A Holistic Approach for the Development of a Digital Twin Focused on Commissioning and Control of Electromechanical Feed Axes

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Abstract: The conventional commissioning of a machine offers numerous starting points for the use of modern methods and technologies. With virtual commissioning, the conventional sequential work tasks can be parallelized, which represents an economic advantage. For the virtual commissioning of machines and systems, an appropriate knowledge of automation technology and processes is necessary. This information can be found in the abstracted image, the digital twin. The digital twin is an application-dependent complex entity. Drive control is part of such an application. In the industrial environment, parameterization is usually carried out once on the basis of empirical methods during commissioning. Knowledge and methods from science and research for optimal adjustment are rarely used. In this publication a holistic approach to the implementation of the digital twin including automation technology of a system with an electromechanical feed axis as well as an approach for recording the information necessary for parameterizing the drive control is shown. The focus is on the ability of the digital twin to process information about the dynamics of the drive system.

1 INTRODUCTION

With the advancement of Industry 4.0 data-driven innovations come to the fore. Within the scope of the product lifecycle a detailed digital twin can open new opportunities and therefore can bring many advantages.

Referring to (Grieves and Vickers, 2016) the origins of the digital twin date back to the year 2002 where it was described as a "Conceptual Ideal for PLM". This concept already had all the features of the digital twin as we know it today. There was the real space, the virtual spaces and the bi-directional links in-between showing the flow of information throughout the whole product lifecycle. Over the years the concept was expanded and the definition was sharpened and in 2010 it was called "Digital Twin" for the first time (Grieves, 2011). In the same year, NASA defined the digital twin as "integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Shafto et al., 2010). In 2011 this concept already plays a huge role in the context of Industry 4.0 (Roth, 2016).

The approach in this paper is based on the definition of the Digital Twin in (Grieves and Vickers, 2016) that's why it is briefly outlined hereinafter. As shown in Figure 1, the Digital Twin includes virtual information which describes a potential or physical entity depending on the phase of the lifecycle. An ideal Digital Twin would contain every measurable information of its physical counterpart. In the field of mechanical engineering a Digital Twin can exist for a product, a machine (tool) or an entire factory. In the scope of this work we are referring to a Digital Twin for a machine tool.

Regarding the potential or physical entity from above there are two types of Digital Twins: Digital Twin Prototype (DTP) and Digital Twin Instance (DTI). The Digital Twin Prototype (DTP) contains all necessary information to create a potential physical version including CAD models, control and regulation logics etc. and is primarily used in the development phase of the product. The Digital Twin Instance (DTI) emerges out of the DTP and is directly related to a specific physical entity and stays connected throughout the whole lifecycle. This also means the DTP and the DTI are in a parent-child relationship.

