Integrating virtual and physical production processes in learning factories

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Abstract

Scaled learning factories are industrial learning environments that provide production systems and processes for learners on a model scale rather than using actual productive machines. This approach has benefits as for instance lower invest, increased approachability and higher safety levels. At the same time, constraints for implementation of actual production processes and required abstraction levels from industrial processes are limitations. To bridge the gap between benefits and limitation we propose the integration of virtual production processes in a prevalent physical learning factories. Resulting mixed reality solutions bear the potential to combine real and virtual objects at the same time and thus extend the physical model environment with virtually represented processes. Based on an initial analysis we develop a concept using spatial augmented reality and a game engine based simulation to realize a virtual integrated production process. The theoretical concept as well as the technical implementation is described. A first evaluation indicates a high rate of acceptance by trainees and illustrates the benefits for learning performance.

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1. Introduction

Industry and especially manufacturing companies are challenged by the need to quickly integrate novel technologies in production, by changing demographics and by increasing technological complexity. These ongoing changes imply the need for adequate competency development of employees [1]. Learning factories are a possible measure for transferring theoretical learning content into practice and thereby create an efficient learning process for industry related topics. Therefore, learning factories aim to provide a hands-on and holistic learning set-up to trainees and trainers. One success factor of learning factories is the provision of a realistic, factory-like environments [2]. This can be achieved by either using the same equipment as in real factories or smaller, scaled systems. While real-scale learning factories offer the least degree of abstraction, the scaled counterparts provide advantages regarding to safety, accessibility, controllability and invest [3]. Exemplary benefits lie in the avoidance of emission emitting production processes and the circumvention of high mechanical forces as well as high voltages. The decision on the suitable learning factory approach has conflicting objectives with the goal to provide safe learning environments against the goal to provide a holistic and realistic environment.

At the same time, technologies such as augmented reality and virtual reality become increasingly prevalent in our everyday life. Among others, these technologies can be summarized under the term mixed reality (MR). MR application aim to combine virtual and real objects and thereby offer the opportunity to extend or complement our physical world with virtual additions [4]. For bridging the gap between demands and limitations of scaled learning factories, MR could be utilized [5]. By integrating virtual elements in mainly physical learning factories, production processes and infrastructure can be complemented and prevalent constraints overcome.

With this motivation the limitations of learning factories were initially analyzed and possibilities for compensations by integrating a mixed reality solution were discussed. On this basis a concept is presented to bridge the shortcomings of scaled learning factories by applying spatial augmented reality. Subsequently, a technical implementation is described and the results of a first evaluation are presented.

2. Learning factories and mixed reality

2.1. Learning factories: limitations and opportunities

The goal of learning factories to offer a realistic production environment [1] comes with limiting constraints. Tisch and Metternich summarize the limitations of learning factories in five points: resources needed, mapping ability of issues, scalability, mobility and effectiveness [6]. Learning factories are often limited by their resources, as a learning factory’s usually has smaller budget compared to traditional factories. Resulting in limitations concerning equipment, space, personnel and more. This relation can favour the implementation of scaled down learning factories, which become increasingly popular in industry and academia (e.g. the modular production systems [7] or learning systems [8]). Scaled down learning factories aim at utilizing the same components and mimic the same behaviour as industrial scale factories. This leads to specific benefits and challenges [3], see table 1.

Another consequence is the abundance of production infrastructure and processes that might exceed budget limits due to the cost of necessary infrastructure or personnel. Additionally, depending on the audience and the concept of learning factories, scaled down learning factories are limited in their scope, as not all production processes have realistic miniature versions. High safety regulations are increase the accessibility of learning factories, as fewer introductions and pre-trainings have to be conducted. Safety regulations, here, is mostly referring to the intentional abundance of high electrical voltages or potentially dangerous physical forces (e.g. 400 V industrial power supply or non-tactile industrial robots). Certain production processes are excluded from implementation, as for instance chemical based processes (e.g. painting, galvanic) or additive/subtractive processes (e.g. deposition welding or grinding). Specific benefits and challenges of industrial scale and scaled down learning factories are summarized in table 1. Based on these potential limitations the initial goal of learning factories is to deliver a realistic production environment for learning is restricted. Here, the opportunity arises to compensate the limitations by complementing
the predominant physical environment with virtual objects. Technology summarized under the term mixed reality offers promising opportunities.

Table 1. Benefits and challenges of industrial scale and scaled down learning factories, adapted from [3].

