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Development and operation of Digital Twins for technical systems and services

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ABSTRACT

Digital Twins are new solution elements to enable ongoing digital monitoring and active functional improvement of interconnected products, devices and machines. In addition, benefits of horizontal and vertical integration in manufacturing are targeted by the introduction of Digital Twins. Using the test environment of smart factory cells, this paper investigates methodological, technological, operative, and business aspects of developing and operating Digital Twins. The following Digital Twin dimensions are considered in scientific and application oriented analysis: (1) integration breadth, (2) connectivity modes, (3) update frequency, (4) CPS intelligence, (5) simulation capabilities, (6) digital model richness, (7) human interaction, and (8) product lifecycle. From this, design elements for the development of Digital Twins are derived and presented.

1. Introduction

Products evolve to Cyber-Physical Systems (CPS) and Cyber-Physical Productions Systems (CPPS) being composed of mechanical, electrical software and communication components while connected to their direct environment or the "cyber-world". The Industrie 4.0 context requires a broad horizontal and vertical integration [1], e.g. including consolidating, analyzing, connecting data derived from sensors and actuators, processes, production machines, the product itself. The Information Factory, as introduced in Ref. [2], refers to this comprehensive interconnection of all necessary information systems (Product Lifecycle Management, Enterprise Resource Management, Supply Chain Management, cloud platforms including. analytics, diagnosis etc.) and delivers expertise for the operator platforms of the future as a core environment for Industrie 4.0 solutions. The *Information Factory* serves as implementation and operation framework for Digital Twins (DT).

DT and their related technologies are an increasing research topic and first experimentation prototypes have been built [3,4] in order to understand the nature and the power beyond the conventional analysis of operational data like in traditional maintenance, repair and overhaul or production in industry. This paper introduces and analyzes the use of the *Information Factory* as enabler for establishing and operating a *Digital Factory Twin* in an experimental setting (Section 4). Basis for this experimental approach refers to the state of the art and technology in digital twinning (Section 2) and to a new model describing the dimensions and the new design and engineering approach for DT (Section 3).

2. State of the art and technology

For the first time DT are mentioned by NASA monitoring a satellite's behavior and simulate possible changes in the settings [5]. DT are defined as a digital representation of an active unique product or service or production system that is characterized by certain properties or conditions [6] used in order to analyze, understand and improve the product, product service system or production. The relevant, characterizing aspect of combining *Digital Master Models* from PLM and *Digital Shadow* data, e.g. from cloud platforms together build a DT [7] evolving along the life cycle.

The role of the *Information Factory* for the representation of DT comprises the following aspects (cp. [2]):

- The *Information Factory* operates different degrees of information technology functions (such as fog, edge or cloud computing or Artificial Intelligence compute environments such as the lambda architecture) in order to create new forms of intelligence (as part of a DT).
- The *Information Factory* output delivers meaningful sets of information such as DT via smart data analytics (in form of correlations, data feature recognitions, trend rules etc.) in order to feed those value oriented deliveries into higher processes of production, product operations and any other sort of service (such as maintenance or distribution).

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- The role of the *Information Factory* is to reveal the appropriate semantics in order to analyze, control and modify technical systems from simples analysis and control levels up to autonomous CPS interactions (e.g. via the innovation core element DT).

Relevant in DT research are the appropriate business models fueling companies' efforts which often focus service development and improvement, e.g. in the field of predictive maintenance. A core enabler for DT is the IT infrastructure including appropriate storage and calculation properties, offered as software products like Siemens PLM Mindsphere, Microsoft Azure, SAP Hana, and focus to current research as well [8]. Yet linkage between the existing brownfield systems and their data is still under development. Steeping into the layer of models and data exchange current research combines dedicated data and models [10] not yet targeting standards or general solutions.

3. Digital Twin modelling dimensions and design elements

The research team of this paper started in 2015 to explore the dimensions by which the intended behaviours and the context of DT can be described. This is critical in the first phase of research in order to study the appropriate DT design elements in the second phase and the correlation of the two in the third phase.

