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CYBER-PHYSICAL EFFECTS ON THE VIRTUAL COMMISSIONING ARCHITECTURE

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Abstract

In order to satisfy the growing customization desire and, thus, effecting an increasing product variability, future manufacturing systems have to be harmonized with new technologies such as cyber-physical systems. This leads to different actual challenges inside various technical working areas, for example, manufacturing and assembly. Beside the implementation of new technologies, developers are faced with the challenge to reduce the time-consuming commissioning of the manufacturing systems by using already established methods, such as the virtual commissioning, which provides the possibility to detect mechanical design errors and achieve a very high maturity level during the planning phase. The basis will set with the generation of a virtual manufacturing model, which can be used to visualize and validate the physical behavior of production systems in a very early phase of the production planning process. These planning strategies have to be set in a transferable method to enable the practical introduction of cyber-physical systems. Therefore, this publication gives an approach of the effects that cyber-physical systems have on the virtual commissioning architecture.

Keywords: Simulation, Virtual Engineering (VE), Systems Engineering (SE), Virtual Commissioning (VC), Cyber-Physical Systems (CPS)

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1 INTRODUCTION

As in the past, the requirements and capabilities of production plants will continuously be determined by the manufactured product in the future. Thus, in the context of the fourth industrial revolution, the increasing customization desire, product variability up to lot size one and innovative technologies such as cyber-physical systems, lead to different actual challenges within various technical areas, for example, the manufacturing and assembly of factories.
Regarding this, significant technological development progress is already forced by the implementation of the fourth industrial revolution. Highly automated plants turn into smart digital factories with local and global communication possibilities between the production stations and the issue of the internet of things. Decentral controlled and self-optimizing systems are new strategies that will fundamentally change actual production methods and set the design complexity on a new level. Furthermore, engineers are faced with the challenge to develop these intelligent systems from the very beginning to the start of production (SOP) in a timely and budget-minded manner. In order to satisfy these two divergent requirements, companies are committed to design new methods to keep the complexity of production technologies on an economical level and describe them in a comprehensive solution. A conventional procedure that combines both divergent properties is known as the virtual commissioning (VC) of technological systems (Krause, 2007).
The VC, being included in the technical planning process, describes an approach which contains the forward displacement of constructional and functional development characteristics and optimization features of technical systems (Makris et al., 2012). By the use of VC-methods, the time-based process expenditures of the real manufacturing ramp-up can be reduced up to 75% (Worm et al., 2012). The idea of VC is to develop a software based construction of a consistently and realistic three dimensional simulation model that allows users to detect technological design errors during the planning phase by simulating the real physical behaviour. By introducing VC and using its advantages it will be possible to simulate, optimize and validate the virtual cyber-physical factory-model and its behaviour long before its actual start of production. The possibility to visualize this model leads to a higher user acceptance level. While the VC is a well-known common method to implement complex technological systems, cyber-physical systems are still in the current state of research due to missing implementation knowledge and unclear technological definitions that lead to realization obstacles. Until now, there are no approaches that discuss the impact of cyber-physical systems and other initially technologies of the fourth industrial revolution on the virtual commissioning process. Therefore, this paper deals with the impact of cyber-physical systems on the VC-model building architecture and takes a look on actual and upcoming technologies. Moreover, this paper takes a look on the implementation of decentral controlled manufacturing equipment by focussing kinematic and communication processes.
The structure of this contribution is as follows. In order to show the impacts of cyber-physical systems on the VC-architecture the state of the art will be discussed in the second section. In the third section the virtual commissioning architecture will be presented with respect to cyber-physical systems. Based on this, the fourth section deals with an application example. Finally, section 5 provides a conclusion and takes an outlook on the forthcoming activities.

2 STATE OF THE ART

In the following section, different terminologies will be explained to get basic insights into the field of cyber-physical systems (CPS) and virtual commissioning (VC).