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Industrial scale</th>
<th>Scaled down</th>
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<tbody>
<tr>
<td>- Realistic depiction of industrial phenomena</td>
<td>- Good approachability</td>
<td>- Lower financial and personnel costs</td>
</tr>
<tr>
<td>- Good transferability of industrial methods and tools</td>
<td>- Lower space requirement</td>
<td></td>
</tr>
<tr>
<td>Challenges</td>
<td>- High efforts for implementation</td>
<td>- Limited functionality of scaled equipment</td>
</tr>
<tr>
<td>- Occupational safety</td>
<td>- Abstraction to industrial problems</td>
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2.2. Mixed reality in learning factories

The term mixed reality (MR) is referring to the combination of real and virtual objects for a user in an application or environment. Virtual objects are characterized by not having a materialistic or formalistic existing. Whereas real objects are characterized by their tangible presence and objective existence. On this basis, Milgram and Kishino developed the reality-virtuality-continuum [4] with total reality and total virtuality acting as the endpoints of the two-dimensional continuum (see Figure 1, middle). This framework enables the allocation of different applications according to their relative share of virtual and real elements. According to Azuma, a MR application has to fulfill three key characteristics: combination of real and virtual objects; being real-time and interactive; the application has to take advantage of three dimensionalities [9]. The term MR and the continuum as overarching framework have been adopted in many application areas in the field of human-machine interfaces and visualizations in the past two decades; from allocating actual hardware solutions in the continuum to approaches selecting technological solutions by key capabilities of MR allocated within the continuum [10].

In an earlier publication [5], the potential of MR in learning factories for learning mixed reality in learning factories [11] and utilizing the benefits of MR in learning factories was analysed, leading to potential fields of application (A-H) summarized in figure 1. The main strength for utilizing MR in learning factories can be seen in virtual extension of a physical environment to improve the learning process. This can be accomplished by virtual scenarios (A), contextual virtual instructions (B), virtual extension of the physical world (D, G) or virtually fostering transparency in processes otherwise not transparent (E) [5].

Fig. 1. The potential of mixed reality in learning factories [5] and the reality-virtuality-continuum [4].
Before and since then, different practical and theoretical application and research about MR in learning factories have been published highlighting the recent interest in utilizing MR in learning factories. The potential of augmented reality as learning medium in learning factories was analysed in several studies [12]. Use-cases were demonstrated providing transparency to complex processes otherwise difficult to understand by MR technologies [13]. Mixed reality applications can enable the collaboration of industry and academia in learning factories [14]. Furthermore, the effect of using mixed reality in learning factories was evaluated [15].

3. Extending the learning scope of a physical scaled learning factory by mixed reality

A potential pathway for bridging the limitations of scaled learning factories is the extension by virtual elements through MR technologies. For the development of a concept to integrate virtual production processes in physical scaled learning factories, a case study for the learning factories at TU Braunschweig and Birla Institute of Technology and Science, Pilani (BITS Pilani) was conducted.

3.1. Requirements and technology choices

The Experience Lab of Die Lernfabrik is based on scaled production modules. A general introduction can be found in [16]. The main topics of this learning factory are energy efficiency [17], cyber-physical production systems [18], resource efficiency and mixed reality [11]. As these topics are overarching the manufacturing domain, a holistic representation of various industrial production processes is required. The learning environment is predominantly used to bring theoretical learned content from university lectures into practice and for conducting industry trainings. Both of these use-cases require a quick introduction of the trainees to the factory and a safe working environment due to existing time constraints. The lecture complementing courses are usually side-projects and the trainings have a one-day scope, limiting available time slots for instructions and safety briefings.

The resulting requirement to represent a realistic, safe and easily approachable learning environment which depicts a broad variety of industrial production processes in a factory environment, result in a goal conflict. Many production processes emit emissions, include significant physical forces and high voltages. For instance, machining, painting or galvanic treatments. On the one hand, a virtual production process depicting these processes enables their implementation. On the other hand, learning factories aim to be realistic and physical to impart training content efficiently, resulting in another conflict of goals. A compromise would require a technological solution to display both, virtual and real objects as well as allowing trainees to interact with these and with each other at the same time. Figure 2 concludes the requirements, present limitation and possible MR based solutions.