Within the first phase, a structured approach for planning the scope and type of DT has been developed. It is called the "Digital Twin 8-dimension model", as depicted in Fig. 1. One can distinguish the dimensions with focus on DT context and environment (left side), and the dimensions with focus on behaviour and capability richness (right side).

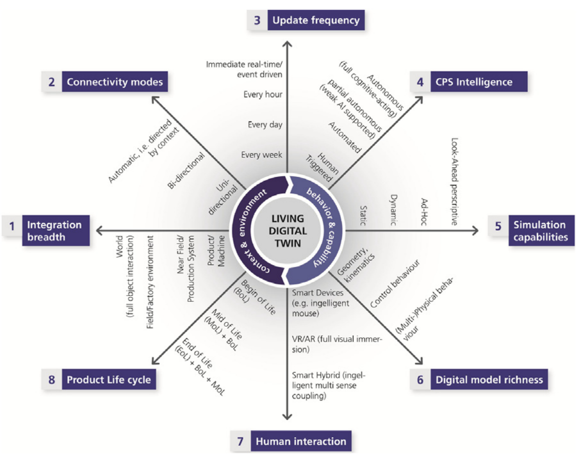

Fig. 1. The "Digital Twin 8-dimension model".

The area of DT environment and context is represented by the four dimensions integration breadth, connection mode, update frequency and product life cycle. The DT behaviour resp. capability richness comprises the other four dimensions, i.e. the CPS intelligence, the simulation capabilities, the digital model richness and the human interaction. Each one of the dimensions provides three or four levels of realization: a higher level is not necessarily better than another but depicts a different and/or unique realization space. Four out of the eight dimensions, dimension 1 (integration breadth), dimension 2 (connectivity mode), dimension 7 (human interaction) and dimension 8 (product life cycle), however, do express with their increasing levels also an increasing degree of richness/fidelity (dimension 2 and 7) and of breadth/extent (1 and 8).

The model allows describing major "behaviour and context capabilities" to which a specific twin is designed for by allowing multiple target levels in each of the eight dimensions. Those eight dimensions are not exclusive or exhaustive but represent the most likely dimensions that are of importance to support the individual business context situations of the specific DT in scope. Engineers and business managers, therefore, are enabled to effectively use the "Digital Twin 8-dimension model" within the following situations:

- As guidance in target setting in the development of completely new product by using an already existing DT.
- To extend existing products with the knowledge gained from the their operational DT or
- To further develop DT as a product or service by its own (i.e. as a template), adding new functions along the eight dimensions as necessary.

In the second phase, the research team concentrated on the theoretical foundation for the DT design framework: search for and identification of the critical set of DT design elements. This was part of the research and development work of four loosely coupled types of research projects between 2016 and 2018:

- A scientific study, with more than 140 experts from academia, information technology and industry, on the future role of DT in smart services and smart products,
- Theoretical (deductive and inductive) research on the history and the original foundation of digital twinning concepts as well as on future directions to perceive DT as a product on their own (research engagement with technology companies in mechanical engineering and aerospace),
- Experimental evaluation to prototype various DT examples in labs of the research institute (see the example smart factory cell in Section 4) and in a pre-development lab at a global automotive OEM, and
- Ongoing research engagement in the German platform Industry 4.0 and its research council.

Considering design elements for DT the following two distinct DT use cases need to be protected in order to allow for most flexible applications:

- The use of a DT on its own (i.e. without owning the physical product, object, gadget or machine) and
- The use of a DT in strict co-ownership with an in logical extension of the reference (physical) product.

Treating those two basic use cases as equal and independent from each other the research team finally embarked on six major design elements, as shown in Fig. 2. The *design element* 1 (certain hardware of the physical product) concentrates on those hardware components, which allow for analysis (sensor), control (actuator) and network interaction of the DT with the entire or certain subsystems of the physical product.

