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Approach of simulation data management for the application of the digital simulation twin

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Abstract

Advanced Systems Engineering combines physical products and digital services and models at an early stage of the product development process. Therefore, more and more sensors cover functional and service assurance of a physical product. The representation of the sensor network enables the efficient archiving, management and processing of sensor data with available simulation models and higher semantics of the sensor data. For this purpose, we defined requirements for the sensor network and designed a conceptual framework. The implementation focuses on the transmission, archiving and processing of the sensor data as an input deck for further simulations.

Keywords: Digital Twin; Simulation Data Management of the Digital Twin; Advanced Systems Engineering

1. Introduction

An estimated 37 billion things will be connected to the Internet by 2020 [1] —37 billion components, products and systems that can record and exchange data. In the course of data-based business models, the need to process real condition data is increasing. One approach for this is the use of simulation models of product development. The main obstacle is the right interpretation of sensor data for use in simulation models. Fig 1 shows the systems of product development and the real product with its sensors schematically. The graphic is divided through the line between virtual and real environments. The virtual environment contains the systems Product Lifecycle Management (PLM), Product Data Management (PDM), Computer-Aided Engineering (CAE) and Simulation Data Management (SDM). At the current state, there is no exchange between the real and virtual environment. To use simulation models of product development beyond the development and design phase, a continuous exchange of data between the real product and the models of product development must exist.

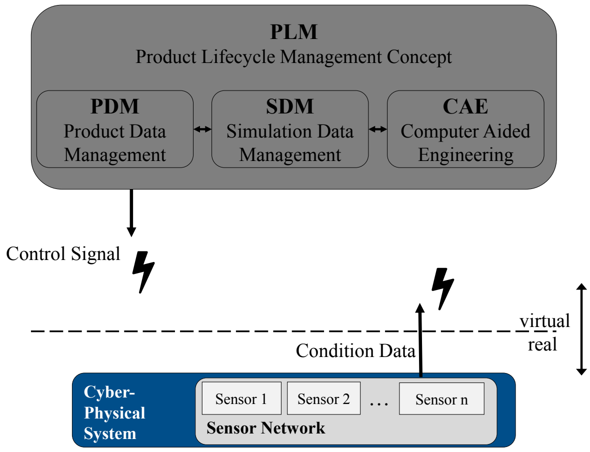

Fig 1 Starting Point: Missing feedback between Cyber-Physical System and Product Development

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The return and use of real condition data to product development would be essential for evaluating simulation models and results. Simulation data management in product development is a key component for this. Simulation Data Management (SDM) is responsible for administering the so-called input decks within the CAE process chains [2]. The input deck describes a calculation model which consists of the CAE data, boundary restrictions, load cases and solver information [3]. The input deck also contains the corresponding CAE models. For the processing, the simulation starts with an existing input deck. Thus, the input deck serves as starting point for the subsequent processing in the CAE tools. The result of the processing is the output deck, which contains the simulation results' raw data. Finally, the simulation data is processed in postprocessing. (cf. Fig 2)

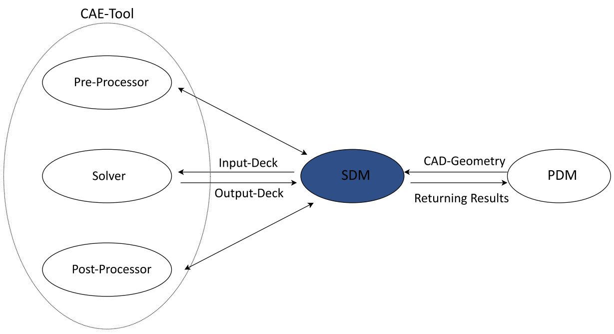

Fig 2. Simulation-Data-Management [3]

The evaluation of condition data and connection of so-called cyber-physical systems [4] is in line with the vision of Industry 4.0, which calls for a new level of organization and control of value chains throughout the entire life cycle of products [5]. A key technology of Industry 4.0 vision is the concept of the Digital Twin [6]. Digital Twins are defined as the digital representations that contain all design-, production- and utilization-information of the physical twin over the entire product life cycle [7]. The use cases of Digital Twins are manifold and can be distinguished for different shareholders and in the depth of data evaluation [6]. Based on the transmitted condition data, the data can be processed in the available simulation models. The Digital Master, together with the Digital Shadow, forms the Digital Twin (Fig 3) [8]

