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Case Study for an Operation-based Topology Optimization Using the Digital Twin Approach

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Abstract

In order to ensure the mechanical load capability of new products, diverse strength and load analysis methods have to be used while the product design process (e.g. FEA). The main objective of these methods is the predictive analysis of the operational load of the product. Based on this analysis, the structure and the topology of the product can be set adequately in terms of an optimal material utilization and load factor. Nowadays, the mechanical structure analysis can only be done based on estimated loading data, which are determined using approximative theoretical calculation methods. Furthermore, this approach does not consider the actual use and load of the product in the field. As a consequence, inaccurate determination of the material stress and product dimensioning can be accrued in most instances. In order to compensate this incertitude, design engineers set a high safety factor while designing new products, which lead to over-dimensioning of the products and to wasteful use of material and resources. Thanks to powerful sensors, data transmission and data processing technologies, it becomes nowadays easy to collect operating data of technical systems and process and to present and process it using a digital model in real time. This approach is known as digital twin. Using the digital twin concept an integrated and a comprehensive data model as image of real systems and processes with continuously update can be created. This approach opens new prospects within the design process of technical systems in terms of efficiency and sustainability. This paper presents and discusses a case study for the implementation of the digital twin approach in the product design of an arbor press. The aim of this case study is the investigation of the digital twin concept to obtain the material stress and load from the product operation accurately and to use them for material-saving product design.

Keywords: Digital Twin; Internet of Things; Operation-based FEA; Topology Optimization

1. Introduction

Traditionally, simulation has been used in the design phase with estimated or historical data as input [1]. This leads in the majority of the cases to high incertitude and precariousness while the determination of the product load and the material strength in the early design phase. In the practice the design engineers have to countervail this design risk using a high safety factor. As consequence, is the development of over-dimensioned products and the wasteful use of materials and resources for production, energy, transportation. A material- and resource-saving design can only be achieved, when exact and detailed operating load and usage data of the products are available in the early design phase. Moreover, the same product can be used by different costumers differently. Therefore, it is important to consider the product operating mode of the different costumers separately to design and optimize costumer dedicated products. The advanced Internet of Things technology with high performing sensors, data transmission, processing and storage equipment are enabling the collecting of product operating data accurately and detailed. Using the right analysis algorithms and tools, this data can be transferred into valuable information to sustainable design and optimize of technical systems and products. In this paper an use case will

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be presented on how to collect the operating load and stress data of a cyber physical system of arbor press and to transform them back to the digital CAD and FEA model in order to execute operating-based stress simulation and topology optimization.

2. Development and definition of the digital twin approach

2.1. Development of the digital twin approach

The idea of the creation of digital twin as mirror of the physical was born in the 1960s. The NASA used in this period physical copy of systems on earth to map and simulate the state of these systems during the space travel. This approach was extremely useful in the Apollo 13 mission. When one of the oxygen tanks in the spaceship exploded, the NASA engineers simulated and solved the technical problems from the ground level at a distance of 300,000 km from the spaceship. However, the concept and model of the digital twin was publicly introduced in 2002 by Grieves at the University of Michigan as a concept for Product Lifecycle Management (PLM) without giving the model a name. Grieves proposed the digital twin as the conceptual model, which asserts that all systems are dual in nature. There is the physical version of the system and a digital/virtual version or the information version of the system [2]. The model was soon named, but the name has changed over time. It was originally named the Mirrored Spaces Model (MSM) [3], but later changed to the Information Mirroring Model [4]. The model was finally referred to as the Digital Twin, a name that John Vickers of NASA had coined for the model in 2010 [5]. While the name has changed over time, the concept and model has remained the same [2]. Though, the actual breakthrough was achieved in 2017. Since then, the digital twin approach has become one of the top strategic technology trends. Specially, the Internet of Things technology has enabled the digital twin concept to become cost-effective so they could become as imperative to business as they are today [6].

2.2. Definition of the digital twin approach

A large number of interpretations of the digital twin can be found in the sciences as well as in practice and there is still no scientifically determined or cross-sector industrial definition. In this chapter an overview about the common definitions used in the research and sciences will be given.

