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Dual Reality for Production Verification Workshops: A Comprehensive Set of Virtual Methods

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Abstract

In automotive industry, planning of manual assembly is getting ever-increasing complex, diverse and variant-rich due to ever-increasing market demands for more models and derivatives with shorter life-cycles. In order to reduce the costs for building physical prototypes before ramp-up processes, we present a comprehensive set of virtual and augmented reality methods for real-time assessments of manual assembly tasks used in interdisciplinary production planning workshops. This novel mixed reality assessment system unifies innovative interaction concepts with display technologies from a variety of domains. True-to-scale floor projections, interactive tangible tabletops, powerwalls and head mounted displays are used in combination with markerless full body motion capture and motion controller interfaces. Therewith, production planners in workshop situations are enabled to collaboratively plan and optimize station layouts, author 3D scenes and assess product and process related topics, such as buildability, reachability, assembly and disassembly routines. An in-depth evaluation on collaborative task performance using differing visualization scenarios is presented and discussed.

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Keywords: virtual production planning; manual final assembly; cyberphysical equivalence; visualization methods; markerless full-body tracking;

1. Introduction

Automotive industry is currently facing changed market requirements. Due to ever-increasing market demands for a bigger variety of models, derivatives and customization options, production planning is getting gradually more complex, since these changes need to come along with more planning and verification effort.

Since early physical prototype cars are highly cost intensive, there is an effort to build less of them during product development process. Additionally not all combination possibilities of derivatives and extra equipment can be physically assessed. Therefor digitalization is one promising approach to overcome these additional efforts [1]. Digital methods for assessment of product and production verification are already well-established in industry, so-called methods of the digital factory [2]. Digital verification methods are able to improve process models as well as product quality. Simultaneously, higher confidence in planning quality and less errors during ramp-ups are achieved in earlier stages [3].

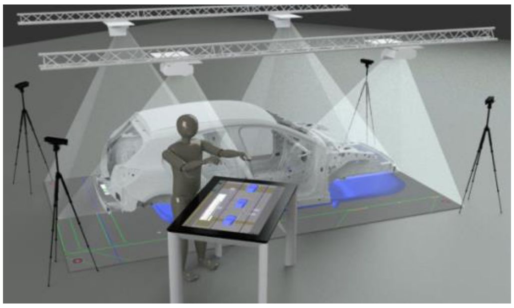

Figure 1: Holistic set of virtual methods integrated to a mixed reality assessment system for production verification workshops

Even when building less physical prototypes, verification tasks have to be performed in the same time-frame and level

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of quality. Filling this gap, physical mock-ups (PMUs) [4], digital mock-ups (DMUs) and mixed mock-ups (MMUs) [5] are used in product engineering to improve product quality and speed up development processes. For production engineering, digital and mixed mock-ups are not deployed for extensive use yet, since virtual technologies still are still in research state or complex expert systems. Additionally the preparation of virtual and mixed assessments scenarios are highly time-consuming.

In contrast to the state of the art, we propose a set of virtual methods (see Figure 1), in order to enable immersive, collaborative and intuitive workshop situations, since these interaction and visualization techniques positively influence task solving performance and quality [6]. Direct interaction using virtual and real models simultaneously, is one of the core concepts for interface components (compare [7]).

The remainder of the paper is structured as follows: It starts with a introduction on state of the art and related work in the context of virtual production planning research. Then an overview on typical tasks in production verification workshops and their organization is given. Based on these insights, a mixed reality assessment system is presented. Subsequently, three exemplary applications using different combinations of technologies are introduced. Then, an evaluation on task performance and error rate within workshop situations using different visualization techniques is presented. The paper concludes with an overall assessment of findings and outlook on further optimizations options.

2. Virtual methods for production planning

In the past decades, various publications have been released in the domain of virtual environments (mostly virtual reality) and interaction design for industry purposes. Two different clusters of publications can be recognized: Conceptual publications on methods and technologies and specific application related publications.

Conceptual publications: In 2010 Seth et al. presented a profound literature review on research in virtual reality for assembly methods [8]. Winkes [9] presented in 2015 a general method on how to use virtual reality for assembly planning and proposed a procedure on how to avoid possible planning failures. Zachmann presented in his doctoral thesis [10] a holistic framework, algorithms and techniques for virtual reality in assembly simulation. The three main contributions are efficient interaction metaphors, an easy to use authoring tool and physics-based simulation with collision detection algorithms.

