

Reviewer #1: Responses to the reviewer comment

Dear reviewer, thank you for your useful comments that will improve our paper and future research. The text marked in red has been added to the paper.

Comment No1:
However, I would like to view more data regarding the simulation process and the results. The subchapter is treated superficially, much more statistical data needs to be presented in the simulation process. What software was used?
Response to the reviewer comment:
PTC Creo software, the Manufacturing module and within it the CMM module were used. A DMIS code is generated as a valid output file. Statistical data in this context makes a lot of sense for measurement process parameters such as velocities and accelerations. However, for the purposes of this research, the defaults were taken from the software and can be changed in the DMIS code relatively easily.
Comment No2:
What methodology?
Response to the reviewer comment:
As a methodology, the basis of the software was used. Creation of metrology operations and configuration of the measurement system based on the CMM is performed using standard software commands. The idea was to create a digital twin quickly and efficiently, then generate DMIS code as an output from the simulation and then use it as an input for a real CMM and real measurement. Although this methodology gives a quick response, in terms of information, its disadvantage is a one-direction digital twin. That means, the flow of information from the real machine to the virtual machine is not possible. Certainly, one of the future screenings will go in that direction.
Comment No3:
What are the results obtained?
Response to the reviewer comment:
The measurement process can be planned and simulated, while the relevant measurement results can only be obtained by execution of the measurement. Also, the main novelty of this approach is (i) simulation, (ii) prediction of collision avoidance and (iii) verification of measuring processes by developed off-line digital measuring twin based on CMM.

19/07/2025

Authors

Reviewer #2: Responses to the reviewer comment

Dear reviewer, thank you for your useful comments that will improve our paper and future research. The text marked in red has been added to the paper.

Comment No1:
The authors aim to create a virtual measurement system that can simulate inspection processes, reduce measurement time, and prevent collisions. While the concept has merit, the execution feels more like a technical demonstration than groundbreaking research.
Response to the reviewer comment:
On the one hand, it can be said that it tends to technical application, however, e.g. "hidden" is an entire kinematic model of the machine that is not included in the PTC Creo software database as standard. Small and medium-sized production companies from us have one to three CMMs. The idea of this paper is to quickly and efficiently modelling their kinematics (virtual CMM), simulate the CAD-based measurement process and generate DMIS code as input for a real CMM.
Comment No2:
CMM simulation could definitely help optimize measurement processes and prevent costly mistakes. However, the execution feels rushed and incomplete.
Response to the reviewer comment:
The measurement process can be planned and simulated, while the relevant measurement results can only be obtained by execution of the measurement.
Comment No3:
The potential is there, but it needs much more rigorous development and validation to become truly useful for the measurement community.
Response to the reviewer comment:
Thank you for comment. Rigorous development and validation, in this approach, is reflected in the accuracy of the DMIS code that is entered into real CMMs. We have developed some processors that filter the DMIS code as an output from the simulation (virtual CMM), but for some CMMs we are planning to develop some processors. The problem is caused by various software and the flexibility of measuring operations (parts).

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VIRTUAL MEASUREMENT SYSTEM BASED ON CMM AND DIGITAL TWIN MODEL

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Abstract: The purpose of this paper is to improve the quality of measurement inspection process, reduce measurement time and eliminate collisions by modeling virtual measurement system based on coordinate measuring machine (CMM). Digital twin models (DTMs) are becoming more significant in industrial environments as they enable monitoring, control, and simulation of measurements, while also offering the possibility of inspecting mechanical parts or manufacturing processes in a digital environment. In this paper, a virtual measuring system based on CMM, a measuring part and a fixture was created and configured. On the other side, DTM includes virtual and physical components, with the virtual component created in a CAD environment using PTC Creo software. The final output from virtual and real measurements are DMIS files. The measuring part underwent an analysis of metrology for defined form and location tolerance, while for the virtual measuring machine, it was necessary to establish kinematic links between all subsystems of the machine. For the virtual twin of the CMM model to have consistent movement, it was necessary to define the connections between the coordinate systems of the part and the measuring probe, as well as between the part and the CMM. The advantage of this DMT is that, in addition to off-line mode, it can be directly integrated (on-line mode) into complex technological systems.

