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An augmented reality training platform for assembly and maintenance skills

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ABSTRACT

Training technicians to acquire new maintenance and assembly skills is important for various industries. Because maintenance and assembly tasks can be very complex, training technicians to efficiently perform new skills is challenging. Training of this type can be supported by Augmented Reality, a powerful industrial training technology that directly links instructions on how to perform the service tasks to the machine parts that require processing. Because of the increasing complexity of maintenance tasks, it is not sufficient to train the technicians in task execution. Instead, technicians must be trained in the underlying skills—sensorimotor and cognitive—that are necessary for the efficient acquisition and performance of new maintenance operations.

These facts illustrate the need for efficient training systems for maintenance and assembly skills that accelerate the technicians' acquisition of new maintenance procedures. Furthermore, these systems should improve the adjustment of the training process for new training scenarios and enable the reuse of worthwhile existing training material. In this context, we have developed a novel concept and platform for multimodal Augmented Reality-based training of maintenance and assembly skills, which includes sub-skill training and the evaluation of the training system. Because procedural skills are considered as the most important skills for maintenance and assembly operations, we focus on these skills and the appropriate methods for improving them.

1. Introduction

Experienced service technicians know how to maintain and repair complex machinery and production facilities. Such technicians have accumulated invaluable knowledge over years of experience, and are able to precisely handle machine malfunctions. Such "skilled" workers play a crucial role in today's companies and ensure the permanent operation of production facilities, contributing to savings in time and cost. Unfortunately, this knowledge is rarely documented and important skills are often restricted to only a few people. Existing quality management and recovery solutions consist of written documentation or video footage of essential maintenance tasks. This results in the following drawbacks:

- Written and video documentation will actually capture only specific tasks,
- often in an incomplete way, and
- will ignore the skills and knowledge accumulated by the technician which were not demonstrated.

The objective of the European project "SKILLS" is to develop advanced multi-modal and multi-sensory systems. One of these systems will be dedicated to industrial maintenance and assembly tasks, which will support a fast and extensive documentation of complex maintenance tasks using a fusion of simulation and capturing techniques, 3D-reconstruction, user-behaviour modelling and tracking, multimodal interaction, 3D-interactive graphics for distributed training, and authoring capabilities.

The captured skills will be transferred to immersive training scenarios that will be used within industrial training facilities. The training will support several different qualities:

- *Distributed web-training*: Using actual 3D-Internet-Technologies collaborative training scenarios can be realised for distributed teams via standard Web-Technologies.
- *Immersive training*: Real-time simulations of object behaviour and multimodal interaction supports the development of complex training simulators that address cognitive skills (e.g., how to react in different troubleshooting situations) and sensorimotor skills (e.g., determining which force to apply in specific assembly steps).

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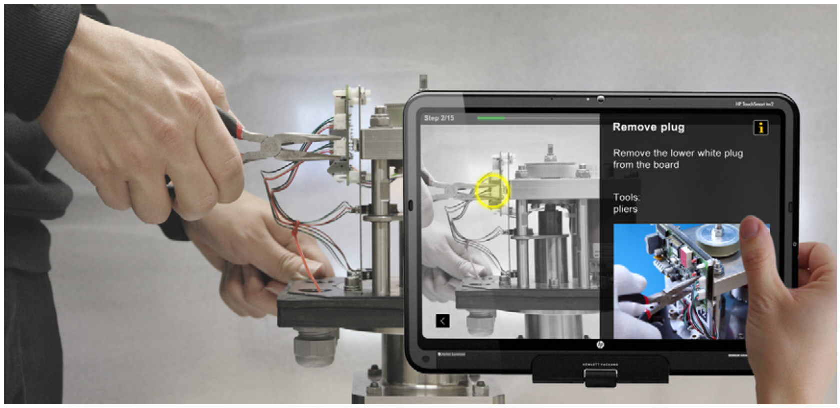

Fig. 1. AR-training of an assembly task using "Adaptive Visual Aids".

- *Mobile training*: The training scenarios can be downscaled to smartphone platforms that will support the service technicians during their jobs, bridging the gap between the training and support systems. The various training scenarios can be easily distributed because the mobile technician can be connected via tele-consultation to a remote expert.