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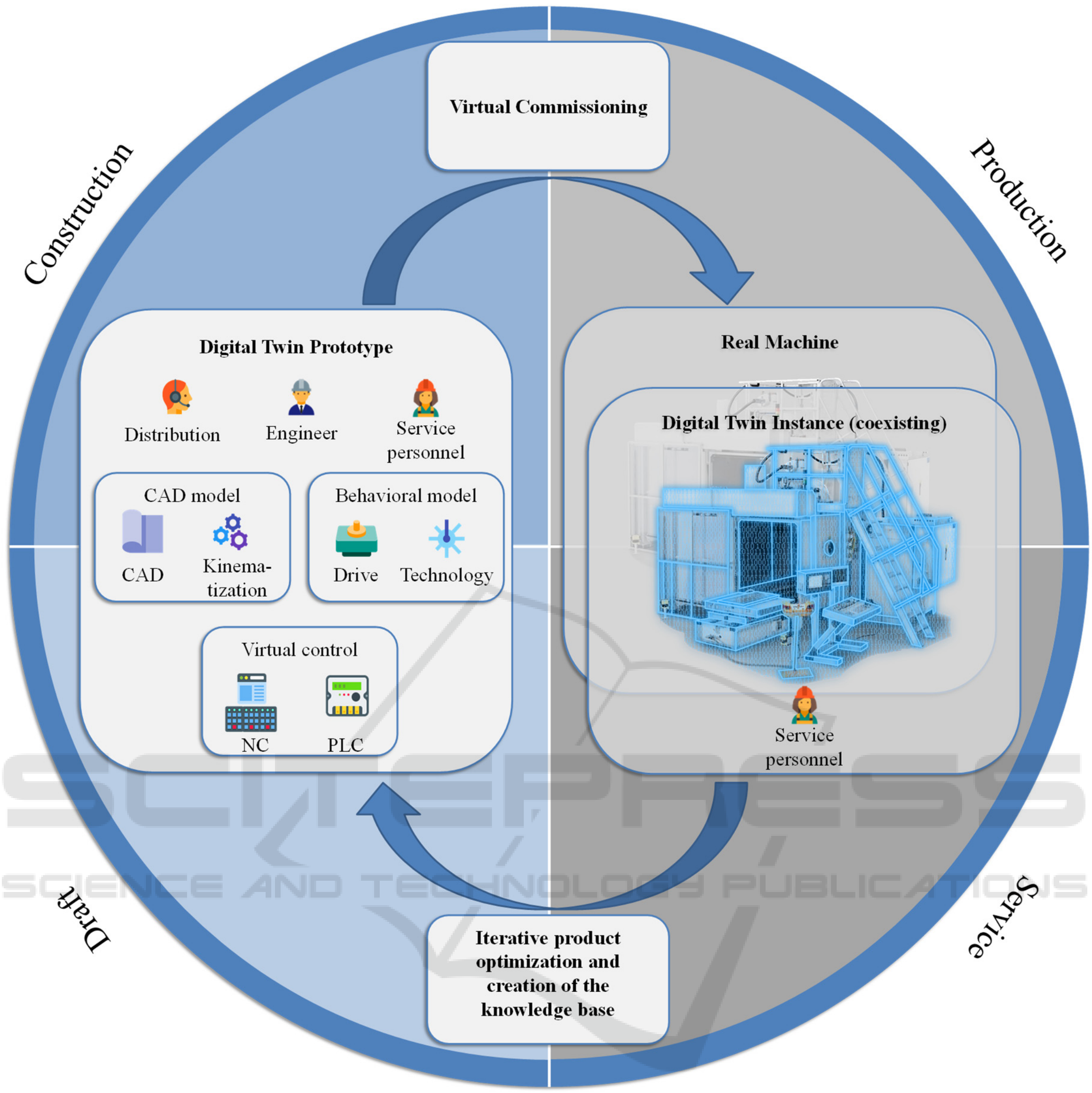

Figure 1: Influence of the digital twin for the product life cycle.

Throughout the lifecycle, many different user groups interact with the machine tool and therefore with its Digital Twin. They add as well as extract information for a specific purpose, e.g. faulty parts for maintenance, CAD models for assembly simulation or requirement specification for marketing. In (Winkler et al., 2020) it is described which role the user and his or her acceptance play during the development and usage of a Digital Twin. It is of vital importance to know and overcome the obstacles for the user in order to exploit the full potential of the Digital Twin. This can be achieved by technological and social solutions for example through an intuitive user- or rather situation-specific user interface and by answering to the question: "What is the benefit for the user?" during the instructions.

This paper particularly focuses on the virtual commissioning of electromechanical feed axes of a machine tool. Especially in the context of commissioning tasks are performed sequentially. Therefore, a process parallelization is proposed in this paper as well as the usage of a consistent data model, the Digital Twin, which offers the opportunity to use the stored information as an input for the parameterization of the electromechanical feed axes.