Key words: Digital twin, Virtual reality, CMM, Measurement System, Simulation.

1. INTRODUCTION

Digital manufacturing and digital quality require process simulation from the simplest units through production plants and even the entire factory. In order for production to be digital and to apply digital quality, it is necessary modeling the units of the production system in virtual reality. One part of the production system is the metrology system, which are usually one or more measuring machines. Modeling this metrology system in virtual reality is a prerequisite for realizing digital quality within the factory. By pairing a real metrology system based on a CMM and a virtual one, also based on the same CMM, a digital twin is realized. Therefore, the digital twin (DT) maps the virtual CMM into a real measuring machine and vice versa. Mapping is

not only about the hardware structure but also its functionality, flexibility and kinematics.

DT is becoming more significant in industrial environments as they enable monitoring, control, and simulation of measurements or inspection various mechanical parts or manufacturing processes in a digital environment. Each CMMs has its own programming software and integrated simulation capability. Due to the fact that the simulation takes only some CMM parameters, it is not a complete digital twin.

In this paper, a virtual measuring system based on CMM, a measuring part and a fixture was created and configured. PTC Creo software, the Manufacturing module and within it the CMM module were used. Creation of metrology operations and configuration of the measurement system based on the CMM is

performed using standard software commands. The idea was to create a digital twin quickly and efficiently, then generate DMIS code as an output from the simulation and then use it as an input for a real CMM and real measurement. On the other side, presented DTM includes virtual and physical components, with the virtual component created in a CAD environment using PTC Creo software. The final output from virtual and real measurements are DMIS files. The advantage of this DMT is that, in addition to off-line mode, it can be directly integrated (on-line mode) into complex technological systems.

2. STATE OF THE ART

According to [1], the DT includes three basic elements: (1) physical products in real space, (2) virtual products in virtual space, and (3) connections that facilitate the exchange of data and information between virtual and real products. The impact of DT on concept Industry 4.0, including their integration, extends beyond technical considerations, thus influencing social, economic and other domains [2].

An effective DT should support various activities including monitoring, maintenance, management and optimization of processes and technologies [3]. Recent developments of DT technologies for manufacturing systems are in the process of verification, application and research in the context of smart manufacturing [4]. Contrary to continuous development, the full potential of DT remains unrealized, conditioned by the collection and manipulation of data [5]. Thus, the paper [6] deals with the collection, storage and distribution of data during real-time inspection, emphasizing the need for efficient use of data.

DT functions as a bridge between physical and virtual measurement environments, while a virtual measurement system based on CMM has been developed to evaluate standard type of tolerances such as concentricity and straightness etc. [7].

The paper [8] presents the optimization of the measurement path for the inspection of prismatic parts on CMM, while [9] introduces a model for planning the inspection of prismatic

parts, with an emphasis on the intelligent concept of inspection planning towards DT.

3. VIRTUAL TWIN OF THE CMM

In this paper, the DT concept is realized through the implementation of a virtual model based on the Mitutoyo CRYSTA Apex CMM. The primary aim is to simulate a comprehensive virtual measurement system and inspection process, with subsequent verification achieved by generating output in the form of .ncl (DMIS) code. All modeling, simulation, and inspection tasks were performed using the PTC Creo Parametric software package.

One of the fundamental aspects of the functioning and application of the DT lies in the real-time data exchange between the digital and physical systems [10]. Two principal approaches define this bidirectional flow of information. The first approach is based on the continuous acquisition of data from the physical system through various types of sensors and their subsequent application to the virtual model [10]. In contrast, the second approach involves implementing data obtained through digital simulation directly into the physical system [11].

In the context of this research, the second approach has been adopted—data generated through digital simulation is subsequently transferred to the real measuring system. This methodology is carried out in an off-line mode with the objective of identifying and eliminating potential disadvantages that may arise during the measurement or inspection process. Furthermore, it serves to comprehensively prevent collisions between any components involved in the inspection workflow.