A variety of MR technologies along the reality-virtuality-continuum (Figure 1) can be applied to this problem space. To retain the physical nature of learning factories, an implementation concept near the reality side of the continuum should be selected. Technological implementations near the virtuality side fade out physical elements and are not suitable. On the reality side of the continuum the implementation concepts tangible interfaces and spatial augmented reality are allocated. Tangible interfaces utilize physical objects to interact with and manipulate virtual elements. In spatial augmented reality, virtual objects are projected into the user’s environment, examples are 2D and 3D projection mapping. According to [10], spatial augmented reality allows immediate collaboration, displaying of real and virtual objects as well as the relation to these, thereby fulfilling the technological requirements.

<table>
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<tr>
<th>Requirement</th>
<th>Limitation</th>
<th>Possible solution</th>
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<tr>
<td>A variety of different production processes are needed</td>
<td>Many processes emit emissions</td>
<td>Virtualization of certain production processes</td>
</tr>
<tr>
<td>Fast introduction to the learning factory and safe environment</td>
<td>Complex and potentially dangerous processes require thorough introduction</td>
<td>Virtualization of certain production processes</td>
</tr>
<tr>
<td>Realistic depiction of an industrial environment</td>
<td>Scaled and virtualized production process are a abstraction</td>
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Fig. 2. Summarizing requirements and connected limitation of scaled learning factories as well as possible solutions.
3.2. Implementation and evaluation

Based on the specific requirements a solution was developed, integrating a virtual painting production process in the physical learning factory at TU Braunschweig and at BITS Pilani using spatial augmented reality. Spatial augmented reality enables the simultaneous depiction of real and virtual elements, while the user is clearly active in the reality and interacts predominantly with physical objects.

The final result consisting of four main elements (a) to (d) is visualized in Figure 3. The implemented hardware-software interaction is illustrated in Figure 4 (left). The general concept utilizes a projector (a) which is beaming on a surface (d) mounted on a generic product transporting module. The production process sequence starts with the product being detected by a sensor while entering the virtual production process, following, the product is stopped by the conveyor belt beneath the projection surface. When while product is stopped, the simulation model is initiated with preset parameters, thereby the model is projected by the projector on the surface mimicking a real production process and displaying additional data. After a defined run-through time of the simulation, the conveyor belt transports the product to the succeeding physical production module.

The virtual simulation model of the painting production process is running on a computer (c). The model is realized using the game engine Unity [19], utilizing the programming language C# for scripting and a specific dynamic link-library for the communication with the learning factories controller. The model itself represents a three stages painting process (priming, coloring and clear coating), which the product is running through virtually. Meanwhile, the used paint volume in liters and the energy demand in watt-hours is simulated and visualized on the projection surface. A product passing a light barrier connected to the programmable logic controller (PLC) of the production module initially triggers the simulation. The PLC (b) is signaling the simulation to initiate. After the run-through, the simulation is signaling the PLC to continue, triggering the production line to move on.

Fig. 3. Schematic visualization and photograph of the virtual integrated production process in a physical learning factory.
For testing the feasibility of the approach, the implementation was presented to university students. The 14 students were already working in the learning factory in the scope of a lecture complementing project. During the experiencing of the virtual implementation the students solved a simple task and were questioned afterwards regarding their experience. The results of the structured questionnaire are visualized in Figure 4 (right). The mixed reality concept was generally well received, the students could understand the technological implications of the virtual production process (4.8/5) and make sense out of the added data (4.2/5). The adaption from physical to a virtual process was rated medium to high (3.9/5), whereas the solution was rated as motivating (4.5/5) and interesting (4.5/5). The students value the virtual extension for a holistic experience (4.5/5). The wish for more MR integrated production processes was only partly present (3.5/5). This could indicate limits of the concept. with multiple virtual integrated processes, a realistic depiction of factory might fail, compromising a main asset of learning factories.

4. Summary and Outlook

The gap between benefits and limitations of scaled learning factories offers the opportunity to be bridged by mixed reality based solutions. In this work a technological concept and implementation based spatial augmented reality is proposed. A first evaluation underlined the applicability of the concept.

The software based simulations models described in the concept can be exchanges between learning factories using the same physical module without additional effort. This trait can enable collaboration between learning factories and software based scalability of developments not possible before. In the future, the concept will be further developed, utilizing the scalable property for joint developments in international collaboration. Another advantage is the reduced maintenance for physical infrastructure, contrary, additional maintenance of the software might be necessary.

A deeper understanding of the implications on the learning success when moving elements from reality to virtuality is necessary. Answering the question, what ratio virtual and real elements is optimal for learning factories can be a fruitful subject for future research.

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