguiendo una determinada trayectoria (tal y como aparece en la diapositiva siguiente).

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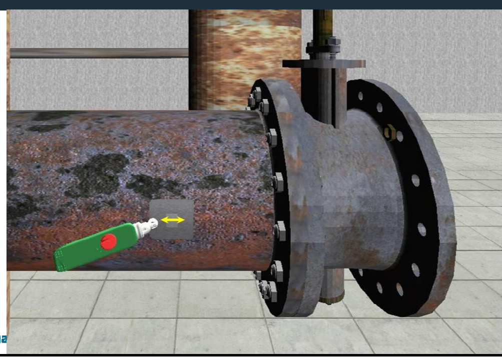
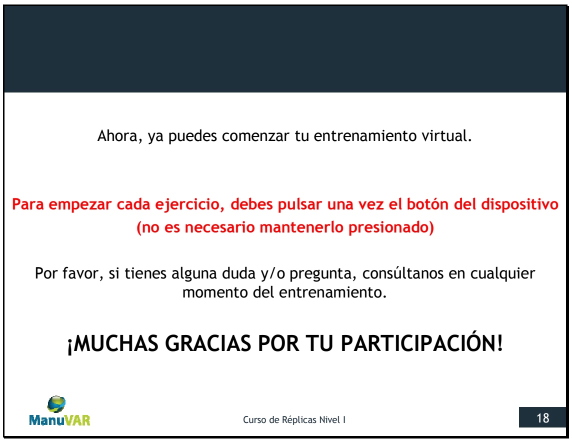
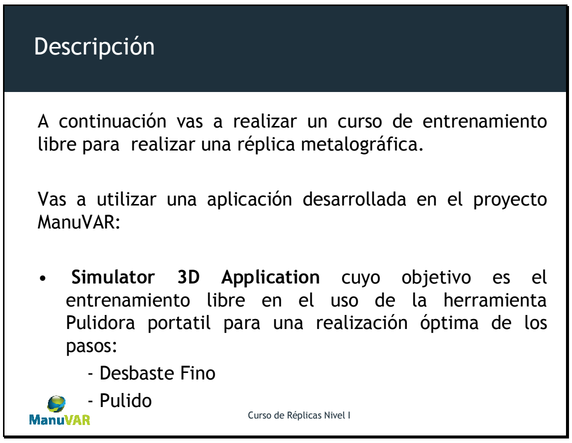
Motor Skills App: Trayectoria requerida



Ma 6



D.2.2.2 *Whole-task training*



Simulator Application

El entorno virtual consiste en:

- Cuerpo de una válvula con un área marcada en gris que representa la zona de trabajo donde se va a realizar la réplica.
- Una herramienta virtual que simula a la Pulidora cuya posición y orientación es controlada por el dispositivo háptico.
- Dos mapas de color:
  - -Sobre el área de trabajo
  - -En la esquina inferior derecha de la pantalla

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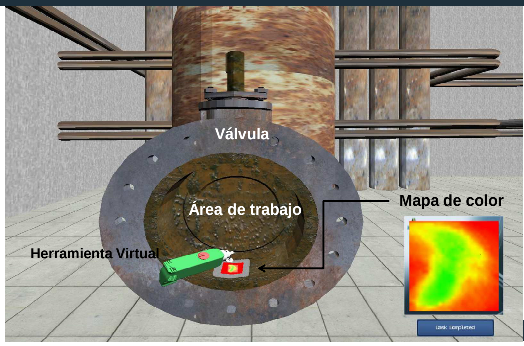
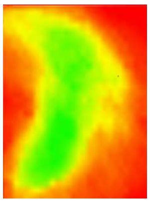
Simulator Application: Entorno Virtual



Simulator Application: Mapa de color

Cada mapa de color muestra el grado de progreso en la ejecución de la tarea. Éste muestra:



- Lugar en el área donde ya ha desbastado o pulido
- Cómo de bien lo está realizando
- Identificación colores:
  - **Rojo: No desbastado/pulido**
  - **Naranja: No desbastado/pulido suficientemente**
  - **Amarillo: Casi desbastado/pulido completamente.**
  - **Verde: Desbastado/pulido completamente**

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Simulator Application : Realización de la tarea

- Antes de empezar el entrenamiento, vas a realizar :
  - Una prueba (no evaluable) que te permitirá entender el concepto de la simulación con mapa de color.
  - Un examen para evaluar tu nivel en la tarea que te fue asignada (debaste fino o pulido) sin mapa de color.
- Al finalizar el entrenamiento, realizarás el mismo examen (sin mapa de color) para evaluar tu aprendizaje después tu entrenamiento.
- Cada examen consiste en realizar tu tarea (debaste fino o pulido) en el simulador durante 3 minutos. Los mapas de color no se mostrarán mientras realizas el examen.

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Simulator App: Realización de la tarea

- El entrenamiento consiste practicar tu tarea (Desbaste Fino o Pulido).
- La tarea se lleva a cabo sin mostrar el mapa de color. Cuando considere que la tarea ha finalizado, podrá ver el mapa de color. Si el resultado no es satisfactorio, podrá continuar realizando la tarea. Esto podrá repetirse cuantas veces quiera, hasta un máximo de 3 minutos.
- Una ejercicio dura 3 minutos durante los cuales debes realizar tu tarea dentro del área de réplica.
- Después de cada ejercicio, irás a descansar. El siguiente alumno entrará a realizar el mismo ejercicio.

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Simulator App: Realización de la tarea

- **IMPORTANTE** Requisito para tu tarea: Es importante no salirse de la área gris de trabajo. Si esto ocurriera, la réplica quedaría invalidada.
- Para el Desbaste Fino y el Pulido se deberá realizar la tarea aplicando un movimiento tal y como aparece en la diapositiva siguiente.

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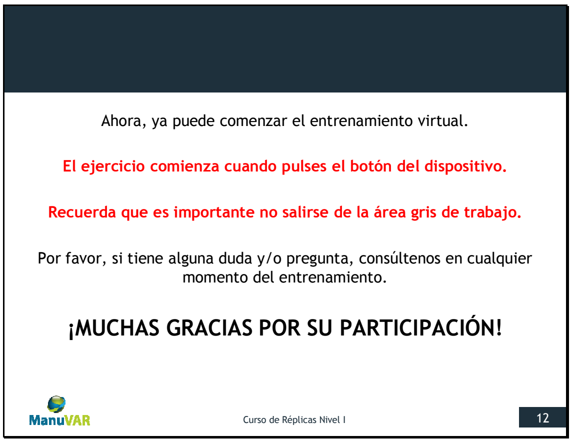
Simulator App: Realización de la tarea


Ahora, ya puede comenzar el entrenamiento virtual.
El ejercicio comienza cuando pulses el botón del dispositivo.
Recuerda que es importante no salirse de la área gris de trabajo.
Por favor, si tiene alguna duda y/o pregunta, consúltenos en cualquier momento del entrenamiento.
¡MUCHAS GRACIAS POR SU PARTICIPACIÓN!
ManuVAR
Curso de Réplicas Nivel I
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D.2.3 Questionnaire for expert metallurgists

Participant ID:

AREA 2: HUMAN FACTORS

ManuVAR Training Tool Evaluation (Expert)

This questionnaire relates to the ManuVAR Training tool. The aim of this questionnaire is to measure the to measure pleasantness, likelihood of acceptance, easiness, and motivation of ManuVAR applications. The effectiveness of your learning will be evaluated through the data analysis. The following questions ask you about your experience and views on what you have seen. Please complete the questions below by ticking the appropriate box to indicate to what extent you agree or disagree with the statements. If the statement is not relevant to the task that you have seen, please tick the 'Not Relevant' box.

Section 1: Open questions

1. What is your overall impression of the technology you have seen today?

2. Which parts of the task or tool did you like? Please explain your answer.

3. Which parts of the task or tool did you dislike? Please explain your answer.

4. Could the training of the task be carried out more easily using the ManuVAR tool when compared to the conventional way of training?

5. Could the training of the task be carried out more accurately using the ManuVAR tool?

6. What type of training/knowledge do you think is required to use the ManuVAR tool effectively, i.e. do users need any pre-lessons for the procedural task?

7. What type of training/knowledge do you think is required to use the ManuVAR tool effectively, i.e. do users need any pre-lessons for the training using the haptic device?

8. In your opinion, how well does the simulator reproduce the task it simulates?

Section 2: Setting up the task

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. The quality of the display image was good						
2. The visual quality of the display did not impact on my performance						
3. It was easy to launch the tool						
4. The user interface for launching the application was easy to use						

Section 3&4: Performing the task and Display of task progress

✌ **Procedural training**

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. I think it's a good tool for learning.						
2. I found it easy to do the task						
3. The object of the task was clear and easy to understand						
4. I found it easy to use the tool						
5. The information on the screen was easy to understand						
6. I think the general principles of metallographic replica performance are covered by this training						
7. I liked the way that the procedural training was represented						

- **Motor skills training**

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. I found it easy to do the task						
2. I found the force feedback helpful to perform my task (S4)						
3. I found the angle feedback helpful to perform my task (S4)						
4. The system provided adequate feedback to show the time that has passed during the task (S4)						
5. I found it easy to learn how to use the haptic device						
6. It was easy to use the haptic device						
7. Virtual representations of objects moved in a natural way.						
8. I liked the way that the motor skills application was represented						
9. I did not experience any physical discomfort during the task						

- **Simulation training**

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. I found it easy to do the task						
2. The user interface seemed intuitive to use						
3. I understood what was happening during the task (S4)						
4. I found the colour map helpful to perform my task (S4)						
5. Virtual representations of objects moved in a natural way						
6. I liked the way the simulation application was represented						
7. I did not experience any physical discomfort during the task						
8. It was easy to use the haptic device						

Section 5&6: Accessing and visualization of data

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. It was easy to access the stored data in the Performance Analyzer tool						
2. The Performance Analyzer tool helped me to understand the results of the training						
3. I like the way the results are presented						
4. The summary of results screen was easy to understand						

Section 7: General Questions

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. Overall, it was easy to learn the task when compared to the conventional method						
2. Overall, I enjoyed using the system						
3. After using the system I would feel more confident about performing the task in the real world						
4. This system is very innovative						

Please provide any further comments

……
……
……
……………………………………………

D.2.4 Questionnaire for non-expert workers

ManuVAR

Participant ID:

AREA 2: HUMAN FACTORS

ManuVAR Training Tool Evaluation (Novice)

This questionnaire relates to the ManuVAR training tool. The aim of this questionnaire is to measure the to measure pleasantness, likelihood of acceptance, easiness, and motivation of ManuVAR applications. The effectiveness of your learning will be evaluated through the data analysis. The following questions ask you about your experience and views on what you have seen. Please complete the questions below by ticking the appropriate box to indicate to what extent you agree or disagree with the statements. If the statement is not relevant to the task that you have seen, please tick the 'Not Relevant' box.