2.1 Cyber-Physical Systems

The terminology of cyber-physical systems, originally coined by Hellen Gill, was defined by (Lee and Seshia, 2011) as a technical link between real and virtual objects as well as real and virtual processes, which are able to communicate among each other through an open and global system.
Due to the increasing technical complexity of today's systems and components, it is necessary to further specify this definition and describe cyber-physical systems as a multifunctional structure of sensors and actuators to register and manipulate their surrounding physical environment and stay in large scale communication with distributed data management systems, global networks such as the internet of

Things (IOT), and, on manufacturing site, with the interdisciplinary virtual twin of the manufacturing equipment (Jablowski et al., 2016; Kowalewski et al., 2012; Monostori, 2014).

2.1.1 Cyber-Physical Systems - Potentials

Through the extension of cyber-physical systems, components and technical systems in the field of manufacturing develop to cyber-physical production systems (CPPS). These smart production systems with wired or wireless local and global communication abilities offer new potentials for the factory of the future such as the decentralization of the product flow, which affect a highly scalable and flexible production line (Schuhmacher and Hummel, 2016; Wahlster, 2013).

A technology that allows an information exchange between product and manufacturing equipment to decentralize the control of the product flow is the digital product memory, which already applies in many modern factories, such as the Siemens' electronic production factory, located in Amberg, Germany (Kreutzer, 2014). In a small microchip, which is directly attached on the product, a unique numeric identification reference is stored. This reference correlates to a database record and can be read out by using various technologies, such as radio-frequency identification (RFID). As a result on manufactures site, manufacturing equipment that is connected to the same database can be designed more flexible and is able to produce products in several variants. At the same time, implemented RFID technology can be used simultaneously by the customers to visualize the current status of their individual product globally via the internet in real time (Schuhmacher and Hummel, 2016).

Ubiquitous global connections and technologies such as cyber-physical systems and RFID real time solutions produce huge amounts of data (Big Data). With the proper use of Big Data and the huge data flows companies are able to create the basis for the implementation of cyber-physical systems in their manufacturing environment by getting the link between physical manufacturing equipment and their virtual twin. Another major potential deals with the efficient data export into companies own clouds and the ability to adapt, develop or maintain the machines globally. The location of the accessing employee is unnecessary if an internet access exits and the access rights onto the virtual machine models are given.

2.1.2 Cyber-Physical Systems - Challenges

To implement the technology of cyber-physical systems, companies are faced with different interdisciplinary challenges that will be discussed hereinafter. The challenges are categorized according to scientific, technical and economic aspects.

A major scientific challenge deals with the creation of transferable methods to get a better understanding of how to implement this technology. Furthermore, there is a distributed knowledge in companies benefited by the allocation into separated working zones. Concerning the interdisciplinary approach of cyber-physical systems, it is necessary to centralize the knowledge by developing a close cooperation between employees. In addition, this procedure enables employees to make their decision based on the overall target agreement instead of specific working zone targets.

In order to design future manufacturing systems with the required variability in cyber-physical context, companies have to implement technical similarities such as system interfaces to set the basis for upcoming production technologies in view of the fourth industrial revolution. Another technical challenge is the increasing amount of data due to the extensive array of sensors, growing networking between the manufacturing equipment and the internet of things, which forced the companies to implement normative communication standards and network protocols between various manufacturing systems. Additionally, produced data have to be distinguished by priority to specify where to save the files. High priority data have to be stored centralized in the company’s data center. Data with comparatively low priority can be export to the company’s own cloud to enable a globally access.

This approach is an individual solution that combines the advantages of the globally access possibilities with a high level of data protection. The practical introduction of data acquisition tools with real-time analyzing features is set to be a major technical challenge for computing devices and their integrated software. Despite the massive grow of unstructured data, new strategies enable the user to process big data in distributed file systems and find new trends in the real-time data flow by using separately prepared algorithms (Freiknecht, 2014).

