An Approach of Development Digital Twin Based on CMM as Support Industry 4.0

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Abstract: *The digital twin (DT) based on CMM as support Industry 4.0, are based on integration of digital product metrology information through metrological identification, application artificial intelligence techniques and generation of global/local inspection plan for coordinate measuring machine (CMM). DT based on CMM has an extremely expressed requirement for digitalization, control, and monitoring of the measurement processes inside Industry 4.0 concept. This paper presents an approach of development DT as one direction information flow based on four levels: (i) mathematical model of the measuring sensor path; (ii) tolerances and geometry of the parts by applying an ontological knowledge base; (iii) the application of AI techniques such as Ants Colony Optimization (ACO) and Genetic Algorithm (GA) to optimize the measurement path, part number of part setup and configuration of the measuring probes; (iv) simulation of measurement path. After simulation of the measurement path and visual checks of collisions, the path sequences are generated in the control data list for appropriate CMM. The experiment was successfully carried out on the example of prismatic part.*
Keywords*: DIGITAL TWIN, CMM, INDUSTRY 4.0, INSPECTION PLANNING*

1. Introduction

Author [1] is one of the first introduced Digital Twin (DT) in 2003, in a course presentation for product lifecycle management (PLM). Also, author [1] incorporated three elements into the model: (i) the physical products of the real world, (ii) their virtual twin and (iii) interfaces that connect the data and information flows from both worlds. The paper [1] define DT as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro level to the macro geometrical level". At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its DT. DT are of two types: Digital Twin Prototype (DTP) and Digital Twin Instance (DTI)" [2]. As a result, physical prototypes can be avoided, and functionality and behavior can be simulated using a model before proceeding into real manufacturing.

The first usage of DT was a year later, by NASA, in Technology Roadmaps [3]. They used it to mirror conditions in space and perform test for flight preparation of their rockets. Since then DT has advanced technologically and expanded its scope of utilization. There is an exponential increase in DT utilization over the last 10 years. Also, increase in potential of DT is expected.

Digital Twins are getting attention because they integrate artificial intelligence (AI), Internet of things (IoT), and machine learning (ML) to bring data, algorithms, and context together, which makes DT a key part of the Industry 4.0 agenda.

Having various definitions has postponed reaching an agreement on a single representative definition of DT. For some members of the community (Schroeder et al. [4], Abramovici et al. [5]) DT is considered as the final product, whereas for others (Rosen et al. [6], Gabor et al. [7]) it is the whole product lifecycle.

Storage of all data in digital format made the implementation of DT conceivable. With arising simulation capabilities, it became possible to perform practical tests in virtual climate. An idea of carrying out a functional DT was embraced by companies like IBM and Siemens.

One of the essential reasons advanced DT technology is quickly being embraced is there are numerous utilization cases across the industrial enterprise: engineering, manufacturing and operations, maintenance and service [8].

Some industries where DT can be highly useful are:

- Industries where developing physical prototypes is costly, time-consuming and resource-intensive (for example manufacturing)- instead of spending time and money building multiple prototypes to test a product, a digital twin is a much more efficient and convenient solution.
- Industries in which exceptional testing is required and such testing is difficult or impossible to perform in laboratories (such as aerospace): The DT can simulate tests that cannot be performed in the lab.
- Industries that require real-time monitoring and prevention plans for dealing with 'emergent behavior' (e.g., health care, supply chain): Keeping an eye on the physical asset's real-time status and being alerted via predictions for an impending problem can be both efficient and effective. This is especially useful for organizations that need to make quick decisions to avoid large losses.
- Industries with multiple parameters that can be optimized cooperatively (such as manufacturing and supply chain): Maintaining and monitoring all sub-components can be a challenging task for very large organizations. Real-time monitoring of all sub-components and collaborative holistic analytics on such large models can be advantageous.

Despite the fact that it is dependent on multiple technologies, which necessitate the use of experts and resources, DT can result in significant cost savings for a one-time investment. DT can shorten design cycles, save money, resources, and time on prototyping, and predict potential hazards in time to mitigate them. This cost reduction could be used as a metric of DT performance for profit-oriented businesses [9].

There are some major areas in which DT has room for improvement:

1. Aspects of Technology: Modular-based DT, Modeling Consistency and Accuracy Enhance DT simulation which allows better monitoring and transparency during processes, VR integration into DT Integration of Cloud/Edge computing and an efficient mapping system between physical and virtual data which reduces uncertainties
2. Aspect of PLM: DT expands into other domains, in other words PLM allows a broader application of DT:
   - Emerging markets (e.g. Construction)
   - Incorporation of smart connected devices into DT
   - Product dependability, security, and privacy throughout the product's lifecycle.
3. Business Aspect: Incorporation of Big Data analytics into DT will provide more insights, resulting in better decision-making support

A modular approach enables the creation of flexible DT, resulting in new application modes while shortening development time [10].

Because of its enormous capacities to realize Industry 4.0, Digital Twin (DT) is attracting ever-increasing attention with the rapid evolution of cyber-physical systems. Businesses in a variety of industries are taking advantage of its capacity to simulate real-time working conditions, forecast and make intelligent decisions, allowing for a quick delivery of a solution to fulfill unique stakeholder demands.

To optimize production performance and maximize profit, digital cooperation is now emphasized with decision-aiding support. The maturity of DT technology reveals its ability to hold a strong position in Industrial 4.0 and manufacturing facility automation, and DT security and privacy concerns are expected to be a key discussion point for future DT [10].

