Designing Collaborative and Coordinated Virtual Reality Training Integrated with Virtual and Physical Factories

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***Abstract*—Rapidly changing customer demands, regulations and technologies drive the complexity of products, processes and production systems, as well as shorter product and factory lifecycles. In order to handle such complexity while decreasing the time-to-market, immersive virtual reality (VR) technologies are increasingly being used in industry to support product and factory lifecycle engineering processes, such as (re)design, validation and verification, learning and training. However, the design and development of multi-user VR training for complex and manual production processes remain a challenge for industry. The integration of VR training simulations with virtual and physical factories could support the handling of such obstacles in terms of efficiency and effectiveness by increasing the precision, accuracy and reliability of data used in VR simulations. In this study, we present a collaborative and coordinated VR training model and its data integration with virtual factory tools and manufacturing execution systems for a wind turbine assembly scenario. A demonstration has been performed and evaluated by industry experts. The preliminary evaluation results show that integrated collaborative VR training has significant potential for more efficient and effective training, as well as enabling new use cases for industry.**

Keywords—Virtual Reality, Virtual Factory, Collaborative Virtual Reality Training, Virtual Reality Simulation

I. Introduction

The design of a new production process and the corresponding assembly training is a complex and time-consuming process. Moreover, rapidly changing customer demands cause increased complexity in product and production systems, as well as a decrease in product and production lifecycles. The foundations of the industry 4.0 paradigm comprise increasing integration of all the production agents (people, machines and resources) in the form of cyber-physical systems and increasing decentralisation of production processes [1]. Therefore, researchers and industry experts are focusing on virtual factory (VF) tools as an integrated high-fidelity simulation in order to handle the concurrent evolution of product, process and production systems [2], [3]. In this regard, industry 4.0 recommends the adoption of a series of technologies known as the nine pillars of technological advancements [4], including the comprehensive simulation of processes, horizontal and vertical integration of systems, and virtual and augmented reality (VR/AR).

VR is used in various ways, including product and process design, training, remote collaboration and communication in different industries [5]. Using a virtual environment for learning and training is a safer and more cost-effective method, especially for dangerous tasks and training with expensive physical builds [6]. VR training is also essential for knowledge management, especially in distributed and manual collaborative assemblies. Collaborative virtual environments provide advantages for interpersonal coordination for the feasibility of transferring the simulation outcomes to the real world [6]. However, the design and development of sophisticated VR training is challenging and requires serious time and effort. Integrating VR training to virtual and real factory environments with bidirectional data synchronisation, as well as utilising technologies like discrete event simulation, 3D laser scanning and a digital twin, could support the design, development and use of immersive VR training simulations. Environmental simulations, for example, can be generated by discrete event simulations to understand CAD objects interacting with the surrounding environment, which can be created quite realistically by using 3D terrestrial laser scanning technology and objects in the VR simulations can be linked to their physical counterpart for more realistic representations. Such an integration concept can enable entirely new use cases. Data integration of VR training with product and production systems can increase the precision, accuracy, reliability of training and efficiency of the design and development of such training. However, there is a need for proper conceptual models, architectures and methods for the integration and evaluation of such artefacts in real-life cases. Thus, this makes the question of how to utilise such new technologies to improve the design, development and use of collaborative and coordinated VR training a relevant research topic.

Decreasing the time-to-market by utilising VR training to improve learning curves, especially for the ramp-up phase, can be considered as the primary motivation for industry.

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Decreasing physical builds for training can also be considered another significant cost saving and motivation in the wind turbine manufacturing industry. Manufacturing Execution System (MES) provides an interface to the actual physical production by capturing and recording "as-built" data regarding the actual/physical transformation of raw materials on the shop floor (e.g. processes, materials, personnel, machines and support services) in real time. Ongoing research activities at the case company, Vestas Wind Systems A/S (Later Vestas), in the context of industry 4.0, including VF, digital twins and 3D laser scanning, provide an opportunity for the development and demonstration of a multi-user VR training integration with physical (MES) and virtual production systems (VF). Thus, a collaborative and coordinated VR training demo is designed, developed and integrated for physical and VF systems for wind turbine manufacturing scenario of Vestas.

