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Using Real-time Feedback in a Training System for Manual Procedures

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Abstract: Human workers remain a crucial part of production environments for conducting manual assembly or maintenance procedures, despite increasing automation. These procedures cannot be automated due to small lot sizes and high product variability. Performing manual procedures requires the application of procedural knowledge and motor skills, such as bimanual coordination and complex hand movements. Many training systems for manual procedures have been proposed. However, these systems focus on declarative knowledge about the sequence of work steps. The inherent haptic characteristics and sense for correct tool and component application gets lost. This paper proposes a training system that introduces haptic components for the training of assembly procedures. The proposed training system instructs the user in mounting two physical components by employing haptic and visual interaction. Augmentations and real-time feedback assist the user during the training and enable the assessment of applying accurate torque on screw connections. An evaluation compared the training system against video-based instructions and indicated advantages for the proposed system in terms of objective measures (time on task, precision) and in terms of subjective measures such as usability.

Keywords: Human-machine interface, training, virtual reality, assembly, man-machine systems.

1. INTRODUCTION

The complexity of industrial environments is increasing, driven by changes on the market towards a rising number of product variants and shorter product lifecycles. Nevertheless, human workers retain a central role since their flexibility is especially important in future production environments that are characterized by increasingly knowledge-intensive tasks and higher variability. Therefore, training and assistance systems remain a necessity.

Training and assistance systems have been developed to support human workers in these environments. Virtual training systems support workers in initial training using immersive visualizations of the machine and the task description. Assistance systems are utilized during procedures and indicate the subsequent work step using Augmented Reality technologies. However, especially virtual training systems neglect the acquisition of precise motor skills since they focus on visual information output and do not provide real-time feedback on the trainee's performance for self-assessment, for instance when having to fasten a screwing connection with a certain torque. Both, procedural knowledge and motor skills, are crucial factors for the safe and efficient conduction of manual procedures under real circumstances.

This paper presents an approach to integrate the training of manual procedures into virtual training systems. Training is supported by physical components and real-time feedback on performance. The system extends the concept that was developed by Loch and Ziegler (Loch et al. 2018) by real-time feedback and video-based instructions. An evaluation of the proposed system against a static system concludes the benefits of the proposed system, especially for trainees with low experience with the trained procedure and the involved tools.

2. STATE OF THE ART

Virtual training system for industrial applications are researched for a long time. Virtual training describes the application of virtual reality technology for training purposes. Virtual training of industrial procedures is motivated by the possibility to provide cheap, flexible, and attractive training of different procedures. A typical application of virtual training is assembly or maintenance (Gutiérrez et al. 2010). These systems apply physical interaction, such as gesture-based interaction (Stork et al. 2012) or the possibility to interact with haptic devices (Bhatti et al. 2009). This section introduces virtual training system that use different forms of haptic interaction. Furthermore, AR-based assistance systems are summarized. A concluding discussion indicates the research gaps that are addressed by this thesis.

2.1 Haptic Interaction in Virtual Training

An important design aspect of virtual training systems is the interaction modality. Several training systems employ haptic devices to allow realistic training of manual procedures. Frequent applications are training system for industrial skills, such as welding or spray painting, that require precise manipulation of a physical device. Konieczny et al. described a training system to simulate the process and characteristics of spray painting (Konieczny et al. 2008). The system is based on a virtual environment, provided on a head-mounted display.

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The trainee interacts with the training system using a physical spray gun. Kim et al. propose a similar system for spray painting (Kim et al. 2007).

The interaction with physical devices has been introduced in training systems to provide a more immersive training experience. Crison et al. (2005) and Liang et al. (2012) introduce haptic interaction devices to simulate the interaction with lathing and milling machines during training. Bhatti et al. (2009) and Gutiérrez et al. (2010) use haptic devices to simulate assembly processes in a training environment. Neges et al. 2018 combine an immersive virtual training system with physical artefacts in an augmented reality system. This allows introducing physical and haptic perception in a virtual training system.

2.2 AR-Training

Augmented-reality training systems are based on the interaction with physical components while carrying out the procedure. Loch et al. evaluate a display-based assembly system (Loch et al. 2018). Funk et al. (Funk et al. 2015) provide an assistance system that provides different types of instructions, for instance by projections on the workbench in the field of view of the operator.

2.3 Discussion

Existing virtual training systems address various use cases, such as assembly or welding. Introducing different modalities to a virtual training system to train different types of worksteps was proposed by the author in a concept for an adaptive virtual training system (Loch et al. 2019). However, most training systems focus on visual information presentation and feedback. Several training systems investigate the benefits of haptic in- and output to transport the feeling of the handling of the work pieces and the tools. However, the haptic sense of the handling of the tools is neglected and vital motor skills are not conveyed to the trainee.

