Transition of Mixed, Virtual, and Augmented Reality in Smart Production Environments
- An Interdisciplinary View -

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Abstract— **The advancing desire of companies to provide their customers highly individualized products so as to gain sustainable advantages over their competitors has unavoidably deep effects on the production process. Although augmented and virtual reality is a quite common topic of research, in order to meet these demands, the analysis of the seamless transition of different reality-states like real reality, augmented reality, augmented virtuality, and virtual reality within one and the same production task is a often neglected subject. In a broad and interdisciplinary approach we want to draw the attention of the research community on this, set the scene and explore the potential benefits and problems. Technical, epistemological, and philosophical as well as economic aspects are discussed. A prototype is presented as well as the results of a first explorative user test to prove the proposed concept.**

I. INTRODUCTION

The production of modern goods is characterized by short life cycles and a rising number of varieties to provide highest technological standards and customer satisfaction. The rising degree of individualization, which is typical for today's products, often affords a vast amount of highly flexible production resources and a frequent changing of the machinery settings and tools. This puts extreme stress on present planning systems, making it time consuming and difficult to control. The intense proliferation of tiny embedded information and communications technology (ICT) systems in machinery, work pieces and tools – so called ubiquitous and pervasive computing – in combination with the use of different hand-held devices and wearables (mobile computing) upgrades the conventional factory to a smart factory, which helps to better address the above mentioned problems [1] [2] [3]. In this paper however, we want to focus only on a small part of this large vision, namely the application of some sort of wearable computing in the form of head mounted displays. As augmented reality (AR) and virtual reality (VR) technologies become mature, we want to show how these new technologies effectively help meeting today's challenges in highly dynamic production environments. Special emphasis is placed here on the transition of different types of realities: real reality, augmented reality, augmented virtuality, and virtual reality. The discussion of this vast class of different mixed realities (MR) and their transition is an often neglected topic, despite – as we propose – it has a lot of benefits.

II. PREVIOUS WORK

Augmented and virtual reality has been widely investigated for application within manufacturing environments. Many scenarios have been found, e.g. factory planning [3] or instruction manuals [4], but there are still more possibilities to use these systems, namely the transition of realities. Therefore, previous work within all above mentioned fields are related.

Tschirner et al. present a system to support manual welding via augmenting the view of the welder with virtual information [5]. Therefore, the limited view during the welding process – due to the extreme brightness – is alleviated. However, the extreme brightness still obscures the view of the reality and also hinders the readability of the virtual information. In contrast, Fast et al. present a virtual training system for welding [6]. The virtual reality system simulates the welding process to train human welders. A user study showed that most users found that the welding simulation produces realistic results, but the training is limited to virtual environments and cannot be used to train or guide a user within a real-world scenario. Thus a combination of both seems to be a valuable step forward.

Navab et al. present a system to augment the reality with floor plans and pipes [7]. The system uses given 2D plans and automatically finds corresponding objects in the 3D world that are additionally used for calibration. The presented work uses only augmented reality to present the information. Some added value could be achieved if AR is combined with a VR mode, e.g., see where a pipe runs along underneath the floor or to virtually follow a pipe.

In the work proposed by Doil et al. augmented reality is used as a tool for manufacturing planning [8]. The focus on augmented reality setup limits the field of application as the system cannot show other/changed configurations of the currently existing manufacturing setup. Therefore, factory planning by slightly changing the current configuration of the manufacturing site is impossible as this would require a so

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called augmented virtuality visualization.

This short survey of previous work shows that many problems can be solved using AR or VR. However, most of the presented systems support only a limited field of application. This major disadvantage can be overcome if different stages of mixed reality are supported within one and the same application. To further classify different mixed reality setups a basic definition is given in the following section.

III. BASIC DEFINITION ON DIFFERENT REALITIES

Milgram and Kishino describe a taxanomy how augmented reality and virtual reality are related [9] [10]. Rather than seeing the two concepts as antithesis, it is more useful to see them as lying at opposite ends of a continuum. Inbetween these two ends, a large class of different mixed reality applications could be imagined.