The need to reduce the time-to-market remains an essential challenge, while the complexity of product and production processes is increasing. Improvements in the hardware and software of VR systems enable the use of immersive VR for learning and training simulations to reduce the ramp-up time. However, despite the sophisticated interplay of the technologies used, VR is not a turnkey solution yet. Designing and developing a multi-user complex VR training and sustaining the precision and reliability of the data used in the simulation remain difficult and costly processes.

The identified problems can be listed as:

- The difficulty for utilising VR for complex (collaborative and coordinated) manual assembly training;
- Low precision, accuracy and reliability of data used in VR training;
- Low efficiency of VR training (re)design.

Bidirectional data integration of VR simulation with a VF, which is considered as a potential solution to integrate product, process and factory domains [7], and MES can support solving the problems above. A VF demo, which was developed for the earlier phases of the research work, provides an opportunity for designing, developing and demonstrating a solution.

The work presented in this study aims to support manufacturing companies in utilising immersive VR technologies for complex multi-user learning and training simulations integrated with virtual and physical factory systems. The objective of this work is to explore artefacts (models, methods and procedures) to solve the abovementioned problems. In particular, the objectives of the work can be listed as follows:

- Designing and developing a multi-user VR training simulation concept for a collaborative and coordinated manual assembly operation scenario;
- Designing and developing a bidirectional automated data integration concept between VR training, virtual and physical production systems;
- Demonstrating the design in a real-life case for enhancing the data-centric model-based VR training simulation.

The rest of this study is organised as follows. The second section presents a review of the relevant works in the literature. The third section presents the conceptual model of integrated collaborative VR training and its data integration and implementation. The fourth section covers the case study development, demonstration and evaluation. The fifth and sixth sections contain the discussion and conclusion, respectively.

II. Related Work

In 1965, Ivan Sutherland envisioned "The Ultimate Display", which conveys information not only to the eyes, but to the ears, hands, nose and mouth [8]. Sutherland set the stage for VR research by stating that: ''The Ultimate Display would, of course, be a room within which the computer can control the existence of matter.'' [8]. However, it took almost 30 years to see VR technology in industry and academia [9]. In the mid-1990s, VR was not mature enough but was still investigated because of its potential by companies including Caterpillar, Chrysler, Boeing and NASA, as well as some academic institutions. Just a couple of years later, there was a remarkable adoption of VR in industry for real-work applications [10]. In the following years, research contributions within the VR knowledge base have been exploited both by industrial and academic communities.

VR is generally described as "a set of technologies that enable people to immersively experience a world beyond reality" [11]. Since the 1990s, VR has been adopted by various industries to serve different needs, including concept design, develop and evaluation [5], learning and training for high-risk procedures [12], experiencing virtual spaces before building physical ones [13] and the visualisation of abstract data [14]. VR is also used to support manufacturing simulations to overcome the complexity of generating various modelling and simulation methods by providing better user interfaces [15]. The use of VR technology for the training and design of product, process and production systems has built up over time. Recent improvements in simulation tools provide an easy-to-use 3D simulation environment together with the capability of VR [16].

Several promising works have used VR in a training and manufacturing context. Al-Ahmari et al. [17], for example, developed a virtual manufacturing assembly simulation system (VMASS) to support training operations for assembly operations. Abidi et al. [18] extended the VMASS study by evaluating VR assembly training in terms of the effectiveness and transfer of training. Their study showed that VR training decreases the actual assembly time and error rate compared with traditional training and provides a risk- and injury-free training environment. A training system based on VR and process mining was developed and evaluated by Roldán et al. and the results showed that the system has competitive advantages over traditional systems [19]. A comprehensive literature review was conducted by Feng et al. [20] to understand the developments and implementation of immersive VR in a serious game approach in the context of an emergency evacuation. They proposed a conceptual framework for the effective design and implementation of immersive VR-based serious games. An interactive and immersive VR training system to simulate human-robot cooperation for educational serious game purposes was presented by Elias, Dimitrios and George-Christopher, with the results showing positive prospects for the use of VR in human-robot collaboration training [21].

