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Vertical Integration and Service Orchestration for Modular Production Systems using Business Process Models

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Abstract

Individualized production challenges established manufacturing approaches in terms of modularization, flexibility and efficient reconfiguration. Modular production systems with high flexibility, capable of interacting with products and humans, and vertically integrated with the business environment provide new possibilities for overcoming these challenges. Such flexible manufacturing approaches require seamless integration between all involved parties from the enterprise resource planning level down to the shop floor. Service-oriented architectures with standards geared towards automation claim to provide easier development and integration of modular production systems. However, in order to support the desired flexibility and integrability, a coherent modeling approach for manufacturing processes is required, in particular focusing on the orchestration between production tasks, resources, humans and services. To address these challenges, we introduce in this contribution a system-level approach for flexible manufacturing comprised of reconfigurable modular production cells, which can be easily composed into production lines. Reconfigurability is achieved through exchangeable process components, the use of lightweight robot manipulators as versatile handling subsystems as well as a cell control scheme based on executable business process models to allow runtime service orchestration. The systemic approach can be applied to realize a customer specific production down to lot size one and was validated in a vertically integrated production line manufacturing an industrial product with high variability. The resulting system has been exhibited at different trade fairs and demonstrates our interpretation of the SmartFactory paradigm for individualized production.

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Keywords: Modular Production System; Business Process Model and Notation; Service-Oriented Architecture; Robotics

1. Introduction

Individualized production challenges established manufacturing approaches in terms of modularization, flexibility and efficient reconfiguration [1]. Major challenges from a business perspective [2] include the needs to minimize the required amount of time from objective definition to start of production, to bridge the gap between enterprise and production levels, i.e. providing near real-time traceability and control of production processes as well as to

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achieve a high level of automation across all involved stakeholders and systems. Hence, increasing flexibility while managing the intrinsic complexity of reconfigurable and vertically integrated production systems is a key issue for future production systems. The vision of a SmartFactory [3] was devised to provide solutions for these challenges. For instance, it shall be capable to efficiently derive production tasks from customer orders as well as to autonomously schedule the execution of the necessary manufacturing steps in a networked system of production modules providing the required manufacturing services.

This contribution describes a step towards this vision by introducing (i) a system architecture that allows decentralized and parallel execution of manufacturing processes for customer-specific products in a production line composed of modular production cells, which are based on (ii) an approach to describe manufacturing processes using the Business Process Model and Notation (BPMN 2.0) as a standardized representation [4]. These models encode the required technical interaction between services exposed by the modular production cells such as PLC-level process component and robot activities, the product and its parts, just as manual actions executed by human workers. Furthermore, we explain (iii) the concept for modular production cells and the vertical integration in a (iv) demonstration scenario that we used to validate our approach in real-world applications.

In the following, Section 2 introduces the related work in the context of modular production systems plus approaches to model the orchestration and coordination of manufacturing processes. Section 3 briefly describes the mechatronic architecture of the modular production cells, while Section 4 explains the overall system architecture by mapping it to the concepts of the Asset Integration Architecture [5] blueprint. Section 5 exemplifies the course of action in the system architecture when executing a customer order within the vertically integrated demonstration system. The paper concludes with a short summary and outlook to future work.

2. Related Work

To cope with the requirements of individualized production, modern manufacturing systems need to dynamically adapt to change, must be easily customizable and configurable from standard parts [6]. One popular approach, which conceptually defines the basis for the work presented in this contribution, are Modular Production Systems (MPS) [7]. Within an MPS it is possible to adapt flexibly to varying demand by the dynamic addition or removal of modules from a production line. Prerequisites for the realization of such systems and the intended re-use are consistent modularization of hard- and software components [8].

Furthermore, versatile manufacturing components are required that support a broad range of manufacturing tasks. Within the system concept presented in the following sections, compliant robotic manipulators are used as versatile handling and assembly systems. Among others, the Rosetta project [9] demonstrated the utility of compliant robots in an industrial context. We utilize compliant robots in the proposed system to exploit their dexterity for assembly tasks and their safety features for close human-robot interaction, i.e. in order to ease the robot task programming in constrained environments [10] as required in the context of the modular production cells.

Besides hardware modularity and versatility, the transformation of static tightly integrated production systems to flexible, rather loosely coupled modular production systems with service-oriented abstractions requires concepts for the design of the software architecture and the coordination of goal-oriented actions in these distributed manufacturing systems. Prominent recommendations on how to organize the layers of connected manufacturing systems are documented in the Reference Architecture Model of Industry 4.0 [11] or the Industrial Internet Reference Architecture [12]. Another less standards-oriented but nevertheless related approach is the Asset Integration Architecture [5]. For the orchestration and coordination of manufacturing processes in these architectures, dedicated modeling approaches are required that go beyond the functionality of the IEC-61131-3 languages, i.e. using dedicated graphical workflow modeling techniques such as GrafChart [13]. However, in the case of connected manufacturing in modular production systems, modeling languages that are standardized, support distributed execution and the orchestration between production tasks, resources, humans and services are required. Furthermore, vertical integration and alignment with business processes are major requirements. A language that supports these requirements, originally developed for description and automation of business processes, is the graphical modelling language Business Process Model and Notation (BPMN) [14]. It has already been used for visualization and alignment of manufacturing and business processes [2], for the modelling of processes and functions at the level of Manufacturing Execution Systems (MES) [15] as well as in the context of architectures for the Internet-of-Things [16].