Section 1: Open questions

1. What is your overall impression of the technology you have seen today?

2. Which parts of the task or tool did you like? Please explain your answer.

3. Which parts of the task or tool did you dislike? Please explain your answer.

4. Do you think that the training of the task was carried out accurately using the ManuVAR tool?

5. Do you think that the training of the task was carried out quickly using the ManuVAR tool?

Section 2: Setting up the task

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. The quality of the display image was good						
2. The visual quality of the display did not impact on my performance						

Section 3&4: Performing the task and Display of task progress

- **Procedural training**

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. I found it easy to do the task						
2. I found it easy to use the application						
3. The information on the screen was easy to understand						
4. The object of the task was clear and easy to understand						
5. I enjoyed the training						
6. After a question I was told if I was right or wrong and after a session I looked at a chart: these elements pushed me to continue the training						
7. I liked the way that the procedural training application was realized						
8. I easily learned the general principles of metallographic replica performance						

- **Motor skills training**

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. I found it easy to do the task						
2. I found the force feedback helpful to perform my task (S4)						

3. I found the angle feedback helpful to perform my task (S4)						
4. The system provided adequate feedback to show the time that has passed during the task.(S4)						
5. I found it easy to learn how to use the haptic device						
6. It was easy to use the haptic device						
7. Virtual representations of objects moved in a natural way.						
8. I liked the way that the motor skills application was realized.						
9. I did not experience any physical discomfort during the task						

- **Simulation training**

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. I found it easy to do the task						
2. The user interface seemed intuitive to use						
3. I understood what was happening during the task (S4)						
4. I found the colour map helpful to perform my task (S4)						
5. It was easy to use the haptic device						
6. Virtual representations of objects moved in a natural way.						
7. I liked the way that the simulation application was represented.						
8. I did not experience any physical discomfort during the task						

Section 5&6: Accessing and visualization of data

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. The Performance Analyzer tool helped me to understand the results of my training						
2. I like the way the results are presented.						

Section 7: General Questions

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Not Relevant
1. Overall, it was easy to learn the task						
2. Overall, I enjoyed using the system						
3. After using the system I would feel more confident about performing the task in the real world						
4. This system is very innovative						

Please provide any further comments

Appendix E. Experimental Study 1: Analysis of Comments

E.1 THEME-BASED CONTENT ANALYSIS

The theme-based content analysis (TBCA) (Neale & Nichols, 2001) proposes a methodological framework to enhance the qualitative evaluation of the usability of interactive technologies (Patel et al., 2005; Cranwell et al., 2012). It has been used in the EU funded research projects KidStory (http://www.sics.se/kidstory/) (Stanton et al., 2001) and ManuVAR (http://www.manuvar.eu) (Langley et al., 2011).

TBCA is a consistent analysis method for qualitative information that prevents the misinterpretation of terminologies when taken out of their original context. Moreover, it provides valuable indications of results by grouping those data into meaningful categories.

TBCA is carried out through a five stages procedure based on coherent isolation and identification of qualitative data relevant topics to be then clustered into categories:

1. Stage 1 consists in the data collection process. In both experimental studies presented in this thesis (Chapters 6 & 7), participants were invited to provide

comments concerning their experience through written questionnaires. Those questionnaires are presented in Appendix D.

2. Stage 2 consists in the data collation process. Collected Data are grouped according to topics that are relevant in the scope of the study and are presented in the form of a simple matrix.
3. Stage 3 consists in the definition of themes and classification process. A team composed of a minimum of two researchers determine raw data themes and group the information according to these themes (Neale & Nichols, 2001). The number of responses falling into each theme is then indicated in the matrix. This stage is generally based on a discussion between researchers which leads to several refinements in the matrix.
4. Stage 4 consists in the selection process of higher order themes which implies determining more general themes as a function of the number of participants responses falling into each of these themes.
5. Stage 5 consists in presenting the classification in a structured and consistent way. A matrix format enables displaying classified qualitative data (raw data, raw data themes and higher order themes with frequency counts to indicate the popularity of each theme) for each group of participants and allows opening discussion between researchers regarding to the addressed hypotheses of the study. Section E.2 presents the content analysis of comments provided by participants in the experimental study 1 (Chapter 6).

E.2 EXPERIMENTAL STUDY 1: CLASSIFICATION MATRICES

Table 21. Content analysis of comments provided by participants from FT group.

Raw data	Raw data themes	Higher order themes
...I was not sure about the force I applied… Applying force was difficult. I never knew how much force I was really used... Force was difficult to feel….	Difficulties to apply correct force (3)	Force (3)
The most difficult part was on maintaining the force		
Slight confusion between too much and too little pressure…		
... The angle was good.	easiness to apply correct Angle(1)	Angle (1)
… Training longer time, training sessions of 15sec were too short.	More training needed (2)	Training (6)
.... To improve upon accuracy, there could have been smaller session after each task to focus on improving small things such as maintaining the correct force or how to improve on keeping the angle constant.		
...Repetitive task really easy to continue doing	Effective training (4)	
...I was able to repeat the training tasks many times to get better practice.		
… (Pressure) It would be easily learnt after a few tasks …I felt that training was good and my performance continued to improve. I feel progress was good throughout all tasks.		
After a series of training, I feel confident for doing the task. ...I feel it very useful to maintain force, angle and trajectory…. The sense of haptic feedback is improved during training sessions... ...With the training, my sense and capability of doing the task are improved. ....Experiencing with few scenarios of trajectory also will help me recognizing what is the best I should do. ... I have been prepared about the task and how the strategy to handle it well... Training helps me to boost my performance		
Slight confusion over orientation of the colour map at the start of the task	Trouble in the orientation of the colour map (1)	Colour Map (2)

Raw data	Raw data themes	Higher order themes
The colour map helps me to understand what I should do with the task, which area should be covered, and how to maximize the coverage area.	Useful indicator (1)	
I got the instructions twice (verbal and presentation). I knew what I had to do…	Clearness of Instructions (7)	Instructions (7)
The instructions on screen and from the demonstrator were very well and clearly explained... *The demonstrator was very helpful and helped me feel at ease…*		
Clear instructions...		
Instructions were clear and repeated to me often...		
Clear and Precise instruction, I totally understood what was expected of me...		
The instructions are easy to understand…		
Instructions were made clear so it is easy to understand...		
The pre-experiment helps use to be familiar to use the device.	Easiness of tool handling (1)	Tool Handling(1)
I do not know if I was on the surface or not and had to lift the device and reapply it.	Contact Issues (1)	Realism of Tool (2)
… (Sense of haptics is increased during training) so when I performed the last task, it is really realistic... *... for the sense of reality, it is fine.*	Realistic haptic perception (1)	
The design is complete.	Realistic environment (2)	Realism of environment (2)
The real representation of the VE of the real situation could improve the understanding from the first training to the last...		
I felt I did the task better than the results!	Frustrated performance (1)	Performance (3)
I think I did a good job.	Successful performance (1)	
I have never looked at the side colour map.…	Self confidence while performing (1)	
...With the up to down trajectory, I feel I could boost my performance.	up to down motion (1)	Trajectory (1)
The screen may have been a bit close to me	Screen distance issues (1)	Setup issues (2)
...The angle of view onto the display when standing was not good onto the display.	Standing posture POV issue (1)	
….Indicators were good for training.	useful Feedback indicators (2)	Feedback indicators (2)
…. With the display, I know where the angle and force should be, and feel it directly. This is a good practice combined with the unseen displays….		
I think the force felt different in the end task-> fatigue	Physical demand (3)	Physical fatigue (3)
I feel a bit tired …		

Raw data	Raw data themes	Higher order themes
The fatigue is also caused by the real haptic and the arm floating in the air …. Some of the circumstances like the arm floating in the air without arm rest, and the sweaty of hand could reduce the performance and increase the fatigue....		
Efforts a lot of force and concentration…	Attention demanding (1)	Cognitive efforts (3)
…. there was not much pressure on me to do the tasks 100% accurately, but in my own way and time. If there was pressure on me, I feel I would not be able to do the tasks to my full potential	Not much mental load (2)	
I found it to be less pressure as the timing was not visible to me like in previous task		

Table 22. Content analysis of comments provided by participants from HT group.

Raw data	Raw data themes	Higher order themes
… I put too much force at the beginning. It showed nothing on the screen.	Difficulties to apply correct force (7)	Force (8)
… It was difficult to know if these were correct.		
I was applying too much force in the beginning, so the colours did not change ….		
... No intuitive feeling of how to apply pressure ….		
... May be about the force (too high may be) but certainly I do not know how to measure it.		
Although it felt like it was difficult to gauge…		
You can´t really be aware of how much force you put on		
… After a while I got better hang of it….	Accustom to apply correct force (1)	
….it was difficult to know if these were correct.	Difficulties to apply correct angle (2)	Angle (2)
Very Difficult to get in suitable position...		
I think applying force during the initial training would have led to a better performance.	Training required (8)	Training (9)
Not enough exercise for the people who watch the video. Especially when we finished the video. We still have no fell about the task when there was no indicator showed up in the screen *More exercise for the operator....* *It does not tell me the*		

Raw data	Raw data themes	Higher order themes
operator/demonstrator how to apply the force and place the handle to finish the task.		
I wish I could practice on angling and applying force.		
No practical hand on aspect to the training		
With a little bit more time using the device rather than watching the film I think I could have achieved the green in a fairly smooth manner *The film did not make a big difference and I think I would have had the same result without it* *With more training of the same kind I think it was helpful.*		
I Feel that Performing training shown on video would have helped *…. For novices like me, the practical training shown on the video would be very necessary.*		
I was hoping to train myself about how to make 1-5N forces and 0-10 degrees angle. At least, there are clues what to do on the task, so basically the training is useful (but for me it is not sufficient enough since I need to practice it, not only watch it).		
It just needs practice, I think. *I still struggled to do the polishing, but it did help somehow.*		
The video part is too lengthy since much of the information has been understood.	Useful training for understanding (1)	
We may need a sensible colour map. Just four colour may be not enough for the operator to feel whether we operate the device right or not. *More colour on the map to illustrate the operator task.*	More advanced colour map needed (1)	Colour Map (4)
I found it easier to look at the working area to see the little progress I appeared to make.	Useful indicator (3)	
...I found that the changing colour and the feel was a better guidance to achieve the green colour. *... The colour was what mattered most and helped me to put a less strong and more efficient force (judging from the colour) towards the end.* *... I let the colour screen be the guiding device.*		
I liked the colour map. I would be able to comment more if I had been more successful but concept of showing where more work is needed is great.		
Clear instructions and answer to questions.	Clearness of Instructions	Instructions (7)