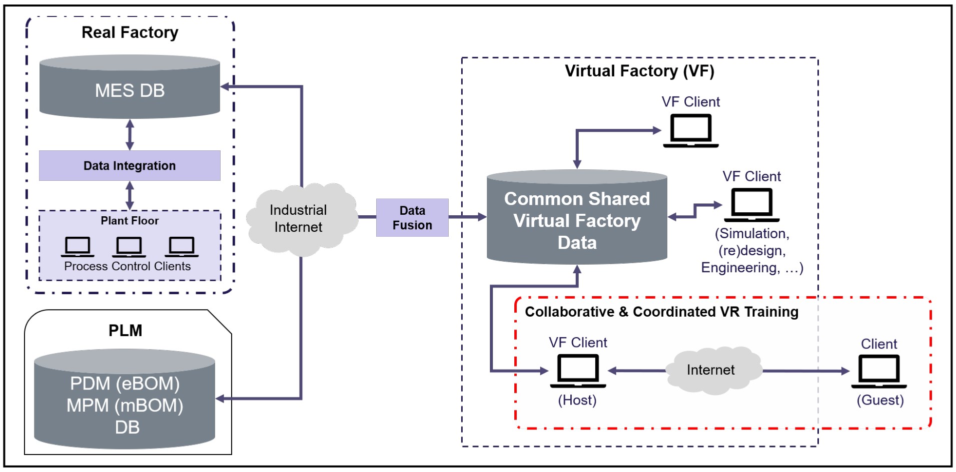

Figure 1 Data integration architecture

Some reviews have focused both on the knowledge base and application contexts, showing the benefits and gaps in the VR training subject. Menin, Torchelsen and Nedel [6] reviewed 63 articles to better understand the impact of VR technology on immersive simulations with serious purposes, to present a taxonomy to VR simulations and to discuss whether methods and participant profiles affect results. Research shows that participants can influence the result of the experiments based on their video gaming experience. Participants who have video game experiences have positive performance in the completion time of the VR training simulation, but such experience does not influence the understanding of the manufacturing operation [22]. Berg and Vance conducted an industry survey covering on-site visits with 18 companies and interviews with 62 people from various companies and disciplines to present the current state-of-the-art of VR, particularly in engineering-focused businesses [11]. They stress that the recent developments in affordable VR hardware and software have increased the potential and strategic importance of VR for investigating questions regarding visibility, ergonomics, quality, data visualisation and communication. They also address several challenges including: 1) the need for environmental simulations that help to understand CAD objects interacting with the surrounding environment; 2) difficulties for model generation in terms of adding colour, texture, kinematic interaction and material properties [11]. Mourtzis, Doukas and Bernidaki [23] investigated the evolution and recent developments of simulation technologies in industry, as well as addressing the gap in the use of VR and computer-aided manufacturing systems for collaboration and communication.

The abovementioned research works show that VR technology has already proved its value in design, evaluation, validation and training. However, there are still challenges in terms of designing and simulating interactive VR environments. The VF, as an integrated simulation environment, provides an opportunity to design and simulate the model in the context of factory, product and process domains. Integrating VR training with virtual and physical factory systems may contribute to handling the challenges addressed above. In this regard, the proposal of a collaborative and integrated VR training system is presented in the next section.

