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Validation of a haptic virtual reality simulation in the context of industrial maintenance

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Abstract
The metallographic replica is a non destructive inspection technique commonly performed during maintenance processes of industrial plants to evaluate the micro-structural integrity of materials exposed to critical process conditions. Previous mechanical preparation of material surface is usually required. Fine grinding and polishing tasks, which required advanced skills in angling and pressuring with power tools, are commonly performed. However, training those skills remains problematic. A VR training simulator enhanced with haptic force feedback, that enables training on the performance of fine grinding and polishing tasks was developed within ManuVAR project and is presented here. This paper also presents some of the results of the demonstration carried out within the ManuVAR project. An experiment was conducted to evaluate the effectiveness of the VR system to train on the performance of both tasks and validate the simulator comparing the performance of six trainees and two expert metallurgists. Results suggested that most of the trainees have improved their performance after training on the simulator. Expert metallurgists performed more effectively fine grinding and polishing tasks than trainees. Thus, external validity was found for the training simulator.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: User Interface—Haptics I/O

1. Introduction

In order to ensure safe and reliable manufacturing processes, industrial plants frequently conduct maintenance campaigns during which inspections of operating components are carried out. Tecnatom S.A., a Spanish company that delivers advanced engineering services in industrial facilities and nuclear power plants, commonly performs non-destructive inspection techniques to evaluate the integrity of materials often submitted to critical process conditions, and prevent failure.

The Metallographic replica is a non destructive inspection technique that enables recording a negative relief of the microstructure of a material surface on a plastic foil. A prior mechanical preparation of the surface is required to reveal cracks and other damages on the microstructure. Mechanical preparation consists in repetitive fine grinding and polishing tasks for which advanced skills in angling and pressuring power tools on the surface of the material are required. The purpose of the mechanical preparation tasks is to remove oxide scale and scratches produced by previous grinding operations to give a mirror-like finishing to the inspected area.

Training unskilled workers on mechanical preparation tasks is troublesome in the extent that the expert metallurgist who supervises the practice, is usually not able to provide accurate feedback on the on-going performance and movements characteristics.

Virtual Reality (VR) enhanced with haptic force feedback provides a technological framework to support training for complex mechanical tasks and thereby supplements conventional training.

This paper presents a VR system enhanced with haptic force feedback, that enables training on the performance of fine grinding and polishing tasks as they are usually performed in real industrial contexts. The purpose of this study is twofold: (1) evaluate the effectiveness of the VR system to train participants in performing the fine grinding and polishing tasks;(2) validate the effectiveness of the VR system to differentiate the level of expertise of low-skilled workers and expert metallurgists.

2. VR and haptic Training

The potential of VR technology to support motor skill training has been widely investigated [BKB*08]. VR offers the opportunity to train on simulations of manufacturing processes in a safe environment and the addition of haptic interaction is believed to bring the concept of VR interaction closer to realistic physical models [AGL*09]. Furthermore, VR simulation can enhance the training experience by providing augmented information feedback that is usually not available in the real world [EYB04].

Several research studies have proposed the use of VR technology and haptic interfaces to train the motor skills required for complex manufacturing processes such as assembly/disassembly in maintenance tasks for the aerospace industry [AGL*09], arc welding [WNC*06], and machining operations [HC06]. Moreover, it has been demonstrated that VR training enhanced with haptic force feedback enables successful development of force skills required in mechanical operations [EYB04] [MTB*07]. It has also been shown that those trained skills can be transfered to real world contexts [SBP*07]. However, no study has currently reported the effectiveness of VR training to acquire tool inclination skills. Wang et al. [WNC*06] only suggested a training method for welding task, in which the incorrectness of angle was fed back using auditory cues.

3. Description of the VR system

The proposed VR training system consists of a training simulator that enables practicing fine grinding and polishing tasks in a virtual environment (VE). A haptic device was used to simulate a portable flexi-drive tool and interact within the VE.

3.1 Training simulator

The training simulator application provides the VE which consisted in a 3.5×4.5 cm area on the lateral of a pipe work located in a factory floor (Figure 1).

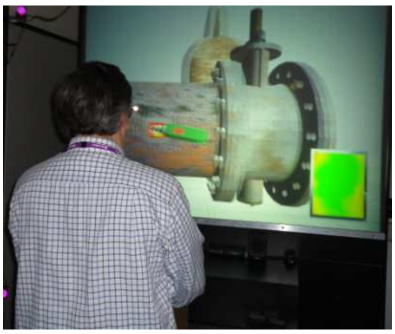

Figure 1. *A worker trains on the performance of a task in the simulator using the colour map indicators*

The simulation enhanced the training experience by providing augmented feedback of performance on the metallographic replica area, which consisted of a colour map indicator that used a colour scale (from red to green) to indicate the completion of the task in the metallographic replica area. The colour map was also magnified and showed in a right lateral window.