Raw data	Raw data themes	Higher order themes
The instructions via the training session were very informative.	(6)	
I understood what I was supposed to do...		
Clear enough to explain what I should do.		
The instructions are detailled and well defined. *On the whole experiment, instructions provide clear information of the experiment and how it should be operated.*		
there were clear instructions.		
Probably needed more instruction i.e.: practicalities - how to hold, how to change angle and how to change pressure	Weakness of instructions (1)	
… I wonder what kind of ways of holding the device to make a correct position and correct effect on the surface (polishing process).	Difficulties in tool handling (2)	Tool Handling (4)
...it was difficult to see how I was holding the device and where I was placing it, it seems like something you need to get used to. It was generally difficult ... to work the device….		
I found it easy for the demonstrator to control the handle and finish the task perfect.	Easiness of tool handling (2)	
…. and easy to handle…		
I would have expected more vibration from the device…	Weakness in vibration realism (1)	Realism of Tool (5)
I thought the sound feedback would reflect the angle and the force but it did not.	Lack of realism of sound (1)	
The contact of the surface can´t be obviously felt by the operator	Contact Issues (1)	
It seems to be quite realistic… *Well, I have never held a polishing tool, well once I did and it was similar to this actually…*	Realistic tool simulation (1)	
It is hard to judge how realistic is the experience was when I have not experienced the real tool….	No comment (2) Ignored	
...difficult to comment.		
…poor environment.	lack of realism (1)	Realism of environment (1)
I think I would do much better a second time.	Not successful performance (6)	Performance (6)
It is a bit upset when you see nothing has changed at all.		
….I was disappointed that I did not appear to get any green "well polished areas" *The colour red as this was the only colour I really saw due to my performance!...*		
... and I did not manage to get it all green,		

Raw data	Raw data themes	Higher order themes
hence not accurate.		
… I was not successful, and I have no experience of power tool…		
Not as easy as I think. *Wonder why I could not do it? ….*		
….I was not doing the movements as I had learned earlier…	No comment (1)	Trajectory (1)
Red colour may be a little too strong(flashy)	brightness issue (4)	Setup issues (4)
The colour red as this was the only colour I really saw due to my performance! Was very intense.		
I feel eyestrain after the experiment...		
….staring at the screen for a long time really hurt my eyes and gave me a headache.		
I did not do the training but I think I would have found it easier if the indicators were just above the polisher so I could see both at the same time.	Feedback indicators would have been required (4)	Feedback indicators (4)
(Lack of feedback)(for the end task) It is better to put a force indicator on the screen to show the operator how much force should be applied on the device because ……		
There was not feedback on the screen to show angle or pressure being applied to device, so it was difficult to know if these were correct. *No practical work so no feedback on angle or pressure to use the tool.*		
I felt dizzy after the experiment and wanted to have physical exercise or stretching.	Physically demanding (1)	Physical fatigue (1)
... You have to be concentrated during the polishing.	Attention demanding (3)	Cognitive efforts (3)
At times the device will go out of control. You need to be concentrated.		
It was generally difficult to concentrate		

Table 23. Content analysis of comments provided by participants from CT group.

Raw data	Raw data themes	Higher order themes
I was not sure if I was applying the correct pressure	Difficulties to apply correct force (7)	Force (8)
... At first, I did not realize what pressure to apply ….		
Not sure why I was not getting it right *I was unsure about how much force I was applying…*		

Raw data	Raw data themes	Higher order themes
… I did not understand what level of pressure to maintain *I was unsure about the pressure levels*		
Took a long time to figure out a way to have an effect on the colour map.		
It was hard to know how much force I was applying without an indicator, was just going on how the device vibrated		
…..I had trouble in getting the…force correct		
… after I got use to it …	Got accustomed to apply correct force (1)	
It was hard to know what angle was the correct angle for polishing…. *After completing the task, I realized I should have changed the angle I was holding the pen at to compensate for the cylindrical shape of the tube.......*	Difficulties to apply correct angle (4)	Angle (4)
Not sure why I was not getting it right. *I could not understand or whether the angle was correct.*		
Took a long time to figure out a way to have an effect on the colour map		
….I had trouble in getting the angle ….. correct		
There is a difference between the training and actually performing the task *I found the task very interesting and with a bit more practice be able to perform the task better*	Training required (4)	Effectiveness of Training (8)
I am sure I would have been more successful with the polisher if I had been given the chance to test it out before using it.		
It is obviously difficult to convert what I saw in the video into physical actions.		
No training, just the video. *Training exercises would be helpful.* *…. Programming response is not easy to interpret from a video alone.*		
The video representation of the positioning of the tool helped me understanding where it needs to be to achieve optimum results. *The videos …. were informative and easily understood.*	Useful training for understanding (4)	
I think it is an effective way of learning and interesting (resembles playing video games).		
I had a good idea of how to perform it after watching the videos *The video was a helpful indicator.*		
Although I saw only the training I thought it was enough to help me perform the task.		

Raw data	Raw data themes	Higher order themes
It is quite hard to assess how much of the area had been polished, for example, the right hand side was not polished at all.	Weak indicator (1)	Colour Map (4)
… It was easy to understand what I was doing using the colour indicator.	Useful indicator (3)	
I would be able to be more specific about the feedback if I had progressed further, but the colour map seemed to work ok.		
Both maps were fine. I was pleased to see they changed colour slightly towards the end.		
Instructions were explained very well.	Clearness of Instructions (7)	Instructions (7)
… instructions were informative and easily understood		
I could understand what I was meant to do and how. *… I understood the idea.*		
I understood how to manoeuvre the haptic tool …		
I understood what was expected of the task.		
Both written and verbal instructions were good.		
They were very clear.		
Haptic device easy to control…	Easiness of tool handling (1)	Tool Handling (4)
… Programming response is not easy to interpret from a video alone.	Difficulties in tool Handling (3)	
It was not easy to handle as I though …		
...It took a moment to be able to coordinate to right direction.		
The force simulation seemed to diminish when excess force was used. *The vibration was realistic but would probably be stronger from the real device*	Weakness in force realism (1)	Realism of Tool (8)
It was hard to tell when the polisher was in contact with the pipe.	Contact Issues (3)	
Lack of indication when tool was in contact with pipe- sound change?... *Not a strong enough simulation of surface contact.*		
It was hard to see why I did not touch the pipe/ make contact with it, especially as it felt I was touching it		
The task was very realistic giving feedback through the device, by vibration etc…	Realistic tool simulation (4)	
I am not sure what to expect as I have never used a polishing tool but I assume it was accurate.		
…. I could feed me feedback so I could distinguish different levels (referring to tangential force).		

Raw data	Raw data themes	Higher order themes
…. The vibration was realistic ….		
		Realism of environment (0)
… I expected to do better.	Not successful performance (2)	Performance (3)
… Not able to physically do what I was needed…		
I managed to perform the task…	Acceptable performance (1)	
...Task distinctly easier when not following the trajectories and the haptic device was stationary.	Increased complexity with trajectory	Trajectory (1)
...I see colours flashing in front of my eyes occasionally (like when you stare into a bright light).	Brightness issues (1)	Setup issues (1)
		Feedback indicators (0)
		Fatigue (0)
		Efforts (0)

Appendix F. Experimental Study 2: Analysis of Comments

This appendix presents the answers provided by participants to open-ended questions proposed throughout the whole ManuVAR demonstration stage.

Table 24. Answers to question 1 from expert and non-expert workers.

What is your overall impression of the potential of the technology you have seen today?		
	Positive responses	Negative responses
Experts	*It's useful for the training to know which step and how it is performed.* *The potential is very good.* *The potential to perform the metallographic replica mechanical work is high and it is a good way to learn how to perform the steps.* *The 3D simulator is very good.* *Changing the point of view is close*	*The haptic device is not close to the tool but it is still good.* *While handling the haptic device, you are looking left and right, but in the real situation you look straight in front.*

What is your overall impression of the potential of the technology you have seen today?		
	Positive responses	Negative responses
	to the real situation, you can think that it feels like holding the real tool, with vibrations and sounds. *...this it is a good tool.*	
Novices	*It is quite useful for learning the metallographic replica.* *Good.* *User performance is improved compared to the beginning of the task.* *Concerning the physical training, its fine ...* *The colour map is useful, you can check the work you are performing and how you perform it.* *It is an innovative and interesting application that is easy to use.* *The application is interesting and it is easy to learn using the application.* *As an introduction, it is fine.* *It is a good tool for introduction and can save you some time in the lab.* *It is hard to see if you are applying the good force or not.* *Concerning force and angle, it is fine ...*	*... more time is required to get use to the haptic device.* *During the last test on the simulator, you don't know where you are performing, so it is not easy to do it.* *But there is a discrepancy of the size of the tool to the real size.* *The application is fine but it is far from what it is in reality.* *It annoying when performing the last task, in contrast when you are performing in the real world you do have a visual idea about how you are doing.* *The work space of the haptic device is not accurate.* *...but the lack of feedback is annoying because in the real world they can see the metal changing.* *It would be good to mount the real polishing tool to the haptic device to perceive angle.* *The graphics need to evolve to a better quality.* *There is a lack of precision for example it was complicated to see where I was touching.* *I had some doubts if I was touching*

What is your overall impression of the potential of the technology you have seen today?		
	Positive responses	Negative responses
		or not touching the pipe.

Table 25. Answers to question 2 from expert and non-expert workers.