Application related publications: Besides theses conceptual and technical advances in research, many specific application related virtual assessment publications have been presented. Already in 1999 Gomes de Sá investigated the steps needed to applicate virtual reality (VR) in the assembly and maintenance process of automotive industry and discussed how to integrate it into business processes [11]. Aurich et al. presented results on virtual reality-based continuous improvement workshops (CIP) for an agricultural machinery manufacturer [12]. CIP workshops are also carried out by production planners but in contrast to production preparation, they focused on critical work stations for their iterative optimization workflows. A large part of the previous work is related to factory and assembly station layout planning [13–15]. In this context, Pentenrieder et al. presented an augmented reality (AR) based application to overlay a shop floor with a virtual model of an assembly line [16].

Besides these academic approaches, there is a wide variety of commercially available virtual reality products for industrial planning, simulation and verification. For example, imk automotive, Dassault Systems, Siemens, ESI, etc. offer software bundles for virtual assembly simulation tasks, like virtual training, station layout design, process and factory planning, knowledge capture or ergonomic evaluations.

Yet, none of the above mentioned systems cover multiple assessment use cases, none offer a mixture of efficient interaction metaphors, none are optimized for collaborative workshop situations, and none offer a seamless integration of PMUs at the same time.

3. Verification workshops for final assembly planning in the virtual continuum

Production planning workshops aim at improving planning quality for multiple disciplines in order to guarantee an efficient and smooth ramp-up of producing products. Since the domain of production planning is cross-functional and interdisciplinary, these moderated workshops bring together managers, planners, product engineers, ergonomics experts, time-measurement specialists as well as assembly operators. All of these stakeholders directly profit from the domain specific knowledge and hands-on experience from each participant.

In purely hardware-based workshop situations, all assembly parts and resources have to be physically present. Assessment tasks are solved by assembling the PMUs. In practice, it depends on the current state of the product development cycle if digital or hardware-based production verification workshops are being held. Overall, the number of traditional PMU-based scenarios is decreasing. However, both for hardware and virtual assessments, typical assessment tasks remain the same:

- Reachability
- Collision free assembly and disassembly paths
- Ergonomic evaluations
- Logistics
- Station layout and walking paths
- Work task description verification
- Time verification of assembly process
- Operating resources and handling equipment verification

Depending also on the product development cycle and the remaining planning vagueness (see [17]), the duration and verification tasks differ vastly. For example, for a new product, multiple verification workshops take place for a couple of weeks, for derivatives only delta-contents are being validated in a couple of hours.

Currently, virtual production verification workshops are carried out either purely with the help of hardware-based prototypes or solely in virtual space but not yet in the virtuality continuum with a continuous transition.

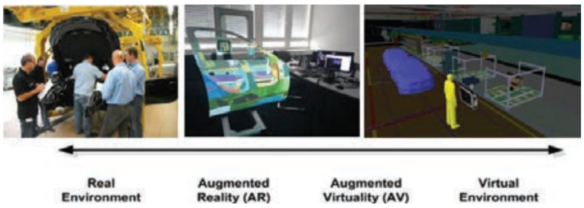

Figure 2: Virtuality continuum for production verification workshops following Milgram and Kishino [18]

As depicted in Figure 2 the virtuality continuum offers several characteristical increments of augmented and virtual reality. Such mixed reality scenarios can be extended to ‘dual reality’ which is defined “as an environment resulting from the interplay between the real world and the virtual world” [19], which inherits the ability to “mutually reflect, influence and merge into one another”. Transferring this idea to the automotive production planning, this leads to various workshop constellations which are held between the traditional hardware-based and digital world. These concepts of Lifton and Paradiso [19] share several characteristics and long-term objectives with research on ‘cyber-physical equivalence’. Both research areas influenced the concept of the proposed methods in chapter 4.

Consequently, depending on the assessment scope and availability of PMUs and DMUs, there are multiple possibilities to match verification tasks in workshop situations with physical and virtual assessment methods (see Table 1).

Table 1. Variation possibilities of assessment elements in virtual and augmented realiy scenarios

Assessment Elements	Physical Mock-up (PMU)			Digital Mock-up (DMU)		
Base part (e.g. car body)	up-to-date, high fidelity PMU	out-dated similar PMU	simplified PMU	up-to-date, highly reliable DMU	out-dated or vague DMU	simplified or erroneous DMU
Assembly parts						
Resources						
Human	Real worker performing task			Full body tracking, manipulation or synthesis of DHM pose and motion		

In general, during product development process PMUs are increasingly available. For example PMUs could be take-over parts from predecessor models, 3d prints or other related products. Therefore similar PMUs could resemble the planned part in terms of geometry, weight and mounting. Since the number of combinatory possibilities of assessment elements with digital and physical models is too high, it is not possible to determine a priori, which method will suit best the requirements of the specific verification task (see [7, 20]). This gap can be bridged by using a system which enables workshop managers to use all techniques instantaneously.