III. Proposal for a Collaborative and Integrated VR Training System

A. Design Science Research Methodology

Since the abovementioned problems and objectives call for a design-oriented information system (IS) research approach by targeting the iterative construction, implementation and evaluation of artefacts, DSRM is considered the relevant methodology, incorporating situational adaptations of the artefacts, as well as covering the broad problem scope [24]. Design science in an IS seeks for the creation of innovations or artefacts that represent the ideas, technical capabilities, actions and products required to achieve the design, implementation, analysis and use of information systems. Thus, "design science research (DSR) is research that creates this type of missing knowledge using design, analysis, reflection and abstraction." [25]. DSR is ideal in contributing to the knowledge domain and application context of digital innovation because DSR focuses on both the design and deployment of its innovative artefacts [26]. Artefacts of DSR evolve through numerous design and evaluation cycles [27], and they are introduced to the problem space when they are mature enough to contribute with prescriptive knowledge. The research activity presented in this study also requires iterative design, implementation and evaluation cycles to achieve defined

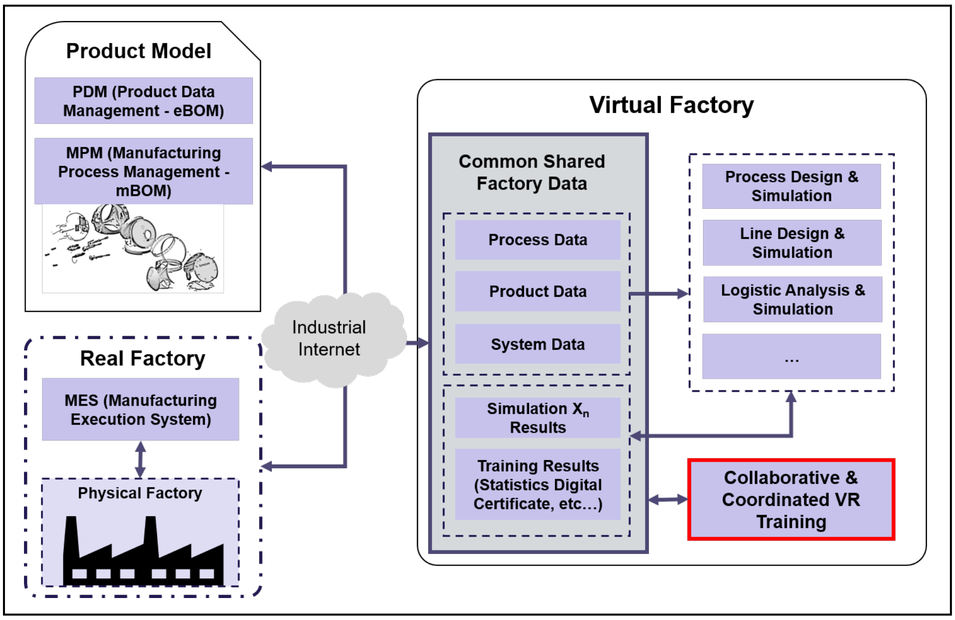

Figure 2. Virtual Factory model extended with collaborative Virtual Reality training.

objectives. Therefore, DSRM is chosen as a primary methodology for this research.

B. Extended Virtual Factory Architecture for Data Synchronisation

A VF, as a high fidelity integrated simulation environment [3], represents a factory as a whole. The VF is also considered as a prerequisite to handling management and concurrent evolution of product, process and production systems [7]. Learning and training are also two of the critical activities in managing changes/evolution in product, process and system domains, mainly to tackle a learning curve and long time-to-market problems. Simultaneous generation of models in these domains becoming more related to designing and developing relevant training in the context of digitalisation. Changes in product models require (re)design of the associated production processes. Such processes generally define the requirements for the corresponding learning/training. The statistical results of learning can be useful for the design and planning of production systems. An increase in the complexity of models created for these activities makes bidirectional data integration significant for efficiency. Thus, it is considered that the integrating VR training to VF architecture, which is also integrated to physical production environment via MES can enable real-time data acquisition in VR training, as well as supporting the simultaneous engineering of models in VF tools.

Integrating physical devices and environments with virtual environments has been tackled by a number of different works [28]. Figure 1 shows the data integration architecture of VF including multi-user VR simulation. The details of the architecture are not disclosed to protect the interests of the industrial stakeholder. Nevertheless, there is no conflict of interest to disclose the number of works for better understanding the integration architectures of physical experimental devices into virtual environments. MIT's iLab Project [29] is focusing the integration of remote experiments and simulations into virtual environments. A remote lab is developed by University of Deusto based on a 3D-based virtual environment Second Life [30] to control remote experiments. An approach for the communication between physical devices and virtual environments was developed by Stevens Institute of Technology [31] and a pilot virtual laboratory system was implemented for remote experiment [28]. An architecture that integrates a number of robotic platforms in immersive virtual environments was presented recently in [32]. The above-mentioned works present integration architectures of VR with physical settings that are examined for the subject in hand.