Figure 1 illustrates Milgram's reality-virtuality-continuum. According to Milgram, virtual reality is characterized by the fact, that the user is totally immersed in a computer-generated synthetic world. Augmented reality is characterized by observing the real environment with added virtual enhancements. In augmented virtuality, most of the surrounding environment is principally virtual, and only few real world objects are left not augmented. From a philosophical point of view, Milgram made a quite good suggestion to classify mixed reality applications by their degree and amount of virtuality. However, we would like to enhance his idea through the introduction of two new terms: reality (Latin: "realitas") and actuality (Latin: "actualitas") - a difference that has often been stressed in the philosophical debates in the course of the centuries [11]. By neglecting this difference Milgram's description of virtual reality, which he defines as "... a completely synthetic world, which may or may not mimic the properties of a real-world environment, either existing or fictional, but which may also exceed the bounds of physical reality..." loses an important difference: the question whether some virtual Actuality is real or not. Virtual Actuality means, that something has a direct effect on us, as it is seen through a head mounted display, heard by an ear phone, felt by some tactile actuators, and so on. It is actually there and affects us. Meister Eckhard, a German philosopher, translated the Latin word "actualitas" to German as "Wirk-lichkeit", and "wirk-en" means, to have an effect on us. Unfortunately, this notion is lost in the English language, as the word "actualitas" is simply translated as actuality. The question whether something, that affects us, is also real or not is the question of its status of reality. So one could ask: is this virtual Actuality real or is it just fictional, exceeding the bounds of nature? The difference between reality and actuality might be better understood by a simple example: War in Iraq is real but, fortunately, not actual for most of us. It only becomes virtually actual for us through technical exchange devices like television, radio internet and other mass media. To sum up, the difference between reality and actuality could be quite useful in describing virtual and mixed reality applications - however our suggestion is diametrically opposed to the usage of the word reality in the scientific community: what is often called "Virtual Reality" is in philosophical terms "Virtual Actuality" where the question arises: is it also real, i.e. what is its status of reality? In the following, after the discussion on some basic epistemological aspects of mixed and virtual reality technologies, we want to focus on important economic aspects.

IV. FUTURE FACTORIES AND THE APPLICATION OF REALITY TRANSITIONS

As ubiquitous computing and virtual and mixed reality start to become more sophisticated and usable, commercial applications gradually become feasible. However, yet there is only a limited knowledge on the impact of these technologies on the production environment. Furthermore, there is also no general answer which applications are value creating and which are not. Companies must explore and determine the effects by pilot projects and detailed cases analysis. Therefore, certain aspects should be stressed:

- Participatory design and communication optimization between planning and production teams: early involvement of potential users in the development process could avoid later cost of change and aversion against new technologies [12] [13]. At the same time the know-how of the employees in the company units can be easily transferred so as to identify process-innovations that should be integrated as soon as possible.
- To determine the benefits of a new technology, it is inalienable to conduct pilot projects. However, it should not be forgotten that pilot projects often do not reflect well actual processes and their interconnection with other processes. The working situation is often some kind of artificial. Therefore it is necessary to analyze the case studies using experts of different field, such as design, production, marketing, but also human resources etc. Also the question arises how so called "soft factors" such as reduced stress-level of the employees, better cooperation with other teams and so forth are considered in the investment appraisal.
- The actual company-wide real-field implementation poses a risk since constraints of existing systems and processes, unpredictable technical challenges, or social and legal issues could delay the roll-out. Therefore, many companies are reluctant to adopt early, also loosing the chance of building up initial competitive advantages.

In the following a prototypical implementation of an example scenario is evaluated to prove the benefit of reality transitions. This may serve as a starting point for first thinking of and identifying possible use cases and later hopefully second for valuable concrete implementations within companies.

V. EVALUATION SCENARIO

A situation where mixed reality can efficiently be combined with virtual reality is the customized production process. It can be widely seen that manufacturing is more often adapted from mass production to individually configured products. This tendency results in a modified production environment

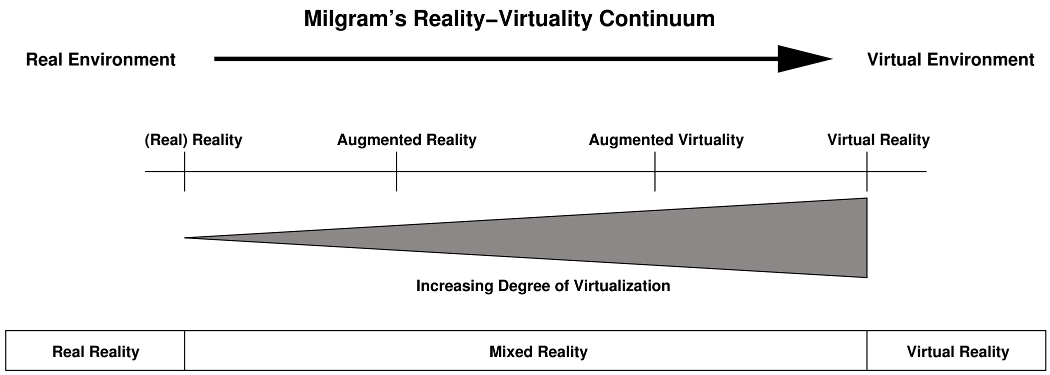

Fig. 1. Milgram's Reality-Virtuality-Continuum to describe different Mixed Reality scenarios.