These training system requirements are accompanied by actual developments in ICT technologies, which are driven by two trends that foster fundamental paradigm changes in interaction and information processing. On one hand, smartphone and mobile computing technologies offer highly sophisticated platforms that integrate multimodal sensors and powerful CPUs, on the other hand, the information is structured in a geo-referenced way, i.e., it links information to specific locations within our environment. As a result of this, Augmented Reality (AR) has become a key technology because it analyses sensor data (camera, GPS, inertial) to derive a detailed pose of the mobile system, with the aim of correlating our real environment to a geo-referenced information space. Therefore, AR uses a camera based interaction for combining Computer Vision with Computer Graphics.

2. Related work

Because maintenance and assembly procedures are complex, training of operators to perform such tasks efficiently has been the focus of many research groups. Numerous studies have investigated the potential of AR-based training systems and its use in guidance applications for maintenance tasks [1–3]. Tümler et al. [4] focused on how long term usage of AR-technology in industrial training results in user stress and strain. They showed that the use of an optimal AR system (no lag, high quality see-through calibration, weight-reduced HMD, etc.) decreases the overall user strain, implying that using AR systems could decrease strain in comparison to traditional training procedures.

Franklin [5] focuses on the application of AR in the context of Forward Air Controller training. The study concluded that the impact of AR for training depends on the specific requirements of the users, specifically required simulation realism. An approach in the context of robot Programming-by-Demonstration is presented in [6]. The authors define learning accelerators, which are implemented and evaluated in AR setups and present a training protocol for training Programming-by-Demonstration skills. Another work showed the potential of AR in the context of human–robot interactions for industrial robots [7]. It was pointed out in the referenced publication [7] that handhelds and monitor based visualization devices are better for industrial environments than Head Mounted Displays because they are more robust.

3. AR and tele-consultation

AR is used for skill transfer in industrial training, addressing the assembly and maintenance of large machinery and plants by integrating capturing and rendering technologies (c.f. Fig. 1):

- Capturing: The camera is used to capture activities (performed by an expert) within a large-scale environment. Considering the different modalities registered the captured activities can be rendered using different output devices. "Adaptive Visual Aids" link contextual information to specific machine parts. By combining forces/torques requirements with multi-media illustrations and audio/video files, "Adaptive Visual Aids" can document complex assemblies and maintenance workflows.
- Rendering: Information captured from each training scenario can be presented in two different modes: a 3D-animation illustrating the current assembly step that is directly superimposed onto the captured video image ("Direct Visual Aid"), or a tracked "Virtual Post-It" icon that indicates what contextual information is available displaying the machine part if the icon is selected by the user ("Indirect Visual Aid"). In this manner, the guidance level can be adapted to the trainees' pre-existing knowledge, resulting in different levels of guidance (c.f. Fig. 2). This approach for "Skills transfer" in industrial training is high impact because it can be integrated in tele-consultation scenarios as follows:
- The trainee uses the mobile AR-Equipment to inspect the machinery (c.f. Fig. 3). The trainee is guided through the training procedure step-by-step. If a problem occurs during the training session, the trainee connects to the remote trainer via UMTS of WIFI.
- The video images captured with the mobile system of the trainee are now transferred in real-time to the trainer. Therefore, the trainer is able to reproduce any problems and is able to modify or enhance the training protocol. The trainer can add new "Virtual Post-Its" to the training protocol that can integrate scribbled annotations to the captured video images (c.f. Fig. 5). The trainer can also link additional Multi-media illustrations to the addressed assembly step. In this way the tele-consultation component is also used as Augmented Reality authoring system: all annotations added by the remote trainer are integrated into the training protocol and are linked to the respective tracked machine parts.