Which parts of the task or tool did you like?	
Experts	*As we have said the best part is the simulator because it makes you feel that you are performing the real metallographic replica.* *For us, the simulator.*
Novices	*I liked the simulator.* *It where you can learn more about making the metallographic replica.* *It fits to the reality of the work.* *Preferred the simulator task with the colour map.* *I liked the training on the simulator.* *I agree; I liked the learning method, it was very similar to performing the real task.* *For the 1st trial everything was fine.* *It is an innovation* *It is a positive application and it is clean, you are getting dirty while using it.*

Table 26. Answers to question 3 from expert and non-expert workers.

Which parts of the task or tool did you dislike?	
Experts	*I think in the simulator the problem is to put the haptic in a good position* *If you are watching the pipe and the haptic is lower.* *Really it would be better if it was the same height.* *There is mismatch between the position of haptic and the screen.*
Novices	*I had trouble applying angles and angling the tool on the simulator.* *When I make the motor skill training with feedback it was ok but without feedback it was hard and not fitting to the real work.* *The indicator is helpful for orientation but when there was no feedback I was*

Which parts of the task or tool did you dislike?	
	trying to remember what I did in the real world. *There is a discrepancy between the angle of polishing tool in MS training and simulator compared to reality.* *Because I am small, I had to use step and this contributed in degrading the quality of the angle.* *The final exam without the colour map.* *I didn't know how it was working, it was blind work. In contrast, in the real world you can see what you are doing. But it doesn't mean I didn't like it. I Just liked it less than the other elements of the application.* *In general there is nothing negative of the tool.* *At first it was uncomfortable and it was hard to perceive the black button in the dark* *The haptic device is warm and constrains the motion.* *It was fine but during the last part, the precision was not accurate.* *The image of the screen was blurry.*

Table 27. Answers to question 4 from expert and non-expert workers.

Could the training of the task be carried out more easily using the ManuVAR tool when compared to the conventional way of training?	
Experts	*Yes I think so.* *It is useful but it could be combined with the conventional training.* *It is useful for the 1st steps.*
Do you think that the training of the task was carried out quickly using the ManuVAR tool?	
Novices	*Yes, it is better and quicker.* *Yes.* *The advantage of using tool is that you can make the training at your workplace and not on-site.* *For the physical training, it is better in the real world.* *After the training received, it might be more efficient to combine with the real world training,* *Yes, training is quicker,*

	Its good using VR as a compliment to real world training and it provides background and knowledge to real world training. *I really like it.* *VR training and physical training are complementary.* *Training is quicker because in real world you have to prepare a lot of thing but both training in VR and real word are complementary.*

Table 28. Answers to question 5 from expert and non-expert workers.

Could the training of the task be carried out more accurately using the ManuVAR tool?	
Experts	*I think that Manuvar is useful to understand some points that we can teach to the students.* *Such as the red signals that let you know that you are wrong, but there is nothing in the traditional training that does this.* *In the simulation, it shows the point in which you have to polish.* *I think that Manuvar could cover some points that the traditional training cannot.* *Motor skills are good to learn the right angle and force.*
Novices	*It is a good tool because for somebody who hasn't done a metallographic replica, it is useful to get the knowledge concerning force and angle.* *It is more complicated to learn in the lab.* *In the lab, instructors just say press more/less but with this tool it is easier to understand how much to press.* *Yes* *It trains you in adapting correct angle and force which drives you to the correct behaviour.* *It is more accurate and it allows you to repeat the task without spoiling the material. So, you are saving cost.* *VR training is complementary to real world training and it is very precise. It would be good to combine VR training and real world training.* *Yes, you can use as a background before the real world training.*

Table 29. Expert only questions.

What type of training/knowledge do you think is required to use the ManuVAR tool effectively, i.e. do users need any pre-lessons for the procedural task?
Not relevant for the experimental study
What type of training/knowledge do you think is required to use the ManuVAR tool effectively, i.e. do users need any pre-lessons for the training using the haptic device?
Nothing, it is very easy to use. *Maybe because we are use to using X-box.* *It is user friendly.*
In your opinion, how well does the simulator reproduce the task it simulates?
Very, very, very good tool. *Despite the graphics could be better but it doesn't matter.* *The environment is very good.* *I like the simulator and I like the results.* *There are no problems in the tool.*

References

Abate, A. F., Guida, M., Leoncini, P., Nappi, M. & Ricciardi, S. (2009). A Haptic-Based Approach to Virtual Training for Aerospace Industry. *Journal of Visual Languages & Computing*, Vol. 20, No. 5, pp. 318-325.

Adams, J. A. (1960). Part Trainers. In G. Finch (Ed.), *Education and training media* (pp. 129-146). Washington DC: National Academy of Sciences.

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior*, Vol. 3, No. 2, pp. 111-150.

Adams, J. R., Clowden, D., Hannaford, B. (2001). Virtual Training for a Manual Assembly Task. *Haptics-e,* Vol. 2, No. 2, pp. 1- 7.

Aggarwal, R., Crochet, P., Dias, A., Misra, A., Ziprin, P., & Darzi, A. (2009). Development of a virtual reality training curriculum for laparoscopic cholecystectomy. *British Journal of Surgery*, vol. 96, No. 9, pp. 1086-1093.

Aggarwal, R., Tully, A., Grantcharov, T., Larsen, C. R., Miskry, T., Farthing, A., et al. (2006). Virtual reality simulation training can improve technical skills during laparoscopic salpingectomy for ectopic pregnancy. *BJOG: An International Journal of Obstetrics & Gynaecology*, Vol. 113, No. 12, pp. 1382-1387.

Ahlberg, G., Heikkinen, T., Iselius, L., Leijonmarck, C. E., Rutqvist, J., & Arvidsson, D. (2002). Does training in a virtual reality simulator improve surgical performance?. *Surgical endoscopy*, Vol. 16, No. 1, pp. 126-129.

Alexander, T., Conradi, J., & Winkelholz, C. (2003, March). Depth perception and visual after-effects at stereoscopic workbench displays. *Proceedings of IEEE Virtual Real, Annual International Symposium*, Los Angeles, CA,pp. 269-270.

Alhalabi, M. O., Daniulaitis, V., Kawasaki, H., & Hori, T. (2005, March). Medical training simulation for palpation of subsurface tumor using HIRO. *Proceeding of the 1st Joint Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2005*, Washington, DC, pp. 623-624.

ASTM E 3 - 01 (2001). Standard Guide for Preparation of Metallographic Specimens. *Annual Book of ASTM Standards,* available at web site: http://www.astm.org/Standards/E3.htm, Vol. 03.01.

ASTM E 1351 - 01 (2001). Standard Practice for Production and Evaluation of Field Metallographic Replicas. *Annual Book of ASTM Standards*, available at web site: http://www.astm.org/Standards/E1531.htm, Vol. 03.01.

ASTM E 7 - 03 (2003). Standard Terminology Relating to Metallography. *Annual Book of ASTM Standards*, available at web site: http://www.astm.org/Standards/E7.htm, Vol. 03.01.

Avizzano, CA, Solis, J.,Frisoli, A., & Bergamasco, M. (2002, September). Motor learning skill experiments using haptic interface capabilities. *Proceeding of the 11th IEEE International Workshop on Robot and Human Interactive Communication (ROMAN 2002),* Berlin, Germany, pp. 198-203.

Aziz, F. A., & Mousavi, M. (2009). A review of haptic feedback in virtual reality for manufacturing industry. *Journal of Mechanical Engineering*, Vol. 40, No. 1, pp. 68-71.

Bajka, M., Tuchschmid, S., Fink, D., Székely, G., & Harders, M. (2010). Establishing construct validity of a virtual-reality training simulator for hysteroscopy via a multimetric scoring system. *Surgical endoscopy*, Vol. 24, No. 1, pp. 79-88.

Balijepalli, A., & Kesavadas, T. (2003, March). A Haptic Based Virtual Grinding Tool. *Proceeding of the11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS 2003),* Los Angeles, CA, pp. 390-396.

Basdogan, C., De, S., Kim, J., Muniyandi, M., Kim, H., & Srinivasan, M. A. (2004). Haptics in minimally invasive surgical simulation and training. *Computer Graphics and Applications, IEEE*, Vol. 24, No. 2, pp. 56-64.

Bernstein, N. A. (1967). *The Coordination and Regulation of Movements.* Oxford, UK: Pergamon Press.

Bhatti, A., Khoo, Y. B., Creighton, D., Anticev, J., Nahavandi, S., & Zhou, M. (2008, September). Haptically enabled interactive virtual reality prototype for general assembly. *Proceedings of IEEE Automation Congress (WAC 2008), World*, Waikoloa, HI, pp. 1-6.

Bhatti, A., Nahavandi, S., Khoo, Y.B., Creighton, D., Anticev, J., & Zhou, M. (2009). Haptically Enable Interactive Virtual Assembly Training System Development and Evaluation. *Proceedings of the 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (SIMTECT 2009),* Adelaide, Australia, pp. 1- 6.

Bossard, C, Kermearrec, G, Buche, C, & Tisseau, J. (2008). Transfer of learning in virtual environments: a new challenge?. *Virtual Reality*, Vol. 12, No. 3, pp. 151-161.

Bouguila, L., Ishii, M., & Sato, M. (2000, August). Effect of coupling haptics and stereopsis on depth perception in virtual environment. *Proceedings of the 1st Workshop on Haptic Human Computer Interaction*, Glasgow, UK, pp. 54-62.

Brashers-Krug, T., Shadmehr, R., & Bizzi, E. (1996). Consolidation in Human Motor Memory. *Nature*, Vol. 382, pp. 252-255.

Browne, S., Clarke, D., Henson, P., Hristofski, F., Jeffreys, V., Kovacs, et al. (2009). Chapter 8: How does the acquisition of skills affect performance?. In Oxford University Press Australia & New Zealand (Eds.*), PDHPE Application & Inquiry Second Edition HSC Course (2nd ed.)* (pp. 149-169). South Melbourne, Australia: Australian Institute of Sport.

Burdea, G.C., & Coiffet P.(2003). *Virtual reality technology (2nd ed.).* Hoboken (NJ): Wiley-Interscience.

Chonoles, M. J., & Schardt, J. A. (2003). *UML 2 for Dummies*. Hoboken, NJ: Wiley Publishing.

Chui, C. K., Ong, J. S., Lian, Z. Y., Wang, Z., Teo, J., Zhang, J., et al. (2006). Haptics in computer-mediated simulation: Training in vertebroplasty surgery. *Simulation & Gaming*, Vol. 37, No. 4, pp. 438-451.

