Assistance System for the Interactive Machine Adjustment (of a Tufting Machine)

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Abstract: The paper illustrates how a digital twin, a virtual representation of a physical asset, and simulation software can be used to find best operating parameters and guide an operator through the adjustment process of the machine. The user interacts with the digital twin either through a 3D GUI or using augmented reality, which allows to display information of the digital twin next to the real twin. The machine is equipped with sensors that continuously measure the state of the machine and are connected to the digital twin through EtherCAT connection. The interactive system gives intuitive instructions that reduce the expert knowledge that is needed such that even trainees can operate the machine and digitizes the process for experienced workers.

1 INTRODUCTION

The adjustment of a mechanical machine like a tufting machine is a cumbersome task. Until today it requires an iterative process of adjusting machine parameters and then test the settings which prohibit frequent changes of the machine e.g., to produce different products. It also relies on the knowledge of experts as the relationship between the adjustment of levers, phases etc. and the change of the machine tools is not easy to understand. However, the trend in industry 4.0 are customizable products which require frequent machine adjustments. Another challenge for small and medium enterprises (SME) is an ageing workforce due to changing demography and how to conserve valuable expert knowledge.

The assistance system developed tries to optimize this process by equipping a machine with sensors to measure tool positions and mirroring tool positions to the digital twin, a virtual model of the real machine, and being able to save these settings to create a database for different products and then compares the current tool positions with the desired positions and gives hints to the user what parameters need to change. This way the expert's knowledge can be conserved. The hints are displayed exactly where the user needs to change a parameter and shows how much to change a certain parameter to achieve a requested accuracy. The parameters can also be optimized in the simulation and then transferred back to the real machine. The assistance system yields reproducible results.

The paper is organized as follows: First, a quick overview of the related literature is given, then the concept of the digital twin-based assistance system for tufting machines is made. Next, the process of the development of the digital twin is described. Then the assistance system itself is presented. Difficulties and benefits along with proposed future work are discussed. The paper ends with a conclusion.

2 RELATED LITERATURES

(Grieves, 2014) first presented the Digital Twin (DT) concept in 2003. In 2014, he published a white paper

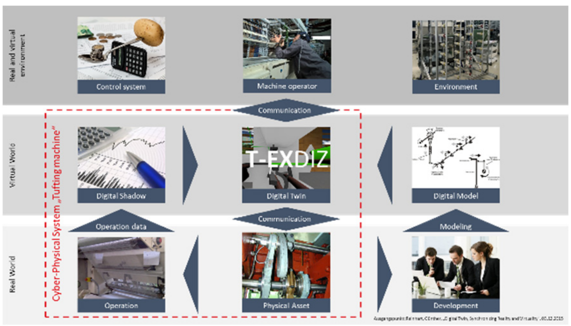

Figure 1: The cyber-physical system "tufting machine" and its components (G. Reinhart, 2015; Roßmann & Schluse, 2020).

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on the Digital Twin, which he defined as a virtual representation of a physical asset fed with data from the real machine and sending data to the real twin. The DT consists of the machine data (called Digital Shadow) and a model of the machine, see Figure 1.

The virtual representation enhances conceptualization, comparison, and collaboration in production processes since it provides a more intuitive perspective compared to 2D sketches or data in tables or regular graphs. As sight is the most important human sense, a realistic visual view is valuable. Different users can easily classify the current state of the machine which is also consistent for different users.

A Cyber-Physical System (CPS) is the combination of the physical asset and the Digital Twin with its corresponding communication infrastructure. CPS are important building blocks of Industry 4.0. Digital twins of different machines can communicate with each other. Application areas of the Digital Twin include health monitoring, production planning (PLM), and the design of new products. An advantage over conventional planning software is that all data related to one product is stored together in one place (the Digital Twin). This presentation has massively increased the value of the data. Although simplified, it tries to model accurate behavior of the real twin.

In (Werner Kritzinger et al., 2018) the terms Digital Model, Digital Shadow, or Digital Twin are used to classify the level of communication between the digital and physical assets. Whereas a Digital Model is independent of its real asset, a Digital Shadow only receives data and only the Digital Twin allows bidirectional communication between digital and physical assets. However, "Digital Twin" is often used for Digital Models and Shadows as well. The literature on actual Digital Twins however is scarce. Especially there is a lack of case studies on a higher level of integration.