Figure 1 presents the CMM model developed within the software environment, incorporating all relevant subsystems and components. The dimensional accuracy of the virtual model is precisely matched to the physical machine, which embodies the fundamental principle of the DT framework—faithful digital replication of the real system.



Fig. 1. Virtual Twin of the CMM Mitutoyo CRYSTA Apex [10]

4. VIRTUAL INSPECTION SYSTEM

The virtual measurement and inspection is based on several equally important steps, each forming a consistent chain necessary for the successful realization of the simulation process. This section provides a detailed explanation of each element in the modeling of the virtual inspection model. The process begins with the modeling of all components involved in the inspection procedure, namely the workpiece, auxiliary clamping tools, and the CMM with all its subsystems. It is essential that the models are fully aligned with the real-world system, as this is a key factor in implementing the DT concept—the integration of the real system into a digital environment.

Once the modeling phase is completed, it is necessary to establish the kinematic links between the CMM subsystems to enable translational movements along the Cartesian coordinate system, identical to those performed by the physical machine. Before conducting the simulation and verification of the complete measurement inspection, the coordinate systems of the machine table, workpiece, auxiliary clamping tools, sensor head, and the spherical tip of the probe must be defined. These coordinate systems ensure proper alignment and precise motion of the virtual measurement system.

4.1 Modeling the measuring system

The essence of this subsection is focusing on the creation of models necessary to represent the complete measurement inspection in a digital format. Following that, the simulation of the measurement inspection will be conducted, along with its verification, which serves as the output and proof of the DT concept.

Modeling must satisfy certain requirements. Primarily, the created models must be visually and geometrically identical to the real ones, fully complying with the specifications of the technical drawing. In order to establish the DT model from the stand point of this requirement, a complete model of the Mitutoyo CRYSTA Apex machine (Figure 1), the workpiece, and auxiliary clamping tools was implemented.

Figure 2 presents the 3D CAD model of the workpiece, modeled also using the PTC Creo Parametric software and fulfills all the specified requirements.

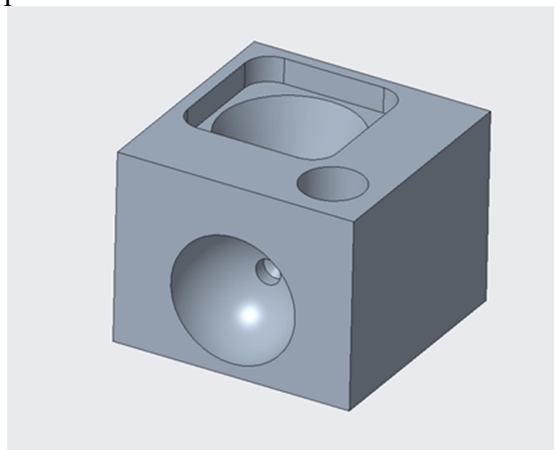


Fig. 2. 3D CAD model of the workpiece

Following the definition of the workpiece model, the modeling of the auxiliary fixture is performed (Figure 3), which plays a critical role in ensuring the accuracy of the measurement inspection. Stability and accessibility of the measurement surfaces during the inspection process have a direct impact on the reliability of the obtained results. Furthermore, to enhance efficiency, the goal is to minimize the number of clamping operations, with the ideal scenario being a complete inspection performed in a single clamping cycle. Each repositioning of the workpiece inevitably introduces additional

time, potential measurement errors, and dependence on the human factor, all of which negatively affect measurement accuracy and repeatability.