2 CONTROL OF MACHINE TOOLS

In machine tools, the creation of a desired shape requires a relative movement between the tool and the workpiece. Movements are realized via feed drives. In modern processing machines, electric feed drives are used almost exclusively (Groß et al., 2006). These are also known as electromechanical axes (Hellmich, 2014). A control is necessary, so that defined movements are observed as precisely as possible. There are numerous strategies for controlling machine-specific variables, such as the position or speed of electromechanical axes, whereby the concept of the cascade structure, also known as servo control, has prevailed (Schröder, 2009). The principle and the simplified structure of the position control in a cascade structure are shown in Figure 2. It is characteristic that the three control loops are superimposed on one another. The current control loop, which is part of the superimposed speed control loop, is inside. At the very outside is the position control loop, which is often supplemented by a feed forward control. This can reduce lag errors. In the industrial environment, additional extensions are usually used, for example filters, band-stops or additional feedback.

With the use of controlled electromechanical drive systems, the increasing demands on machine productivity and thus on dynamics can be met with higher accuracy. Nevertheless, there are ongoing efforts to improve manufacturing strategies and processes in terms of stability, quality and efficiency. The parameterizations of the control and the control quality have a significant influence on the process and the product quality. Accuracy and productivity can be maximized by optimally utilizing the control potential. However, studies have shown that the control on machine tools are very often not optimally designed (Schönherr, 2012). Various methods are available for parameterizing the controller. Very good results can be achieved with a systematic design. However, this requires the use of identification procedures, which are associated with a significant additional expenditure of time. For this reason, this procedure is rarely used in industrial practice. Here, the control is usually designed purely empirically based on the knowledge of the commissioning engineer. At this point, the use of the Digital Twin offers enormous potential for improvement, especially in combination with virtual commissioning.

3 VIRTUAL COMMISSIONING

Appropriate data and knowledge according the handling of information are required for virtual commissioning (VC). The real machine is built based on the VC and the model data of the DTP. The digital twin prototype also creates the DTI of this specific machine. This DTI already exists during the actual commissioning. The data obtained in this way (e.g. frequency response, sensor data, etc.) are used for the digital twin prototype and thus for the design phase of the next machine. In this way, a knowledge base for the products is created.

In addition, a large amount of data is generated in the real operation of the producing machine. This data enables direct or indirect conclusions to be drawn about the machine status. Furthermore, the coexisting DTI is used for process monitoring and setting. For example, processing steps for new workpieces can be virtually implemented and optimized beforehand using the digital twin. This leads to a minimization of the machine downtime.

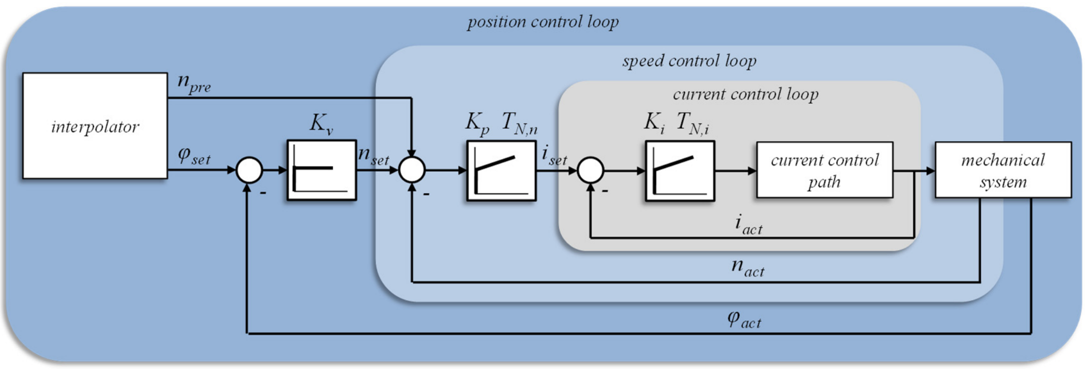

Figure 2: Principle and structure of cascade control.