Glaessegen et al. [7] define digital twin as an integrated multiphysics, multiscale, probabilistic simulation of a complex product, which functions to mirror the life of its corresponding twin. Digital twin (DT) consists of three parts: physical product, virtual product and the linkage between physical and virtual product. According to Grieves [2], the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. Tao et al. [8] determine the digital twin as a real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them. The approach defined by Bolton et al. [9] consists of a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning. For Söderberg et al. [1], the digital twin concept is the using a digital copy of the physical system to perform real-time optimization. Referred to El Saddik [10], a digital twin is a digital replica of a living or non-living physical entity. By bridging the physical and the virtual world, data is transmitted seamlessly allowing the virtual entity to exist simultaneously with the physical entity.

One can be observed while the literature research and analysis, all the definitions are focusing on the three components of the digital twin concept: the physical model, the digital model and data transmission. However, in order to realize the basic idea of the digital twin approach an expanded definition with further components are needed. For the present research contribution, the digital twin approach is defined as follow: Digital twin is a system (figure 1) that comprises a real environment with real objects and systems (e.g. humans, technical systems, process, ICT systems, etc.) that are able to sense their state using different sensors and to send them to a corresponding digital environment. The digital environment presents a mirror of the real environment with the relevant properties dependent on the observed lifecycle phase and the problems to be solved. The digital environment can be defined in different data types and can have different appearances (e.g. CAD model, simulation model, functional model, VR, software algorithm, etc.). Furthermore, the digital environment should contain appropriate digital sensors to be able to receive the data sent by the physical environment. Due to the handled high data volume the digital twin system should have a reliable data transmission and a data storage infrastructure. In order to convert the collected data to useful information, the digital twin system should have a data analysis and processing application. The analysed and processed data can be transferred to the digital and the real environment for example to simulate different environment state, to optimize the current operation of the real environment. A very important component of the digital twin system represents the data visualization tool so-called dashboard, which visualizes the collected and analysed data and information end-user-friendly.

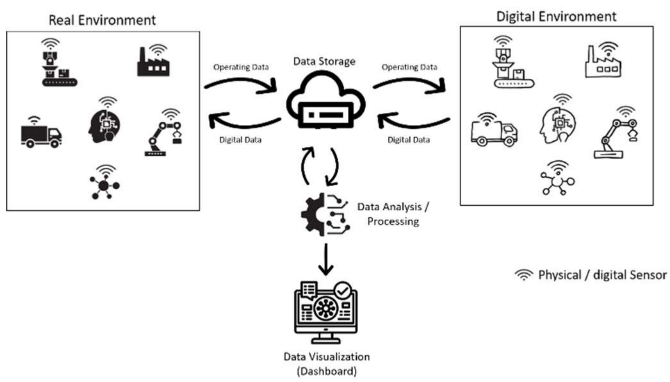

Fig. 1. Digital twin system.

3. Addressed research subject and the used method

Due to advanced and high-performance IoT equipment e.g. sensors, data transmission, data storage, data analysis tools, the implementation of digital twin systems as shown in the section 2.2 in practice has become practicable, realizable and manageable for the research and the industry. In order to analyse the application of the digital twin approach and to investigate its potential for a material- und resource-saving product design, a case study was implemented within this work at the Digital Engineering Lab of the University of Applied Sciences Karlsruhe. The case study addressed the product topology optimization for an arbor press based on collected operational product load data in place of estimated or experience data, in order to reduce the use of materials and to avoid material waste. The realization of this work was done in practice-oriented way and in very close discussion and exchange with industrial partners. Instead of the development of a general theoretical approach and then its practical implementation and validation, the author decided in this work to start with a practical implementation of the case study and then its validation. Afterwards, the won experiences were analysed and discussed to generate new topics for future research works. Due to the missing experiences with the application of the digital twin approach in the product design and due to the missing of practical guideline how to use this approach, the scrum project management framework was applied in the work. Scrum is an agile process framework for managing complex knowledge work, with an initial emphasis on software development, although it has been used in other fields and is slowly starting to be explored for other complex work, research and advanced technologies [11]. Scrum is suitable for development projects dealing with new innovative technologies with unpredictable challenges and outcomes such as the digital twin approach, for which conventional predictive and planned product design and project management approaches are not suited [11].