Training systems that apply haptic interaction mostly rely on commercial in- and output devices. They are therefore only able to provide simulations of the actual interactions between the components and cannot provide the feeling of interacting with the real components. Loch et al. (2018) proposed a system that uses real physical work pieces and tools to simulate manual procedures. This system lacks the abilities of providing in-context, real-time feedback about whether the user handles the tools properly (e.g. whether a connection was fastened with the right torque). This paper extends this system by these functions and presents an evaluation.

3. CONCEPT

The proposed training system enables haptic interaction by employing visual feedback and manipulation of physical components. An exemplary procedure is trained on a workbench utilizing physical components, as they are used at a real worksite. The procedure requires the user to establish a screwing connection with a certain torque using a hex key and three screws. AR-technology augments the workbench with visual instructions, animations, and real-time feedback to assist in performing the procedure. The physical components are equipped with sensors to measure the applied torque and enable the display of real-time feedback. The trainee can familiarize with the component's physical properties. Fig. 1 shows the initial setup of the training system.

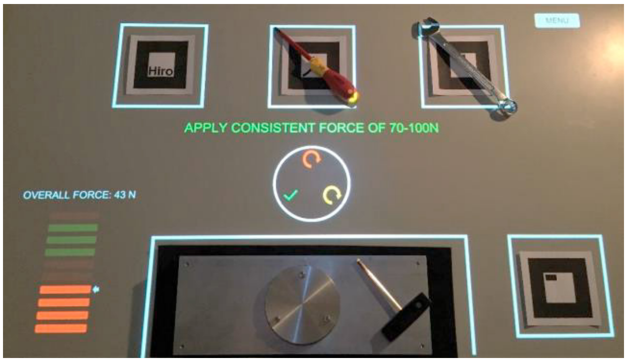

Fig. 1: Image of the workbench with real-time feedback provided by the training system.

3.1 Motivation of the Proposed Training System

Humans are physical creatures that favor interaction with physical objects (Saffer 2009). Similarly, the interaction with physical components such as tools or work pieces is an integral part during the performance of assembly or maintenance procedures. The integration of haptic interaction is expected to yield a natural and satisfying interaction with the training system. Evaluations of training system that included interaction with haptic devices provided indications that this increases the effectivity of the training process (e.g. (Bhatti et al. 2009)). Compared to haptic interaction devices, the physical constraints of the interaction with real components are of natural origin and do not need to be simulated.

The successful performance of manual tasks in industrial environments requires knowledge about the sequence of work steps in the procedure and motor skills to carry out each step correctly. The integration of haptic interaction with physical tools allows getting acquainted with the characteristics of the real tools during initial training. After having used the real components during training, the trainee is expected to be familiar with bimanual coordination and fine force control for performing the manual procedure. Integrating haptic interaction is anticipated to reduce errors and hazards. Application speed and quality in the real working environment are expected to increase.

3.2 Concept for a Haptic Training System

This section explains the main components of the training system. These are the interaction with haptic devices, the provision of real-time feedback and the augmentation of procedural instruction in the form of videos.

Haptic Interaction. The trainee communicates with the training system by physically interacting with the components (e.g. picking up, placing, and mounting components).

The proposed procedure consists of multiple tasks. If a task is executed successfully, the training system transitions to the next task automatically. The training system uses marker tracking and force sensing technology to perceive the trainee's actions and obtain data for task transition. If a task requires the trainee to pick up a tool or component, it is highlighted with green color. The 'pick-to-light' principle enables fast perception of the desired component. The task is accomplished if the trainee picks up the correct tool or component and unveils a hidden marker that now becomes perceivable to the training system.

If the trainee picks a wrong tool, the area of the tool is highlighted in red color and textual instructions advise to return the tool. The implementation of easy reversion of actions motivates to explore the training system and reduces stress (Dix et al. 2004).

Real-Time Feedback. If the trainee is required to establish a screw connection, the training system uses the force sensing system to measures the forces applied on the connection. The information obtained by the force sensors is utilized to augment real-time feedback on the workbench and assist the trainee in applying the correct forces (see Fig. 1). The overall force is shown as a bar diagram on the left side. It is calculated as the average of forces applied to all screws together. To accomplish a task successfully, the overall force must lie within a given range. If the applied force is correct, the status bar's green partition is activated. In case the force is too high or too low, the status bar remains red and blurs according partitions.