When combined with modern simulation technologies (such as FEM, fluid dynamics, multibody dynamics), the digital twin becomes an experimentable Digital Twin (Schluse & Rossmann, 2016). The digital twin ensures that results of several simulations are stored in the digital twin and thus through co-simulation exchanged between them thereby circumventing incorrect results if those simulations were carried out independently. With the introduction of simulation to the Digital Twin not only visualization of the current data becomes feasible but also the generation of new data, hence "a look into the future". It opens the digital twin to artificial intelligence techniques that can optimize the assets behavior.

As a mediator, the Digital Twin can process the machine data, find suitable settings for a given task, and display valuable information, that is otherwise invisible, in an understandable way, such as suggesting actions to be taken through a human-machine interface. In (Cichon, 2019) a concept to facilitate the interaction of humans and machines is presented. Among others, joysticks, screens and Augmented or Virtual Reality (AR/VR) allow direct interaction with the Digital Twin. The user interacts with the virtual machine like with the real machine and can observe its status via the Digital Twin.

(Andre Schult et al., 2019) have developed an assistance system that records machine data and then uses machine learning algorithms to estimate the state of the machine. This state is compared with a user created database with common faults to detect faults and give recommendations to fix those.

In the project virtual textile learning, (Haase et al.) work on assistance systems in the textile sector. Their focus is on using digitalization and 2D/3D visualization for learning in the textile sector.

(Minoufekr et al., 2019) built an assistance system based on the Microsoft HoloLens for CNC machine tools that allows for much quicker and error tolerant testing of the machining process. Like the tufting machine used in our project, their model was based on kinematic chains, that they modelled in the game engine unity.

3 CONCEPTS

A tufting machine stitches yarn into a backing material. It is commonly used to produce carpets or artificial grass. A shaft continuously rotates and thereby moves the tools. The tools commonly consist of grippers, knives, and needles, although variations exist. The needle stitches the yarn through a backing material which is then grabbed by the gripper. When the needle moves back up the knife cuts through the loop formed by the gripper.

The assistance system proposed is based on an experimentable digital twin of the tufting machine. The experimentable digital twin was first presented in (Hüsener et al., 2022). A digital model of the machine was created that accurately describes the kinematics of the machine. It is possible to adjust the machine just like the real machine, but much simpler and much more settings can be tried. The behavior of tools such as needle, gripper and knife can be estimated.

Different settings can be shown as ghosts (Figure 2) that allow to compare different settings in a way not possible in the real machine.

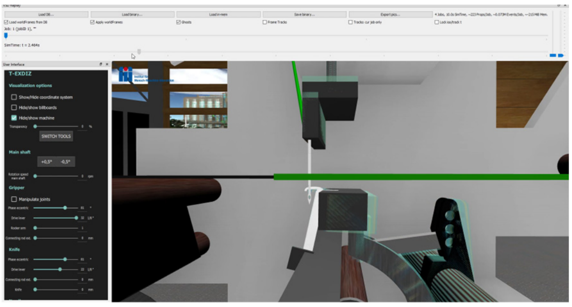

Figure 2: "Digital ghosts": Simulation allows to visualize effects of different settings.

Parameters are adjusted through sliders that when hovered highlight which part will change when a particular parameter is adjusted, see Figure 3. The opacity of the machine case can be adjusted to show what's going on inside the machine.

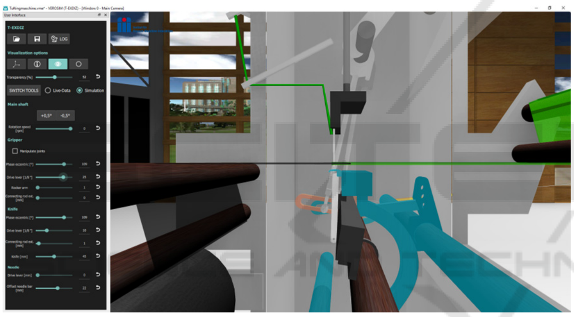

Figure 3: Assistance system to adjust machine parameters intuitively with immediate visibility of changes and the option to return to a previous setting.

The machine was equipped with sensors that continuously send their measurements to a PC where the simulation runs (digital twin). The measurements are then preprocessed, and tool positions are calculated using kinematic relations between sensor changes and tool position changes.

The simulation model combined with the real machine data yields the experimentable digital twin of the tufting machine.

To close the cycle from the machine to the simulation back to the machine the assistance system will guide the user to transfer settings stored in a database or found in simulation back to the machine.

The benefit of the digital twin is that it constantly receives new data so it can easily control the user has made settings as desired. The accuracy can be specified and is limited by the accuracy of the sensors.

