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Consolidation of product lifecycle information within human-robot collaboration for assembly of multi-variant products

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Abstract

Human-robot collaboration is a key technology for realising and optimising the assembly of multi-variant products. However, the long-term and economic operation of collaborative systems requires eligible methods for the consolidation of lifecycle information and the transfer of operational and product data from the shop-floor into planning systems and vice versa. The paper introduces a systematic approach for information management and exchange in the field of collaborative assembly, based on a service-oriented architecture including process and product data exchange through AutomationML, virtual commissioning, and manufacturing execution. The methodology is evaluated in a laboratory use case and a reconfigurable demonstrator system is realized.

Keywords: Assembly, Simulation, Human-robot collaboration

1. Introduction

Manufacturing companies use distinctive IT systems for planning support, especially in the area of product development. The concept of Product Lifecycle Management (PLM) is used increasingly to support the exchange of information and to define workflows, both cross-phase and cross-disciplinary [1]. Variant management within PLM systems is of particular importance. In order to meet market requirements for customized solutions, the product range of a company can be mapped with modular systems [2]. Thus, companies benefit from a high degree of reuse of similar parts and from standardization options. The assembly of customer-specifically configured products leads to increasingly deviated processes. Due to its proximity to the market as the final production step, assembly is particularly influenced by fluctuations in demand [3].

High flexibility and robustness of processes and resources are among the core requirements of modern production systems and will raise the pressure for the development of innovative automation solutions [4, 5]. In practice, manual assembly, in which skilled workers use simple but universally applicable tools and devices, is usually more economical than automation. This is due to the lack of scalability of the operating equipment solutions between purely manual and fully automated processes. The latter are unattractive, especially in the product ramp-up phase, due to the usually small quantities and the high investment risk in combination with acquisition costs.

Collaborative assembly systems, in which a skilled worker interacts with automated components, offer a great application potential. This approach enables the adaption of different skills of humans and robots to variable requirements and phases in the product life cycle [6]. Collaborative assembly systems contribute to further increasing the productivity of an assembly worker

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through specifically optimised processes. In addition, human-robot collaboration enables both human and robot to combine their complementary skills instead of limiting each other [7,8].

This paper closes the gap between the concepts on integrated product and process development of multi-variant products and the adaptable dynamic execution of collaborative assembly tasks by developing an overall method based on PLM data and simulation. The hypothesis is, that the assembly of multi-variant products can be simulated in advance with existing data, using a virtual environment. As a result, the programming of collaborative robots and the setup of the production system for new product variants is realized entirely by PLM data. The implementation of a PLM based collaborative assembly system is tested in a laboratory case study on a demonstrator that connects a virtual and physical environment.

2. Information Management in collaborative assembly

The implementation and efficient use of collaborative systems requires a consistent PLM approach that considers not only the product structure but also the special requirements of collaborative systems in the plant design and deployment phases. Advantages of PLM result especially for the product design [9] and for the organization of production processes [10] into an integrated approach for product and process development. With regard to collaborative assembly systems, there are new requirements for PLM solutions that include context descriptions for efficient human-robot interaction, planning tools for safeguarding collaborative processes, and comprehensive knowledge and process management for long-term planning to short-term scheduling and even during real-time interaction (e. g. online programming). This is particularly important for a multi-variant product portfolio like individualized products, in order to enable flexible adaptation and transfer to new product design.

A method for information management in a flexible production environment is the implementation of service-based manufacturing systems that enable production systems to adapt automatically to changing system states and external requirements. Pfrommer et al. [11] presents an overall system design and shows how high-level information about the manufacturing system and the products are derived for automated manufacturing processes and how they can be executed at runtime. The application of skill based-planning aims at supporting the life-cycle management of technical assets in long to short term planning activities as well as the vertical integration between different IT systems in a manufacturing enterprise [12]. The executable skill system is based on existing standards (e. g. OPC UA and AutomationML) and aims at more flexible production systems in the sense of plug & produce. In order to establish the communication between all units, each component (either hardware or software) must be able to describe itself and its skills and capabilities and provide this self-description to other units within the production system [13]. The aspects on planning and execution of human-robot interactions within assembly systems are still not appropriate addressed.

Even though current research includes planning tools for collaborative processes [14, 15], and virtual techniques for flexible work place and manufacturing system design [16, 17], there are currently no approaches for consolidate information management on collaborative human-robot assembly of multi-variant products that sufficiently take into account all the requirements. In practice, continuous system connections can be found in some areas, but these lack a suitable digital representation and suitable integration mechanisms to link planning, simulation and execution across systems. An approach that combines the strength of a virtual simulation with the extensive data lake from planning (PDM/ERP) and control system (MES/PLC) realized through a service oriented architecture is the key for the challenges of a multi-variant assembly based on human-robot collaboration.