The VC is defined in detail in (VDI, 2016). It describes the overall test of the automation system without a real machine. The development stages software in the loop (SIL) and hardware in the loop (HIL) can also be used to describe the testing of automation solutions.

The digital twin is intended to support the VC on the one hand and to coexist with the real system on the other. The new possibilities thus obtained should be used in a value-adding manner based on (VDI, 2018). For example, business models in the area of control and process control or via projects based on simulation integration can be developed.

4 MECHATRONIC DESIGN

4.1 Modularity and Standardization

To improve the overall mechatronic design of a corresponding product, the modularization of products has become established in recent decades. This modularization brings with it a standardization of components. A modular design simplifies the collaboration of knowledge carriers from different areas over the entire product lifecycle. The overall mechatronic system includes disciplines in electrical, mechanical and computer science (van Beek et al., 2010).

To improve the usability of the digital twin, a modular approach of the machine or system under consideration should be carried out or assumed. For this purpose, for example, libraries can be used in the area of CAD as well as for automation technology. Those libraries often depend on the specific framework. The libraries correspond to the modules. Usually these are specific machine components, such as devices, drive systems, gears, etc.

If the environmental conditions resulting from the location of the specific machine (e.g. temperature fluctuations, vibrations, etc.) are neglected, the modularity of the production system enables the module-related data to be returned from the digital twin instance to the digital twin prototype. Different instances of a machine, information from individual modules (e.g. drive system, gearbox, etc.) and their effects should be almost identical and reproducible.

4.2 Level of Detail

Every component can be modeled and every data point can be called up, from the system through the machine to the drive. Depending on the task, different aspects are focused. Suitable data management for the digital twin is discussed in (Winkler et al., 2020). An application- and goal-oriented selection of the data to be recorded is therefore just as important as the definition of the system boundaries when creating the digital twin. The amount of data must be kept lean and the system clearly defined.

4.3 Estimating the Dynamics of an Electromechanical Feed Axis

In order to improve the information content of a Digital Twin of a machine, data from the real process and model knowledge should be embedded. For example, moments of inertia and friction can be determined based on knowledge of the used geometries, materials and material pairs. In addition, models of the electromechanical axis have to be developed to reflect the actual behavior.

This data and real recorded frequency responses are intended to enable the digital twin to access information on estimated frequency responses of the virtual machine. In addition, algorithms are available to determine the parameters for the drive control from this information.

The estimated frequency responses must be validated and adjusted using real frequency responses of the real machine. On this basis, an improvement of the drive dynamics model is expected. The digital twin prototype thus has the ability to make a statement about the dynamic properties of the drive system from CAD- and metadata. This approach concerns the digital twin prototype that is decoupled from the real machine.

To estimate further machine states, a module is to be developed that coexists with the real machine and accesses drive and sensor data. Figure 3 shows possible software solutions for this. Using the example of the vertical electromechanical feed axis shown in Figure 3, data from the CAD model such as masses and moments of inertia are transferred to the behavior model. With the SIMIT software from Siemens, this data can be transferred to TwinCAT via OPC UA. The advantage of TwinCAT is the open structure and the possibility to use Matlab Simulink models. SIMIT offers a separate interface to the CAD software NX and the corresponding kinematics tool Mechatronics Concept Designer (MCD). The tool chain of an automated machine is completed by PLCSimAdvanced. This enables the simulative functioning of the PLC applications. The final step in completing the digital twin approach is to build coexistence between the digital and physical twin. This is also done via the SIMIT core element. This offers corresponding interfaces to physical controls. The approach thus includes both SIL and HIL.