4 DEVELOPMENT OF THE DIGITAL TWIN

The Digital Twin was modelled using VEROSIM, a simulation software for rigid-body mechanics. The software was developed with digital twins in mind and has plugins for interfaces to popular communication infrastructures, such as TCP/IP, ROS or MQTT communication.

At first, the kinematic relations of a particular tufting machine were measured at the real machine to create a digital model of the tufting machine. The simulation is already able to simulate the behavior of the real machine with all the adjustments that can be made on the real machine, but adjustments can be made much quicker and easier and are reversible allowing to test different machine settings.

In a second step, the machine was equipped with sensors to measure the current positions of axis or the phase of the main shaft. At first those values could be stored inside an csv file that contains a timestamp and each sensor value and then be read by the simulation software which then shows a virtual representation of that values. Multiple settings can be overlayed so changes from one setting to another can be inherently noticed.

Once the simulation can reproduce the measured data, it can be used to (automatically or manually) search for optimal settings for the intended use.

Third, an interface to directly receive values from the sensors inside VEROSIM was written. The interface uses ADS which is a communication protocol by Beckhoff TwinCAT that supports real time communication. The digital twin is notified whenever a value changes and updates its representation accordingly. If the machine is available remotely, then the digital twin can be shown on any computer.

To get the virtual representation of the current state of the machine, a script was written that transforms sensor values into tool positions. Not all parameters can be measured with sensors, such that manual measurements are necessary for machine calibration. A dialog box allows the user to change lever arms and offsets used for this calculation to account for varying placement of the sensors.

Finally, if the user has adjusted the virtual digital twin in simulation mode and wishes to transfer these adjustments back to the real machine, this paper proposes an assistance system that aims to achieve just that.

Figure 4 shows all the system components of the experimentable digital twin of the tufting machine.

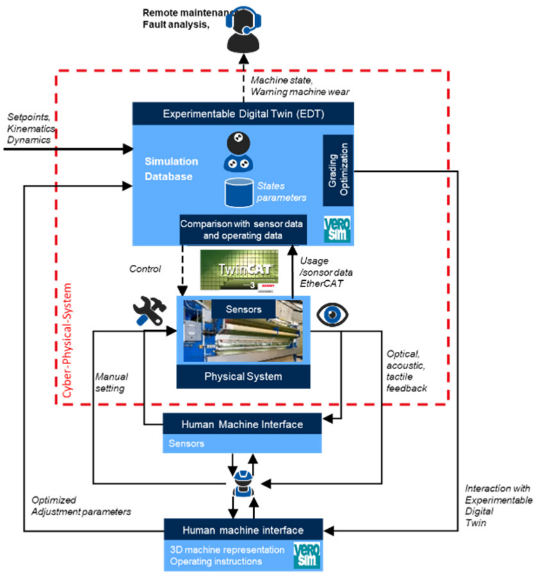

Figure 4: Conceptual description of the system.

The user interacts through a human machine interface with the digital twin. The digital twin consists of a database that can store old machine settings and a simulation engine that can find new enhanced settings.

5 ASSISTANCE SYSTEM FOR INTUITIVE ADJUSTMENTS

Handbooks specify how the curves of gripper on the needle must look like. It must hit the needle at the phase, see Figure 5. Similarly, handbooks give specifications of the relative curves of gripper and knife or the stroke of the needle. However, if changes are made to the machine, e.g., due to wear or production changes and now different tools are needed, then it not obvious which parameters need to change how much to get as close as possible to the desired setup.

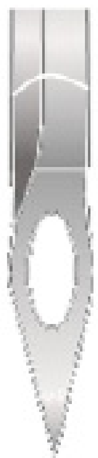

Figure 5: Drawing shows the desired curve representing gripper and needle relative positions from handbooks.

So, normally it is necessary to make some adjustments based on the experience of the operator, test the new settings, and then readjust the machine if necessary. This can be a costly task.

Simulation however can test various machine settings with a fraction of the cost.

At first the needle is adjusted to yield just the right amount of stroke, and then the gripper is adjusted accordingly.

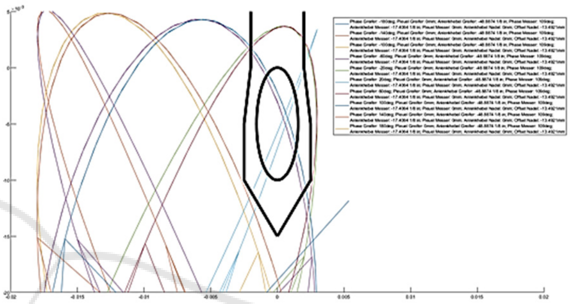

Figure 6: Sketch of needle with curves of relative gripper positions for varying parameters.