3. Approach

The approach of PLM-supported asset programming is the reusability of data that is created or generated during the lifecycle. As a first step, a digital twin is modeled based on CAD data and enhanced with further meta data of other applications in the next step, so that further planning can be created [18]. Meta data consists of, for example, gripping points, tool interfaces, technical data or properties. In addition, the modeling of the product includes a machine-parsable work plan, which later provides the basis for the workflow processed by humans and robots. The biggest part of this data accumulates in the life cycle of the product or resource anyway, but is not used in a restricted way. By using industrial modeling standards such as AutomationML, OPC UA, JT/PMI or the IEC 62264 and central storages, data can be flexibly reused with minimal effort [19]. Thereby, more interoperable systems for planning, executing and teaching human-robot interaction can be connected.

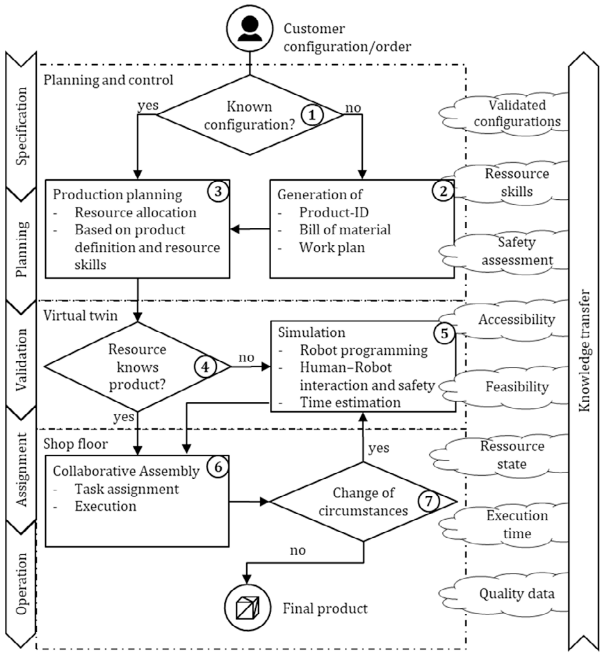

Figure 1. Workflow from customer order to final product

Figure 1 illustrates the workflow of consolidating and utilizing the data model for virtualization and transfer to the shop-floor. If the customer places an individualized order via an ERP system, all existing data is used for planning and production. The focus is on products with many variants, which the customer can configure individually such for constrained but also for variants that have never been assembled before (1). If a new variant is involved, a type-specific product ID including „Bill of Material" (BoM) and a work plan must be created firstly (2). In the following production planning (3), the existing orders are assigned to the available resources (robot-based assembly cells or manual workstations) under consideration of various optimization criteria. Skill-based allocation can take place, for example, via product/resource definitions (e. g. gripping planning [20]) or via machine learning algorithms [6]. If a resource has not yet been used in a certain work step in the past (4), this will be validated in a simulation in a virtual environment (5) [21, 22]. Therefore, the production process is simulated based on the digital twin and accumulated with the data from the new variant and resource configuration. Based on a Virtual Reality (VR) simulation, collision-free robot paths are automatically generated, gripper planning is accomplished and the safety of human-robot interaction is verified. This step is important, because the human is a non-deterministic element. By recording the actions and movement during a VR simulation of the assembly process, some unforeseen circumstances could be disclosed. The resources are parameterized from the simulation and the information is saved in the work plan and used to execute the assembly task on the selected resources (6). If unforeseen circumstances occur during execution (7), these will be verified by integration runtime parameter in the simulation during the assembly time (5). This may signify that the robot has to adapt its movement depending on human behavior or that the pick-up position of the components is undefined and is detected by cameras only during assembly. Through that loop the execution on the shop floor can be directly changed and optimized (6). The knowledge that is generated during the work flow is consolidated and transferred to improve the production process continuously as well used for reconfiguration and maintenance of the system.