4. Related research works

The development and the application of the digital twin approach in the different product lifecycle phases are the subject of numerous research projects and activities since few years. All those projects have the same research question: how can the digital twin approach make the product engineering, manufacturing, and recycling sustainable? In following an overview will be presented about the research projects related to this paper without a right to completeness.

The work by Fei at al [8] presents a digital twin-driven product design (DTPD) framework, which can guide manufacturers to create a digital twin, and utilise the information provided by the digital twin to support the product design process. The presented approach presents a theoretical framework on how to develop a digital twin that can be used for the design of new products. Erkoyuncua et al. [12] have developed a new digital twin design framework that uses ontologies to enable co-evolution with a complex engineering system by capturing data in terms of variety, velocity, and volume across the asset life-cycle. The core of the presented work is an ontology-based data model that enables the data exchange between a digital model and physical technical system. A practical implementation and validation of this approach were not presented and discussed in this work. The paper of Söderberg et al. [1] specifies and highlights functionality and data models necessary for real-time geometry assurance based on the digital twin approach and how this concept allows moving from mass production to more individualized production. The developed approach was applied exemplary for the sheet metal assembly station. However, the paper does not give any details about the technical implementation of this approach and how can be translated to further assembly system. Stark et al. [13] have created a new architecture design approach for modularized design of cyber physical production system (CPPS) that comprises modular construction kits. With the presented approach, virtual prototyping and validation of new CPPS architectures is enabled. The proposed approach presents a rough architecture for the setup of CPPS. However, the authors did not describe the way how to apply this approach in the practice. In the paper of Schleich et al [14] a comprehensive reference model based on the concept of Skin Model Shapes is proposed, which serves as a digital twin of the physical product in design and manufacturing. The main contribution of this paper is the provision of a theoretical and conceptual framework for the digital twin, which is to be enriched by the design and production engineering community in the future. The paper of Göbel et al [15] presents a reference framework for digital twin-driven product design (DTPD). Combining the concepts of system lifecycle management and closed-loop systems engineering the holistic approach introduced in the paper defines how smart product systems can be improved by using modelling, simulation and virtual prototypes as enabler. This approach has been prototypically applied at the example of a test be of an autonomous construction area system of systems. Taira et al. [16] have proposed a general concept of digital twin of artifact systems (DTAS), which can be applied to an extensive range of artifacts, from huge artifact systems like nuclear power plants to popularized artifacts like home appliances. The presented approach is mainly based on the application of the ultrasonic technology to detect the microstructural changes due to the material load. This approach is already established in the area of the experimental material testing and cannot be considered as digital twin approach. The aim of the presented work by Anderl et al. [17] is the development of a method for the topology-invariant modification of geometric product representations for use in Digital Twins. The modification is based on the 3D CAD geometry model and selected, real dimensions of its physical counterpart using the standardized, non-proprietary STEP data format. Using this approach, an increase in the level of detail of the digital representation of the physical component can be achieved. Abramovici et al [18, 19] have introduced a conceptual approach for the reconfiguration of Smart Products, which considers dynamical, virtual models of each real product instance using the concept of virtual product twins and an Internet of Things platform. The conceptual approach is prototypically demonstrated by considering a model environment for smart cars, which are temporarily reconfigured during their use phase.

The intensive literature research conducted in this work has shown, that the majority of the carried-out research projects focus on the application of digital twin for fault diagnosis, predictive maintenance, product configuration, process monitoring and performance analysis. Moreover, the results of the analysed research projects are limited to theoretical approaches with lacks on technical and practical implementation details.