The colour map consisted of a texture of 64 × 64 pixels overlaid on the metallographic replica area. Each pixel of the colour map was identified as an element of the matrix $A_{64\times 64}(t)$. Each element of $A(t)$ stored the time of correct performance of the task on the corresponding pixel. Each element of $A(t)$ was expressed as in equation 1.

Correct performance for the fine grinding task consisted of generating horizontal or vertical scratches by flattening the rotating wheel on the material surface and maintaining applied angle and force within ranges of correctness respectively set to 75º to 90º and 1N to 5N. These thresholds defined a segment area S_+ on the flattened rotating wheel in which produced scratches had the desired direction. Outside these thresholds, the flattened rotating wheel generated scratches with inappropriate direction. The area in which scratches were inappropriate was named S_-.

Correct performance for the polishing task consisted of flattening the rotating wheel by maintaining applied angle and force within ranges of correctness respectively set to 0º to 20º and 1N to 5N. These thresholds defined a segment area S_+ on the rotating wheel, considered as the optimal flattening on the material surface. In the case of the polishing task, there was no area S_-.

$$\left.\begin{matrix}\forall\, i \in [1{,}64]\\ \forall\, j \in [1{,}64]\end{matrix}\right\} \Rightarrow a_{i,j}(t) = a_{i,j}(t-1) + b_{[i,j]}(\mathrm{t})$$

Eq. 1

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

$$b_{[i,j]}(\mathrm{t}) = \begin{cases} 0 \Leftrightarrow \begin{cases}[a_{i,j}]_{m\times n}(t) \notin S_+\\ [a_{i,j}]_{m\times n}(t) \notin S_-\end{cases} \\ \Delta T \Leftrightarrow [a_{i,j}]_{m\times n}(t) \in S_+ \\ -\Delta T \Leftrightarrow [a_{i,j}]_{m\times n}(t) \in S_- \end{cases}$$

Eq. 2

Where ΔT is the elapsed time between two graphical frames.

3.2 Haptic rendering

The haptic device simulated the weight of the portable flexi-drive tool and its functioning by rendering two force models: (1) a vibration model and (2) a tangential force model. Both force models were parameterized by two expert metallurgists from Tecnatom S.A.

3.2.1 Vibration force model

This model consisted of a periodical alteration of a force $\overrightarrow{FV}$ of magnitude m with an angular frequency ω on the x and y local axis of the haptic device referred in the *Eq. 3* by their respective unit vectors $\hat{R}$ and $\widehat{Up}$.

$$\overrightarrow{F_V} = m \times \left(\hat{R} . \cos \omega t + \widehat{Up} . \sin \omega t\right)$$

Eq. 3

3.2.2 Tangential force model

This model enabled simulation of the tangential force and resulted from the contact of the rotating wheel of the tool with the surface of the material. The tangential force $\overrightarrow{F_T}$ was calculated as a function of the penetration x of the punctual inter-actuator of the haptic device in the geometry and its velocity v considering the parameters of stiffness k and damping d of the material (*Eq. 4*).

$$\overrightarrow{F_T} = (k.x - d.v).\left(\frac{\vec{N} \times \overrightarrow{Up}}{\|\vec{N} \times \overrightarrow{Up}\|}\right) \qquad \textit{Eq. 4}$$

Where $\vec{N}$ is the normal vector at the contact point with the geometry, and $\overrightarrow{Up}$, the vector on the y local axis of the haptic device.

4. Validation of the VR system

An experiment was conducted during the demonstration session of the EU funded project ManuVAR [KDCV10], in order to (1) evaluate the effectiveness of the VR system to train participants in performing the fine grinding and polishing tasks and (2) validate its effectiveness to differentiate between low and high-skilled performers.

4.1 Participants

Six trainees (1 female and 5 males) aged from 30 to 55 and two expert metallurgists (2 males) aged 31 and 35 took part in the validation process. All participants were workers in Tecnatom S.A. One trainee stated to be skilled in performing the metallographic replica technique, other four had little knowledge and another was a complete novice. All participants went through a prior motor skill training that enabled them to shortly practice independently angle and force skills within ranges of correctness defined for both tasks. Therefore, participants had acquired previous knowledge of haptic device handling and VR technology.

All participants filled in a consent form and were informed about the purpose of the study and publication policies. Participants reported no arm or wrist disabilities and only one trainee reported colour blindness as uncorrected visual impairment.