Figure 2 shows the VF architecture extended with multi-user VR training simulation. VF system is connected to the MES database and updating the real production data at particular time intervals, which can be set as seconds. Different VF design/simulation tools can import process, product, and production data and/or output data from other design/simulation tools. VR training simulation is designed to import the data from a common shared data repository automatically. The architecture also allows for designing and developing Digital Twin (DT) of physical entities on the shop floor.

A suitable VR training, VF and MES data integration model as a proof-of-concept is decided together with shop floor workers and developers. Details of the integration design are presented in the next section.

C. Virtual Reality Training and Virtual and Real Factory Data Integration Model

The data integration between VF, MES and VR training simulation is shown in Figure 3. VR training simulation and VF line simulation both are connected to MES, which provides real-time shop floor operation data and common shared factory data repository, which stores data from other VF design and simulation tools. This integration can enable the use of data in multiple simulation tools and multiple times. Extension of this integration of simulation tools for multidisciplinary analysis and optimisation of manufacturing

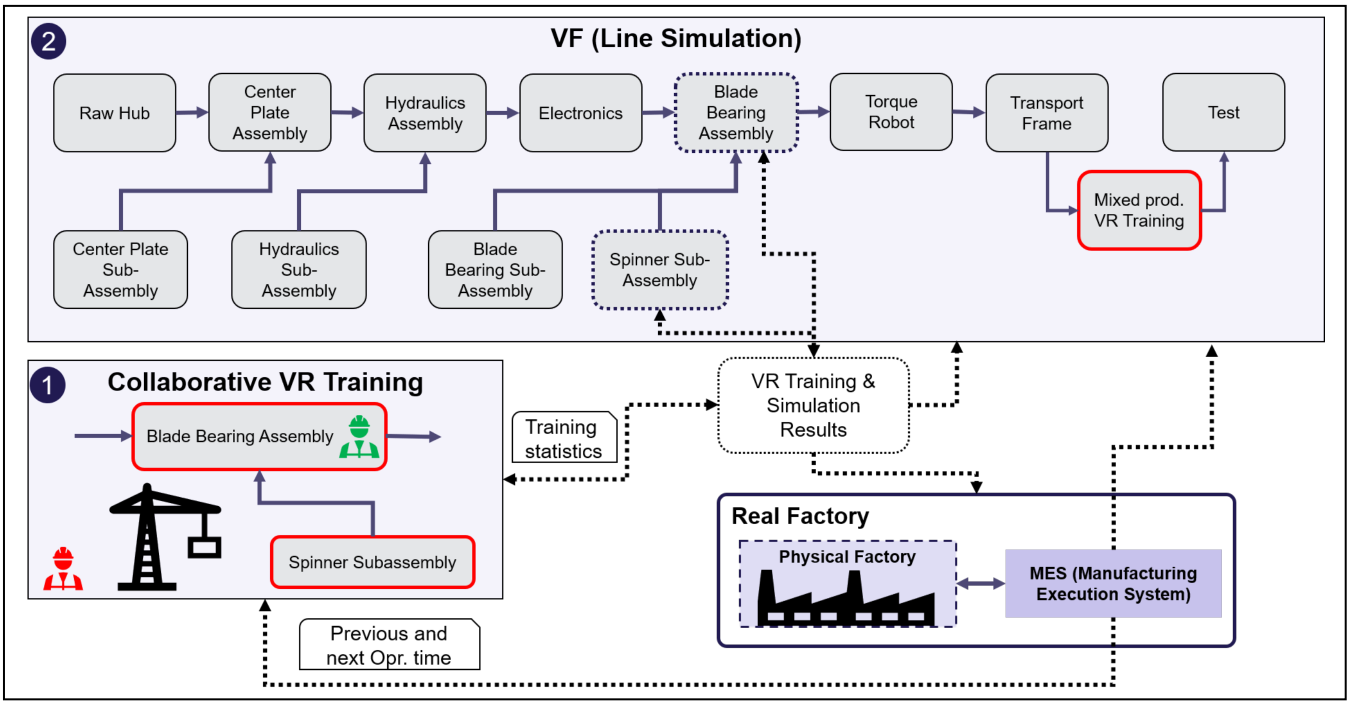

Figure 3. Virtual Reality training, Virtual Factory and Manufacturing Execution System data integration model.

systems and its potentials for optimisation and efficiency is also addressed by Delbrugger et al. [33].

IV. Case Study – Collaborative and Coordinated Training Scenario

The definition of collaborative work is often cited in the literature to be that of Karl Marx "multiple individuals working together in a planned way in the same production process or in different but connected production processes" [34] while coordination is defined as the "management of dependencies among independent activities" [35]. Collaboration virtualisation theory [36], containing three categories of constructs that affect collaboration virtualisability, namely, team, task and technology, was utilised during the design of the scenario. Figure 4 shows the concept of collaboration and coordination work scenarios.