5. Case study: topology optimization for the arbor press

In this case study a digital twin approach for an arbor press (figure 2) press has been implemented. The arbor press is made of high-quality grey cast iron GG-30 and has a very robust design. The press can be loaded up to 1000kg. It is ideally suited for manually pressing out and assembling of bearings and bushings. It can also be used for light punching, bushing, straightening and bending of metal parts. The finite element analysis (FEA) has shown that the main body of the arbor press is over-dimensioned and has very low material utilization factor $A = (\sigma_V{=}15\ N/mm^2)/(\sigma_{V,max}{=}250\ N/mm^2) = 0{,}06\ (6\%)$. In order to increase the material utilization factor adequately and to avoid any operational risk, a material reducing for the main body of the arbor press based on operational loading data will be carried out. For this propose a digital twin system was set up that mainly comprises the CAD model and the real physical model of the arbor press. The real model is equipped with different physical sensors which record the operation loading data and refeed them to the digital sensors imbedded in the digital model of the arbor press. Subsequently, this data can be used for a FEA and topology optimization of the arbor press in the simulation tool. In the following sections the implementation of the digital twin system will be outlined.

Fig. 2. Physical model of the arbor press.

5.1. Creation of the digital environment

The basis of the digital model is the 3D CAD model of the arbor press that was created in the CAD system Creo parametric as an assembly model with all associated parts. To define the digital sensors, CAD models that represent the real physical sensors were modelled and were imbedded at the same positions as the real sensors into the basic CAD model of the arbor press. The digital model of the arbor press contains 5 sensors (figure 3). The force sensor is placed in place of the workpiece in order to determine the existing pressing forces. The rotation angle sensor is mounted on the shaft of the press lever arm with a connection to the main body of the arbor press. This ensures that the relative rotation of the lever to the main body is measured. The temperature sensor is used to measure the operating temperature of the arbor press. 2 resentence strain gauges serve to measure the deformation of the material at the critical area of the main body while the operating. After the modelling and the embedding of the CAD models the parametrization of the digital sensors was done. For this, the IoT module Product Insight of the platform PTC Creo was used. With the module Product Insight, different parameters (e.g. force, mass, pressure, length, temperature) for the CAD models can be defined individually and can be used as digital sensor data. Thereby, the CAD models can act as digital sensors and send and receive data to and from the real physical sensors. The individual parameters of the digital sensors can be defined as XML file and additionally imported to the CAD models (figure 4).

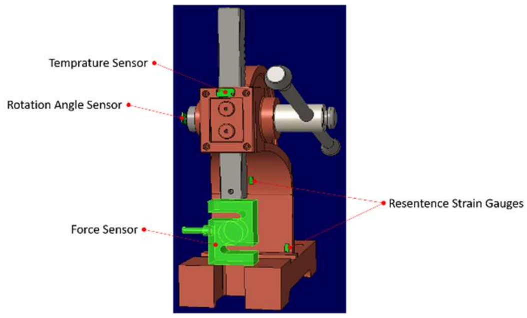

Fig. 3. Digital model of the arbor press with digital sensors.

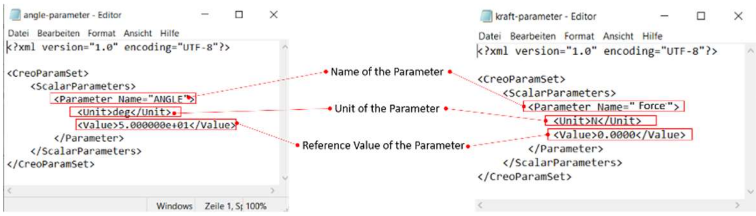

Fig. 4. Definition of the sensor parameters for the rotation angle (left) and force sensor (right)

5.2. Creation of the real physical environment

The main task while the set-up of the real physical environment was the application, the bringing and the wiring of the physical sensors to the real arbor press (figure 5). Especially the selection of the right sensors with the suitable measurement data resolution and their fitting and fixation on the arbor press are very crucial for the recording of the operating data and for the realization of the digital approach. To ensure the same positioning of the real physical sensors and the digital sensors in the arbor press, several measurements on the digital and on the real model were needed. Any small positioning deviation between the digital and physical model leads to unreliable operating data transformation and assignment and to incorrect data analysis.

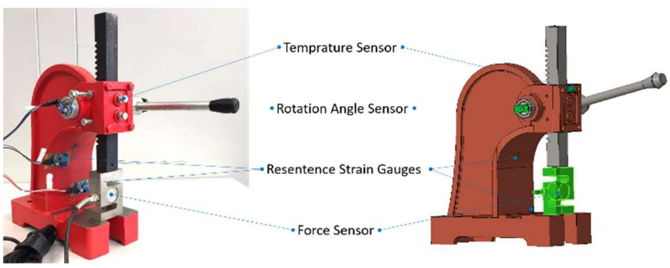

Fig. 5. Digital twin model with physical and digital sensors.