Once the desired specifications for the needle have been met, we can simulate various curves of the gripper relative to the needle and compare the curves with the desired result, see Figure 6. A MATLAB was written that compares the curves considering the hit point, the direction, and the distance from the loop to recommend a curve. The simulation range and step width can be adjusted to meet the requirements of the operator. The settings for the knife are then found similarly by considering relative movement between gripper and knife. The process can be adapted to other textile machines.

The process of finding optimal parameters will be the subject of another paper. Instead, in this paper I want to focus on how the experimentable digital twin can help to adjust the real machine according to the newly found optimized parameter sets.

If the operator has found optimal settings, he starts the assistance system. The system can show all the necessary steps on the digital twin, yet it is able to also use the HoloLens to display the steps on the real machine or let a trainee operate on a machine that looks and works just like the real machine but is only virtual, thereby enabling training without access to a real machine.

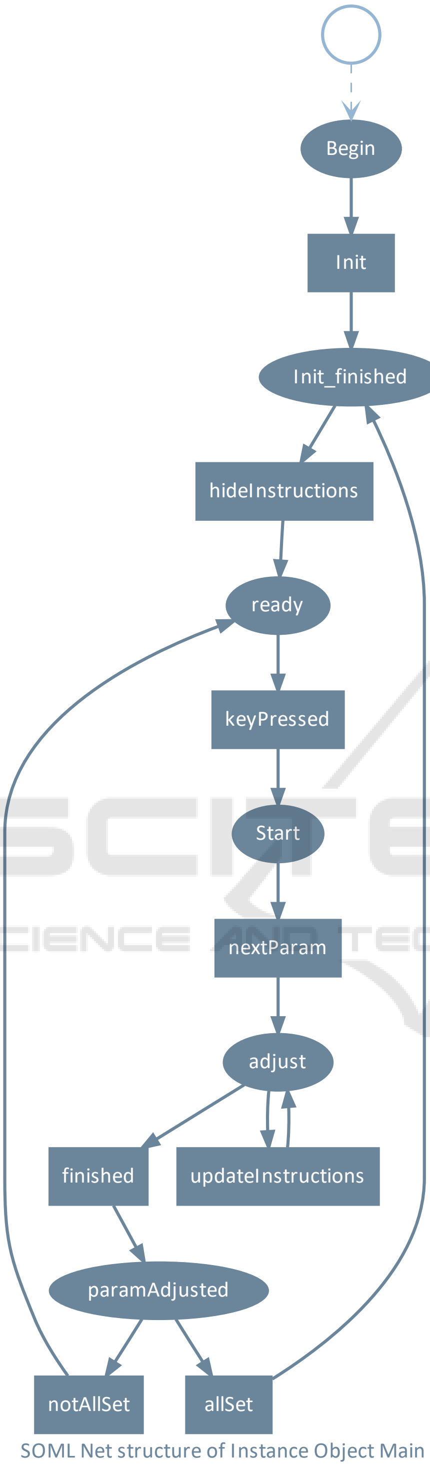

Figure 7: Process for the assistance system.

The process is shown in Figure 7. In the initialization step a class containing among other information the desired positions, a link to the kinematics, and a camera view for each parameter is created. “hideInstructions” makes sure that all panels and arrows are hidden, e.g., if the adjustment process is aborted.

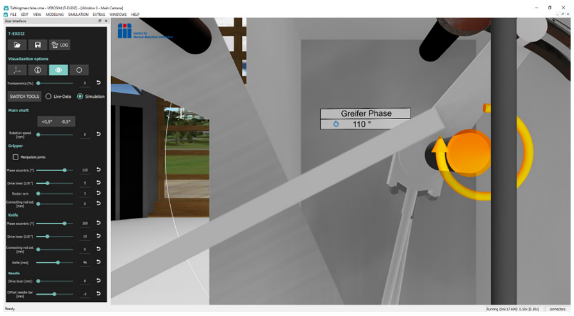

Figure 8: Close-up view inside the machine showing pane with instructions on how to adjust machine and an arrow indicating that the operator should turn the excentre clockwise.