A manual assembly scenario that requires a collaboration of two workers in one task with coordination of one worker between two tasks was suggested by the shop floor workers of Vestas for the design and development of the demo. Figure 5 shows the training scenario of multi-user VR training for blade bearing (BB) assembly operation. The VR training simulation imports the historical operation data directly from the MES and shows the average operation time in the VR training environment (Figure 6). This operation time allows trainees to know whether their performance causes a block or hunger in the assembly line. The operation starts by moving BB to the hub for assembly by a crane operator who has a fixed location in a VR environment. The crane operator is needed to be guided by the assembly operator who can have a better visual of moving parts. When the BB is located, the assembly operator fixes the BB with the first bolt. After the first bolt is assembled, the crane is free to support spinner assembly operation. The crane operator should coordinate his or her time until the assembly operator finishes installing the bolts. As soon as installing the bolts task finishes and the hub is turned for the new BB, the cycle starts from the beginning and repeats three times in total. When all tasks are finished, the training simulation extracts the total training time data to be used in other VF tools and MES. Development and

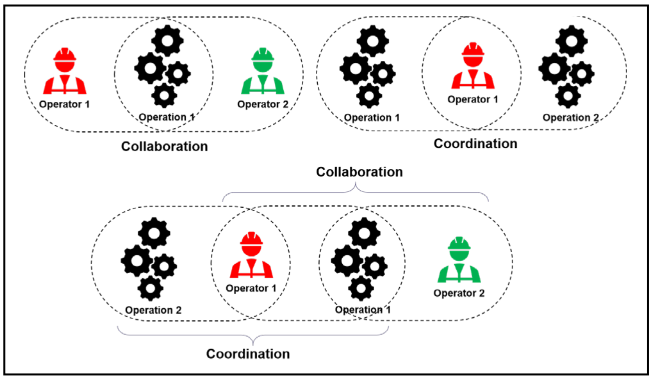

Figure 4 Collaboration and coordination concept

demonstration of the designed system are presented in the next section.

A. Development

The CAD models of the product parts were exported from the product data management system and processed by Creo software to simplify the models. A Unity 3d™ game engine was used for the compilation of assembly, rendering, physics, and simulation of multi-user VR training. Photon Unity networking packages were used to enable multiplayer by integrating multiple builds in runtime. These packages allow us to develop and use flexible, scalable and real-time VR simulations/games just by connecting to the internet. Two immersive head-mounted devices supporting head tracking are used to fully exploit the tracking, navigation and immersion capabilities of the VR training system. SQL server and management tools were used for data integration between MES and VF simulations. In order to connect the industrial internet, one of the PCs provided by the case company with required networking and encryption tools was used.