4. System architecture

The central component of the system architecture used in this project is the integration bus based on a manufacturing service bus concept [23] added with the approach on asset administration shell [24]. The service oriented architecture of the integration bus allows the connection of various interfaces and data formats, and the storage and evaluation of sensor and monitoring data related to the digital twin of the asset in order to secure a closed loop between the engineering and production division. Figure 2 shows in the upper half the integration of the virtual environment. The simulation includes a robot simulation that is connected to a VR and augmented reality (AR) device. By using an AR and VR environment, the interaction between user and robot can be simulated in advance and in a save surrounding. The lower half of the figure shows the components of the physical production environment. The first OPC UA Server represents the integration layer, including assets and systems, the other represents the human-robot domain, including the Industrial PC (IPC) and Programmable Logic Controller (PLC), which in turn controls the robot and the other tools, sensors and actuators. The OPC UA Server connected to the PLC makes the sensor data available for storage, analysis and integration into the next engineering cycle. The implemented architecture is an extension of existing production IT, due to a needed direct capability-based assignment of tasks from the source applications (ERP, PDM, MES) and the increasing autonomy of collaborative systems and production resources in general. Individual modules of the planning process work on the consolidated data sets and expand them according to the workflows defined in the PLM concept bundled in AutomationML (AML) format. They are stored centrally and can be retrieved as required (e. g. for further analytics). The concept is realized through the consistent use of OPC UA. This allows the resources to provide current production and sensor data, technical data, properties and functions, which are assigned to explicit executable skills and made available back to the planning modules. The resource functions can be either called directly from the integration bus or sent to a cell control. The cell first interprets and distributes to the robot and human, including further needed resources.

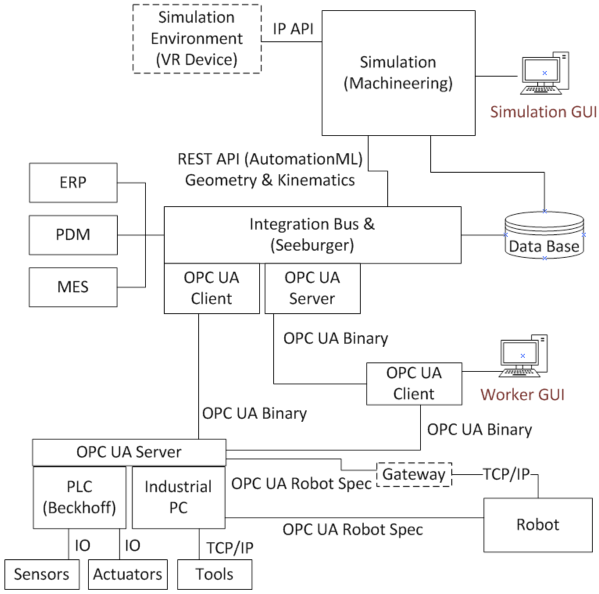

Figure 2. System architecture

Table 1 illustrates exemplary skills that are owned by the resources human, robot and gripper. Each executable skill has different attributes that are variable for a specific assembly task. These skills are used in the simulation as input and output variables for testing and integrating the assembly of new product variants. If a process is verified, the skills will be assigned to the production system over the integration bus.

Table 1 Exemplary Resources, Executable-Skills and Attributes

Resource	Executable Skill	Attribute
Robot	Pick & Place	Position n Position n + 1 PreProductConfiguration PastProductConfiguration (...)
	Screw Driving	Tool Position PreProductConfiguration PastProductConfiguration (...)
Worker	Screw Driving	Tool Position PreProductConfiguration PastProductConfiguration (...)
Gripper	Move gripper	Width Force (...)
	Set Tool Center Point	Position (...)

5. Case study

For validating the method, an assembly scenario has been chosen, in which a worker assembles a marble mace in collaboration with a lightweight robot. The aim of the scenario is to virtually program the robot based on the simulation data, using the architecture and workflow that is presented in this paper. A demonstrator has been developed which is available both in a simulation environment and as a physical assembly system. The workstation has been used to evaluate the information flow, especially regarding the connection between the simulation and the physical assembly system. The basic structure of the workstation consists of an industrial manual workstation equipped with assembly tools and a Universal robot UR5.