5.3. Data transmission and data storage

The interface between the real and the digital environment was implemented using the microcontroller Arduinio MEGA (figure 6). Via the microcontroller the operating data of the real sensors are collected and prepared (e.g. data stamping, data initialization, data calibration, data filtering) for the data storage and data transmission to the digital environment in the PTC Creo platform. The data storage was realized in two different ways: local data storage and cloud data storage. The operating data can be saved locally in the computer file system as text files (.txt) or as CSV files (.csv) and manually loaded to the digital environment. This data storage variant allows an offline use of the digital twin system. Additionally, the IoT and cloud platform ThingWorx of PTC has been used to online save and transfer the operating data automatically and continuously. This method enables a permanent and a comprehensive operating data gathering that enables detailed and precise studies and analysis on components.

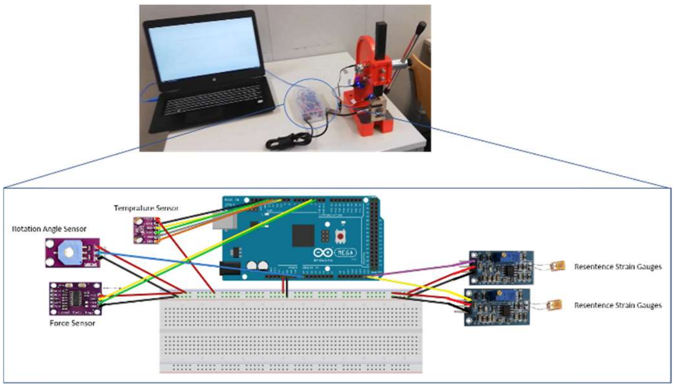

Fig. 6. Wiring of the physical sensors and data transmission system.

5.4. Data visualization

To enable an end-user-friendly data visualization a dashboard for the digital twin system was implemented. This same dashboard was implemented as local application fed by the local stored operating data and as online application in the ThingWorx platform based on the operating data saved in the cloud. The displayed data on the dashboard corresponds to the data collected by the physical sensors and are plotted as 2D graph (figure 7): angle of rotation, press force, temperature, strain of the resentence strain gauges.

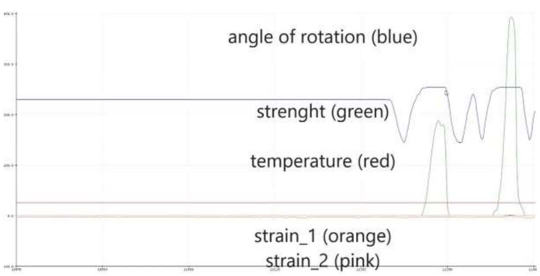

Fig. 7. Visualization of the physical sensors data.

5.5. Use of the operation data in the digital environment

To import the operating sensors data is the IoT module Product Insight in the PTC platform Creo used. The import of physical senor data can be done from the local computer file system using the already saved txt.files and the csv.files or from the cloud platform ThingWorx. Based on the name convention of the sensors, the operating data will be directly assigned to the digital sensors imbedded into the CAD model of the arbor press. Afterwards, the application and the visualization of the loaded and the assigned operating data within the CAD model can be executed. In this case the digital arbor press will be animated based on the data of the angle of rotation senor and at the same time the related data for the force, resentence strain gauges and temperature sensor will be changed and shown accordingly (figure 8). This information is useful for the operation-based dynamic and motion analysis of the arbor press and can provide valuable insights into the product usage that can be incorporated into the development of new products.

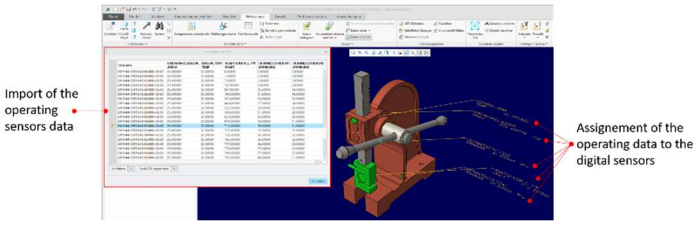

Fig. 8. Use of the operation data for FEA.

