Virtual Reality Extension for Digital Twins of Machine Tools

Valentin Holzwarth, Christian Hirt, Joy Gisler, and Andreas Kunz

Abstract Digital twins (DTs) provide numerous opportunities for value creation in manufacturing. Services enabled by DTs include remote monitoring of assets' conditions and predictive maintenance. In this paper, we introduce novel, previously unexplored services based on a fully virtualized machine tool, which are targeted at increasing machine operators' productivity. This allows conducting procedures, such as operator training at a virtual machine tool, which results in the real machine tool being available for value adding activities. Beyond operator training, we envision further potential applications of the virtual machine tool including the run-in of new processes and collision detection.

Keywords Digital twin · Manufacturing · Machine tools

1 Introduction

The manufacturing industry is changing fundamentally due to the influence of the fourth industrial revolution, also referred to as "Industry 4.0". Its main drivers are digitization and networking of processes, systems and machines. The focus of this paradigm shift is the human, who is constantly confronted with new challenges. As the complexity of processes increases, the demands placed on the work to be

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performed increase significantly. It is expected that employees will cope with the increasing range of tasks in their daily work routine as usual. Shortened periods of action, however, require an increased understanding and ability to learn, which cannot or only partially be guaranteed with proven training and support measures.

At the same time, providers of industrial equipment, such as machine tool manufacturers, face increasing customer demand for services that complement or even replace their traditional product-based offering. A recent example is the Equipment-as-a-Service (EaaS) offering by DMG MORI,[1] one of the world's leading manufacturers of machine tools. Within this service, customers enroll for an annual subscription combined with an hourly usage fee. The subscription not only includes machine delivery, commissioning and maintenance, but also the training of machine operators. However, the training of machine operators is a challenging endeavor, since operators have to travel to a training center for multiple days and are unavailable for value adding activities during this time. Thus, training services that can be accessed on-demand and location-independent would be favored from the perspective of a machine tool manufacturer and machine operator. While currently available e-learning systems and instructional videos partly satisfy this need, they come with a major drawback: They cannot ensure that the machine operator can transfer the acquired theoretical knowledge onto the real machine tool.

Within this work, we propose a novel, previously unexplored solution to mitigate the issue by harnessing the digital twin (DT). This DT is comprised of a fully virtualized machine tool that can be accessed through virtual reality (VR) technology. By these means, operating, maintenance, and repair procedures can be trained without requiring the real machine tool. This is not only useful for new operators, but also for simulating changes in work procedures, re-training experienced operators, and knowledge transfer between production facilities. Unlike prior approaches, which require the cumbersome remodeling of both, machine tool behavior and geometry, our DT enables additional services even beyond the main use-case of operator training. Such additional services include virtual commissioning of new machines, run-in of new production processes and virtual process setups, providing insight, if and how a desired product can be manufactured on a given machine.

In combination, these opportunities will shorten the time-to-market for the machine tool manufacturer. Furthermore, the machine operator will benefit from a significant reduction in the time between ordering a machine tool and its productive use. These benefits can be only realized by having the machine tool's DT at hand, which will result in a competitive advantage for the machine manufacturer and create further value (e.g. through increased sales or novel monetization strategies).

[1] https://de.dmgmori.com/produkte/payzr.

2 Related Work

The DT of a machine tool can be defined as an entire representation of a machine, comprising geometric data, machine control, as well as live data from the real machine (Davis et al., 2012; Grieves & Vickers, 2017). This replaces former hardware-in-the-loop approaches (Dierssen, 2002) and enables various industrial applications, such as maintenance planning for aircrafts (Kraft, 2016) and optimizing production processes for punching machines (Moreno et al., 2017).

While these approaches do not yet have a maturity level to be widely used in industry, leading software companies in mechanical engineering are creating their own packages for the DT as a platform for establishing the it in a wider context (Magargle et al., 2017). However, according to Luo et al. (2019), the DT requires the availability of sensor data stemming from the real machine e.g., for deep learning prediction of service intervals (Luo et al., 2020), motion compensation (Liu et al., 2021), or for an automated machine reconfiguration (Leng et al., 2020). Thus, the DT always follows the behavior of the real machine tool. This paradigm limits the potentials for DT-enabled value creation to the cases, where the real machine tool is operational and has already produced enough data for the desired analysis. Another substantial element, which has yet been investigated by only few works, is the interface through which the DT can be accessed by the machine operator (Ma et al., 2019). For this interface, VR technology is highly favorable, since it allows the machine operator to interact with the DT in an analogue manner than with the real machine tool. In this context, prior works have already investigated on utilizing VR technology for machine tool training (Hirt et al.. 2021), commissioning (Pérez et al., 2020), and industrial workplace analysis (Gorobets et al., 2021).