4. Haptic hints

When completing maintenance and assembly tasks, operators mainly use their hands. Therefore, the application of haptic

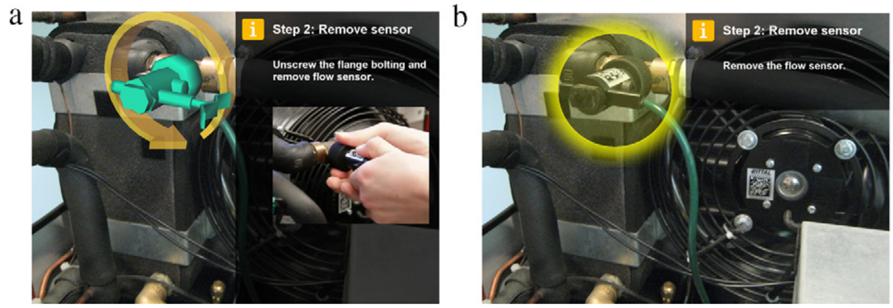

Fig. 2. Adaptive Visual Aid with activated content object (a) at a strong guidance level and (b) at a softer guidance level.

Fig. 3. Mobile AR component including a haptic bracelet.

feedback to the trainees' hands during training can assist in task comprehension and performance. Haptic feedback can be accomplished using vibrotactile bracelets, which can apply vibration stimuli to the human arm, forearm, and wrist (c.f. Fig. 4).

Vibrotactile bracelets are equipped with six vibration actuators that are placed at equal distances from each other inside the bracelet and around the user's arm. The intensity of each actuator can be individually controlled. In this manner, various sensations can be generated that provide hints for rotational or translational movements. In general, a lot of visual information has to be processed in complex working scenarios, whereas there is tactile information to be processed. Additionally, vibrotactile feedback is very intuitive because the stimuli are directly mapped onto body coordinates.

Because vibrotactile feedback provides soft guidance that "channels" the user to the designated target instead of directly manipulating the user's movements, it does not prevent active exploration of tasks by the user. In this sense, vibrotactile feedback can give the trainee additional movement hints, such as rotational or translational movements cues, and guide the trainee to specific targets. For example, if the trainee needs to rotate his arm for performing a sub-task, the rotational direction (clockwise or anti-clockwise) may be difficult to recognize in an instructional video. A vibrotactile bracelet could allow the trainee to more easily identify the rotational direction. Additionally, translational movements can be conveyed using vibrotactile stimuli.

Also, it is useful to apply vibrotactile stimuli for presenting error feedback, such as communicating whether the right action is performed (e.g. the right tool is grasped). This is a significant factor, as it can prevent the user from performing errors at an early stage. In addition, vibrotactile stimuli should be used to provide subtle instructions that assist in learning the movement and direct the trainee's attention to a specific body part.

5. Augmented Reality based training

The main advantage of using Augmented Reality for training is that the trainee can interact with real world objects and simultaneously access the virtual information for guidance. Therefore, the trainee can easily create a mapping between the training and the real task. Additionally, the trainee can perform the actual task while accessing additional training material, facilitating additional learning. With regard to Fitt's model of skill acquisition [8], AR enables the trainee to learn a task's basics by observing the augmented instructions and trying to perform instructed sub-tasks. This allows the trainee to develop behavior and movement patterns when performing the sub-tasks, and to redefine motor patterns while repeating specific tasks (i.e. during training). By accessing augmentations during task training, the trainee can become particularly skilled. The trainee's skill level begins to develop when the trainee performs the real task for the first time.

Another advantage of AR-based training is that the trainee has real tactile feedback when performing the training task because they can interact with real objects. Virtual objects provide additional information about the task and supplement the trainee's

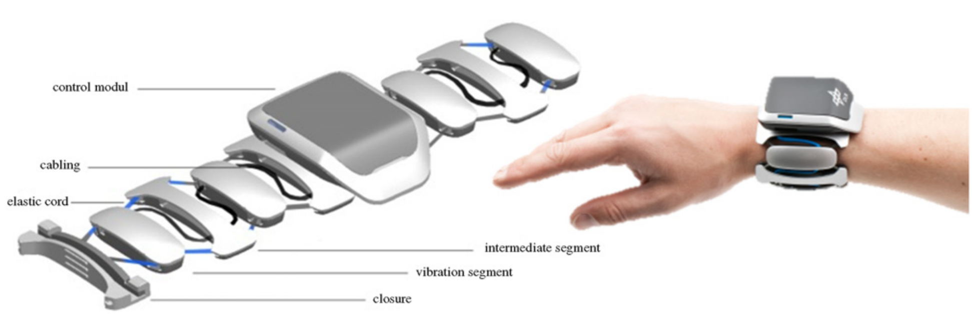

Fig. 4. Vibrotactile bracelet.