The interactive part is started when the user presses a predefined button. It then iterates over all parameters and shows a board with the component to change, the value the component needs to change and an indication in which direction a value needs to change, see Figure 8. It thereby transforms sensor values and desired values from their mathematical value to a meaningful representation for that machine, e.g., move by 10° or move to notch 2/32. The needed accuracy for continuous values was set to 0.1° or 0,5 mm but can be set according to the operator’s need. The instructions are updated at every simulation step to recalculate the required change as the operator changes the value. If the desired and measured value are within a tolerance the assistance system moves on to the next unset parameter and repeats the process until all parameters have their desired value.

6 DISCUSSION

Since many operators of tufting machines have different backgrounds, it is expected that they can benefit from an assistance system that gives intuitive instructions how to adjust the tufting machine for a given use case.

The experimentable digital twin has several advantages over the real twin. Changes to machine parameters are non-destructive, with one click an adjusted value can be restored. The digital twin allows simulation to search for optimal parameters, but it also has access to the current state of the machine. Yet, it can enhance the real machine by displaying additional virtual information. Therefore, it combines features of simulation and the real machine.

Benefits of using Twin CAT for the communication between the sensors in the machine and the digital twin are the frequent use of Twin CAT in industry as well as the fast communication so that the user gets feedback when he changes machine values with little delay.

To ensure that the simulation produces viable results, validation of the simulation model is necessary. While some parts of the machine can be simplified it is important that the tool movement is accurately modeled so that the results found through simulation can be transferred back to the machine, and if done so, yield the expected results. To check visually that the movement of the tools is similar, a camera was placed in the machine and simulation, based on sensor data, and the video can be compared, see Figure 9.

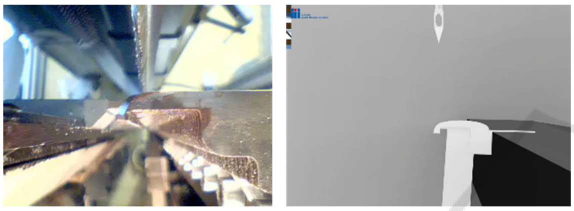

Figure 9: Camera and simulation alongside for validation.

For more accurate results the tool positions of the simulation can be compared with the real tool positions calculated from current sensor values. It was found that at first the position was somewhat off, but the simulation model was adjusted accordingly. The real positions can be rendered on top, so at every point in time it can be seen if the simulated and real positions are close, see Figure 10. By calculating the distance between two frames the error can be quantified. It needs to be considered that the movements of needle and gripper are idealized as linear movements and only the linear component is measured by the sensor.

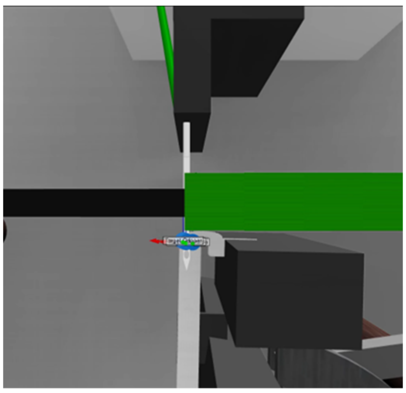

Figure 10: Simulation of the tools with real tool positions overlayed.

On the HoloLens the operator has his hands free to adjust the machine but can see the instructions simultaneously. Also, the HoloLens can be used to visualize the tool movement with the current parameters without turning the machine. In future, a digital ghost of the target position of all machine parts could also be shown alongside the instructions that might even be more intuitively but when small changes need to be made quantitative instructions should yield more accurate results.

It is also suggested that the assistance system is evaluated in practice, therefore it needs to be extended for other set of tools or machines. Input from industry experts can provide hints how the usability of the assistance system might be enhanced. It is expected that in the long run, an assistance system can significantly reduce the time needed to adjust a machine and thus reduce downtime and ultimately cost. Evaluation could help quantify this effect.

In further projects the experimentable digital twin system shall be used for educational purposes to demonstrate effects of errors in machine usage.

7 CONCLUSIONS

As was shown in this paper, manual tasks can benefit from an assistance system that gives intuitive instructions how to adjust machine settings for different uses. An experimentable digital twin of a tufting machine was developed that uses simulation to find optimal adjustment parameters and a simulation-based assistance system that uses real-time sensor values to compare desired and actual state and generate instructions to adjust the machine accordingly. With time, the assistance system can be extended with a database containing relevant settings for different use cases. The benefits are repeatability, reduced times to setup the machine, and a learning environment for trainees. While the process was shown and developed with a particular tufting machine in mind, the system can be extended to other tufting or textile machines with similar mechanics. The main effort is in creating a digital twin – if a CAD model of the machine already exists the system could be adapted with minimal effort.

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