4. Mixed reality assessment system

The presented integrated verification system is particularly designed for collaborative assessment workshops. The proposed system setup enables workshop managers to combine and blend traditional hardware-based elements with virtual elements, depending on the assessment task. Technical operators are supporting the workshops and they are enabled to define the degree of virtuality as needed for their specific verification task. This mixed method assessment system offers an integrated and co-located mix of physical and virtual components.

The core of the applied virtual reality software framework is a proprietary 3d engine. It uses a visibility-guided out-of-core rendering technology, so that CAD product data can be visualized in real-time, mostly independent of the data volume. It supports stereoscopic rendering for powerwalls.

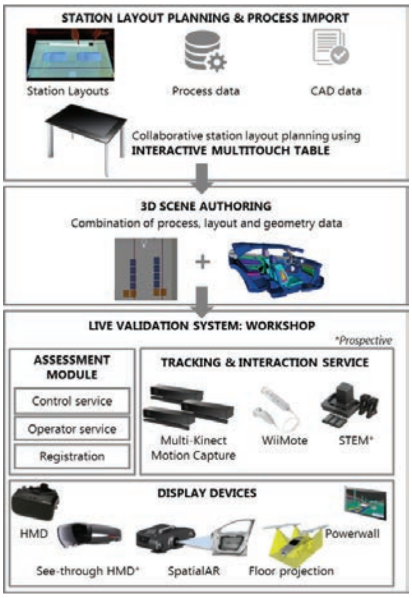

Figure 3: Preparation and live verification workflow and system components of the mixed reality assessment system.

This software framework has been built in order to serve the following purposes:

- Interactive station layout planning, process planning and walking paths simulations in bird’s eye view using the interactive tabletop Microsoft PixelSense.
- Interactive process verification, buildability and reachability assessments using VR technolgies.
- Ergonomics evaluation with a digital human model by direct pose manipulation or real-time tracking.

In order to enable these use cases, the following features have been integrated into this system:

- Interactive distributed rendering between controller service and Microsoft PixelSense bird’s eye view layout planning
- Multiple VR interfaces and tracking devices via standard communication protocols (VRPN, ARVIDA).
- Head mounted display enabled rendering (Oculus Rift)

Before using the live validation system in a mixed reality workshop situation, a virtual manufacturing scenario has to be generated. Therefor multiple data sources have to be fused, such as assembly station layouts, CAD data and processes:

Layout planning and process: Process data contains textual information on work task descriptions. This data also includes preplanned task duration, sequences and references to the material of assembly parts. Optionally the whole CAD factory layout data can be imported. All assembly parts have to be correctly assigned to the carriers and task descriptions.

3d scene authoring: Secondly, the whole CAD product data is imported, converted into a high-performance VR data format and visualized. Subsequently, all process information and product assembly parts have to be merged, so that the status of assembly at the respective station can be visualized. For this process, automatic assignment of both product and process supports fast authoring for the VR scenes.

Besides this data preparation workflow, several technical steps have to be carried out to set up all tracking and display devices and their associated services for the live assessment. For each work task the technical operator activates the tracking components and display devices which are needed for the respective assessment.

5. Live Validation System

Having prepared the virtual manufacturing environment and having registered all technical components, the mixed reality assessment workshop system can be utilized. During workshop situations, a technical operator is handling the control service to continuously optimize the viewpoint for the powerwall visualization, augmenting virtual models on PMUs and handling progress of assessment. The assembly operator performs the manual assembly tasks within the tracking environment. They use the HMD device optionally to immersively execute the task in situations with few PMUs available. Since this system offers markerless full-body tracking system, workshop participants can effortlessly switch roles. They are able to navigate through the working steps by using the WiiMote interface and influence the assembly status during immersive assessment (see Figure 4). Virtual assembly parts can be interactively moved and mounted by attaching and detaching them from the virtual hand.