Fig. 5. Authoring/tele-consultation-tool for the specification of the training protocol.

task knowledge. Accordingly, the trainee can access the training material (e.g. the virtual instructions) and the real environment without the need to use "external" separate training material (e.g. a user manual).

Furthermore, the use of a training platform that involves virtual elements, such as an Augmented Reality platform, allows for the measurement and evaluation of each trainees' performance with a level of detail that is not possible when performing the actual task without virtual components. By using technology that provides virtual elements, it is also possible to respond to the trainee's performance and present corresponding feedback in a way that is not available without this technology. In addition, the type and order of presented sub-tasks can be adapted, which is not possible in the real world.

A potential danger of AR applications is that users become dependent on AR features such as visual instructions. As a result, the user might not be able to perform the task when those features are not available or when the technology fails. Therefore AR training programs should include phases in which the amount of AR features is reduced (less virtual components, e.g., only instructions for the current sub-task without additional information about the device, tools, etc.) and the level of provided information is reduced (e.g. only spatial hints without detailed instructions). Therefore, the level of guidance in the AR training system has to be adaptable to the current training phase. AR-based training applications must clearly differ from AR-based guiding applications, as they must actually train the user and not simply guide the user through each task. This can be achieved only by accounting for cognitive aspects in the training.

6. SKILL transfer evaluation

To evaluate the developed technologies, the skills transfer study was conducted with the following goals:

- to analyze the efficiency of the training platform as a training tools for industrial maintenance activities, and
- to compare the trainee performance with trainees trained using traditional methods.

This evaluation involved two experimental groups:

- Group 1—Control: participants performed once the physical task while they were watching an instructional video showing the task steps.
- Group 2—AR: participants performed the physical task once using the Augmented Reality platform (Fig. 6).

The experimental task was composed of 25 steps grouped into six sub-tasks. Twenty technicians from Sidel served as participants. They had at least 2 years of experience on field assembly/disassembly operations and a discrete competence in the use of personal computers and advanced technology. So each trainee was assigned to only one experimental group. Each group contained 10 participants. Before beginning the evaluation, the participants filled in a demographic questionnaire that was used to homogeneously distribute the participants. The previous "assembly capability" of participants was tested through a simple assembly task before starting the capability test.

Each experimental group followed the same protocol. In the morning, participants were trained in the target task, which as how to assemble an electro-mechanical actuator. The Control group performed the training procedure using traditional training materials, whereas the AR group performed the training procedure using the AR system. In the afternoon, the trainees had to perform the same physical task without any assistance. However, if they could not continue with the task, they could consult a book with photographs of the task. Consulting the book was recorded as using an "aid". At the end of the day, the AR group was requested to fill out a further questionnaire to gather feedback on the ease of use and the effectiveness of both platforms. The training time, task performance, and subjective evaluation were analyzed (Table 1).

The demographic data and capability test scores were similar among the groups. In general, real task performance was better for participants trained using AR methods. Tasks were performed without aids and with almost no unsolved errors. While the performance time and the number of solved errors was not significantly different from the control group, the number of unsolved errors was significantly smaller in comparison to the control group: ($t(18) = 2.52, p = 0.02$) for the AR group. This result is important because it indicates that traditional training results in many unsolved errors (1.3 in average for this short task). This is possibly due to overconfidence. Proper AR training can help to prevent these errors by emphasizing each task's key objectives. In addition, when using the AR platform, trainees can gain experience using the system and solve technical issues using, making the system more effective for future uses/users.

7. Conclusions and future work

This projects presents results of the development and testing of a novel platform for multimodal Augmented Reality-based training of maintenance and assembly skills. After analyzing existing AR-based training systems and skill training systems, the relevant aspects of skill acquisition and training were compiled. These aspects included the decomposition of skills into sub-skills and approaches for skill training and ability assessment (see [9] for more details). This study also analyzed technologies that are relevant for AR-based skill training, such as capturing and rendering technologies. We analyzed the use of Augmented Reality and multiple modalities for general purpose training. The application of Augmented Reality technologies and the provision of multimodal feedback – and vibrotactile feedback in particular – were found to have a high great potential for skill training enhancement. We also presented an approach for the development of training programs for multimodal training. Because humans absorb most of the information through their eyes and vision dominates the perception in the majority of cases, the visualization of information is vitally important for

Fig. 6. Evaluation of the AR-based training at Sidel training center for service technicians.