B. Demonstration

The first version of the multi-user VR training simulation was demonstrated to six industry experts who have more than five years' experience and two scholars at the MASSIVE

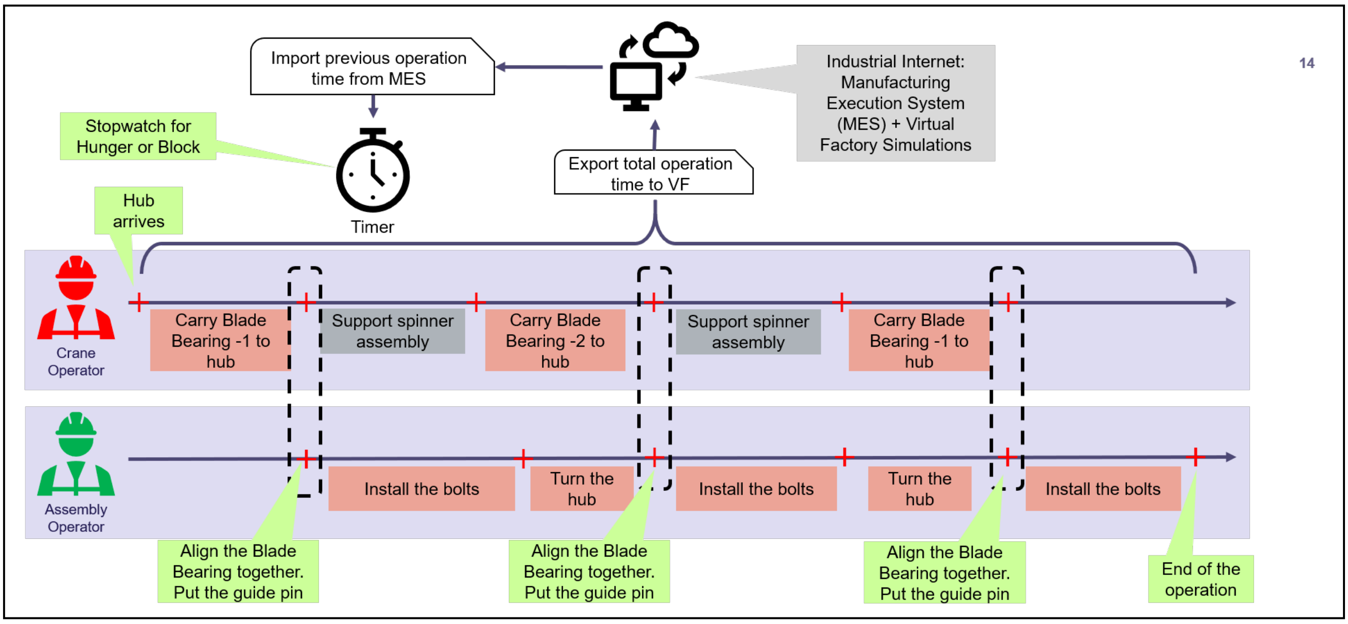

Figure 5. Collaborative and coordinated VR training scenario.

Virtual Reality Laboratory of INESC TEC. The scenario and the system architecture were explained to the industry experts. The VR training simulation requires subjects to individually perform the training that is required to collaborate in a virtual environment while sharing the same physical environment (Figure 6). Training performance data was extracted and used in the line simulation together with the data from the physical production system.

Several demonstrations are planned to be performed at different manufacturing plants of the case company. The objectives of the first demonstration which is presented here are to present the research work to the senior experts from the industry and to enable the evaluation of the design, development and implementation of the artefacts presented in this study. Experts evaluated the demonstration with unstructured interviews.

Figure 6. Collaborative and coordinated VR training demonstration.

C. Evaluation

The objectives of the preliminary evaluation of the demonstration are to understand the potential value of the proposed architecture and approach in terms of solving the problems presented above and to explore the high value promising use cases for integrated multi-user VR training simulation for the industry. The outcomes of the first evaluation are also expected to contribute to the design of forthcoming, developments and more comprehensive evaluation scenarios.

A vice president, a senior director of manufacturing systems, two senior specialists and two expert engineers were among the participants who evaluate the proposed VR training system.