4.2 Apparatus

The VR system ran on the ManuVAR platform distributed on two workstations. PC 1 supported the ManuVAR technological elements in charge of the management of the platform [PRF*11] 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 degrees of freedom, enabled interacting within the VE. PC 2 displayed the simulator training application 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 VE at 60Hz refresh rate. The VE was visualized through a pair of passive stereoscopic glasses tracked by 6 infrared cameras from Natural Point Optitrack. A separate laptop located in an adjoining room was used to display the instructions.

4.3 Procedure

The experiment procedure consisted of a within-subject design involving expert metallurgists during the first day, and the trainees during the two next days. Trainees were assigned a unique identification number and were randomly distributed in two groups: One performed fine grinding task training (FG) and the other trained on polishing task (POL).

Before starting, participants received verbal, textual and graphical instructions about the purpose of the task and were explained how to interpret the information provided by the colour map indicators.

Participants stood at about 1 m in front of the 3D screen. The haptic device was placed in front of them and elevated so the haptic workspace physically matched with the manipulation workspace in the VE. Participants handled the haptic device as if it was a real portable power tool.

Trainees performed a pre-evaluation step composed of two items of 3 minutes long: (1) a familiarization item during which they were asked to perform the task they were assigned being assisted by colour map indicators; (2) an evaluation item during which they performed the task without feedback of performance.

Then, trainees practiced performing the task in two training items of 3 minutes. For each item, colour map indicators were displayed on demand continuously for 10 seconds. Between each item, a trainee rested in an adjoining room while a trainee from the other group performed the same item.

Finally, trainees went through a post evaluation step which consisted of performing the task during 3 minutes with no colour map.

Expert metallurgists went through the training procedure described for trainees for both tasks.

4.4 Data Measurements

The average completion rate of the task reported on the colour map was measured for each participant during the pre and post-evaluation steps in order to be compared.

5. Results & discussion

All participants from FG improved their performance after training on the simulator application (Figure 2).

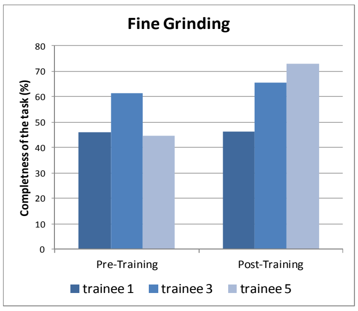

Figure 2. *Completion of the fine grinding task before and after training with the simulator*

Two participants from POL improved their performance with training on the simulator (Figure 3), although one of them was colour-blind. However, for one participant, training resulted in a negative effect. The trainee had trouble distinguishing whether the virtual tool was in contact or not with the pipe work. A possible explanation would be that poor visual cues dominated haptic cues. Therefore, additional visual cues in the VE may improve this aspect.

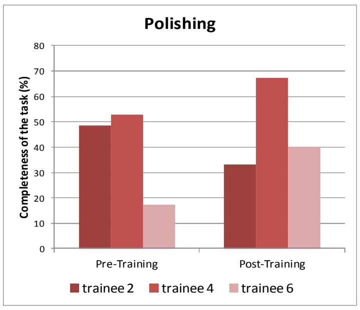

Figure 3. *Completion of the polishing task before and after training with the simulator*

The difference in the performance of fine grinding (Figure 4) and polishing (Figure 5) tasks between expert metallurgists during the pre-evaluation step and the equivalent performance of trainees, validates the system as a good representation of the real world task.

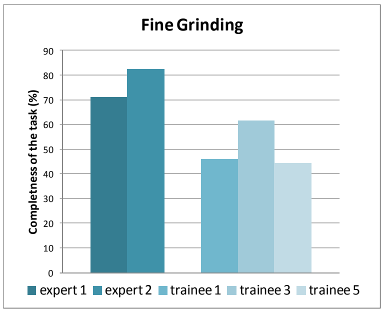

Figure 4. *Experts performed much better than trainees in the first trial on the simulator with the fine grinding task*

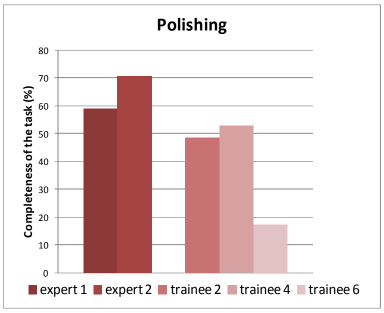

Figure 5. *Experts performed much better than trainees in the first trial on the simulator with the polishing task*

6. Conclusion

This study reported the effectiveness of a VR system enhanced with haptic force feedback, to improve the performance of complex mechanical tasks simulated in a VE. Moreover, performance measures enabled discriminating between expert metallurgists and trainees. Thus, external validity for the simulator was found.

In the future, we plan to adapt the colour map for colour-blind people.

7. Acknowledgements

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