Table 1
Evaluation results of the AR-based training for service technicians at the Sidel training center.

Participant	Age (years)	Experience	Skill (1–5)	Capability test (s)	Training time (s)	Number of aids	Performance time (s)	Number un-solved errors	Number of solved errors
Control	34.9	4.4	3.8	304.3	682.0	0	517.1	1.30	0.30
AR	33.5	4.1	3.9	297.3	851.9	0	494.0	0.30	0.30

developing efficient training systems. Therefore, we determined how detailed information such as text can be displayed in interactive Mixed Reality environments. Furthermore, a novel concept for displaying location-dependent information in Augmented Reality environments has been introduced, which can compensate For tracking imprecisions. In this context, the pointer-content metaphor of annotating documents has been transferred to Augmented Reality environments and Adaptive Visual Aids (AVAs) have been defined. Each AVAs consists of a tracking-dependent pointer object and a tracking-independent content object, which both providing an adaptable level and information type. Therefore, it is easy to control the guidance level of Augmented Reality overlays in AR-based training applications. AVAs can be used to substitute traditional Augmented Reality overlays (i.e. overlays in form of detailed 3D models or animations), which suffer from tracking inaccuracies.

In conclusion, AR has the potential to be a useful technology for maintenance and assembly training. AR training methods allow instructions and location-dependent information to be directly linked and/or attached to physical objects. Because most machines contain a large number of similar components (e.g. screws, plugs, etc.), the provision of location-dependent information is vitally important for maintenance training. Another advantage of AR-based training is that it takes place in a real/physical environment with physical devices that are involved in the training scenario. Therefore, the trainees practice the physical performance of the task during training, and the corresponding sensorimotor skills are acquired. Furthermore, in Augmented Reality-based training sessions, the availability of an on-site trainer is not necessary.

Our evaluation shows that after one training session, the skill level of technicians who trained with the developed training platform was higher than the skill level of those who used traditional training methods. On average, technicians who trained with an AR-based training platform made less errors and achieved better performance times. The duration of one AR training cycle was only slightly higher than traditional training cycles. The multimodal skill training platform and concept developed in this work enhance and improve training in the field of maintenance and assembly operations. Accordingly, specified training strategies and accelerators – that are implementations of information exchange elements and protocols aimed at optimizing the training process and at stabilizing learning – can be considered as design guidelines for the development of Augmented Reality-based training systems for maintenance and assembly skills.

Future work in the field of Augmented Reality-based maintenance and assembly training should give special attention to the capturing and interpretation of underlying skills. The recognition of the user's intention during the performance of single actions can be useful for providing well-directed and systematic feedback. Furthermore, if the maintenance skills of experts can be captured on a large scale, the data can be used to "train" the training system. For example, it can be used to refine the workflow and the instruction data. In this manner, the information and the instructions provided to the user during training can be improved. Future studies should analyze the integration of an additional remote component. The presented concept of Adaptive Visual Aids makes it easy to attach annotations to objects (i.e., for attaching location-dependent information). When a trainee needs additional help for performing a training task and the trainer is not available on-site, but can remotely observe the trainee's performance of the task, then it may be useful for the trainee to receive additional location-directed hints from the remotely connected trainer. These hints can be in form of annotations that the trainer creates on-the-fly and attaches to the dedicated machine parts. Because of this, it is advisable to evaluate if such a remote component for maintenance and assembly training improves training. In addition, it would be useful to explore different devices that can providing haptic hints (i.e., simple, abstract haptic information). Future studies should also examine which kind of information and/or hints can be provided using various devices and what is the best presentation method. Being able to clearly present various types of information would enhance the possibility of providing information via the haptic modality in Augmented Reality environments. This would enable an intensified exploitation of the advantages of providing haptic stimuli during training.

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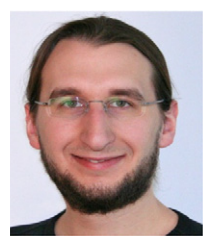

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