The *design element* 2 (ECU SW of the physical system/component) ensures the description of the DT characteristics for the product or service on-board control algorithms and analytics. The *design element* 3 (data repository and core elements of the information factory) provides the capability to describe compute environments, associated data repositories, sets of analytic toolboxes as well as network connectivity information technologies. The *design element* 4 (*Digital Master* and *Digital Prototype* models) comprise all relevant digital models which form the base for DT (reference) capabilities. The *design element* 5 (*Digital Shadow* data and information sets) allows the integration of characteristics stemming from physical product or service operation, i.e. from measurements of data and related direct analytics. Last but not least, the *design element* 6 (intelligence and state machine) represents an interlink element between various other design elements and offers a wide variety of linkage richness and rigidity resp. flexibility.

As part of the third research phase Fig. 3 depicts the influence factors of DT design elements on DT dimensions. Five levels of influence scale are distinguished: critical (full circle, score 4) means that an adjustment of the design element is indispensable and even drives other design elements in order to reach the next

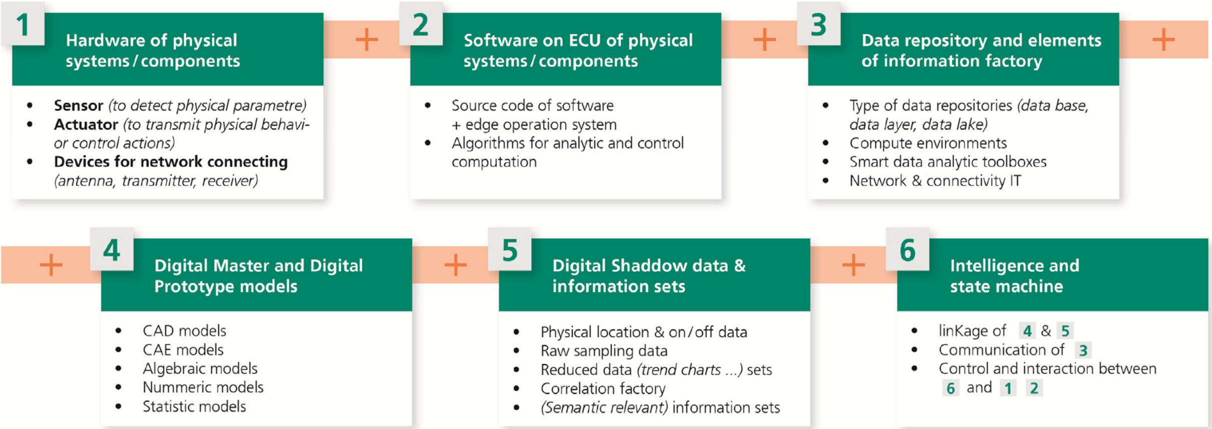

Fig. 2. Digital Twin design elements.

Influence factors of DT design Elements (DE) per DT Dimension (D)

Dimension	Design Elements 1	2	3	4	5	6	"Drivable score per DT Dim"
1	4	4	3	4	4	4	23
2	2	3	2	2	2	4	15
3	0	4	3	2	2	3	14
4	4	4	4	4	4	4	24
5	0	0	3	4	2	3	12
6	0	0	1	4	2	3	10
7	1	1	3	2	4	2	13
8	1	1	3	4	4	2	15
"Influence score per DE"	12	17	22	26	24	25	↑ max. 24 ← max. 32

Influence scale					
Scale	critical	signifikant	partial	possible	none
Score	4	3	2	1	0

Fig. 3. Influence of DT design elements on DT dimensions.

level within the individual DT dimension. Significant (three quarter of a circle, score 3) means the same as critical but without necessary impact on another design element. Partial (half of a circle, score 2) indicates that an adjustment is likely but not necessary, whereas possible (quarter of a circle, score 1) means that an adjustment is possible but not likely. None (empty circle, score 0) indicates no influence on the DT dimensions.

As it is noticeable from the analysis shown in Fig. 3, the DT *design elements* 4, 5 and 6 (*Digital Master*/*Digital Prototype*), *Digital Shadow* and Intelligence/state machine) have the highest influence on the DT dimensions. Hence, they will receive major attention by ongoing research and by first DT developments in industry. From the perspective of DT dimensions the analysis confirmed that the dimension 1 (integration breadth) and the dimension 4 (CPS intelligence) are highly and equally dependent on all of the *DT design elements*.