As a consequence, the possibility to implement cyber-physical systems in the existing manufacturing line is currently to decide in the individual case and describes an economic challenge due to missing transferable methods. Therefore, it is necessary to determine the status of the company’s infrastructure by analysing the existing technological architecture. Since large business companies are faced with different challenges as small-scale enterprises, an individual requirement analysis is needed to define the intended technological degree of implementation. According to the higher complexity of adjusting an existing manufacturing system in a cyber-physical context, it is recommended to implement new technologies step by step. Especially, in smaller businesses a gradually technological adjustment and the application of advanced know-how will be the key to success and will offer the possibility to reduce the inventories and storage costs that will lead to achieve the economic goals of the company.

2.2 Virtual Commissioning (VC)

The terminology virtual commissioning (VC) describes the software based on the generating of a virtual three dimensional simulation model, which is used to validate the real physical behaviour of a future manufacturing system (Makris et al., 2012). With the use of VC, users enable the possibility to detect mechanical design errors and achieve a very high maturity level during the planning phase.
The VC is a wide spread process that is much beyond the research stage and takes place in many planning departments in the manufacturing industry, e.g., as a part of Daimler's integra automation framework or to validate production processes of BMW's three series, which has already been proven 2006 in their plant located in Leipzig, Germany (Kochan, 2006; Süß et al., 2016). Basically, a VC of a technical system consists of various partial models, which will be presented below.

2.2.1 Mechatronic Geometrical Model

The mechatronic geometrical model consists of a mechanical, electrical and fluidic construction. The principal aim of this model is to generate an interdisciplinary construction to visualize the future manufacturing system. To be effective by generating the mechatronic geometrical model, it is recommended to import the parts directly from the manufacturers' component libraries, if offered (Hoffmann et al., 2010; Süß et al., 2016). Independent of this, every manufacturing company should create its own part library to be able to store standard parts and carry-over parts in a clear structure. In addition to the mechanical construction, geometrical end positions and movement axes are defined, sensors and actuators are positioned and the material flow is visualized (Makris et al., 2012). Subsequently, the generated mechatronic geometrical model can be edit with kinematic properties.

2.2.2 Kinematic Model

In order to implement kinematic properties into the mechatronic geometrical model, future relevant parts have to be edit with moving references. According to Puntel-Schmidt and Fay (2015), moving references consist of rotational and translational activities, which are defined by numerical limits and have to be defined in the software based model of movements or, additionally, are offered by the manufactures where the parts are obtained. Physical parameters such as external and internal forces and moments acting on the real manufacturing equipment are disregarded and will be considered in the model of physical behaviour (Puntel-Schmidt and Fay, 2015). Currently, the points of product editing and integrated logical algorithms define the process paths of the production utilities that prevent a collision between the product and the manufacturing equipment.

2.2.3 Model of Physical Behaviour

This model contains the logical and temporal behaviour of the manufacturing equipment and their connected super-ordinated control unit. In order to increase the user's acceptance, it is useful to process, on the one hand, the logical in- and outputs and, on the other hand, the visualization of the virtual manufacturing system. The numerical references, defined and implemented as kinematic properties in the model above, are now needed to complete the equations of motion, which will visualize the systems movements by calculating the temporal change of the joint parameters (Hoffmann et al., 2010). In addition, it is considered to determine the system movements in discrete and continuous processes. Discrete processes can be illustrated as state diagrams, containing transfer functions to describe the change of two or more conditions. To provide a clear overview, it is recommended to describe different possible conditions in a status table (Bergert et al., 2010). In order to describe continuous processes within the model of physical behaviour, currently used state charts have to be developed to hybrid-state charts. In hybrid-state charts frequency response functions can be declared as continuous functions of time and can be classified in separate time intervals (Bergert et al., 2010). The major advantage of using hybrid-state charts is the possibility to constitute real-time systems, which consists of continuous equations of motion. To keep the computation of the equations of motion on a simple level, it is recommended to divide them into several partial movements and describe them separately. Additionally, the physical model of behaviour can be classified in two areas, which are known as the wanted technical cautious and the unwanted physical-based cautious. The wanted technical cautious, also known as sequencing, deals with the controlled, deliberately created behaviour of manufacturing equipment generated by the users control commands. The unwanted cautious, in contrast, describes the systems behaviour that is provoked by physical influences and also known as the uncontrollable behaviour. Furthermore, the physical model of behaviour can be differentiated between the products and the behaviour of the manufacturing equipment. But that aspect will be disregarded in this publication. With the successful development of this model, the user enables the possibility to execute a model in the loop (MIL) simulation, which will run by connecting the model of physical behaviour with the mechatronic geometrical model, as mentioned in (Damrath et al., 2014), and its kinematic properties. Due to the generation of the model of physical behaviour, it is recommended to use a common exchange format to be able to transfer gained knowledge into the following model that deals with software programming.