The individual forces on each screw connection are augmented above the work piece by utilizing rotary arrows advising the trainee the direction of tool manipulation (see Fig. 1). If the force applied to a screw is too low, the respective icon is displayed in red color and symbolizes tightening the screw. When the trainee applies the correct force, a green hook is augmented respectively. To accomplish the mounting task, all forces need to be within a given range. Feedback about the measured force on each screw allows the trainee to acquaint precise motor skills, since the displayed force measurements can be directly linked to the manual manipulations. The trainee is expected to develop a sense for the application of correct force.

Procedural Animations. Novice workers may have little experience with the adequate application of tools. The training system displays expressive animations on the workbench to show the correct execution of the task and ensure correct training (see Fig. 2). The animation is displayed in the trainee's field of view above the component for manipulation. These animations should reduce the cognitive load during training.

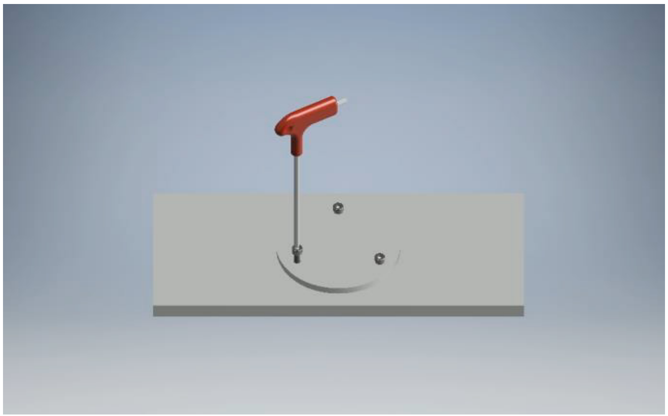

Fig. 2: Procedural animations to indicate actions in a language-independent way.

4. IMPLEMENTATION

Fig. 3 shows the components of the training system. The *System Controller* is the core of the training system. It processes the data from the *Force Sensing System* and the *Marker Tracking System* to generate visualizations and real-time feedback.

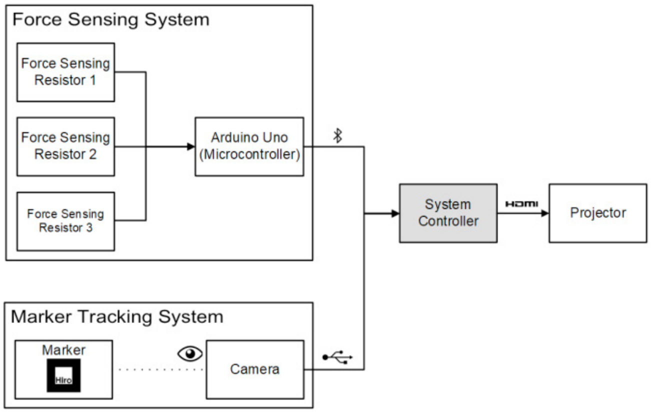

Fig. 3: Soft- and hardware components of the training system.

For the implementation of the *Force Sensing System,* three force sensing resistors are mounted to the baseplate of the screw connection and connected to an Arduino UNO microcontroller. The microcontroller measures the resistance at the force sensing sensors over electric currents and translates the data to force values in Newton [N]. The resistance of the force sensing sensors changes according to the force applied at the respective screwing connection. The force values are then sent to the *System Controller* via a Bluetooth connection. The *System Controller* uses the force values to detect whether a task was executed successfully.

The second component is the *Marker Tracking System*. A camera mounted above the workbench captures the training scene. Several markers are placed on the workbench. In the initial state of the training process, each marker is covered by a tool or component. The camera captures the current scene and sends this data to the *System Controller* via USB. This data is used to determine if a marker is visible for the camera. By perceiving the visibility of the markers, the *Marker Tracking System* detects whether a tool or component is in its supposed position. With this information, it can be derived if a task (e.g. pick a component to screw two parts) was completed.

The *System Controller* was implemented using the Unity game engine. ARToolkit was applied for the *Marker Tracking System* and the displaying of the instructions. A consumer-grade webcam and projector were used in the prototype.

5. EVALUATION

An evaluation validated the benefits of haptic interaction and real-time feedback. The training system was compared against a video-based training system that provides procedural animations and does not enable real-time feedback and haptic interaction. The instructions have to be switched by the user with a button. The comparison was carried out based on objective measurements (e.g. mistakes or completion time) and subjective measurements, such as usability, that were obtained by questionnaires.

Video-based training served as the baseline measurement since it provides an intuitive training method and can also be used in an unsupervised training setting. Furthermore, the video-based training system provided the same instructions as the training system. A scenario created for the evaluation, required the establishment of three screw connection with the application of forces within a given range. Therefore, a circular flange had to be mounted onto a baseplate. The following sections describe the hypotheses of the experiment, the course of the experiment, and discuss the obtained results.