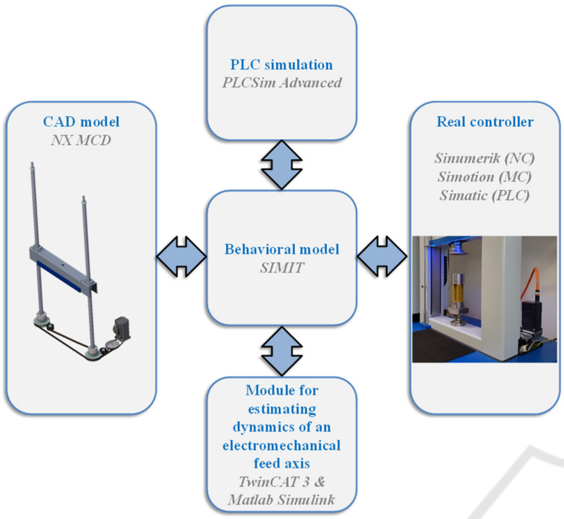

Figure 3: Exemplary structure of a testbed for an integration of an estimation of machine conditions in the digital twin.

The estimating module in TwinCAT receives targeted data for example in order to make estimates for the drive control from real drive data. (Schöberlein, 2020) describes the disturbance variable monitoring of speed-controlled mechatronic drive systems by implementing corresponding estimation algorithms. The information obtained in this way is also fed back into the digital twin prototype in order to make runtime information available.

Thanks to the already mentioned modularization of the machine, information for the virtual commissioning of the drive can be generated automatically. For example, libraries can be used for the overall mechatronic design of a machine, which feed data to algorithms and models running in the background. When the draft is completed, they already provide information and recommendations for the parameterization of the drive. Knowledge from research and science can thus be used intuitively for technical staff and service personnel.

5 USAGE AND CONCLUSION

As part of the development of production plants, the implementation of a holistic approach across the entire product life cycle (as shown in Figure 2) offers enormous potential for improvement and savings. The focus is essentially on the electromechanical feed drives. The use of the digital twin is of great benefit for all areas of the product life cycle.

As already described in the previous chapter, important information can be stored and linked to one another in the design phase of the machine. In this way, effects on the drive control can be assessed at an early stage. Constructive adjustments can be made retrospectively, for example to influence resonance frequencies. In this way, an overall mechatronic design can be implemented.

The digital twin is of particular interest for the commissioning phase. As part of virtual commissioning, complex identification procedures can already be used and automated. In this way, all the information required for commissioning can be stored and made available in advance. This drastically reduces the effort during commissioning. In addition, the non-reproducible empirical procedure is substituted by scientific methods. A significant improvement in controller performance can therefore be expected. The prerequisite for this is of course a sufficiently precise database. Mechanical parameters such as masses, moments of inertia, stiffness, damping and friction values are particularly relevant for the controller parameters. However, communication, computing, cycle and dead times that result from the control components must also be included.

These parameters are of interest for ongoing operation even after commissioning. A change in the mechanical system over the running time of the machine is conventionally hardly detected. The digital twin can be used to feedback real sensor and drive data from the machine. These are to be made available for disturbance variable monitoring with appropriate estimation algorithms. This enables permanent monitoring and automatic adjustment of the parameterization in perspective.

In addition, the inclusion of the processing task in the sense of forward-looking process planning offers additional potential for improvement. If information regarding the workpiece masses and disruptive process forces is stored in the digital twin, this can also be included in the controller parameterization. This enables a design that is optimized for different machining tasks. Furthermore, the digital twin serves to generate a knowledge base and iterative process and product optimization.

In the course of future research work, the creation of a digital twin of an electromechanical feed axis is initially being considered. The focus is on demonstrating the functionality of the structure illustrated in Figure 3. Basis is the test setup shown in Figure 3. The corresponding CAD model and the data from control components are already available. With the implementation of the software infrastructure, the data can be transferred to parametric models in Matlab Simulink via the interfaces. These models are used to carry out systematic identification procedures. This enables the calculation of controller parameters and the assessment of the controller performance, too. In addition, this data is in turn made available for virtual commissioning. After validation, the successive expansion with the additional modules for monitoring and automatic adjustment of the parameterization during operation is planned.

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