Clawson, D. M., Healy, A. F., Ericsson, K. A., & Bourne Jr, L. E. (2001). Retention and transfer of morse code reception skill by novices: Part-whole training. *Journal of Experimental Psychology: Applied*, Vol. 7, No. 2, pp. 129-142.

Coker, C.A. (2009). Chapter 8 Principles of practice design. *Motor Learning and Control for Practitioners (2nd ed.)* (pp. 181-205). Scottsdale, AZ: Holcomb Hathaway Publishers.

Coles, T.R., Meglan, D., & John, N.W. (2011). The role of haptics in medical training simulators: A survey of the state of the art. *IEEE Transactions on Haptics*, Vol. 4, No. 1, pp. 51-66.

Cranwell, J., Golightly, D., Fischer, J., Sharples, S., & ‘O’Malley, C. (2012) Using Mobile Applications that Combine Self-Report Micro Surveys to Enhance GPS Tracking Data. *To appear in International Journal of Psychology of Education and Assessment. Special Issue: Self-Reports in Survey Research: Issues in Measurement*.

Crespo, L. M., & Reinkensmeyer, D. J. (2008). Haptic guidance can enhance motor learning of a steering task. *Journal of motor behavior*, Vol. 40, No. 6, pp. 545-557.

Crison, F., Lécuyer, A., Savary, A., Mellet-d’Huart, D., Burkhardt, J. M., & Dautin, J. L. (2004, June). The use of haptic and pseudo-haptic feedback for the technical training of milling. *Proceedings of the EuroHaptics Conference*, Munich, Germany,pp. 361-364.

Cuevas-Rodríguez, M., Poyade, M., Reyes-Lecuona, A., & Molina-Tanco, L. (2012, October). A VRPN server for haptic devices using OpenHaptics 3.0. *Proceedings of the 13th International Conference on Interacción Persona-Ordenador*, Elche, Spain, pp. 32-36.

Da Dalto, L., Benus, F., & Balet, O. (2010, July). The use and benefits of Virtual Reality tools for the welding training. *Proceedings of the 63rd Annual Assembly & International Conference of the International Institute of Welding.* Istanbul, Turkey.

De Visser, H., Watson, M. O., Salvado, O., & Passenger, J.D. (2011). Progress in virtual reality simulators for surgical training and certification. *Medical Journal of Australia*, Vol. 194, No. 4, pp. 38-40.

Deering, M. F. (1993, May). Making Virtual Reality More Real: Experience with the Virtual Portal, *Proceedings of Graphics Interface '93*, Canadian Information Processing Society, Ontario, Canada, pp. 195-202.

Defense Acquisition University (DAU) PRESS (2001). *Systems Engineering Fundamentals*, DAU Press, Fort Belvoir, VA, US Department of Defense, available from web site http://www.dau.mil/pubs/pdf/SEFGuide%200101.pdf.

Delle Site, C., De Petris, C., & Mennuti, C. (2006, September) NDT Tools for Life Assessment of High Temperature Pressure Components, *Proceedings of European Conference on Non Destructive Testing (ECNDT 2006)*, Berlin, Germany,

Dodgson, N. A. (2004, May). Variation and extrema of human interpupillary distance. *Proceedings of Electronic Imaging, International Society for Optics and Photonics*, Vol. 5291, pp. 36-46.

Edmunds, T., & Pai, D. K. (2008, March). Perceptual rendering for learning haptic skills. *Proceedings of the symposium on Haptic interfaces for virtual environment and teleoperator systems (haptics 2008),* Reno, NE, pp. 225-230.

Eid, M.A., Mansour, M., El Saddik, A.H., & Iglesias, R. (2007, September). A haptic multimedia handwriting learning system. *Proceedings of the international multimedia conference (MM'07) - ACM Workshop on Educational Multimedia and Multimedia Education (EMME),* Augsburg, Germany, pp. 103-107.

Esen, H., Yano, K., & Buss, M. (2004). A virtual environment medical training system for bone drilling with 3 dof force feedback. *In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004)*, Sendai, Japan, Vol. 4, pp. 3631-3636.

Esen, H., Yano, K., & Buss, M. (2008a, August). Force Skill Training with a Hybrid Trainer Model. *Proceedings of the 17th IEEE International Symposium on Robot and Human Interactive Communication*, Munich, Germany, pp. 9-14.

Esen, H., Yano, K., & Buss, M. (2008b). Bone Drilling Medical Training System. *The Sense of Touch and its Rendering - Springer Tracts in Advanced Robotics*, Vol. 45, pp. 245-278.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, Vol. 39, No. 2, pp. 175-191.

Feygin, D., Keehner, M., & Tendick., F. (2002, March). Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill. *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'02)*, Orlando, FL, pp. 40-47.

Fitts, P.M., & Posner, M.I. (1968). El rendimiento humano [*Human performance*]. Alcoy, Spain: Marfil S.A.

Fluke Corp. (2009). Introducción a los principios de la termografía. *Technical Report (ISBN 978-0-8269-1535-1)*.Orland Park, IL: American Technical Publishers Inc.

Fried, G. M., Feldman, L. S., Vassiliou, M. C., Fraser, S. A., Stanbridge, D., Ghitulescu, G., & Andrew, C. G. (2004). Proving the value of simulation in laparoscopic surgery. *Annals of surgery*, Vol. 240, No. 3, pp. 518-528.

Fried, M. P., Satava, R., Weghorst, S., Gallagher, A., Sasaki, C., Ross, D., et al. (2005). The use of surgical simulators to reduce errors. *Advances in Patient Safety: From Research to Implementation*. Vol. 4, pp.165-177.

Friedenthal S., Moore A., Steiner R. (2008). *A practical Guide To SysML: The System Modeling Language*, Burlington, MA: Morgan Kaufmann Publishers, Elsevier.

Gandy, D. W., Viswanathan, R., & Findlan, S. J. (1996). *State-of-the-Art Weld Repair Technology for High Temperature and Pressure Parts: Volume 1: Repair Guideline-Life assessmente and Run, Repair and Replacement Decisions*. Technical Report (TR-103592-V1). Palo Alto, CA: Electric Power Research Institute (EPRI).

Gentile A. M. (1987). Skill acquisition: Action, movement, and neuromotor processes. In J. H. Carr, R. B. Shepherd, J. Gordon, A. M. Gentile, & J. M. Hind (Eds.), *Movement Science: Foundations for Physical Therapy in Rehabilitation* (pp. 93-154). Rockville, MD: Aspen Publishers.

Gopher, D. (2012). Skill training in Multimodal virtual environments. *Work.* Vol. 41, Supplement 1, pp. 2284-2287.

Gravetter, F. J., & Forzano, L. B. (2011). *Research methods for the behavioral sciences (4th eds.)*, Belmont , CA: Wadsworth/Thomson Learning.

Guthrie, E. R. (1952). *The psychology of learning (Rev. ed.).* Boston, MA: Harper & Bros.

Gutiérrez, T., Rodríguez, J., Vélaz, Y., Casado, S., Suescun, A., & Sánchez, E.J. (2010). IMA-VR: A Multimodal Virtual Training System for Skills Transfer in Industrial Maintenance and Assembly Tasks. *Proceedings of the 19th IEEE International Symposium on Robot and Human Interactive Communication*, Viareggio, Italy, pp. 12-15.

Hambling, C. J. (2005). Transfer of training from virtual reality environments (Doctoral dissertation, Wichita, MO).

Hannaford, B., & Okamura, A. M., (2008) Chapter 30: Haptics, In Siciliano, B. & Khatib, O. (Eds.), *Springer Handbook of Robotics* (pp. 719-739), Springer Berlin Heidelberg.

Haque, S., & Srinivasan, S. (2006). A meta-analysis of the training effectiveness of virtual reality surgical simulators. Information Technology in Biomedicine, *IEEE Transaction on Information Technology in Biomedecine*, Vol. 10, No. 1, pp. 51-58.

Haribhakti, P. U. (2010). Use of In-Situ Metallography for Plant Health Assessment Studies and Failure Investigations. *Proceeding of the 13th Middle East Corrosion Conference and Exhibition (NACE 2010)*, Manama, Kingdom of Bahrain.

Hassan, S., & Yoon, J. (2010a, October). Haptic based optimized path planning approach to virtual maintenance assembly/disassembly (MAD). P*roceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Taipei, Taiwan, pp. 1310-1315.

Hassan, S., & Yoon, J. (2010b, October). Haptic guided optimized aircraft maintenance assembly disassembly path planning scheme. *Proceedings of International Conference on Control Automation and Systems (ICCAS)*, Gyeonggi-do, Korea, pp. 1667-1672.

Hayward, V., Astley, O. R., Cruz-Hernandez, M., Grant, D., & Robles-De-La-Torre, G. (2004). Haptic interfaces and devices. *Sensor Review*, Vol. 24, No. 1, pp. 16-29.

He, X., & Chen, Y. (2006). A Haptic Virtual Turning Operation System. *Proceedings of the IEEE International Conference on Mechatronics and Automation*, Luoyang, China, pp. 435-440.

Heckbert, P. S. (1989). Fundamentals of texture mapping and image warping (Master's thesis, University of California, Berkeley).

Heemskerk, C. J. M., de Baar, M. R., Boessenkool, H., Graafland, B., Haye, M. J., Koning, J. F., et al. (2011). Extending Virtual Reality simulation of ITER maintenance operations with dynamic effects. *Fusion Engineering and Design*, Vol. 86, No. 9, pp. 2082-2086.

Heyes, C.M. & Foster, C.L. (2002). Motor learning by observation: Evidence from a serial reaction time task. *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*, Vol. 55, No. 2, pp. 593-607.

Higgins, S. (1991). Motor Skill Acquisition. *Physical Therapy,* Vol.71, No. 2, pp. 123-139.

Holliman, N. (2006). Three-Dimensional Display Systems, In Dakin, J. P. and Brown, R. G. W. (Eds.), *Handbook of Optoelectronics*, (Vol. 2, pp. 1067-1100), Boca Raton, FL: Taylor & Francis.

Hornby, T. G., Campbell, D. D., Kahn, J. H., Demott, T., Moore, J. L., & Roth, H. R. (2008). Enhanced Gait-Related Improvements After Therapist-Versus Robotic-Assisted Locomotor Training in Subjects With Chronic Stroke A Randomized Controlled Study. *Stroke*, Vol. 39, No. 6, pp. 1786-1792.