3 Contribution

Based on the identified research gap and the machine tool operators' demand for novel services, we develop a concept for implementing a DT, which can be accessed through VR technology. This concept is envisioned for the use case of machine tool operator training, which traditionally comes with numerous disadvantages.

Current training of machine operators is conducted through: (i) a hands-on training on a new machine, (ii) having a hands-on training on an arbitrary machine for the same purpose, or (iii) visiting a training center, which is operated by the machine tool manufacturer. All three approaches come with specific disadvantages:

(i) When the new machine tool is delivered to the machine operator's site, no trained personnel is available. This leads to a delay in utilizing the machine tool for value-adding activities. Further, the machine tool consumes energy and raw materials also during training. Additionally, during training the likeliness of machine damage due to faulty operation is increased. Moreover, a second person is required as an instructor.

(ii) The machine operator to be trained by an instructor only gains basic knowledge, but not the specific skills required for the new machine. Again, the machine being used for training is non-productive for this period of time and requires raw materials and energy for the training.
(iii) The person to be trained has to travel and is thus not available for production and operating other machines. Again, an instructor is required and the machine consumes energy and raw material during the training.

Based on available software packages, we develop a concept for a VR extension for the DT of a machine tool, which allows the machine operator to be fully immersed and to behave similarly as with a real machine, including real walking and interaction with the virtualized human-machine interface. We employ a first person learning perspective, which is proven to be more effective than the third person perspective, which is typically used in traditional training (Hirt et al., 2021). The concept also comprises a software architecture that allows for a seamless integration of such a virtual learning environment into existing business processes and data flows (see Fig. 1).

The novelty of this concept is that it significantly reduces the modeling effort, since it automatically retrieves data from existing sources, such as the virtualized machine control, virtual machine and tooling geometry, as well as its simulation model for control commands. Moreover, this concept also proceeds from an animated machine to a simulated machine, since it also integrates the virtualized machine control in real-time. Since the data, which is combined and integrated within a game engine can also be deployed standalone, the machine operators that access the DT are not required to set up any additional software. This also allows for connecting multiple stakeholders with the same DT in real time, which is beneficial for collective learning and problem solving (see Fig. 2).