– workers have to decide which part and configuration has to be chosen to, e.g., build up certain customized machines. A conventional augmented or virtual reality system cannot fully support a worker in these tasks. Both technologies can only cover some aspects, whereas the proposed MR/VR system combines the advantages of both systems via the ability to seamlessly change the amount of reality versus virtuality. First, a virtual reality preview of the deployment environment helps the user to choose the basic product and its configuration for this individual installation. While assembling the product the worker may choose – based on the difficulty of the task or his experience – the level of build-up instructions. Several levels of mixed reality can be supported within the range of no instruction (reality) and virtual reality. The decision which of the different configuration option has to be chosen for this specific product installation can easily be made in an augmented virtuality view. The product is virtually installed in its deployment site in the current state of assembly. The worker can orient and position the product and view it form different points of view while the virtual installation environment is always displayed in the corresponding orientation. This way, an intuitive interaction supports the worker to visually choose the best available configuration option, e.g. connectors are installed on the most adequate position for accessing, installation, service, etc. Figure 2 depicts a worker using the proposed prototype to assemble a control unit with a power supply.

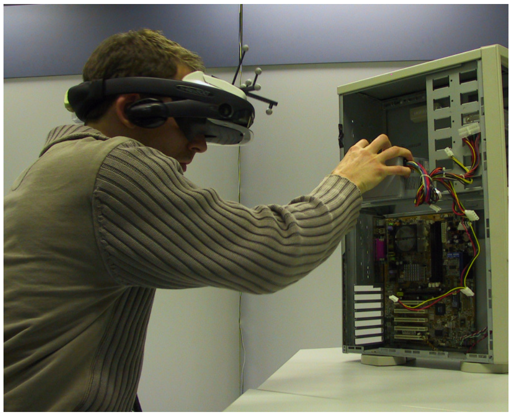

Fig. 2. A Worker assembling a Control Unit using the presented Prototype.

A. PROTOTYPE IMPLEMENTATION

For the implementation of a system that supports multiple mixed reality modes there are a number of requirements on hard- and software. Systems and applications that are limited to only a single reality domain – real environment, augmented reality, augmented virtuality, or virtual reality – already utilize dedicated hard- and software. However, a prototype that supports transitions between different reality stages needs even more specialized technology, as proven by our prototype. In the following the requirements and the arising scientific challenges are presented.

When using MR technology in manufacturing environment safety aspects have to be considered. Therefore, MR systems are limited to utilize optical-see-through head mounted displays (HMD), since in emergency cases or system malfunctions the real environment can still be observed, in contrast to video-see-through HMDs. To support multiple reality stages the HMD must support different operation modes: see-through, non-see-through, and – at best – intermediate modes. The challenge is to utilize optical-see-through HMDs and, thereby, support these requirements. Some HMD prototypes that meet the mentioned requirements are proposed in research projects [14] [15], but none of these are on the market up to now. Therefore, in our prototype we utilized a Sony Glasstron HMD that supports a manually operated transition of mixed reality, ranging form real reality up to virtual reality. If the prototype software changes the reality mode, the user is instructed to adjust the manually operated transition level. This circumstance could be overcome with a computer controlled transition interface.

In order to deploy such a system at manufacturing sites where it is operated by workers an important requirement is an intuitive interaction interface. Here the challenge is to utilize error insusceptible techniques that also allow hands free operation. The research community already invented many options as, e.g., speech recognition, wearable interfaces, data gloves, etc. For the prototype a single-button interface was designed that uses the user's viewing direction and a single button for all needed interaction with the system. More sophisticated

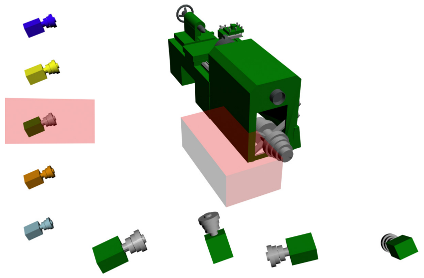

Fig. 3. A lathe. The red box indicated the area of assembly. On the bottom different views of the chosen basic motor type is displayed. On the left a list of other possible basic types can be seen.