2.2.4 Software Modelling

The field of software modelling contains all important program-technical integrations in the context of virtual commissioning, which deal with the control system. The software development allows to create a high level of authenticity with respect to the VC-process. With the help of the software modelling, the user enables the possibility to execute a software in the loop simulation, which allows to identify control program errors in a very early stage. Currently, several components can be virtually connected and simulated to validate their individual function and avoid logical errors. By transferring the generated program via a common exchange format to the programmable logic controller (PLC), it is possible to execute a hardware in the loop (HIL) simulation. After the successful HIL-simulation the PLC can be disconnected from the simulated system and can be plugged into the real physical manufacturing equipment without changing any logical function of the implemented generated software (Kufner, 2012). Some HIL-configuration does not support the logical functions for safety-critical components. Therefore, users have to check the function of these components separately.

Whereas the virtual commissioning is an established process, the technology of cyber-physical systems is still in their research phase. The possibility to use the virtual commissioning process to implement cyber-physical systems in the manufacturing equipment is actually not discussed. The same applies to the effects the cyber-physical systems have on the virtual commission architecture. Nevertheless, the process of the virtual commissioning is providing a method that enables the possibility to introduce and validate cyber-physical systems and their functionality in a very effective way.

In this publication the effects of cyber-physical system on the VCs architecture will be discussed. A special focus will be set on the influences on the mechatronic geometrical model and the following implementation of kinematic properties.

3 CYBER-PHYSICAL EFFECTS ON THE VIRTUAL COMMISSIONING - ARCHITECTURE

In order to constitute, what effects cyber-physical systems have on the modelling of the kinematic properties of the manufactures equipment, it is recommended to consider the mechatronic geometrical model in the same context. To go in more detail, both models are constituted in different categories. The first category deals with the acquisition of data. After that, the cyber-physical systems' influences according to the equipment of the manufacturer and the product as well as material flow will be discussed. Finally, the technical changes with respect to the local and global implemented communication systems will be addressed.

3.1 Data Acquisition

The process of generating the mechatronic geometrical model was discussed in section 2. Due to the future implementation of cyber-physical systems, manufacturers are faced with various challenges. In the area of data acquisition the number of sensors and their technical complexity will be highly increased due to the technological diversity. Beside the optimization of the geometrical position determination, where sensor systems are implemented, the electrical scope of interconnection will be increase, too. Furthermore, these interconnections have to be implemented and visualized in the virtual model of the manufacturing line. In addition, the technology of sensor systems is actually changing. Currently, sensor systems are status detection based equipment. The actual trend goes in the direction of the implementation of virtual sensor systems, which use the captured states to insert them into sensor-integrated logical algorithms. With the use of these algorithms, developers enable the possibility to acquire comprehensive data of the technological product processing and visualize them partially in real time. The parameters that are used to solve the integrated algorithms of the sensors have to be determined in an early phase of the production planning process to force the implementation of virtual sensor technologies. Due to the intended changeability of future manufacturing systems, companies have to run a forecast of their future product variants to ensure that the planned system is able to produce them.

3.2 Manufacturers Equipment

To be more efficient in future planning of manufacturing systems, developers have to cooperate closely with other manufacturers, because they represent the major source to receive CAD data files, which is needed to generate the virtual manufacturing system on a high level of technological authenticity. In addition, the electrical and fluidic components have to be visualized to ensure their geometrical implementation possibility. Due to the increasing process complexity, a forecast is needed to guarantee the producibility of future product varieties. Furthermore, the working limits of the manufacturing equipment, such as robots, will be defined by the geometrical limits of the cell, in which the system is installed, and the logical algorithm to avoid a collision between the product and the manufacturing equipment and other systems. In conjunction with the implementation of the digital product memory, future systems will be able to be self-organized and configured themselves. To ensure these abilities, the information of the digital product memory and the correlated processing data stored in various databases is needed by the manufacturing equipment to decide, which tool is required to edit the product.