Figure 4: Mixed reality assessment system: Exo-perspective on powerwall (left) and first person perspective rendering with menu in 3d space (right)

The remaining experts are examining, analysing and discussing both the real and virtual world, each one with respect to his specific domain. To show up the potential of the integrated mixed reality assessment system in the following chapter three exemplary use cases will be evaluated.

5.1. CAD data quality assessment using a powerwall

A typical task in the early production verification process is the assessment of product geometric data. This aims at first ensuring that data quality is good enough to be used for the assembly simulation second identifying optimization potential in terms of buildability and assembly-oriented product design. Typical use cases are:

- Verification of product geometry (collision detection in static assembled position)
- Verification of assembly sequence (collision detection during assembly operation)
- Identification of tool needs
- Verification of design for manufacturing topics (for instance prevention of blind assembly, standardization of fastening elements to avoid multiple tool use or checks of "poka-yoke" principles)

The focus during this phase lies on the product, not on the execution of the assembly process itself. Therefore the main components of the verification setup are visualization components (VR on Powerwall and SpatialAR using PMUs).

5.2. Accessibility and Ergonomics Assessment using HMD and tracking

Before starting the optimization of assembly processes, an important aspect in verification phase is to ensure the buildability of the car components by humans. In other words, it has to be ensured that a worker can access all the mounting points of interest necessary for the assembly tasks.

Moreover, different process alternatives have to be evaluated like various assembly operator postures or positions (out of the car, inside the car etc.) or sizes. Not only accessibility but also ergonomics aspects have to be analyzed.

The assessment itself is being carried out via a markerless Multi-Kinect tracking (see [21]). However, since it must be ensured that their movements are as close as possible to reality and that the verification results are reliable, the tracked user needs to have a 3d perception of the scene and thus the possibility to evaluate virtual distances. This feature is realized by using a HMD which depicts the scene from the user's point of view. This requires also a precise and real-time tracking of the operation head position.

5.3. Interactive Station Layout Planning using interactive tabletop surface and large scale floor projection

During production preparation, station layouts for the future assembly lines have to be determined and optimized. This also comprises process optimizations, like sequence of task descriptions. Currently in automotive practice, static simulations are carried out with paper-based methods or PowerPoint-based station layout descriptions.

To optimize this process of layout planning and to perform dynamic simulations, an interactive tabletop hardware Microsoft SUR40 is employed with tangibles (see Figure 5). For station layout planning, the assessment system switches to bird’s eye view and offers functionalities to plan and optimize material zones. The strong perceptual coupling between the tangibles and visual representations of the station layout helps the users to understand spatial connections. The user interface is designed for multi-user collaboration between the workshop participants and therefore engaging all participants to interact with the virtual model. A scalable floor projection enabling a true to scale visualization supports the planners to verify their digital planning data easily [22].

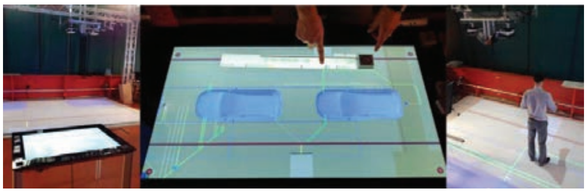

Figure 5: Interactive and cooperative station layout planning and simulation (middle) in combination with true to scale floor projection system (left and right)

6. Evaluation on collaborative workshop situations

In order to gain insights into the performance of the proposed system, an in-depth evaluation is presented: Two different visualization technologies (monoscopic display and SpatialAR) are examined how they support the generation of a common spatial understanding in a PMU-based workshop situation. The baseline is a traditional verbal communication without the support of display devices. In this abstracted, but nevertheless representative task, two participants have to get a common understanding on spatial relations of mounting points (e.g. for assembly parts) on the PMU. Therefore, a process expert (PE) has to locate the position of all relevant components within the CAD model and subsequently share this knowledge with the technical operator (TO). This task is performed in three different ways: pure verbal explanations, using a 75” display with CAD data and using Spatial AR, highlighting the respective parts directly on the PMU.

6.1. Experimental Setup

As depicted in Figure 6 a car chassis is placed in the middle of the experiment’s room. Next to it a 75” monoscopic display and the SpatialAR projector are located so that the contents can be seen by the TO and both devices can be controlled by the PE.