The development work of the VR training was performed in five working days by two experienced developers. Establishing data integration between the VR training system, MES and VF system is achieved in 4 h by one IT expert. During the data integration process for a particular product model used in the VR simulation, MES did not return any results to the SQL query run by the VR training simulation because of the recent production changes in the shop floor. As a result of this, developers had to update the product type based on physical production operations. This unexpected incident showed that the integrated design of the VR training supports the reliability and accuracy of the data used in the VR simulation.

Unstructured interviews performed with the industry experts and their subjective evaluations based on personal experiences, comments and ideas are grouped and summarised below based on defined problems:

- The difficulty for utilising VR for complex (collaborative and coordinated) manual assembly training.

"Photon Unity network packages make multi-user VR development and use a lot easier than we expected."

"While local content production projects are increasing, being able to provide multi-user VR training simulation for users from different production plants can enable more effortless knowledge transfer and support serious cost savings."

- Low precision, accuracy and reliability of data used in VR training.

"Knowing that real operation times utilised in the VR training increase the feeling of seriousness and responsibility to finish the task on time as well as the precision, accuracy and reliability of the VR environment and the scenario."

"We have all actual task/operation times in MES at present. We intend to use VR training for critical new tasks and we will be able to extract training times and send back to MES and/or VF tools with bidirectional data integration. Such data integration enables our engineers to make comprehensive time studies (planned/training/actual time) more effectively and efficiently during the earlier phases of product introduction processes such as product or process design."

"Data integrated VR training can be more effective and valuable, especially for more data-intensive learning and training scenarios such as circuit board assembly."

- Low efficiency of VR training (re)design.

"Creating a common shared data repository and integrating it with VF tools and MES can provide structured and updated data during the design/redesign and development of VR training. This can enable developing and utilising DTs in VR training, and virtual objects in VR training can be adjusted according to their physical counterpart."

"Integration of VR training with VF tools is promising for decreasing the design and development time not just for VR training but also product, process and production systems."

V. Discussion

VR technology has already been adopted by industry and proved its value in design, evaluation and training. Multi-user VR training is promising for expansion for their utilisation areas in industry. Integrating VR training with virtual and physical production systems enables more efficient and effective data utilisation among these systems.

Preliminary discussions with industry experts on an integrated collaborative VR system show that its value lies in the ability to explore possible future horizons. Data integration enables new use cases such as time studies and DT-based VR training, and it also brings the need for more comprehensive evaluations for specific use cases. Such integration could support modular VR training system development in the future.

The approach presented in this study can be used for similar collaborative and coordinated training design and developments in industry. This study also contributes to the VF concept by extending the VF architecture with real-time data synchronisation and multi-user VR training simulation. Research work presented in this work also provides insights regarding industry expectations in relation to a proposed collaborative and integrated VF training system.

Precision and reliability of data collection on the shop floor were out of the scope during the work presented in this study. The number of experts from the industry was limited because of time and geographical limitations. Demonstration of a VR training system to a higher number of industry experts from different manufacturing plants and more comprehensive evaluations are needed. Further demonstrations and evaluations are in progress.

VI. Conclusion

The increase in the complexity of product and production lifecycles and the need for shorter lifecycles requires more and more integrated design, development and the use of technological advancements in industry. VR technology, as one such technological advancement, has a more significant role in supporting the processes of such lifecycles. However, there are some problems related to the utilisation of VR in industry. We present an integrated design and development approach to utilise VR with physical and virtual factory systems and a demonstration.

Early results of the research work show that this approach is promising more efficient and effective development and use of VR in the context of collaborative and coordinated manual assembly training simulation.

More comprehensive demonstrations and evaluation of the VR training together with VF tools in specific product and production lifecycle processes will be performed for the future works. A more conceptualised integration model is also needed. VF data model such as [37] and its applicability for real-life cases should also be investigated.

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Disclaimer

The use of the commercial software systems identified in this study to assist the progress of design, development and understanding does not imply that such systems are necessarily the best available for the purpose.

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