3.3 Product and Material Flow

Currently, conveyors constitute the companies most used solution to transport their products within the plants. Research-institutes are testing the feasibility to realize a transport technology, based on geometrical undefined factory tracks. Therefore, the product is fixed on a transportation that is able to find the products next processing station by using comprehensive sensor systems or induction loops, implemented in the factory floor. Through the implementation of cyber-physical systems in the product flow, many new benefits are delivered according to the digital product memory. With regard to the technology of radio frequency identification, which are able to operate at distances of up to several meters, this means that the positioning of the reading units have to be defined in the mechatronic geometrical model. The electrical connection of the RFID-units has to be also defined in the mechatronic geometrical model. If the database is stored in the company’s globally used cloud, the interconnection between the manufacturing systems and the cloud is visualized in the virtual simulation model. Fundamentally, the complexity of the factories future transport systems will be highly increased by the implementation of cyber-physical systems, decentral control of the product flow and the self-organized ability of the manufacturing equipment.

3.4 Local and Global Communication

The effects of the implementation of cyber-physical systems in the field of the local communication between product and manufacturing equipment will be discussed in this section. Future manufacturing equipment will be highly interconnected, which affects an increasing data transfer. To ensure that systems of different manufactures have the same understanding of structured and unstructured data, new communication abilities need to be integrated, such as semantic interoperability (Cousin et al., 2015). Another solution of harmonizing systems with different ontologies describes the implementation of an API-management system that is able to adjust communication protocols with various standards. In addition to the local communication, cyber-physical systems provide the possibility to interact with the internet of things (IOT) and addresses global communication opportunities. The terminology of internet of things (IOT) describes the totally global and wireless interconnection of objects that lead to smart products and are able to communicate with each other. Applying these technologies on the virtual commissioning process, the manufactured systems that will be equipped with these communication systems need to be determined during the generation of the mechatronic geometrical model with respect to the additionally required geometric integration of the communicating components. The following

Figure 1 shows the schematic virtual commissioning architecture with respect to the integration of cyber-physical systems.

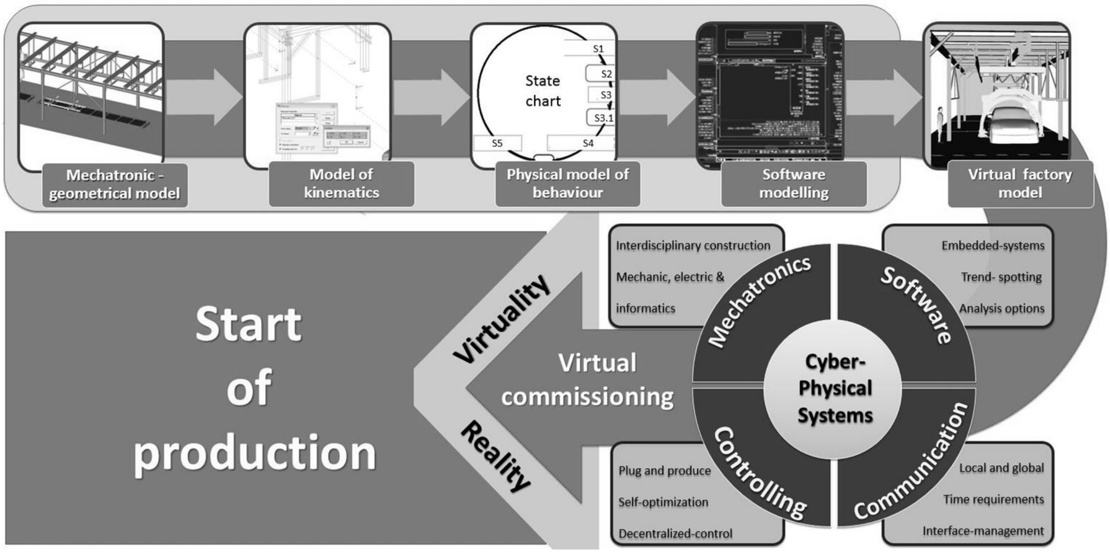

Figure 1. Virtual commissioning architecture in context of cyber-physical systems