Hulshof, H. J. M., Welberg, P. G. M., & de Bruijn L. E. (2005, September), Creep Strain Measurements for Risk Based Monitoring of Steam Pipes and Headers, *Proceedings of European Creep Collaborative Commitee (ECCC) Creep Conference*, London, UK, pp. 513-518.

Hulshof, H. J. M., Welberg, P. G. M., & de Bruijn, L. E. (2005). Creep Strain Measurements for Risk Based Monitoring of Steam Pipes and Headers. *Proceeding of the 1st European Creep Collaborative Committee Conference*, London, United Kingdom, pp. 513-518.

Iwata, N., Fujiwara, M., Kodera, Y., Tanaka, C., Ohashi, N., Nakayama, G.,et al. (2011). Construct validity of the LapVR virtual-reality surgical simulator. *Surgical endoscopy*, Vol. 25, No. 2, pp. 423-428.

Joas, H. D. (2006, November). Metallographic Replicas and Creep-Strain-Measurement for Lifetime-Assessment at High-Temperature Components, *In proceedings of the COMFA/IMS Seminar*, Pha Lai, Vietnam.

Johannesson, E., Olsson, M., Petersson, G., & Silén, C. (2010). Learning features in computer simulation skills training. *Nurse education in practice,* vol. 10, No. 5, pp. 268-273.

Johnson, K. B., Syroid, N. D., Drews, F. A., Lagarre Ogden, L., Strayer, D. L., Pace, N. L., et al. (2008). Part Task and Variable Priority Training in First-year Anesthesia Resident Education. *Anesthesiology,* Vol. 108, No. 5, pp. 831-840.

Jordan, J. A., Gallagher, A. G., McGuigan, J., & McClure, N. (2001). Virtual reality training leads to faster adaptation to the novel psychomotor restrictions encountered by laparoscopic surgeons. *Surgical Endoscopy*, Vol. 15, No.10, pp. 1080-1084.

Källström, R. (2010). Construction, Validation and Application of a Virtual Reality Simulator for the Training of Transurethral Resection of the Prostate (Doctoral dissertation, Linköping, Sweden).

Katz, B. F., & Picinali, L. (2011). Spatial audio applied to research with the blind, In Strumillo, P. (Ed.), *Advances in Sound Localization* (pp. 225-250), InTech.

Kelso, J. A. S., & Schöner, G. (1988). Self-organization of coordinative movement patterns. *Human Movement Science, Vol.*7, pp. 27-46.

Kikuuwe, R., & Yoshikawa, T. (2001). Haptic Display Device with Fingertip Presser for Motion/Force Teaching to Human. *Proceedings of the IEEE International Conference on Robotics & Automation*, Seoul, South Korea, Vol. 1, pp. 868-873.

Kim, W., Tendick, F., & Stark, L. W. (1987). Visual enhancements in pick-and-place tasks: Human operators controlling a simulated cylindrical manipulator. *IEEE Journal of Robotics and Automation*, Vol. 3, No. 5, pp. 418-425.

Klapp, S. T., Nelson, J. M., & Jagacinski, R. J. (1998). Can people tap concurrent bimanual rhythms independently?. *Journal of Motor Behavior,* Vol. 30, No. 4, pp. 301-322.

Klein, J., Spencer, S. J., & Reinkensmeyer, D. J. (2012). Breaking It Down Is Better: Haptic Decomposition of Complex Movements Aids in Robot-Assisted Motor Learning. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* Vol. 20, No. 3, pp.268-275.

Knapp, B. (1967). *Skill in Sport: The Attainment of Proficiency.* London: Routledge & Kegan Paul.

Kolozsvari, N. O., Feldman, L. S., Vassiliou, M. C., Demyttenaere, S., & Hoover, M. L. (2011). Sim One, Do One, Teach One: Considerations in Designing Training Curricula for Surgical Simulation. *Journal of Surgical Education*, Vol. 68, No. 5, pp. 421-427.

Konttinen, N., Mononen, K., Viitasalo, J., & Mets, T. (2004). The effects of augmented auditory feedback on psychomotor skill learning in precision shooting. *Journal of Sport and Exercise Psychology,* Vol. 26, No. 2, pp. 306-316.

Krassi, B., D'Cruz, M., &Vink, P. (2010a, july). ManuVAR: a framework for improving manual work through virtual and augmented reality. *Proceedings of the 3rd International Conference on Applied Human Factors and Ergonomics (AHFE 2010),* Miami, FL.

Krassi, B., Kiviranta, S., Liston, P. Leino, S.P., Strauchmann, M., Reyes-Lecuona, A., et al. (2010b, July). ManuVAR PLM model, methodology, architecture, and tools for manual work support throughout system lifecycle. *Proceedings of the 3rd International Conference on Applied Human Factors and Ergonomics (AHFE 2010)*, Miami, FL.

Krassi, B., Strauchmann, M., Kiviranta, S., Leino, S.P., Viitaniemi, J., Reyes-Lecuona, A., et al. (2010c,June). Virtual Model for Supporting Communication of Manual Work Information Throughout System Lifecycle.*Proceedings of the Fraunhofer Institute for Factory Operation and Automation (IFF) days,* Magdeburg, Germany.

Langley, A., Sharples, S., D'Cruz, M., Patel A., Reyes Lecuona, A., & Poyade, M. (2011). Investigating Augmented Feedback for Improving Virtual Reality Haptic Training in the Performance of a Complex Inspection Task in a Real Manufacturing Case Study, Pending on submission.

Langley, A., Sharples, S., D'Cruz, M., Patel, A., Poyade, M., Reyes Lecuona, A., Molina Tanco, L. (2012). Impact of multimodal feedback on vr training for manufacturing manual work. *Proceedings of the International Conference on Manufacturing Research (ICMR 2012),* Birmingham, UK.

Leberman, S., McDonald, L., & Doyle, S. (2006). *The transfer of learning: Participants' perspectives of adult education and training*. Aldershot, England: Gower Publishing, Ltd..

Lee, T. D., & Schmidt, R. A. (2008). *Learning and Memory: A Comprehensive Reference. (J. Byrne Editor).*Oxford, UK: Elsevier.

Li, Y., Huegel, J. C., Patoglu, V., & O'Malley, M. K. (2009, March). Progressive shared control for training in virtual environments. *Proceedings of Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2009,* Salt Lake City, UT, pp. 332-337.

Lindsley, O.R. (1992). Precision teaching: Discoveries and effects. *Journal of Applied Behavior Analysis*, Vol. 25, pp. 51–57.

Liu, J., Emken, J.L., Cramer, S.C., & Reinkensmeyer, D.J. (2005). Learning to perform a novel movement pattern using haptic guidance: slow learning, rapid forgetting, and attractor paths. *Proceedings of the 9th International Conference on Rehabilitation Robotics (ICORR 2005)*, Chicago, IL, pp. 37-40.

Lu, X., Qi, Y., Zhou, T., & Yao, X. (2012). Constraint-Based Virtual Assembly Training System for Aircraft Engine. *Advances in Computational Environment Science,* pp. 105-112.

Luciano, C. J., Banerjee, P. P., Bellotte, B., Lemole Jr, G. M., Oh, M., Charbel, F. T., et al. (2011). Learning retention of thoracic pedicle screw placement using a high-resolution augmented reality simulator with haptic feedback. *Neurosurgery,* Vol. 69(Supplement Operative), ons14–ons19.

Magill, R. A. (2007). *Motor Learning And Control: Concepts And Applications (8th ed.).* McGraw-Hill.

Mansour, M., Eid, M., & Saddik, A. E. (2007, November). A multimedia handwriting learning and evaluation tool. *Proceedings of Intelligent Interactive Learning Object Repositories (I2LOR),* Montreal, QC, Canada, pp. 103-108.

Mark, W. R., Randolph, S. C., Finch, M., Van Verth, J. M., & Taylor II, R. M. (1996, August). Adding force feedback to graphics systems: Issues and solutions. *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques,* New Orleans, LA, pp. 447-452

Martin, P., Férey, N., Clavel, C., Darses, F. & Bourdot, P. (2012). Sensorimotor Feedback for Interactive Realism: Evaluation of a Haptic Driving Paradigm for a Forklift Simulator. *Haptics: Perception, Devices, Mobility, and Communication. Lecture Notes in Computer Science*, Vol. 7282, pp. 314-325.

Massie, T. H., & Salisbury, J. K. (1994, November). The phantom haptic interface: A device for probing virtual objects. *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems,* Vol. 55, No. 1, Chicago, IL, pp. 295-300.

McLaughlin, M. L., Hespanha, J. P., & Sukhatme, G. S. (Eds.). (2002). *Touch in virtual environments,* Upper Saddle River, NJ: Prentice Hall Inc.

Mellet-d'Huart, D., Michela, G., Burkhardt, J. M., Lécuyer, A., Dautin, J. L., & Crison, F. (2004, May). An application to training in the field of metal machining as a result of research-industry collaboration. *Proceedings of the 6th IEEE Virtual Reality International Conference (VRIC 2004)*,Laval, France.

Mishra, S., Kurien, A., Ganpule, A., Muthu, V., Sabnis, R., & Desai, M. (2010). Percutaneous renal access training: content validation comparison between a live porcine and a virtual reality (VR) simulation model. *BJU international,* Vol. 106, No. 11, pp. 1753-1756.

Mononen, K. (2007). The effects of augmented feedback on motor skill learning in shooting: a feedback training intervention among inexperienced rifle shooters (Master 's thesis, University of Jyväskylä, Finland).

Moody, L., Baber, C., & Arvanitis, T. N. (2001). The role of haptic feedback in the training and assessment of surgeons using a virtual environment. *Proceedings of Eurohaptics 2001*, Birmingham, UK., pp. 170-173.

Morris, D., Sewell, C., Barbagli, F., Salisbury, K., Blevins, N.H., & Girod, S. (2006). Visuohaptic simulation of bone surgery for training and evaluation. *IEEE Computer Graphics and Applications*, Vol.26, No. 6, pp. 48-57.

Morris, D., Tan, H., Barbagli, F., Chang, T., & Salisbury, K. (2007). Haptic Feedback Enhances Force Skill Learning. *Proceedings of 2nd Joint EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2007, WHC'07*, Tsukuba , Japan, pp. 21-26.

Mujber, T.S., Szecsi, T., & Hashmi, M.S.J. (2004). Virtual reality applications in manufacturing process simulation. *Journal of Materials Processing Technology*, Vol. 155, pp. 1834-1838.