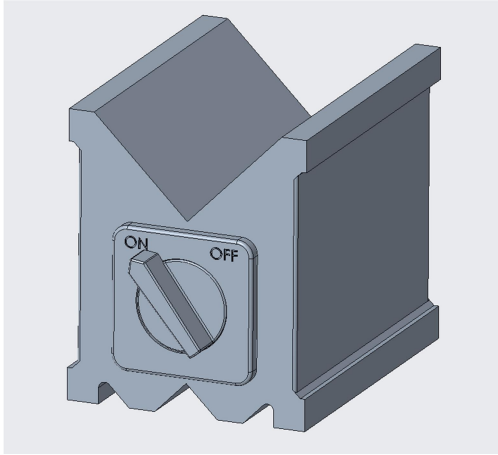


Fig. 3. 3D CAD model of the auxiliary

A properly designed and positioned clamping tool contributes to the reduction of total quality control time, thereby optimizing the overall production process.

To ensure conciseness and efficiency in the implementation of the DT model, a magnetic auxiliary fixture was designed for prismatic workpieces. This clamping concept fully satisfies the stability and accessibility requirements during measurement inspection, making it an optimal solution for the specific case study.

After completing the modeling of all components as well as the subsystems of the measuring machine, the workpiece, and the auxiliary fixture, the next step is to define the kinematic links between the subsystems of the CMM in PTC Creo Parametric software package.

According to previous chapter and Figure 4, we define the three main components of the measuring machine [10]:

1. Machine base—provides stability and support to other components;
2. Measuring bridge—allows the measuring probe to move along 3 directions (X,Y,Z) and take the necessary positions during the inspection;
3. Z-axis that contains the rotating head, the control unit of the CMM, as well as the probe itself on its top [12].

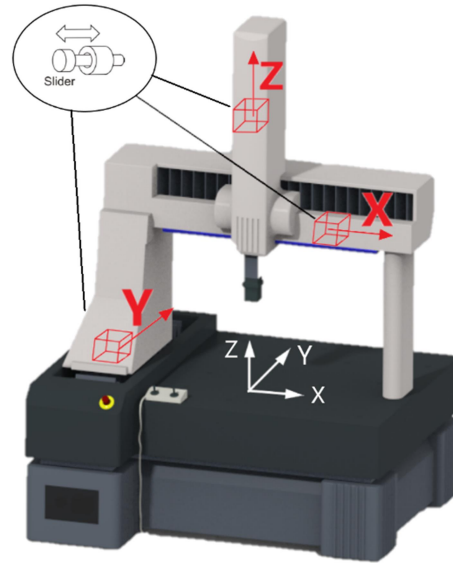


Fig. 4. Overview of kinematic links on the CMM Model [10]

The kinematic configuration of the virtual CMM is established to accurately emulate the motion behavior of the corresponding physical system. In the case of the selected moving-bridge CMM, it is necessary to define three independent translational degrees of freedom along the X, Y, and Z axes. Within the PTC Creo Parametric software environment, these linear motions are implemented through the use of “slider” constraints, as illustrated in Figure 4. In addition to defining these constraints and their mutual associations, it is essential to specify motion boundaries that correspond to the physical travel limits along each axis of the measuring system [10].

The final step is definition of coordinate systems for the workpiece, the measuring probe, and the CMM, as shown in Figure 5. The establishment of these coordinate systems ensures proper alignment and precise movement of the virtual machine, while also enabling effective interaction among system components that directly influence the accuracy of the inspection process and the prevention of collisions.

According to [10], it is necessary to define coordinate systems on:

- working table - MACH_ZERO,
- workpiece - MACH_ZERO,
- head of sensor - TOOL_POINT, which axis is defined with same direction and

orientation as the axis of coordinate system on workpiece, and

- probe - TOOL, if it is necessary to create own probe [13].