Another possibility for the use of the sensors data is the operation-based finite element analysis (FEA) and topology optimization. For this the Creo FEA module Creo Simulate has been used. The only difference to a conventional FEA is that when defining the load, the data from the digital sensors are utilized instead of the manually inserted value. This approach makes an FEA with a realistic product use data possible. This procedure can also be transferred to other analyses, such as dynamic analysis, fatigue analysis or thermal analysis. The FEA showed that when applying about 8000 N press force while the operation, the main body of the arbor press will only be stressed with about σ_v=15 N/mm², which corresponds a very low material utilisation factor A = 6% (figure 9). As consequence, a topology optimization using the operation-based FEA was conducted within this case study. The outcomes of the FEA were inputted to the Creo module Topology Optimization that calculated a new material-saved topology with about 60% material-reducing for the arbor press (figure 10). The new calculated topology as shown in the figure can be used by the design engineers as a design draft for new lightweight arbor press generation.

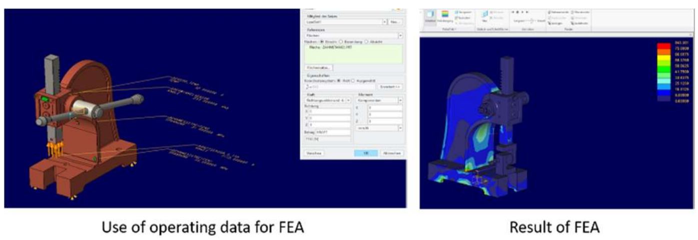

Fig. 9. Use of the operating data for FEA.

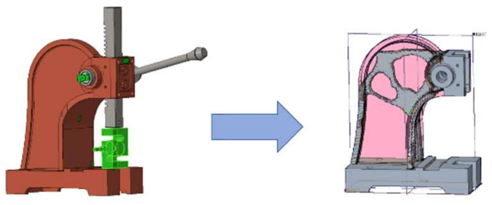

Fig. 10. Use of the operating data for the topology optimization.

6. Conclusion of the case study

6.1. Sensors

Within a digital twin system, the sensors are essential for the reliable operating data collecting. Especially for the accurate sensing of loading and material deformation data, the application of robust sensors with an appropriate sensitivity and data resolution is a basic prerequisite. Another significant aspect is the embedding and the fixation of the sensors in the real physical and in the digital model. The placement of the sensors must be chosen, so that a representative measurement of the loading and material deformation with a high repeatability can be ensured. For this are several iterations of measurements and sensors calibration between the real physical and the digital models needed. For future products and system, it is recommended to consider the embedding of such kind of sensors while the product design.

6.2. Data storage

In this case study two different ways for the data storage were applied: a local data storage and data storage in the cloud. The local data storage uses a computer or server file system and presents a simple and a safe practice for data storage and allows an offline digital twin system. However, it demands a high effort regarding the implementation and maintenance of proprietary interfaces to the digital and physical sensors and proprietary data visualization dashboards. The new IoT platforms (e.g. ThingSpeak, ThingWorx) provide cloud-based systems with standardized functions for the creation of sensors logging applications, sensors data storage, analysis and visualization. Using such IoT platforms makes the setup of online digital twin networks that include several digital twin systems and parties (e.g. companies, costumers, users) possible and helps to profit from the various sophisticated IoT functions and to accelerate the introduction of the digital twin approach.

7. Summary

Operating data are very valuable for the optimization of the current products and the design of new improved product generation. High-performance IoT equipment (e.g. sensors, data transmission, data storage) makes the collecting of such data and their refeeding into the digital product model practicable. This paper presents the technical implementation of a digital twin system for arbor press. With this concept the FEA of the arbor press can be done based on operating data in place of estimated data. As a result, operating-based and dependable load analysis was done that helps to optimize the topology and to reduce the material use for the arbor press. The won experiences while the realization of the case study have been discussed as a conclusion in this paper. Those experiences will serve to generate new topics for the future research works.

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