5.1 Hypotheses

H1 – Participants who trained with the proposed training can apply the correct force more precisely than participants who received video-based training. H1 was expected to be valid since the real-time feedback provides a continuous feedback on the trainee's performance. This hypothesis was evaluated by depicting the number of participants which applied the correct mean force on the screw connection. The force at each screw was measured to determine whether the trainee applied a consistent force over the circular flange.

H2 – Participants who trained with the proposed training system commit less mistakes and can carry out the procedure more quickly than participants who trained with the video-based training system. H2 was expected to be valid since haptic interaction and real-time feedback allow the trainee to get familiarized with the task in more detail than with the baseline system. This hypothesis was evaluated by measuring the procedure completion time and by obtaining if the tasks were executed in the right order. A subsequent interview should ascertain whether the participants would feel confident in applying the learned skills under real conditions.

H3 – Participants who trained with the proposed training system perceive it more positively on the USE questionnaire for usability and in interviews than participants who trained with the video-based system. H3 was expected to be valid since the visualizations on the workbench, the real-time feedback, and the automatic switching of the instructions was expected to improve the immersion of the training system and yield a more positive perception of the system. Positive perception of the training system is linked to a higher intrinsic motivation, which is expected to provide a positive impact on the success of the training procedure. This hypothesis was evaluated by comparing the results to the USE questionnaire for usability of Lund (2001) for both training systems. A subsequent interview with the trainee should ascertain if the trainee could interact intuitively.

5.2 Description of the Evaluation

The evaluation was set up as a between-subject design with the training system as the independent variable to receive unbiased information on the differences between both systems. The participants were randomly divided into the experimental group that trained with the proposed system and the control group that trained with the video-based system.

Participants. The participants of the study were recruited randomly among students and staff of the university ($n = 20, Age\colon M = 22$, 6 female). 18 participants reported previous professional experience in the application and handling of mechanical tools.

Baseline system. The proposed training system was compared against a system that used only the procedural videos of the proposed training system. Animations that showed all steps of the procedure were created. The participants could transfer between the steps of the procedure by pressing a button.

Steps of the evaluation. The evaluation began with a briefing of the participants about the aim and the course of the evaluation. Afterwards, the participants were asked to fill in a demographic questionnaire. Afterwards, the training systems (experiment and baseline system) were introduced. Both groups were told that both training systems would be tested for their efficiency in teaching a procedure.

Both groups trained an exemplary procedure with the respective training system and performed the procedure in a test afterwards without support by the training system. The procedure consisted of the following tasks:

1. Pick the circular flange from the workbench.
2. Place the circular flange on the baseplate with the screw holes aligned to the baseplate.
3. Pick the hex key from the workbench.
4. Place the three screws in the screw holes of the circular flange. Mount the circular flange by engaging the screw connections with consistent force of 70–100 Newton using the hex key.
5. Return the hex key to its original position on the workbench.

The experimental group used the training system with haptic interaction and real-time feedback. The participants conducted the instructions with the physical components and tools of the training system. The training ended, when the five previously described steps were executed. The control group trained with the video-based training system. The video-based system provided the same textual and animated instructions. The participants of the control group were asked to observe the instructions before carrying them out.

The participants conducted a test where they recalled and applied their knowledge after each training. The participants were instructed to execute the procedure in the correct order and apply the desired range of forces between 70 and 100 Newton. The participants could end the test if they felt to have applied the correct forces. After submitting the test, feedback about the performance was provided. The feedback contained information about the total execution time, the applied forces on each screw, the applied overall force, and whether the operations were carried out in correct order. The results were logged into a document for analysis.

A usability questionnaire (the USE questionnaire of Lund (2001)) was handed out at the end of the experiment. Two items about the intuitiveness of the training system and the confidence of performing the procedure under real conditions were added. The experimental group was asked to list positive and negative aspects of the training system to gather suggestions for improvements.

5.3 Results

H1 – Participants who trained with the proposed training can apply the correct force more precisely than participants who received video-based training. The force measurements indicate that more participants applied the correct mean force on the circular flange using the proposed training system. Fig. 4 visualizes the results in a bar chart. These results indicate that training with the proposed training system led to better results with regards to the precise application of the given forces. Users of the experimental system are therefore considered to have applied better precise motor skills than the users of the video-based training system.