4 USE CASE

The following use case describes an approach that will constitute possibilities of the virtual commissioning of decentral controlled manufacturing equipment and allows the user to validate the systems behaviour without having any real physical manufacturing equipment built up. As shown in Figure 2, a robot of type UR10 is used and mounted above the production line.

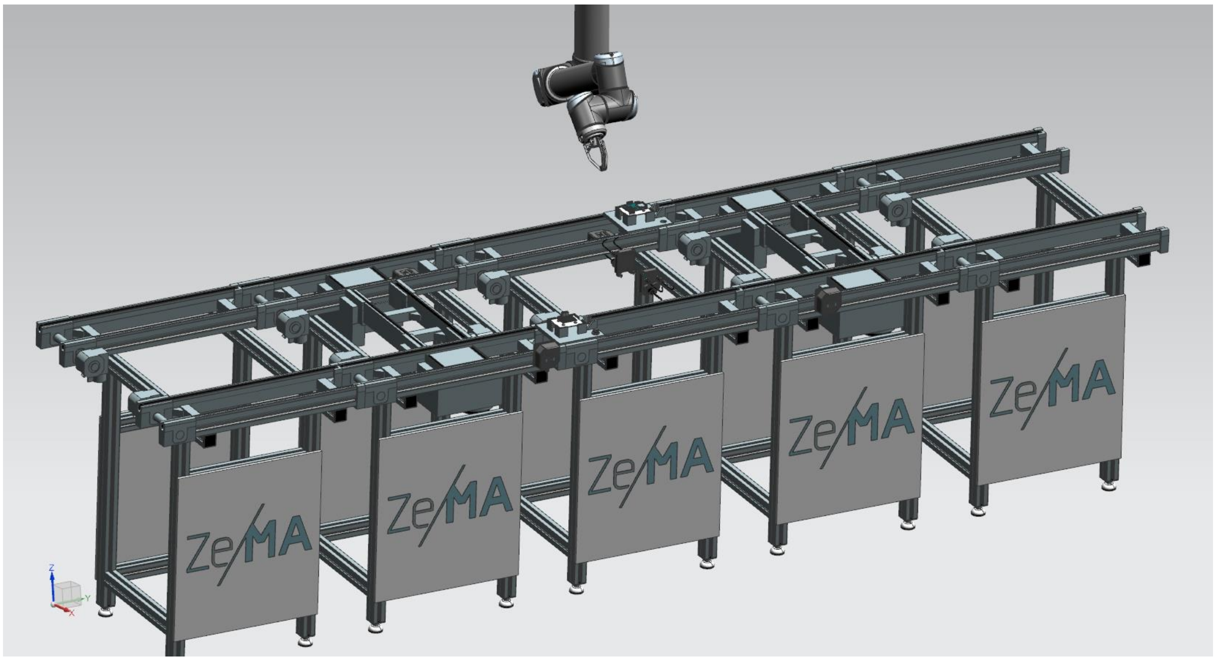

Figure 2. Virtual commissioning of a highly-interconnected robot with cyber-physical abilities