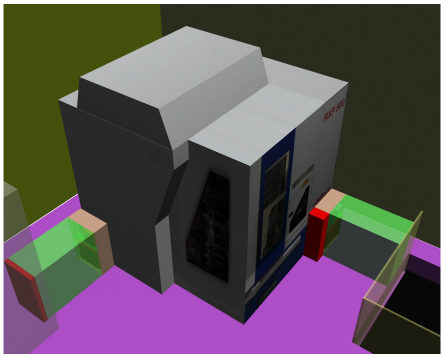

Fig. 4. Virtual Reality Preview of the Customer's Manufacturing Site with a visualization of possible Installation Options and Maintenance Areas.

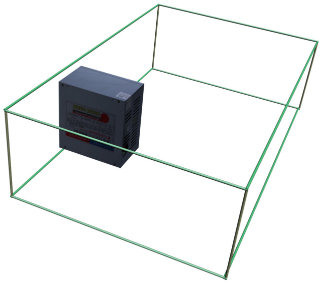

Fig. 5. Rendering of the Augmentation used to show the User the placement of real Objects via virtual Placeholders.

interaction tasks, e.g. navigation within a VR environment, have to be simplified as much as possible in order to achieve an efficient system.

An additional requirement is a highly accurate tracking system to track the position and orientation of the user's head and the parts that have to be assembled. Again, a factory site characterizes a tough scenario for tracking technologies, as there might be strong magnetic fields and possibly many optical occlusions. For the presented prototype an ultrasonic tracking system was analyzed to overcome some of these problems, but magnetic sensor elements included in the tracking system were influenced by magnetic fields of manufacturing environments. Therefore, the final prototype utilizes an optical tracking system which, in contrast, has the disadvantage that an optical line-of-sight is needed form the tracked objects to the tracking system.

Besides the technological hardware challenges, also the utilized software technology is relevant. Special considerations have to be taken to achieve a system with minimal latency for the mixed reality visualizations in order to minimize the orientation difference of real and virtual objects. To achieve low-latency visualizations the prototype implementation is based on the OpenGL scene graph OSG [16]. Another software aspect of the proposed system is the support of several different modes for operating in different mixed realities. For each mode the reference coordinate system, e.g. virtual vs. mixed reality, the interaction technique, and the tracked objects may change and has to be correctly handled by the software which, therewith, combines all the challenges of common augmented and virtual reality applications.

In the following, the implementation aspects of the aforementioned modes are described in the following paragraphs.

TUTORIAL VIDEO – For training personal to perform a certain task it is often more efficient to show a pre-recorded video clip of real, already trained workers accomplishing the same task. New users can mimic what can be seen in the video and later adapt the approach to their personal preference. The video clips can be shown as a tutorial before assembly or in repeating parts of the whole clip during the assembly. For rendering video streams are decompressed, copied into a texture, and afterwards used to render a textured quadrilateral for each frame during the playback. This mode was not used during the user evaluation.

VR PREVIEW – This mode displays a VR scene on the HMD and the user is able to navigate, i.e. manipulate the virtual camera used for presenting the scene to the user. Some objects in the scene can be rendered with different material to reflect their importance to the user. The camera interaction is controlled via head tracking. The preview is also able to display a list of possible basic attachment parts that can be install in the scene. Figure 3 shows a rendering of a lathe witch can to be equipped with a motor. The list of available basic types and the different views of the selected object are pre-rendered images and displayed at a fixed screen position, independent of the scene orientation. In addition, to the single 3D model of a machine the whole installation environment can be shown, to give the user hints how the machine is placed in the customer's manufacturing site. Therewith, the worker who has to configure additional units to be installed on the machine can easily see collision problems and can select the best available installation option for each customer. The prototype renders the machine opaque, whereas the manufacturing site and maintenance areas, which are also considered, are rendered semi-transparent. Figure 4 illustrates a milling machine with the possible placement of the control units (orange). The attached maintenance area is visualized in green if no collision was detected and red if the area is obstructed by other installed parts of the manufacturing site (Figure 4 left). In order to simplify the interaction interface for the navigation in the VR scene the view of the worker is always directed to the machine. This limitation was introduced to reduced the distraction of the user form the VR environment, as we noticed during tests that users tend to discover the VR environment and start looking around, not solving their task.

When the user has chosen the installation position of the attachment using the VR preview the prototype switches to an augmented reality manual for the configuration of the attachment part.

AR MANUAL – The internal configuration of attachment parts, e.g. a control unit, is often dependent on the position, where the part is mounted on the machine. The system automatically augments the real environment with virtual parts that have to be installed within the control unit at the correct position. The worker can then easily place the real objects at exactly the same position as the virtual ones, without the need to read technical plans or installation manuals. The interaction during the configuration phase is designed to work with only a single button press which switches the installation manual one step forward to show the next task. The prototype thereby shows virtual, possibly animated installation parts, mounting points, screws to be installed, arrows to mark important positions, and text labels for short textual information. In addition, distinctive features of the control unit are also shown to give the users further hints to recognize the spatial relation, i.e. the edges of the control-unit case as shown in Figure 5.