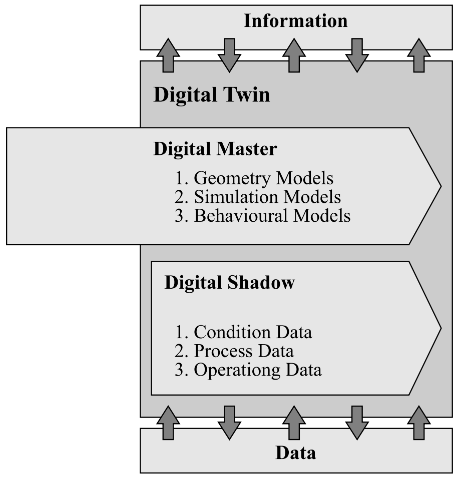

Fig 3. Concept of Digital Twin including Digital Master and Digital Shadow [8]

The Digital Master contains the models developed in product development. The models are divided into three categories:

1. Geometry Models
2. Simulation Models
3. Behavioral Models

The Digital Shadow, on the other hand, archives the condition data and represents the data basis for the simulations. For processing, the condition data are referenced to the models of the Digital Master [8]. Referencing the condition data, the data can be processed in different models and reduces the amount of data to be managed while maintaining a high data consistency level [9, 10].

For further procedure, the approach of sensor data-driven simulations is combined with the Digital Twin concept. Accordingly, the simulation models are transferred from product development and the condition data are transferred from product utilization to the Digital Twin. The challenge lies in the continuous processing of simulation models with condition data. An essential step forward is linking the condition data of the Digital Shadow with the simulation models of the Digital Master. For this purpose, two approaches are distinguished. One approach deals with the extensive condition data acquisition and archiving in Digital Shadows. The data archiving takes part separately from the respective processing of the data. The objective is high quality data, which allows flexible processing with simulation models. For this purpose, a semantic enrichment according to the principles of the knowledge pyramid is used [11]. The approach of the so-called simulation data management described Abramovici [12]. One use case could be the processing of high-quality data with upcoming simulation models during the utilization phase. Based on the simulation data management and the semantic enrichment it is still possible to process the historical data.

Another approach is the preparation of the simulation models at product development for use in the Digital Twin. The simulation models should be applicable even with a low quality of data. Therefore, developed simulation models from product development will be prepared with comprehensive metadata. The provided metadata enables the evaluation and preparation of the condition data for processing with the simulation models. One use case is evaluating of sensor data by using threshold values based on the metadata of the product development. The additional required information like the sensor setpoint, maximum and minimum values come with the metadata set of simulation models.

Due to the connection between Digital Master and Digital Shadow, there is an interaction between the approaches. In this paper, requirements for sensor network representation based on existing simulation models' metadata are described, and a conceptual framework will be designed. The concept and implementation are carried out using an exemplary Cyber-Physical System as Physical Twin.

2. Requirements for the sensor network representation

We define sensor network representation requirements for evaluating, preparing, and processing sensor data with simulation models. The requirements are based on state-of-the-art research on Digital Twins and CAE (computer-aided engineering)-simulation experts. We distinguish between fixed requirements (F), which the concept must fulfill, and desirable requirements (D), which would be desirable to achieve. An overview of the requirements is shown in Table 1.

- **Requirement 1 (F): The representation method must contain all relevant sensor data.** (measuring range, deviation, accuracy, etc.)

The concept aims to link the sensors with the models and information from the product development phase and to achieve a higher semantics of the sensor data and therefore, better interpretability. If a sensor is selected for a product during the development phase, this is done based on specific requirements. Possible requirements are measuring range or the measuring method. To ensure that this information is not lost, the representation method must contain all relevant sensor specification. Relevant sensor information, such as the measurement accuracy help to make statements about the accuracy of the simulation results. Another example would be the fast plausibility check of sensor measurement values during operation.

- **Requirement 2 (F): The representation method has to consider the positioning and orientation of the sensors.**

In addition to the sensor specifications the positioning and orientation of the sensors must be considered in the method. This information is essential so that the load collectives from the sensor data can be correctly included in the simulation.