The production line consists of three modules that are mechanically and electrically connected to each other. Every module consists of a frame with a belt conveyor unit mounted on the top with a separate electrical drive. On every module a RFID reader and writer, integrated in one component, is also attached on the side of the belt conveyer unit. Regarding the product transport, product carriers, which have an integrated RFID chip with a unique reference code stored in it, are used. Due to the unique reference

codes the three different product variants can be simulated and virtual commissioned. To complete the various product variants the manufacturing equipment has to perform different assembly tasks, which all have to be simulated to detect design errors during the planning phase as soon as possible.
In order to constitute the moving tasks of the robot to simulate the assembly of several product variants, the information of the assembly sequence and exact assembly process of the three products are needed. Due to the focus that was set on the virtual commission of decentral controlled manufacturing equipment, the example of the product selection and product assembly will be held simple in the first simulation project. Therefore, a circuit board is used and various components will be fit on it to simulate the different product variants. In order to edit the product boards the company's product planning department is held to hand over the needed information of product assembly. As shown in Figure 2, the mechatronic geometrical model is successfully generated and the kinematic properties can now be implemented.
First of all, users need to generate the simulation study for each assembly process to detect design errors or collisions and ensure the geometric accessibility. With respect to the human robot collaboration and cooperation strict safety requirements and procedures are needed additionally. Subsequently, the virtual assembly processes of all three product variants are generated consistently. To put the decentral control of the manufacturing equipment into virtual operation, RFID tags with unique reference codes, stored in its microchips, have to be applied to the simulation model to get the communication link between the robot and the products. The reference code correlates to the product editing information that the robot needs to process and is stored in a virtual database. The robot's virtual superordinate control system is connected to the database on the one side and to the simulated robot on the other side and is responsible for the communication process between them.
To go into more detail, an electric component, e.g. a capacitor, has to be assembled on the first circuit board. As shown in Figure 3, the RFID codes (hexadecimal reference) of all three board variants are read out and displayed in a separate interface.

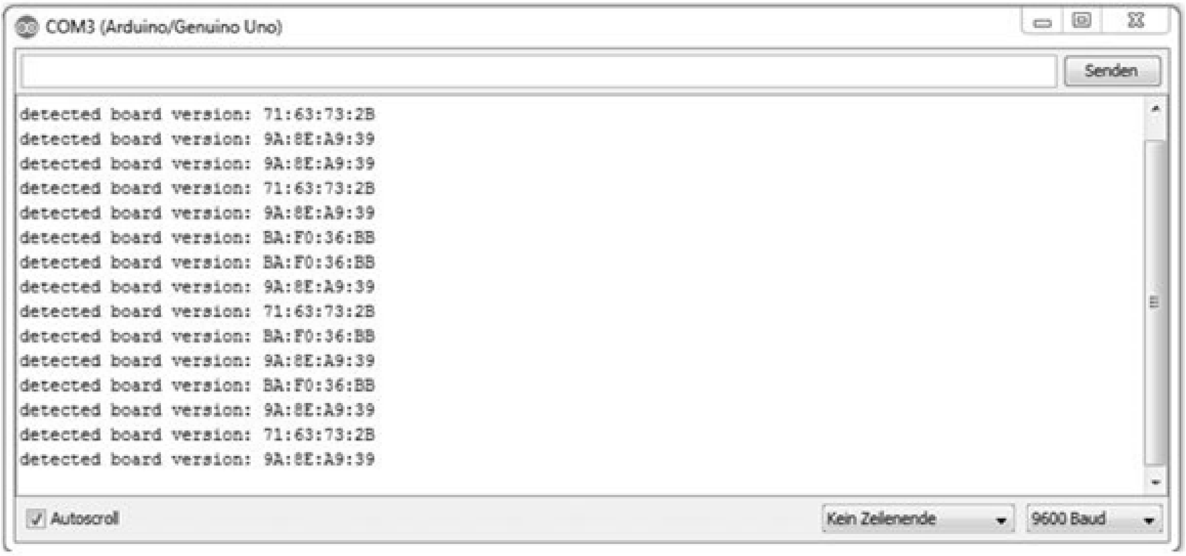

Figure 3. Detected board reference code via RFID

By transferring the information of product editing from the digital product memory via the database up to the robot's control unit, the manufacturing process is started. The robot is now able to pick up the electric component that is needed to complete the production variant.
Furthermore, the capacitor will be placed in the right position on the circuit board and the simulated assembly process is finished as shown in Figure 4. As a result, the robot will turn to an intelligent manufacturing equipment, based on the integration of the digital product memory.