4. Example for Digital Twin development and operation

Smart Manufacturing refers to a data-driven paradigm that creates manufacturing intelligence based on the acquired data in order to optimize, monitor and visualize every aspect of the factory [11]. The smart factory cell (see Fig. 4) serves as example to demonstrate and evaluate the application of *Smart Manufacturing*. Within the team's research, the smart factory cell is an instantiation of a digital production twin: operational data of the physical smart factory cell is linked to the digital master respectively the digital prototype model. The smart factory cell focuses on the following aspects of the *Information Factory* (see chapter 1):

- A service for individualization of products that interacts directly with its production is in operation.
- The factory operates this service via cloud computing into machine control and
- The factory is linked to its digital master in that way, its interactions can be processed, controlled and modified in real-time.

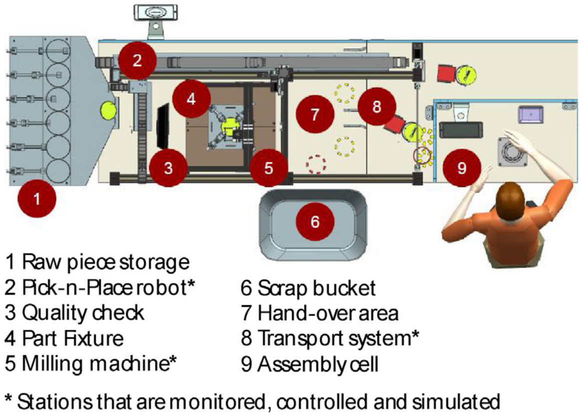

Fig. 4. Principal setting and process of the smart factory cell.

4.1. Development of the smart factory cell

The smart factory cell comprises three major aspects of *Smart Manufacturing*: real-time condition monitoring, control and simulation. In the context of the *Information Factory* these demands can be instantiated for the DT of the smart factory cell using the example of the "Digital Twin 8-dimension model" (cp. Fig. 1):

1 Integration breadth: production system.
2 Connectivity modes: bi-directional.
3 Update frequency: immediate real-time.
4 CPS intelligence: automated (in ms).
5 Simulation capabilities: dynamic.
6 Digital model richness: geometry kinematics.
7 Human interaction: smart devices.
8 Product lifecycle: mid-of-life.

Fig. 4 shows the principal setting (stations) of the smart factory cell, as it is physically build. Furthermore, the process sequence through the various operations is shown.

The physical development of the smart factory cell elaborates on the *design elements* 1 and 2. These are not discussed in this paper because they only show the physical part of DT. *Design element* 3 focuses primarily on communication and storage of data, thus, it is not described in detail in this paper either. On the other hand, the *design elements* 4, 5 and 6 are described in detail below:

- *Design element 4* (*Digital Master* and *Digital Prototype* models): certain numeric as well as CAD and CAE models of the factory comprise all relevant digital models and they form the base for DT capabilities.
- *Design element 5* (*Digital Shadow* data and information sets): the collection of data about the position information of moving parts

as well as of the motion of the motors allows the integration of the real behaviour into the digital models.
- *Design element 6* (intelligence and state machine): the linkage richness is based on the synchronization of the collected data with a to-be status and, which in turn allows the control the operation of the smart factory cell.

The central element for monitoring, controlling and simulating the smart factory cell is the smart factory DT. It covers the following intelligence of *Smart Manufacturing*:

- Condition monitoring: Monitoring positions of every step: baselining, order, transport, moving mill, milling, waiting, transport, end of run.
- Control: The activity of controlling the manufacturing processes with the DT enables an individualized manufacturing process, due to the simulation of the whole process simultaneously. The information collected in the field is used together with the simulation and other information sources to give the control to the DT itself. One example for controlling is the monitoring for collisions or intrusion, which would lead to a stop of the pick-and-place robot.
- Real-time simulation: The controlling of the manufacturing process with the DT needs the information about the status of the process and the positions of every object. The positions of moving objects are continuously updated for the real-time simulation of the DT. They are directly connected to the mill and the pic-and-place robot.