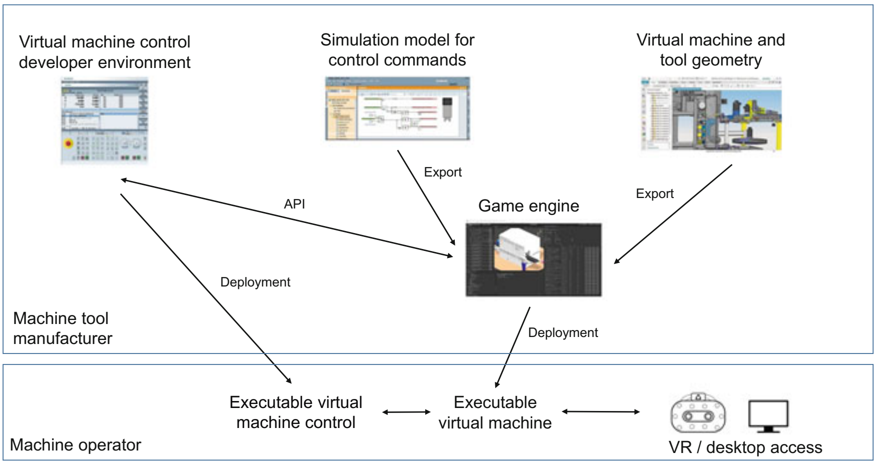

Fig. 1 The concept of the proposed VR extension for the DT of a machine tool

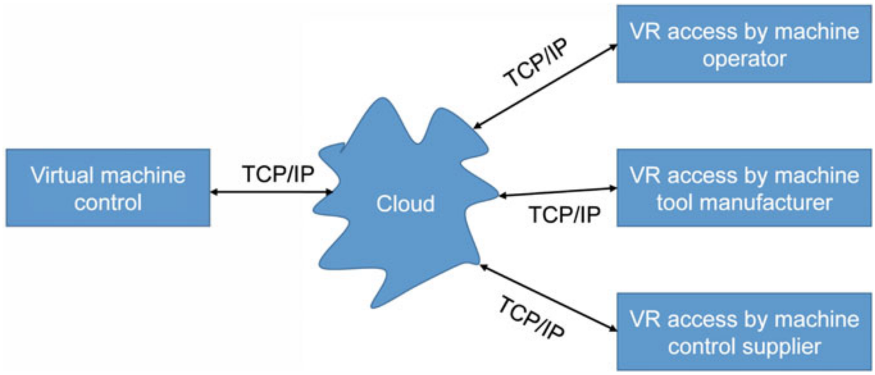

Fig. 2 Connecting multiple stakeholders with the same DT in real-time

4 Initial Implementation

In a first implementation, we show the feasibility of the developed concept within a training scenario for using the virtualized machine control along with the virtual machine. Figure 3 provides an overview of a machine operator's view in VR, which is provided by the HTC Vive Pro VR System including the Vive Wireless Adapter.

Within the training scenario, the machine operator is instructed to do the following tasks:

Fig. 3 The machine operator's view in VR, including an assignment board on the left and the virtual machine tool including the virtualized machine control on the right

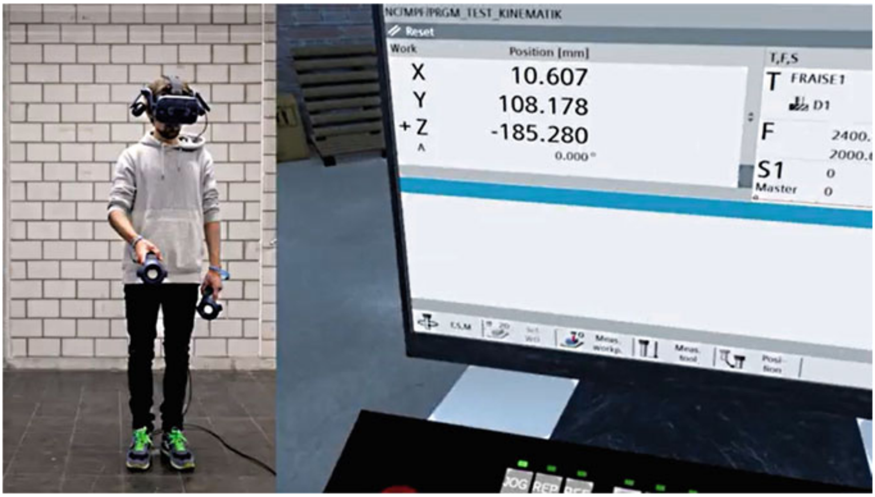

Fig. 4 A machine operator accessing the machine's DT through VR (left) and a VR view of the virtualized Human-Machine Interface (HMI) (right)

- Pick up safety helmet in left cabinet
- Put on helmet
- Pick up work piece
- Place work piece in machine
- Replace air filter
- Close door

Whenever a task is completed, the machine operator presses a button on the game controller to switch to the next task. Once these initial tasks are completed, the machine operator has to overwrite the programmable logic controller (PLC) variables to access the machine control and to run the machine in a manual jog mode (see Fig. 4).

Afterwards, the machine can be run in auto mode, which allows the user to observe the program sequence. Finally, the user can access and read the machine simulation data.

5 Conclusion and Future Work

Within this work, we have proposed and initially implemented a VR extension for the DT of a machine tool. The preliminary implementation focuses on a training scenario for machine operators. Future work will focus on the verification of the training scenario within a user study with machine operators as participants. Furthermore, additional use cases will be implemented and verified along the machine tool life cycle, such as virtual commissioning, virtual process setups and virtual run-in of new processes. Finally, the concept should be generalized by implementing different types of machine tools and rolled out by integrating the VR extension for the DT of machine tools in the service portfolio of machine tool manufacturers.

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Andreas Kunz was born in 1961 and studied electrical engineering in Darmstadt/Germany. After his diploma in 1989, he worked in industry for 4 years. In 1995, he became a research engineer and Ph.D. student at ETH Zurich, Switzerland in the Department of Mechanical Engineering. In October 1998, he finished his Ph.D. and established the research field "Virtual Reality" at ETH Zurich. and Kunz founded the research group ICVR (Innovation Center Virtual Reality) in 2004 and became a private docent at ETH. Since July 2006, he is an adjunct professor at BTH, and since 2015 also an adjunct professor at ETH Zurich. Since 1995, he has been involved in students' education, and since 1998, he has been giving lectures in the field of virtual reality.