- **Requirement 3 (F): The representation method must contain the historical sensor data over the relevant time range.**

In addition to real-time evaluation and display of the current condition of a product, the sensor data should be stored historically over a period that is reasonable for the application. Thus it is possible to perform a detailed analysis of the operating status and to derive findings. Besides, only with stored data it is possible to combine data from several digital twins to recognize patterns in fleets using AI methods, for example.

- **Requirement 4 (F): The method must allow further processing of the sensor data within the digital twin.**

Since the sensor data are to be used to generate an input deck for simulations, further processing of the sensor data must be guaranteed. This also includes the possibility to access the stored data at any time.

- **Requirement 5 (F): The representation method must contain an exact representation of all sensors**.

With the increasing complexity of the systems, the number of used sensors also increases. There is a need for an overview of the sensors for the developer and the user as well.

- **Requirement 6 (F): The method must allow to add/remove sensors**.

Since the product utilization phase is becoming more and more dynamic, and thus products can be supplemented by additional sensors, the representation method must keep up with this development. Therefore, it must be possible to add other sensors placed on the product in the representation method. The removal or replacement of the sensors is a scenario that has to be considered as well.

- **Requirement 7 (D): The method should be independent of the chosen IT tools and programming languages**.

An implementation of the concept independently of the IT tools and programming language is desirable. The independency would make it possible to supplement existing Digital Twins of different architectures with the concept and thus increase the added value and potential of Digital Twins.

- **Requirement 8 (D): The method should support as many use cases as possible for using a Digital Twin**.

The concept of a Digital Twin provides for a wide range of possible use cases. The use of Digital Twins covers all phases of the product life cycle. The variety requires a representation method that is as independent from the use case.

- **Requirement 9 (F): The representation method must enable the use of sensor data in CAE process chains**.

This requirement is an extension of no. 4 and explicitly aims at the further processing of the sensor data in CAE process chains (multi body simulation – MBS, finite element method – FEM, computational fluid dynamics – CFD). With the processing in the CAE process chains, a linkage of the sensor data with the CAE models takes place.

Table 1. Requirements

No.	Requirement	Fix/Desire.
1	The representation method must contain all relevant sensor data.	F
2	The representation method has to consider the positioning and orientation of the sensors.	F
3	The representation method must contain the historical sensor data over the relevant time range.	F
4	The method must allow further processing of the sensor data within the digital twin.	F
5	The representation method must contain an exact representation of all sensors.	F
6	The method must allow to add/remove sensors	F
7	The method should be independent of the chosen IT tools and programming language.	D
8	The method should support as many use cases as possible for using a Digital Twin.	D
9	The representation method must enable the use of sensor data in CAE process chains.	F

3. Concept

In the following, we develop a conceptual Framework based on Fig 3 and under consideration of the superordinate objective of linking the physical product's condition data with the simulation models of virtual product development via the digital twin concept. The considered simulation models are the CAE process chains multi-body simulation (MBS), finite element analysis (FEA) and computer fluid dynamics (CFD). These models are developed at the product development phase for optimization purposes.

The concept (cf. Fig 4) is also divided into a real and virtual environment. The entire product development takes place in the upper area of the virtual environment. The Digital Twin is now the link between the product development and the physical product. The Digital Twin contains the results of product development and administers simulation variables. Two steps are of importance for the representation of the sensor network and the processing of the data with the simulation models. Before archiving the condition data in the Digital Shadow, a **preselection** takes place. In the second step, the Digital Shadow data are transferred as discrete data sets into the simulation data management of the Digital Twin (**SDM-DT**). We will now describe both elements further.

Preselection: he preselection filters the condition data, identifies faulty sensor data at an early stage, and excludes them for further processing. The preselection defines a threshold for an automatic input deck generation in addition to detecting sensor measurement errors. Therefore, a program reads out the available metadata out of the XML-file of the available simulation models. In case of sensor data outside the already simulated value range, the program reads out sensors value at the current time step and generates a specific input deck.