4.2. Operation of the smart factory cell

The DT enables an individual manufacturing process with which virtual and physical interaction takes place. The activity of controlling the manufacturing processes with the DT enables an individualized manufacturing process, due to the simultaneous simulation of the process. The information collected in the field is linked to the simulation and other information sources in order to give the control to the DT itself. Fig. 4 shows the principal setting of the smart factory cell, including its certain stations and process operations. The operations monitored, controlled and simulated are baselining, order, transport (station 2), moving the mill, milling (station 5), waiting and transport (station 8).

The DT centrally controls the motion of the machines and the condition monitoring with the sensors. Fig. 5 shows the relevant hardware and software, their interactions, the transport protocols and the measuring points of the smart factory cell.

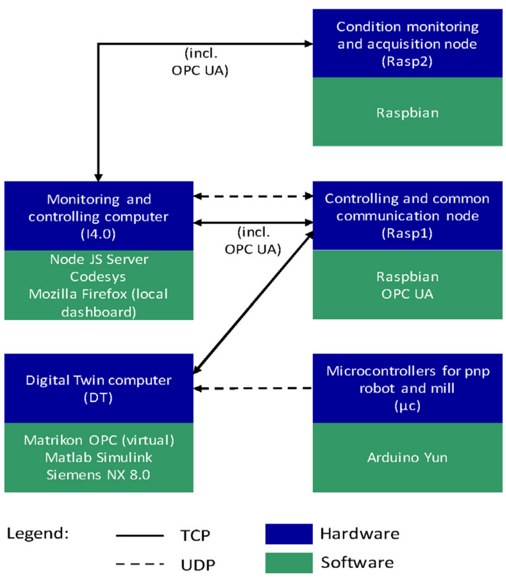

Fig. 5. Setup of the smart factory cell with a DT.

The positions of the controlled machines are continuously updated within the DT simulation, which is run on the DT computer. There are intermediate Raspberry Pis (Rasp 1 and 2), which are directly connected to the sensors and actuators, collecting data and synchronizing the position information and control. The I4.0 computer interacts with the Rasp 1, which is a Programmable Logic Controller (PLC)-shield, and the Rasp 2, a mini computer with Wi-Fi communication. Additionally, two microcontrollers (μc) translate the commands into the motion of the motors of the pick-and-place (pnp) robot and the mill. Each μc serially communicates with the motors of the pnp robot and the mill respectively. They continuously send the position data to the DT. Rasp1 is used to communicate the monitoring and control commands among the I4.0 and DT computers.

For condition monitoring (temperature, power, energy consumption) the average package size is around 408 bytes (TCP) and 208 (UDP) with a minimum of 60 bytes and a maximum of 1296 bytes). The package sizes for motion control for one simple manufacturing process (milling) is in average 187 bytes (DT control) with a minimum of 130 bytes and a maximum of 198 bytes).

5. Conclusion and outlook

The research team has advanced two development support models that are essential for the design of DT solutions. The first model, the “Digital Twin 8-dimension model”, was used to set scope and principal targets of the DT solution for a smart factory cell. The current version of this model provides a framework of the major dimensions of a DT solution. It is helpful in reflecting the individual DT dimension levels and identifying the interdependencies between them. The model needs refinement in cross dimension dependencies and to provide more explicit step by step design reasoning. The second model, the DT *design elements* and their influence factors towards the DT 8-dimension model was applied to the development and for the ramp-up activities of the smart factory cell. The categorization of the core DT *design elements* provide core engineering clarity in order to determine functional understanding, logical layout and intended behavioral interplay between physical system elements, related software controlled systems and data-driven analytic *design elements*. Future research work should concentrate on model and model-traceability aspects in order to allow for MBSE (model-based systems engineering) development approaches for DT solutions.

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