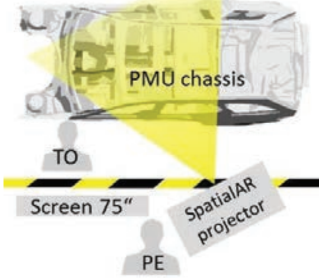

Figure 6: Experimental setup on user collaboration: A process expert (PE) explains the technical operator (TO) spatial relations using three different methods: verbal description, support of display and SpatialAR

The PE receives textual process descriptions with corresponding names of assembly parts from the experiment leader. Therewith the PE has to locate the mounting points of the assembly part in CAD model and has to guide the TO, which part has to be assembled on the real chassis. The TO has to locate and reach the respective spot on the PMU as fast as possible with his index finger. Three different scenarios have been carried out:

- *Verbal descriptions:* PE stands behind the projector and verbally describes the position without pointing.
- *Monoscopic 75” screen*: PE shows the CAD model to the TO on a monoscopic 75” screen.
- *SpatialAR:* PE projects the mounting points directly onto the PMU using SpatialAR.

Time-measurement begins when the experiment leader passes the instructions to the PE. The TO and PE have to collaborate in order to solve this task. The experiment ends, when the TO touches a mounting point with his index finger both agreed on. The experiment leader will measure the overall execution time and error rate.

The experiment has been carried out 11 times with 22 participants who are all production planning employees. Each team has carried out all 3 scenarios with each 10 data sets (330 data sets in total). 40 different mounting spots have been prepared and presented in a randomized order for each run with no repetition.

6.2. Results

The results showed up a strong correlation between collaboration performance and the use of different visualization technologies for achieving the same goal: A common understanding of spatial relations in a workshop situation.

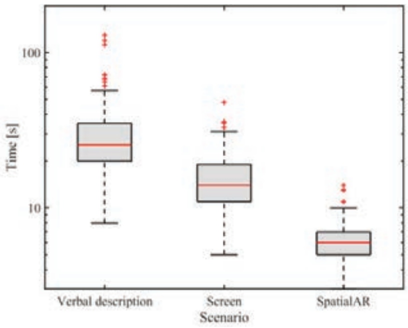

Figure 7: Evaluation on mean times and standard deviations (sorted by descending verbal description results)

Whereas verbal descriptions averaged in a completion time of 25.5s (19.5s mean standard deviation) the same tasks could be achieved almost twice as fast (14.0s mean time and 7.5s mean deviation) by using a DMU on a 75” screen (see Figure 7). Using SpatialAR technology in this experiment leads to an additional significant reduction of almost 2.5 times (6.0 s mean time and 2.1 s mean std. deviation) in comparison to the usage of DMUs on the monoscopic screen and almost five times as fast as verbal descriptions. The results from both visualization scenarios are error-free, whereas in the results of the verbal description scenario one error in 110 data sets has occurred.

6.3. Discussion

Two major influence factors could be determined for the significant reduction of time by using these visualization technologies: During verbal descriptions, collaboration was negatively influenced by differing mental coordinate systems (COS) of the users. For instance the participants did not agree on, if the word “left” refers to the car’s, the PE’s or the TO’s COS, whereas this effect is eliminated, when both participants could see a visualization. A second major impact factor was time-parallelization during task solving. Both visualization technologies enabled the TO anticipating the search of the spatial position within the DMU.

The experiment leader intentionally gave no explicit information on the trade-off between task solving speed and error rate. As the results showed, only 1 out of 330 data sets failed. This shows up, that the participants rather double-checked their results with higher times than getting faster at the expense of a higher error rate.

This evaluation does not include quantitative performance measurements for all proposed visualization and interaction technologies presented in chapter 4. But it can be summed up that an adequate choice of methods and tools for workshop situations has a positive, significant influence on the overall workshop performance.

7. Summary

We presented a holistic set of virtual methods integrated to a so-called mixed reality assessment environment. This novel system enables production planners and workshop participants to interactively and immersively validate their respective processes, such as product buildability or assessment of layout planning.

Furthermore, workshop situations directly profit from the proposed mixed reality assessment environment, since the variety of offered display possibilities support user collaboration. While single users are using immersive display technologies the other workshop participants still have the powerwall visualization for assessment. This system offers two key advantages in comparison with state of the art commercial virtual assembly tools: It is natively designed for collaborative situations and by giving the workshop managers the flexibility to choose from a variety of display and interaction devices, discussions can be held more efficiently.

In the next steps, multiple new technologies will be integrated in the mixed reality assessment environment. Object tracking for part assembly will be enabled by markerless edge tracking system. Additionally optical see through HMDs will augment virtual data onto the PMUs.

Besides the technical improvements, the integrated mixed reality assessment system will be evaluated in several pilot cases with productive data.

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