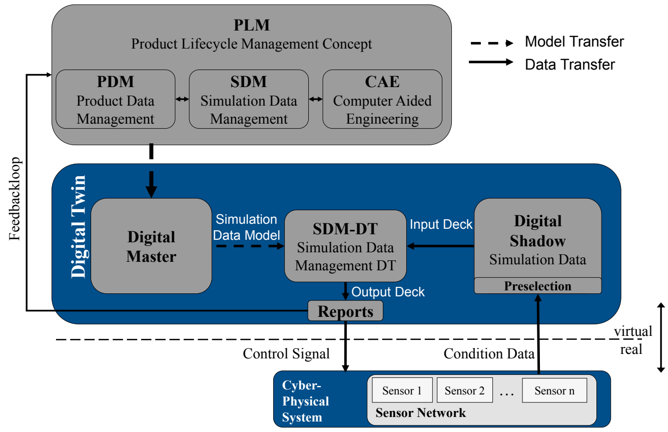

Fig 4. Concept of Sensor Data Representation

The Simulation Data Management System (SDM) is typically responsible for archiving, manage and providing simulation and calculation data. It is located between the PDM system and the CAE tools (cf. Fig 4). The advantages of an SDM system are the administration of different geometry idealization levels based on the master geometry and the raw data administration depending on different simulation parameters. The SDM system leads to a reduced time required for adapting the simulation models. For the developed concept, a modified SDM system of the Digital Twin is used.

The simulation data management system in the Digital Twin (SDM-DT) enables the management of sensor-based simulation data for a particular application in the Digital Twin. The SDM-DT also receives PDM data, as well as information and requirements from product development. For example, by knowing temperature limit values from development, it is possible to detect values differing from the expected value range. Without information about the expected value range, it isn´t easy to interpret sensor values. The SDM-DT increases the efficiency by automating simulations. Also, simple and straightforward documentation can be established, which is essential for traceability and evaluation standards. Furthermore, a feedback loop back to development increases the database for following product development processes.

4. Implementation

For the following implementation, the conceptual framework was prototypically implemented using an exemplary use case and evaluated based on the requirements. The implementation covers the sensor data acquisition on the physical product, data transfer to the Digital Twin, preselection and archiving in an SQL database, and the generation and provision of input decks via a user interface to the SDM-DT. Thus, the boundaries are the sensor network, consisting of a temperature and humidity sensor and an XML file with the information from product development (PDM). An overview of the transmitted data can be taken from Fig 6.

The implementation includes a server-client architecture, according to Fig 5. Connectivity is provided via a Mosquitto broker on a Raspberry Pi 4. Using the MQTT protocol, the 3 clients can send and receive data. Clients II and III consist of an ESP32 microcontroller and a sensor (temperature sensor (KY-001) and humidity sensor (KY-015)). The SQL database (Client IV) receives the sensor data and aggregates it with the product development information. The user interface enables evaluating the SQL database and creates time discrete input decks as XML files for further simulation.

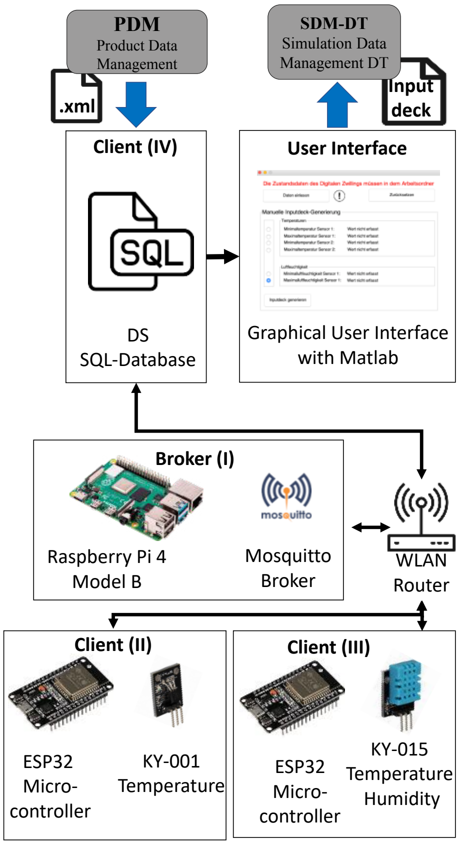

Fig 5. Architecture of the prototypical implementation

Two use cases are distinguished for the implementation:

1. Initial instantiation of the sensor representation
2. Runtime generation of input decks

During **initial instantiation**, the product is put into operation for the first time and the SQL database is created in the Digital Shadow. In this process, each sensor is described according to its attributes. For the sensor definition, the information sensor type (sensorType), sensor position and orientation in the physical product (sensorPosition, sensorOrientation), sensor measuring range (sensorRange) and the expected minimum and maximum measured value (minNormal, maxNormal) are taken from the XML file of product development. The user defines the corresponding sensor ID during commissioning. The continuous sensor values are assigned with a timestamp to their corresponding sensor and stored in the SQL database.