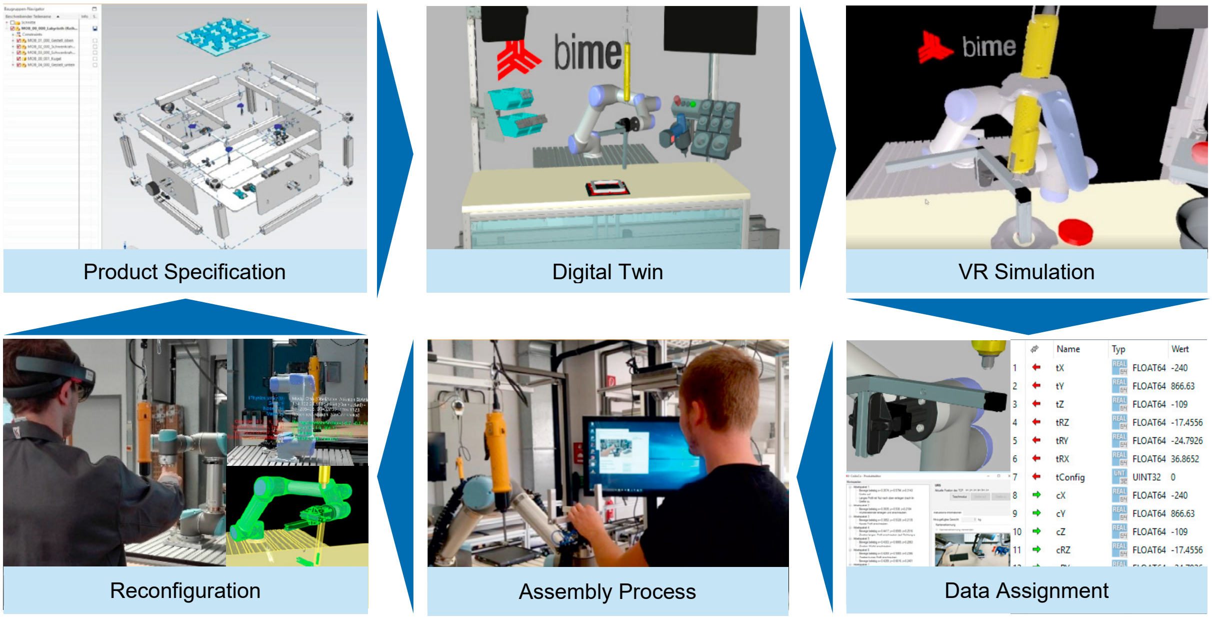

Figure 3. Case Study on PLM based robot programming

Figure 3 shows the approach that has been followed with the demonstrator and that is derived from the workflow in Figure 1 and based on the architecture in Figure 2. As a first step, the used resources of the assembly cell as well as the product are specified in a CAD system and described by its geometry and features. The configuration of the product can vary, for example, by size of the aluminum profiles. Since the changes affect the robot program and the accessibility for the worker, each new product variant and new configuration of the resources (toolings, equipments, etc.) has to be virtually secured. Therefore, the 3D-models are transferred into the simulated production system, using an API between CAD system and the Industrial Physics Simulation tool. The digital twin of the production system is established by a connection between the simulated robot control and the physical robot control and its representation in the PDM (Teamcenter) and MES systems by the AML-file over the integration bus. For programming the robot and securing the assembly process, a virtual environment is used. Based on the virtual reality hardware HTC Vive, the user can interact with the simulation in real-time. The position and point of view of the user is tracked and the controller movement is used to interact with the environment. The robot is teached by the user according to a needed executable skill from the working plan. The resulting robot path is checked for collision and if the virtual assembly is successful, the information is stored in the database according to the previously described parameters [Table 1], which are now assigned to the asset. If all information that is needed for the assembly has been consolidated, the assembly process will can be evaluated simultaneously on the physical demonstrator. The same work plan that has been used in the simulation is conducted with the real assembly product, using the robot path that has been retrieved from the simulation. If the assembly process has been executed successfully, the product variant would have been saved into the database as a known resource. If errors or nonconformance occur during the assembly, a reconfiguration of the assembly plan will be conducted. This can be done either on the job, using an AR device that is connected to the simulation, or by repeating the circular process. If the circular flow starts again, the information that has been retrieved during the physical information will be used for improving the digital twin by adding more details or restrictions. Observed deviations that have been crucial for the consistency between the simulation and the assembly process, e. g. the level of details of the assembly station can be eliminated by improving the digital twin.

6. Conclusions

The assembly of multi-variant products by human-robot collaboration has a high potential for raising the productivity. This needs consolidated PLM methods and approaches for data and system integration to execute the tasks directly based on information from product design and production planning and to transfer operational and product data from the shop-floor back. By combining the features of a simulation with a continuously information flow of a PLM-oriented integration system, the assembly of new product variants can be simulated in advance and during execution, allowing a reconfiguration of the production system according to new requirements. The industrial standards AutomationML and OPC UA are suitable for the implementation of the integration architecture. By using an approach based on executable skills, different abilities of each resource are modelled and further specified through simulation or knowledge from the assembly process. Accordingly, tasks can be allocated to robot or worker for an individual assembly scenario and be reused for planning. The method has been successfully tested for a use case that is focusing on robot programming for collaborative assembly of a multi-variant product. Further research will examine the virtual reality simulation environment, focusing on the consistency of the simulation results with the physical production system. Current operations also attempt on implementing the method in three different industrial application cases which cover different assembly and quality criteria. The presented method establishes a foundation for the monetary evaluation of collaborative assembly processes due to its holistic approach.

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