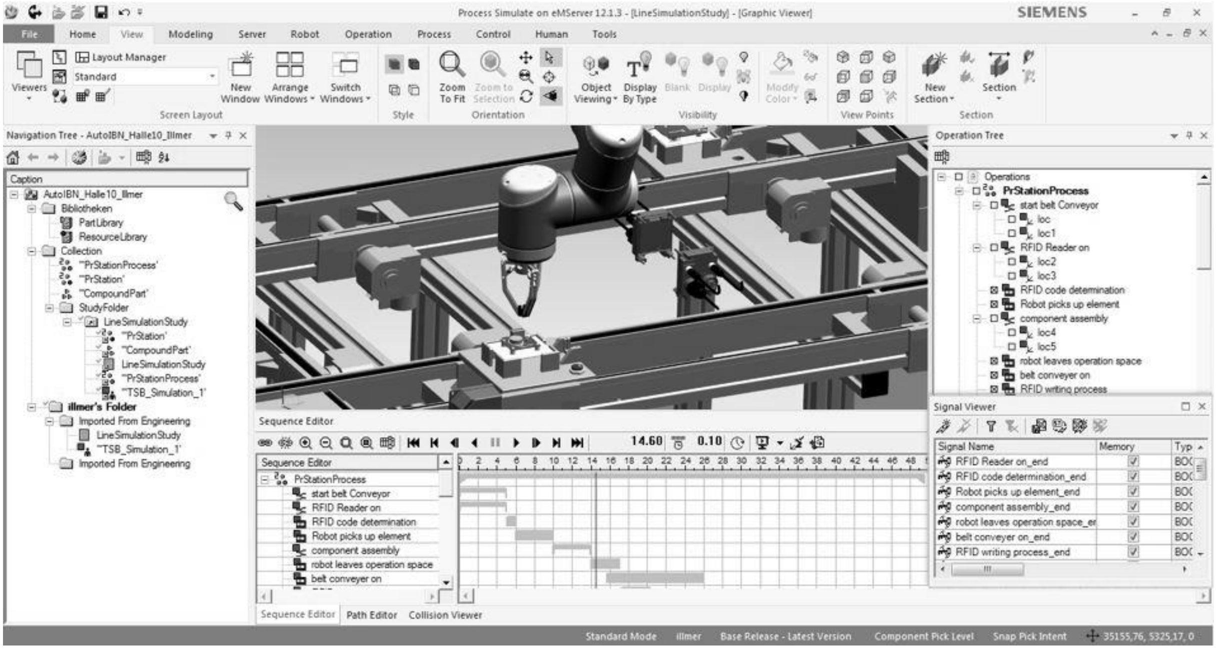

Figure 4. Assembly process of an electrical component on first board variant

5 CONCLUSION & OUTLOOK

To sum up, this publication provides an approach of the effects that cyber-physical systems have on the virtual commissioning architecture. The various models, built in the virtual commissioning process, seem to be an appropriate tool to introduce complex technologies such as cyber-physical systems into the manufacturing systems. It is shown that the implementation of cyber-physical systems in existing manufacturing systems is more time-consuming than developing completely new system solutions. By means of the comprehensive interconnection possibilities, future components (e.g. virtual sensor systems and decentral controlled product flows) will lead to a sharp increase of data transfer. If the companies are able to use the produced data effectively, they may create economic advantages. Due to the application of new approaches, which define the system movements and working limits, future manufacturing equipment will be able to handle the customization desire.

However, technologies such as the digital product memory and self-organized manufacturing equipment must be further developed. In the next steps, the integration of the digital product memory in the virtual commissioning architecture will be checked. Therefore, it will be intended to create a transferable method to be able to transfer the gained knowledge on other working areas. In addition, a model in the loop simulation that contains the technology of decentral controlled manufacturing systems will be developed.

Furthermore, a more general consideration of possible changes on the digital VC, and thus indirectly on production and assembly, due to new lightweight design approaches in terms of the continuously increasing introduction of industrialized fiber-reinforced composites and/or modern 3D-printing technologies will be investigated next.

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