AV REVIEW – For the final inspection of the control unit and its inner configuration an augmented virtuality view of the real control unit, combined with either a virtual machine or even the whole customer's manufacturing site is supported. Again, the interaction plays an important role for the efficiency of the system. The prototype uses the case of the control unit as an anchor point to the virtual machine or respectively the entire manufacturing site of the customer. The user is able to move the case where the system automatically adapts the augmented virtuality – the machine or the entire manufacturing site – to match the new location. This interaction technique is very intuitive as the user only manipulates real-world objects. Further, the user's viewing direction is also updated which allows the user to examine the real assembled control unit within a virtual environment from arbitrary positions. This mode is very useful for the final control of the assembled unit in order to recheck the location and inner configuration of any collisions or other hindrances.

B. *EXPLORATIVE USER TEST*

So as to gain first information about efficiency and effectiveness, the prototype was evaluated in a small explorative user test. Ten persons divided into two groups participated individually in the test. The task for the persons of both groups was to correctly assemble a computer-control unit casing which is an exterior extension of a customer's CNC machine. The first group was asked to assemble the casing in the traditional way without the usage of the proposed prototype. Therefore a unit-location plan of the customer's factory floor and detailed engineering drawings of the machine in front, top and lateral view were provided. Based on this information, the participant should decide in regard of certain maintenance and clearance distances on which side of the machine the casing should be fixed. Furthermore, dependent on the mounting position, the participants had to determine inner setting and arrangement of the casing. The second group instead was asked to use the developed prototype for the whole task utilizing all the features mentioned in the previous section. The research design of the user test combined qualitative and quantitative methods. As quantitative performance measures the amount of correct task completion and the total assembly time were used. But most information – as appropriate for an explorative study – was gathered through qualitative methods like task surveillance, non-standardized interviews and a think-aloud usability test. During the test the respective participant was observed in detail and his behavior was noted. Moreover the participant had to verbalize his train of thought and his thought process during task completion. Afterwards the subjects answered additional questions regarding the ease of the task completion and their opinion about the way of working. Drawbacks as well as suggestions for improvements were mentioned.

C. *RESULTS*

The result of the usability test shows, that the difference between the two groups is significant: Four of the five participants with mixed and virtual reality support were faster than the participants using the traditional method. The average assembly time was 3:38min in contrast to 5:66min by a task completion rate of 100% in both groups. The huge range of the assembly time of 3:46min in the group using the traditional way in contrast to 1:46min to the AR-VR-Group, however, indicates major problems in reading technical drawings thus rising the question whether the sample was representative enough or not. The qualitative data collection further confirmed the difficulties in reading the floor-plans and the drawings. The MR-VR group mainly complained about unaccustomed wearing of the head-mounted display and the limitation in the field of view which hampered orientation and movement in the room. Some complained on the darkness of the optical-see-through display and the low brightness of the augmented objects. Another problem which was mentioned form participants that were not used to AR visualizations was the slightly misplaced augmentations of a few millimeters. Overall, the results of this first explorative user test indicate potential benefits of MR-VR-support in flexible manufacturing environments, which must be further evaluated with participants and more complex, life-like tasks out of real business practice.

VI. CONCLUSIONS AND FUTURE WORKS

The increasing use of CAD systems makes 3D-models easily available and thus paves the way for wide-spread usage of the proposed MR/VR-systems in the production of highly customized goods. The implemented prototype demonstrates how multiple reality stages can be combined for practical applications and the results of the user test clearly indicated valuable benefits: lower assembly times and error-rates and thus a higher quality, e.g. among other things through an AV review as final inspection at the customer's manufacturing site. Particularly inexperienced workers benefit for the proposed system, as the system provides support for each task via different mixed reality setups. The proposed system may show its real strength in very complex tasks with tricky technical drawings like in the manufacturing of capital goods which is stamped by a high percentage of custom-made solutions, by high numbers of product varieties with simultaneously low batch sizes. In future, we will continue to research applications of different mixed-reality configurations and further evaluate the proposed reality transition systems with co-operation partners of the capital goods industry. Another idea is to use the difference reality vs. actuality vs. virtuality to better characterize different ICT systems. Further, the development of an improved HMD with support for automatic configuration of the AR-VR transition is planned.

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