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Innovations in digital modelling for next generation manufacturing system design

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ABSTRACT

Interlinked and autonomous manufacturing systems provide new opportunities in smart manufacturing. Today's manufacturing system design processes and architecture still are based on traditional engineering methods and can hardly cope with increased system complexity. Hence new cyber physical production systems (CPPS) design and architecture principles as well as corresponding validation and verification methods are necessary. This paper presents firstly a new architecture design approach for modularised design of CPPS. Secondly, new capabilities in designing with modular construction kits, simulating functional behaviour and validating with virtual, functional prototype are introduced. Thirdly, a proposal for the development approach and virtual validation is presented and risks as well as challenges are discussed.

1. Introduction

Increasing product variants and customisable products request more flexible production systems. Industrie 4.0 envisions interlinked and autonomous manufacturing systems self-organizing the production of small batch sizes up to lot size 1.

For this, new design paradigms in manufacturing system design are necessary. According to [1] cyber physical systems in Industrie 4.0 will manage the interconnection between physical components and the computational capabilities. Mechatronic systems could transform to cyber-physical systems (CPS) by extension with additional communication skills and autonomy in behaviour on external influences and internally stored settings [2]. Cyber physical production systems (CPPS) are in addition interlinked with the internet of things (IoT) enabling smart manufacturing. Consequently, such an architecture needs to be tested and validated and requires new engineering capabilities.

CPS design is characterized by a software oriented approach while mechatronic system design follows up a mainly hardware-driven approach. Mechatronic systems design differs from the design of cyber physical systems according to [3] by functional integration with dematerialization, while the mechatronic approach realizes functional integration by physical integration of mechanical and electric/electronic hardware (Fig. 1). CPS create new functionalities by dematerialization: the functional integration is managed with computed feedback loops by affecting physical processes and vice versa [4].

CPS also need to be reliable and predictable [5] as embedded systems are, but therefore they need testbeds and simulation frameworks to ensure real-time performance and error management analysis.

For testing during ongoing operation, the interaction between several CPS and the linked impact, a "Digital Twin" of the CPS must be present [6]. Sensor data of CPS are recorded and accumulated for the Digital Twin generating knowledge for the users of CPS. In addition models for simulation of the CPS and the CPPS architecture are necessary [1].

Due to incomplete or limited definition of a Digital Twin [6–8], researchers of Fraunhofer IPK and TU Berlin propose the following definition which provides a separation of usage data and models for simulation: "A Digital Twin is the digital representation of a unique asset (product, machine, service, product service system or other intangible asset), that compromises its properties, condition and behaviour by means of models, information and data".

Today every instance of an individual product or production system produces a digital shadow by means of operation and condition data, process data, etc. Hence an instance of a Digital Twin consists of: an unique instance of the universal Digital Master model of an asset, its individual Digital Shadow and an intelligent linkage (algorithm, simulation model, correlation, etc.) of the two elements above (Fig. 2).

Today's manufacturing systems design in industrial praxis still miss the software-oriented approach for the design of such digital master models: Plant manufacturers still follow-up a sequential, mechanic centred design and a late PLC-design and validation (Fig. 3). Manufacturing systems are usually designed as systems

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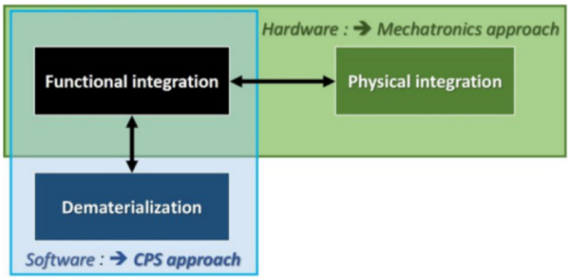

Fig. 1. Mechatronic vs. CPS approach [3].

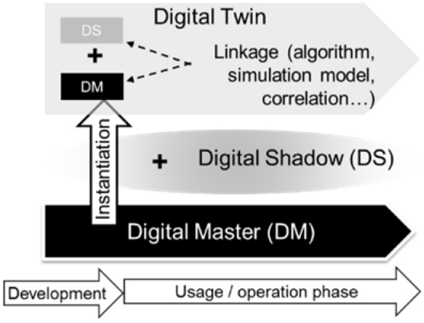

Fig. 2. Digital twin, digital shadow and digital master.