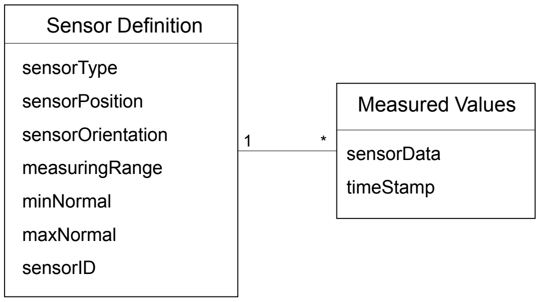

Fig 6: Sensor Definition Model

Using the database editor DB Browser for SQLite, the database is set up according to the data model and sensors can be edited, added or removed.

For the **runtime generation** of input decks, an user interface was developed in MATLAB that accesses the SQL database's data. Runtime generated input decks can be generated automatically or manually. Automatically generated input decks are triggered based on threshold values. For this purpose, the current sensor value is compared with the threshold values (minNormal, maxNormal) during preselection. If the value is outside the thresholds, the existing sensors' values are aggregated in an input deck at the current time and transferred to the SDM-DT as an XML file. For the manual creation of input decks, a graphical user interface is available, displaying the maximum and minimum measured values of each sensor over the entire measuring range. Based on this representation, input decks with values from different times can be manually compiled in an input deck.

5. Results

In the following part, we validate the developed concept with the described requirements of chapter 2 (cf. Table 1). For this purpose, the defined requirements and the prototypical implementation are used to validate the conceptual framework. According to the data model, all relevant sensor data could be represented consistently by aggregating the development data and sensor data in a SQL database. Due to the available contextual information, a higher semantics of the individual sensor could be obtained (Requirement 1). Likewise, the installed sensors' respective position and orientation in the product could be stored in the database (Requirement 2). For the use case, different environmental influences were tested under laboratory conditions. The collected measurement series could be completely archived in the database as historical data (Requirement 3). For further processing of the generated input decks with the simulation models, the XML file structure was designed according to the simulation tool Siemens NX. An adaptation of the representation for further simulation tools is possible (Requirement 4). For the exact representation of all sensors (Requirement 5), the developed data model (cf. Fig 6) may have to be extended. For the implementation, sensor information could be mapped completely. Conceivable for future investigations is the representation of the sampling frequency of sensors. Due to the flexible structure of the SQL database, it is possible to add or remove single sensors (Requirement 6). The request for a representation of the input deck independent of a specific IT tool could not be fulfilled. For the implementation, Siemens NX was taken as a basis for the structure of the XML file. A system-independent representation is desirable for the application of Digital Twins. However, existing approaches do not include the neutral representation of the input deck (Requirement 7). Likewise, the input deck application was only validly tested in one use case (Requirement 8). Finally, the utilization of the input deck for the CFD process chain could be tested. Further, CAE process chains (FEM, MBS) are therefore still pending (Requirement 9). According to the evaluation, 5 requirements could be achieved completely and three requirements partially. Only one requirement was not met.

6. Conclusion

The Digital Twin concept promises manifold potentials but needs to be elaborated in detail for widely use. The present work contributes to the representation of sensor data in the Digital Shadow. Transferring sensor-defining information from product development to the Digital Twin leads to a higher semantics of sensor data. Thus, the processing of sensor data with available and newly added simulation models is facilitated.

Based on literature research, there are now requirements for representing sensor data in the Digital Shadow and an elaborated conceptual framework of a simulation data management for the application in the Digital Twin. The elaborated framework is based on existing approaches and extends them by the entity of a simulation data management of the Digital Twin (SDM-DT). The sensor representation provides a basis for sensor-based simulation in the Digital Twin. Further work is now required for the design and elaboration of the SDM-DT.

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