Muresan III, C., Lee, T. H., Seagull, J., & Park, A. E. (2010). Transfer of training in the development of intracorporeal suturing skill in medical student novices: a prospective randomized trial. *American journal of surgery*, Vol. 200, No. 4, pp. 537-541.

Nagata, S. (1993). How to Reinforce Perception of Depth in Single Two-Dimensional Pictures.in Ellis, S. (Ed.), Pictorial Communication in Virtual and Real Environments (pp. 527-545). London, UK: Taylor & Francis

Nakao, M., Kuroda, T., Komori, M., & Oyama, H. (2003, December). Evaluation and user study of haptic simulator for learning palpation in cardiovascular surgery. *Proceedings of the International Conference of Artificial Reality and Tele-Existence (ICAT)*, Tokyo, Japan,pp. 203-208.

Nappi, M., Paolino, L., Ricciardi, S., Sebillo, M., & Vitiello, G. (2009, August). Advanced Maintenance Simulation by Means of Hand-Based Haptic Interfaces. *Proceedings of 12th IFIP TC13 Conference on Human-Computer Interaction (INTERACT 2009)*, Uppsala, Swenden, pp. 76-88.

Naylor, J. C., & Briggs, G. E. (1963). Effects of task complexity and task organization on the relative efficiency of part-task and whole training methods. *Journal of Experimental Psychology*, Vol 65, No. 3, pp. 217-224.

Neale, H. R., & Nichols, S. C. (2001). Theme based content analysis: A method for user centred design and implementation of Virtual Environments. *International Journal of Human-Computer Studies*, Vol. 55, No. 2, pp. 167–189 .

Newell, K. M, & Vaillancourt, D. E. (2001). Dimensional change in motor learning. *Human Movement Science*, Vol. 20, pp. 695-715.

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade, and H. T. A. Whiting (Eds.), Motor Development in Children: Aspects of Coordination and Control (pp. 341–360). Dordrecht: Martinus Nijhoff.

Newell, K. M. (1991). Motor skill acquisition. *Annual Reviews Psychology*, Vol. 42, pp. 213-237.

Newell, K. M. (2003). Schema Theory (1975): Retrospectives and Prospectives. *Physical Education, Recreation and Dance,* Vol. 74, No. 4, pp. 383-388

Nikolic, D. (2007). Evaluating relative impact of virtual reality components detail and realism on spatial comprehension and presence (Doctoral dissertation, Pennsylvania State University).

Nishino, H., Murayama, K., Shuto, K., Kagawa, T., &Utsumiya, K. (2011). A calligraphy training system based on skill acquisition through haptization. *Journal of Ambient Intelligence and Humanized Computing*, Vol. 2, No. 4, pp. 271-284.

Nonaka, I., & Von Krogh, G. (2009). Tacit knowledge and knowledge conversion: Controversy and advancement in organizational knowledge creation theory. *Organization Science*, Vol. 20, No. 3, pp. 635-652.

NT NDT 010 (1991). *High Temperature Components in Power Plants: Remnant Lifetime Assessment, Replica Inspection*, Nordtest Method Report UDC 620.179.1.

O'Malley, M. K., Gupta, A., Gen, M., & Li, Y. (2006). Shared control in haptic systems for performance enhancement and training. *Transactions-American Society Of Mechanical Engineers Journal Of Dynamic Systems Measurement And Control*, Vol. 128, No. 1, pp. 75-85.

Oren, M., Carlson, P., Gilbert, S., & Vance, J. M. (2012, March). Puzzle assembly training: Real world vs. virtual environment. *Proceedings of IEEE Virtual Reality Workshops (VR)*, Orange County, CA., pp. 27-30.

Ott, R., Thalmann, D., & Vexo, F. (2007). Haptic feedback in mixed-reality environment. *The Visual Computer: International Journal of Computer Graphics*, Vol. 23, No. 9, pp. 843-849.

Pan, J. J., Chang, J., Yang, X., Zhang, J. J., Qureshi, T., Howell, R., & Hickish, T. (2011). Graphic and haptic simulation system for virtual laparoscopic rectum surgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*, Vol. 7, No. 3, pp. 304-317.

Panait, L., Akkary, E., Bell, R.L., Roberts, K.E., Dudrick, S.J., & Duffy, A.J. (2009). The role of haptic feedback in laparoscopic simulation training. *Journal of Surgical Research*, Vol. 156, No. 2, pp. 312-316.

Patel, H., Stefani, O., Sharples, S., Hoffmann, H., Karaseitanidis, I., & Amditis, A. (2006). Human centred design of 3-D interaction devices to control virtual environments. *International Journal of Human-Computer Studies*, Vol. 64, No. 3, pp. 207-220.

Pfautz, J. D. (2000). Depth perception in computer graphics (Unpublished doctoral dissertation, University of Cambridge, UK).

Poyade, M., Molina-Tanco, L., Reyes-Lecuona, A., Langley, A., D'Cruz, M., Frutos, E., & Flores., S. (2012, October). Validation of a haptic virtual reality simulation in the context of industrial maintenance. *Proceedings of the Joint VR Conference of euroVR (JVRC 2012) and EGVE*, 2012, Madrid, Spain.

Poyade, M., Molina-Tanco, L., Reyes-Lecuona, A., Langley, A., D'Cruz, M., Sharples, S. (2013). Experimental evaluation of haptic-based part-task training for motor skill learning in industrial maintenance operations. *IEEE Transaction on Haptics* (Pending on acceptance).

Poyade, M., Reyes-Lecuona, A., & Viciana-Abad, R. (2009). Influence of Binocular Disparity in Depth Perception Mechanisms in Virtual Environments. In J.A Macias, T. Granollers & P. Latorre (Eds.), *New Trends on Human–Computer Interaction* (pp. 13–22), London, UK: Springer-Verlag, London.

Poyade, M., Reyes-Lecuona, A., Frutos, E., Flores, S., Langley, A., D'Cruz, M., Valdina, A., Tosolin, F. (2011). Using virtual reality for the training of the metallographic replica technique used to inspect power plants by TECNATOM S.A., *Proceedings of the Joint VR Conference (JVRC 2011) of euroVR and EGVE*, Nottingham, UK, pp. 53-57.

Ranganathan, R., & Newell, K. M. (2009). Influence of augmented feedback on coordination strategies. *Journal of motor behavior*, Vol. 41, No. 4, pp. 317-330.

Rhienmora, P., Haddawy, P., Suebnukarn, S. Dailey, M.N. (2011). Intelligent dental training simulator with objective skill assessment and feedback. *Artificial Intelligence in Medicine*, Vol. 52, No. 2, pp. 115- 121.

Ritter, E. M., & Scott, D. J. (2007). Design of a proficiency-based skills training curriculum for the fundamentals of laparoscopic surgery. *Surgical innovation*, Vol. 14, No. 2, pp. 107-112.

Rodríguez, J., Gutiérrez, T., Casado, S., & Sánchez, E. J. (2010, October). Training strategies for learning a 3D trajectory with accuracy. *Proceedings of the IEEE International Symposium on Haptic Audio-Visual Environments and Games (HAVE)*, Pheonix, AZ, pp. 1-6.

Roessingh, J. J. M., Kappers, A. M. L., & Koenderink, J.J. (2002). Transfer between training of part-tasks in complex skill training. *Technical Report (NLR-TP-2002-646)*. Utrecht, Neitherland: National Aerospace Laboratory NLR.

Roscoe, S. N., & Williges, B. H. (1980). Measurement of transfer of training. *Aviation psychology*, pp. 182-193.

Rose, F. D., Attree, E. A., Brooks, B. M., Parslow, D. M., & Penn, P. R. (2000). Training in virtual environments: transfer to real world tasks and equivalence to real task training. *Ergonomics*, Vol. 43, No. 4, pp. 494-511.

Rosenbaum, D. A. (2009). *Human Motor Control (2nd ed.).* San Diego, CA: Academic Press.

Rosenberg, L. B. (1993, September). The effect of interocular distance upon operator performance using stereoscopic displays to perform virtual depth tasks. *Proceedings of IEEE Virtual Real, Annual International Symposium*, Seattle, WA,pp. 27-32.

Saga, S., Kawakami, N., & Tachi, S. (2005). Haptic Teaching using Opposite Force Presentation. *Poster session presented at the 1st WorldHaptics conference*, Pisa, Italy, pp. 18-20.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin*, Vol. 95, No. 3, pp. 355-386.

Schmidt, R. A. (1975). A Schema Theory of Discrete Motor Skill Learning. *Psychological Reviews*, Vol.82 (4), pp. 225-260.

Schmidt, R. A. (2003). Motor Schema Theory After 27 Years: Reflections and Implications for a New Theory. *Physical Education, Recreation and Dance*, Vol. 74, No. 4, pp. 366-375.

Schmidt, R. A., & Wulf, G. (1997). Continuous concurrent feedback degrades skill learning: Implications for training and simulation. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 39, No. 4, pp. 509-525.

Schmidt, R.A., & Wrisberg, C.A. (2008). *Motor learning and performance: a situation-based learning approach (4th ed.)*, Champaign, IL.: Human Kinetics Publishers.

Selvander, M., & Åsman, P. (2012). Virtual reality cataract surgery training: learning curves and concurrent validity. *Acta Ophthalmologica*,Vol. 90, No. 5, pp 412-417.

Sewell, C. and Blevins, N.H. and Peddamatham, S., & Tan, H.Z. (2007). The effect of virtual haptic training on real surgical drilling proficiency. *Proceedings of 2nd Joint EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2007, WHC'07*, Tsukuba, Japan. pp. 601-603.

Seymour, N. E., Gallagher, A. G., Roman, S. A., O'Brien, M. K., Bansal, V. K., Andersen, D. K., & Satava, R. M. (2002). Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Annals of surgery*, Vol. 236, No. 4, pp. 458-464.

So, J. C., Proctor, R. W., Dunston, P. S., & Wang, X. (2012). Better Retention of Skill Operating a Simulated Hydraulic Excavator After Part-Task Than After Whole-Task Training. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 55, No. 2: pp. 449-460.

Solis, J., Avizzano, C. A., & Bergamasco, M. (2002, March). Teaching to write Japanese characters using a haptic interface. *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '02),*Orlando, FL, pp. 255-262.

Solis, J., Avizzano, C. A., & Bergamasco, M. (2003, October). Validating a skill transfer system based on reactive robots technology. *Proceedings of the 12th IEEE international Workshop on Robot and Human Interactive Communication.* Millbrae, CA, pp. 175-180.