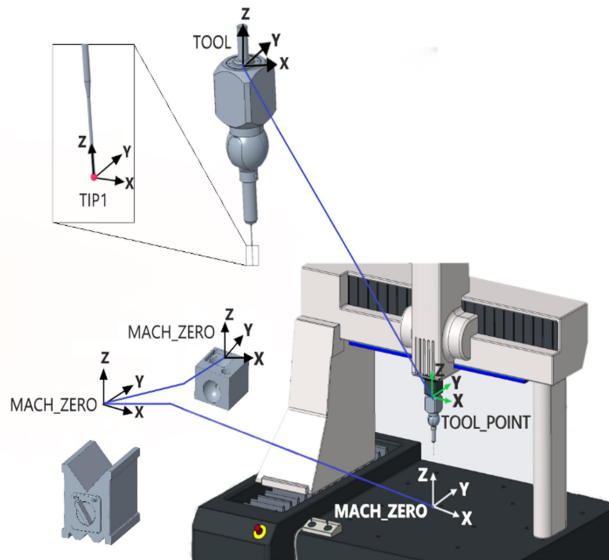


Fig. 5. Coordinate systems and connections between them

As depicted in Figure 5, the coordinate systems labeled MACH_ZERO, defined on the workpiece, fixture and CMM, serve to establish alignment. These systems facilitate the precise placement of the fixture onto the virtual machine's worktable, followed by the accurate clamping of the workpiece onto the fixture. A similar procedure is applied to the coordinate systems TOOL and TOOL_POINT, which are used to define the positioning of the measuring probe on the sensor head. Additionally, the coordinate system TIP1 is defined at the center of the spherical end of the measuring probe.

4.2 Simulation

In this paper, simulation is employed for the measurement or inspection process using a virtual CMM. The simulation serves elimination of the need for designing and producing costly physical prototypes, the ability to visualize and monitor the measurement process, and significant savings in both time and resources. Furthermore, simulation facilitates the detection and prevention of collisions within the actual system. Moreover, simulation serves a critical

role in validating the functionality, reliability, and overall performance of the design prior to the execution of the actual measurement inspection process.

Figure 6 illustrates the simulation environment within the PTC Creo Parametric software package. As previously emphasized, the simulation must include all components involved in the inspection process under real working conditions. This comprehensive integration enables not only the generation of objective output results but also facilitates visual tracking of the inspection process, allowing for the identification of potential collisions between system components.

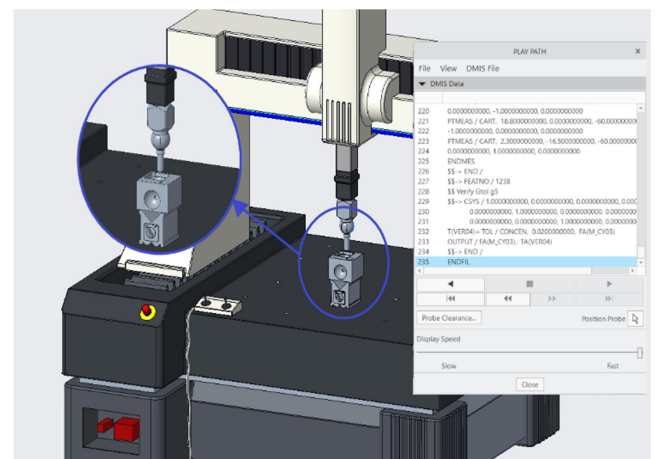


Fig. 6. Measuring path simulation on virtual CMM – one window

Furthermore, Figure 6 highlights a verification of the quality control process, which is essential for realizing and confirming the DT concept. The simulation output serves as a validation of the measurement results, represented by the generated path of the measuring probe, specifically the center of its spherical tip. This path is stored in a Cutter Location (CL) file. The CL file contains the DMIS program, which provides a set of instructions for the actual CMM during physical inspection. The generated DMIS (.dms) code, as visualized within the PTC Creo working environment, is also shown in Figure 6.

5. CONCLUSION

A digital twin is a static and dynamic, digital replica of a physical object, or in this case, a

CMM. It remains in a constant state of updating with real data to more faithfully reflect the state and behavior of its physical copy. The twin presented in this paper can be used for simulation, analysis and continuous monitoring, thus becoming the basis for predictive maintenance and process optimization. Twin remains updated with data collected during inspections. By analyzing the twin, we can predict maintenance needs, assess quality and optimize processes, thereby contributing to improving overall efficiency and quality. It should be emphasized, the measurement process can be planned and simulated, while the relevant measurement results can only be obtained by execution of the measurement.

6. REFERENCES

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