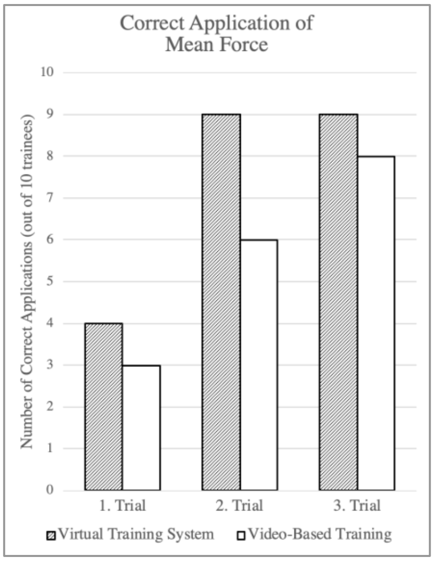

Fig. 4: Graph showing number of correct applications of the mean force over all three trials out of 10 trainees.

H2 – Participants who trained with the proposed training system commit less mistakes and can carry out the procedure more quickly than participants who trained with the video-based training system. The results indicate that participants that used the proposed training system were able to complete the procedure more quickly. Fig. 5 provides a boxplot of the results. The mean procedure completion time of the experimental group in the first trial is 54.8 seconds, whereas the participants of the control group required 71.5 seconds. The completion times converge in the subsequent trials. The observed difference in the completion times over all three trials $(Exp.: M = 47.83, Control: M = 62.53, p < 0.0003)$ and within all three trials $(p = 0.002, p = 0.028, p = 0.036)$ were significant.

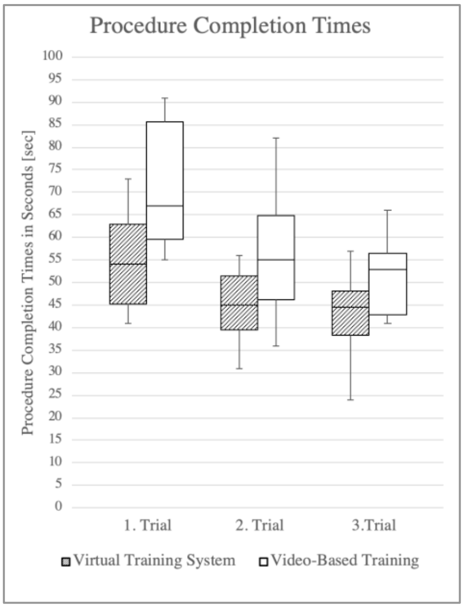

Fig. 5: Completion times for the procedures in seconds for the experimental system and the baseline system.

H3 – Participants who trained with the proposed training system perceive it more positively on the USE questionnaire for usability and in interviews than participants who trained with the video-based system. The results from the USE questionnaire and the interviews support H3. Especially the measurement of satisfaction received a more positive response $(Exp: Mdn = 5, Control: Mdn = 5)$. Usefulness was also perceived positively $(Exp: Mdn = 6, Control: Mdn = 5)$ and ease of learning received the same positive result for both systems.

This could be justified by the circumstance, that interacting with the proposed training system is physical. Task completion is automatically perceived by the training system and the instructions for the next task are evoked automatically. Participants of the experimental group confirmed that they could use the system without written instructions. This is expected to indicate that the interaction with the training system is intuitive and does not require further assistance.

6. CONCLUSION AND OUTLOOK

This paper presented a training system that introduces interaction with physical components. Real-time feedback that is projected on the workbench supports learning the interaction with the tools. These improvements are expected to provide a more efficient training environment that a system without these abilities. The training system facilitates the acquisition of fine force skills and bimanual coordination. Furthermore, the training system promises efficient education for inexperienced and low skilled workers because of the intuitive interaction and the comprehensible explanations with augmented assistance during the training.

The training system was realized using standard and open-source software components. This makes the proposed system cost-efficient and facilitates its extension. The hardware is mobile and uses consumer-grade components. It therefore enables to transfer existing work places into training systems and apply the system in educational settings (e.g. in schools for mechanical training).

An evaluation ($n = 20$) against a video-based system was carried out to validate the expected improvements. The evaluation indicated that the proposed training system is superior in terms of time-on-task, number of errors, and subjective perception regarding the usability of the training system.

Improvements to the training system could be made by employing further interaction modalities. See-through HMD could be implemented to provide additional visual instructions. A voice-controlled interaction could extend or replace the visual instructions to enable an intuitive and enriched training experience. To address the trainee's haptic perception proficiencies, vibration motors could be installed in the involved tools to provide haptic feedback to indicate when a trainee applied the correct force. The proposed training system could be integrated into a virtual training system with several components. As soon as the training system requires the performance of a manual task, the training system could be activated to teach the procedure with physical components.

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