Sposito, G., Ward, C., Cawley, P., Nagy, P., Scruby, C. (2010). A review of non destructive techniques for the detection of creep damage in power plant steels. *NDT & E International*, Vol. 43, No. 7, pp. 555-567.

Srimathveeravalli, G., & Thenkurussi, K. (2005). Motor skill training assistance using haptic attributes. *Proceeding of the 1st Joint Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, World Haptics 2005*, Washington, DC, pp. 452-457.

Stanton, D., Bayon, V., Neale, H., Ghali, A., Benford, S., Cobb, et al. (2001, March). Classroom collaboration in the design of tangible interfaces for storytelling. *Proceedings of the SIGCHI conference on Human factors in computing systems,*Seattle, WA, pp. 482-489.

Steinberg, A.D. and Bashook, P.G. and Drummond, J., & Ashrafi, S. and Zefran, M. (2007). Assessment of faculty perception of content validity of Periosim©, a haptic-3D virtual reality dental training simulator. *Journal of Dental Education*, Vol. 71, No. 12, pp. 1574-1582.

Ström, P., Hedman, L., Särnå, L., Kjellin, A., Wredmark, T., & Felländer-Tsai, L. (2006). Early exposure to haptic feedback enhances performance in surgical simulator training: a prospective randomized crossover study in surgical residents. *Surgical endoscopy*, Vol. 20, No. 9, pp. 1383-1388.

Suebnukarn, S. and Haddawy, P. and Rhienmora, P., & Gajananan, K. (2010). Haptic virtual reality for skill acquisition in endodontics. *Journal of Endodontics*, Vol. 36, No. 1, pp. 53-55.

Sung, R.C.W., Ritchie, J.M., Lim, T., Dewar, R., & Weston, N. (2011). Knowledge Capture inside a Haptic Soldering Environment. *Proceedings of the 6th International Conference on Virtual Learning (ICVL 2011), Workshop on Haptic Feedback Systems in Education*, Cluj-Napoca, Romania, pp. 38-44.

Šustr, V. (2010). Computer aided calligraphy in haptic virtual environment. *Proceedings of the International Conference on Computational Science and Its Application (ICCSA),* Fukuoka, Japan, pp. 103-110.

Taylor II, R. M., Hudson, T. C., Seeger, A., Weber, H., Juliano, J., & Helser, A. T. (2001, November). VRPN: a device-independent, network-transparent VR peripheral system. *Proceedings of the ACM symposium on Virtual reality software and technology,* Banff, Canada, pp. 55-61.

Teague, R.C., Gittleman, S.S. & Park, O. (1994). A review of the literature on part-task and whole-task training and context dependency. *Technical Report TR1010 (AD A285 954).* Alexandria, VA: US Army Research Institute for the Behavorial and Social Sciences.

Tholey, G. and Desai, J.P., & Castellanos, A.E. (2005). Force feedback plays a significant role in minimally invasive surgery: results and analysis. *Annals of surgery*, Vol. 241, No. 1, pp. 102-109.

Todorov, E., Shadmehr, R., & Bizzi, E. (1997). Augmented Feedback Presented in a Virtual Environment Accelerates Learning of a Difficult Motor Task. *Journal of Motor Behavior*, Vol. 29, No. 2, pp. 147-158.

Utley, A., & Astill, S. (2008). *Motor control, learning and development*. London: Taylor and Francis.

Van der Meijden, O. A. J., & Schijven, M. P. (2009).The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surgical Endoscopy*, Vol. 23, No. 6, pp. 1180-1190.

Verdaasdonk, E. G., Stassen, L. P., Monteny, L. J., & Dankelman, J. (2006). Validation of a new basic virtual reality simulator for training of basic endoscopic skills. *Surgical endoscopy*, Vol. 20, No. 3, pp. 511-518.

Vereijken, B., & van Emmerik, R.E.A. (1989). The acquisition of coordination: Preliminary analysis of learning to write. *Human Movement Science*, Vol. 8, pp. 17-32.

Vereijken, B., van Emmerik, R.E.A., Whiting, H.T.A, and Newell, K.M. (1992), Freezing degrees of freedom in skill acquisition. *Journal of Motor Behaviour*, Vol. 24, pp. 133-142.

Von Sternberg, N., Bartsch, M. S., Petersik, A., Wiltfang, J., Sibbersen, W., Grindel, T., Tiede, U., Warnke, P. H., Heiland, M., Russo, P.A.J., Terheyden, H., & Pohlenz, P. (2007). Learning by doing virtually. *International Journal of Oral and Maxillofacial Surgery*, vol. 36, No. 5,pp. 386-390.

Wagner, C. R., Stylopoulos, N., & Howe, R. D. (2002, March). The role of force feedback in surgery: analysis of blunt dissection. *Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Orlando, FL, pp. 73 -79.

Wagner, C.R., Stylopolous, N., Jackson, P. G., & Howe, R.D. (2007). The Benefit of Force Feedback in Surgery: Examination of Blunt Dissection. *Presence*. Vol. 16, No. 3, pp. 252-262.

Wang, D., Zhang, Y., & Yao, C. (2006). Stroke-based modeling and haptic skill display for Chinese calligraphy simulation system. *Virtual Reality*, Vol. 9, No. 2, pp. 118-132.

Wang, Y., Chen, Y., Zhang, W., Liu, D., & Huang, H. (2009). Study on underwater wet arc welding training with haptic device. *Proceeding of the IEEE International Conference on Virtual Environments, Human-Computer Interfaces and Measurements Systems (VECIMS '09)*, Hong Kong, China, pp. 191-195.

Wang, Y., Nan, Z., Chen, Y., & Hu, Y. (2006). Study on Welder Training by Means of Haptic Guidance and Virtual Reality for Arc Welding. *Proceeding of the IEEE International Conference on Robotics and Biomimetics (ROBIO '06)*, Kunming, China, pp. 954-958.

Wanger, L. R., Ferwerda, J., & Greenberg, D. P. (1992). Perceiving spatial relationships in computer-generated images. *IEEE Computer Graphics and Applications*, Vol. 12, No. 3, pp. 44-58.

Webster, R. W., Zimmerman, D. I., Mohler, B. J., Melkonian, M. G., & Haluck, R. S. (2001). A prototype haptic suturing simulator. *Studies in health technology and informatics*, pp. 567-569.

Wierinck, E., Puttemans, V., Swinnen, S., & Steenberghe, D. (2005). Effect of augmented visual feedback from a virtual reality simulation system on manual dexterity training. *European Journal of Dental Education*, Vol. 9, No. 1, pp. 10-16.

Wightman, D. C. & Lintern, G. (1985). Part task training for tracking and manual control. *Human Factors*, Vol. 27, No. 3, pp. 267-283.

Williams II, R. L., Srivastava, M., Conaster, R., & Howell, J. N. (2004a). Implementation and evaluation of a haptic playback system. *Haptics-e*, Vol. 3, No. 3, pp. 160-176.

Williams II, R. L., Srivastava, M., Howell, J. N., Conatser Jr, R. R., Eland, D. C., Burns, J. M., & Chila, A. G. (2004b, October). The virtual haptic back for palpatory training. *Proceedings of the 6th international conference on Multimodal interfaces (ICMI 2004)*, State College, PA, pp. 191-197.

Winstein, C. J., & Schmidt, R. A. (1990). Reduced Frequency of Knowledge of Results Enhances Motor Skill Learning. *Journal of Experimental Psychology:Learning, Memory, and Cognition*,Vol. 16, No. 4, pp. 677-691.

Winstein, C. J., Pohl, P. S., & Lewthwaite, R. (1994). Effects of physical guidance and knowledge of results on motor learning: support for the guidance hypothesis. *Research quarterly for exercise and sport*, Vol. 65, No.4, pp. 316-323.

Wulf, G., & Shea, C. H. (2004). Understanding the role of augmented feedback. In A. M. Williams & N. J. Hodges (Eds), *Skill acquisition in sport: Research, theory and practice*, (pp. 121-144). London: Routledge.

Wulf, G., Shea, C. H., & Matschiner, S. (1998a). Frequent feedback enhances complex motor skill learning. *Journal of motor behavior*, Vol. 30, No. 2, pp. 180-192.

Wulf, G., Shea, C. H., & Whitacre, C. A. (1998b). Physical-guidance benefits in learning a complex motor skill. *Journal of Motor Behavior*, Vol. 30, No. 4, pp. 367-380.

Wulf, G., Shea, C., & Lewthwaite, R. (2010). Motor skill learning and performance: a review of influential factors. *Medical education*, Vol. 44, No. 1, pp. 75-84.

Yang, X.D., Bischof, W.F., & Boulanger, P. (2008). Validating the performance of haptic motor skill training. *Proceedings of the symposium on Haptic interfaces for virtual environment and teleoperator systems (haptics 2008)*, Reno, NE, pp. 129-135.

Young, D. E., & Lee, T. D. (2001). Skill Learning: Augmented feedback. In W. Karwowski (Ed.), *International Encyclopedia of Ergonomics and Human Factors: Vol. 1*, (1st ed., pp. 558-562). London: Taylor & Francis.

Youngblood, P. L., Srivastava, S., Curet, M., Heinrichs, W. L., Dev, P., & Wren, S. M. (2005). Comparison of training on two laparoscopic simulators and assessment of skills transfer to surgical performance. *Journal of the American College of Surgeons*, Vol. 200n No. 4, pp. 546-551.

Zhang, L., Grosdemouge, C., Arikatla, V. S., Ahn, W., Sankaranarayanan, G., De, S., Jones, D. Schwaitzberg, S., & Cao, C.G.L. (2012). The added value of virtual reality technology and force feedback for surgical training simulators. *Work: A Journal of Prevention, Assessment and Rehabilitation*. Vol. 41, pp. 2288-2292.

Zhou, M., Tse, S., Derevianko A., Jones, D. B., Schwaitzberg, S. D., & Cao, C. G. L. (2012). Effect of haptic feedback in laparoscopic surgery skill acquisition. *Surgical Endoscopy*, Vol. 26, No. 4, pp. 1128-1134.

Zorcolo, A., Gobbetti, E., Pili, P., & Tuveri, M. (1999, May). Catheter insertion simulation with combined visual and haptic feedback. *Proceedings of the First Phantom Users Research Symposium (PURS',99)*,Heidelberg, Germany,