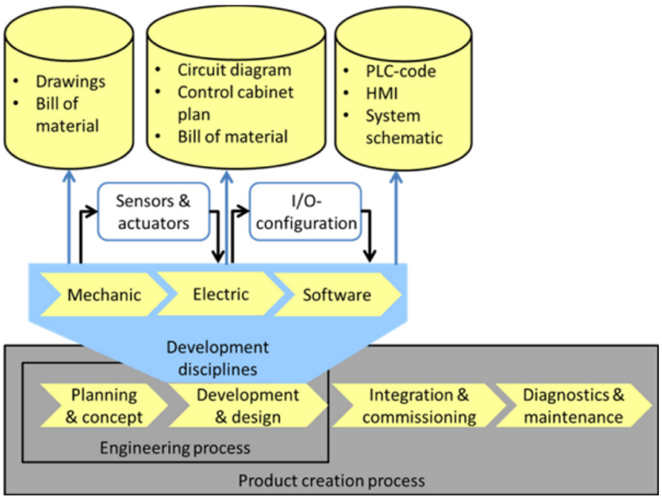

Fig. 3. As-is design process in manufacturing system design [10].

with a single controller and specific task: a set of actors, sensors and machines are combined to fulfil a dedicated set of functional requirements and constraints [9]. The controller design of a manufacturing system includes usage of the actors and sensors as well as communication with MES and SCADA systems, but is realized late during manufacturing system engineering.

In reality, the manufacturing system design barley even follow up a systematic design approach: it is still common praxis to let each design engineer work within its own discipline by using specific design and engineering models and to mitigate late integration issues by best possible PLC code adoption or mechanical interface correction without any true systems engineering design opportunity.

To transform the manufacturing system design towards a cyber physical system architecture, a new design approach as well as a new validation framework are proposed.

2. Solution proposal

For a CPS design approach for manufacturing systems, the fixed process chain as well as the usage of a single controller need to be replaced by functional units with versatile executable functions and skill negotiation for the manufacturing and assembly operations.

With help of skill negotiation, several independent CPS are able to execute flexible process chains and can be combined to a new CPPS. The skill negotiation must include information of possible process parameters and its hardware constraints (e.g. for milling the dimensions of the workspace, performance specification and power of the drive, etc.). With skill negotiation, the functional units can be combined to a new manufacturing system architecture. With the introduction of skill negotiation and flexible process execution, additional design and validation steps are necessary: beside the multi-discipline validation of existing designs, the skill communication, negotiation and execution need to be validated during CPPS design.

According to [11], a domain validation is enabled by behaviour modelling. By extending existing virtual commissioning approaches and their behaviour models with the communication and negotiation of skills, the combination of functional units to a new CPPS architecture can be validated and design requirements for CPS-units identified. With preliminary behaviour modelling extended by skill negotiation and execution, the future system can be simulated. The CPS component interaction can be analyzed. After simulation, detailed requirements for CPS components can be derived and detail engineering started.

Mechanic as well as electric and software design today are tested at the final manufacturing system in time-consuming commissioning processes at the customers' production facilities. To enable an early, software centred manufacturing system, the interaction of functional units must be tested with the help of a functional, virtual prototype of the future CPPS (also compare [12]). As CPS are defined as “physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core” [13] the virtual prototype as testbed for the CPS modules and the CPPS architecture is proposed. For this, also the architecture definition and validation need to be considered during design process.

3. Modularised functional design with a construction kit

3.1. Construction kit capabilities

To address these additional, new requirements for modelling of CPS (see Chapter 1) a new modular construction kit was designed. The construction kit is capable to extend the traditional, sequential design process by functional behaviour models. As a major prerequisite for integrated manufacturing system design the digital representation of the manufacturing system needs to be capable for subdivision into separate functional units (so called modules). This approach enables a multi-disciplinary view on each single module and is able to provide a variety of partial models for each design discipline. With the help of the sum of interdisciplinary partial models for each functional unit, the traditional design models like geometry (CAD model), circuit diagram (electric projecting) and plc code (control design) are extended by kinematic, logic and physics behaviour models including skill communication, negotiation and execution capabilities (Fig. 4a).

Enriched with these partial models it is then possible to cover different design phases of the manufacturing system design process from early spatial layout planning by building a virtual mock-up with the ability of immersive experience in virtual reality (Fig. 7) up to a highly defined signal testing for the PLC programming in the case of virtual commissioning. After test and optimisation of behaviour models as well as skill negotiation and execution, the requirements for mechanic, electric and controller design are derived and can be addressed to the design disciplines (Fig. 4b). The presented construction kit allows a systematic and model based design approach for flexible manufacturing systems and provides the ability for interdisciplinary concurrent engineering, validation and testing (Fig. 4c).

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