Presented approach for development of DT in this paper refers to already machined PW (Part Work-piece), that is the chain of measurement data retrieved ends with data on measured value generated by software CMM DEA-IOTA-2203 after statistical data processing. The chain of retrieved machine data, the primary goal of this paper, ends by generating DMIS (Dimensional Measurement Interface Standard) code for DEA-IOTA-2203.

The novelty of the research is application into today's trend of industry 4.0 of its production and production metrology. Also, the novelty of the work is that in an efficient and dynamic way it integrates the entire production into one compact whole and thus solves the problem of production costs.

The main contribution of this paper is off-line DT based on DMIS file. The measurement system based on CMM DEA-IOTA-2203 was used as a physical twin, and a virtual machine, generated after modeling and configuring in *PTC Creo* software of both the machine itself and the prismatic parts and fixture clamps, was employed as a digital twin.

Presented approach leaves the possibility of using Web interface and server, because it affords DT simulation and is accessible to participating clients on a cloud platform. On this way, DT allows the activities to be implemented wherever there is an end-client.

2. Metrological Modeling

Metrological modeling generally includes modeling based on metrological features. Metrological features are in fact standard types of tolerances or tolerances defined by the ISO 1101 standard. Depending on the type of tolerance, metrological features may consist of one or more geometric features. In order to metrologically modeling geometric features, they are generally described by a set of parameters [11] whose numerical values uniquely determine each geometric feature.

Metrological modeling can also be based on CAD software. For example, *PTC Creo* software offers a CMM module that can recognize geometric features as metrological and thus perform the distribution of measuring points and form a point-to-point measuring path. This requires prior CAD modeling of the PW and import into the mentioned software module (Figure 1). This method of modeling does not offer the user the ability to enter the new different method of distribution of measuring points.

The application of EO as an object-oriented programming paradigm gives good results. One example of EO implementation in Protégé software is presented in [12]. The main advantage of this AI technique is the classification of knowledge according to the rules of decomposition. The starting point is the standard ISO 1101 and the standard forms of tolerance defined by it, and the end is individual, i.e. special forms of tolerance (for example. parallelism between two defined planes, cylinder etc.).

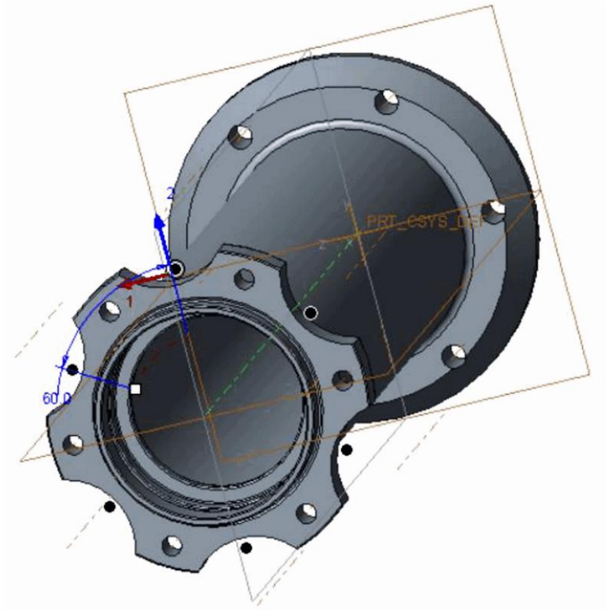


Fig. 1 *Modeling in PTC Creo software - display of the "Pattern" command in the "Model Taboo" palette*

In order to automate the retrieval of feature parameters from e.g. IGES or STL files, this method use the algorithms presented in [11]. By combining CAD software (their output files) and metrological modeling based on geometric features, a hybrid model is obtained that offers the possibility of arbitrary input of measuring point locations. This fact primarily affects to the measurement uncertainty.

3. Optimization and Simulation

3.1 Measuring path optimization

After the distribution of measuring points by geometric features and the generation of the initial measuring path, its optimization follows. It is based on the Ants Colony (AC) technique presented in [13] and methodology presented in [11].

It consists of defining the starting point from which the colony starts and the potential points that the colony visits. In doing so, the weighting factors determine which point has priority in the next iteration of the visit. When touring the points, the colony generates pheromones along the path.

The optimal trajectory is defined by the maximum number of laid pheromones. Compared to the manually programmed path on the CMM and the path generated in the PTC Creo software, this optimized path offers savings from 12% to 23%.

In order to complete the DT, it is necessary to conduct an analysis of the setup of PWs and the configuration of measuring probes for each setup. The analysis and then the optimization was carried out in [14]. After the analysis, the optimization of PW setup and configuration of measuring sensors was performed. As a result, it has the optimal number of PW setups and the optimal configuration of the measuring sensors for each setup.

3.2 Measuring path simulation

After optimizing the measurement path from the point of view of visually check the collision and generating an execution file for further post-processing, it is necessary to simulate the measurement path. Depending on the way the path is generated, the simulation is performed in MatLab or PTC Creo and PC-DMIS software. The reason for this division lies in the fact that CAD software that integrates CMM inspection does not allow arbitrary input (distribution model) of measuring points.

Simulation in the MatLab environment involves preparation in the form of algorithms or procedures as well as writing code that defines the point-to-point measurement path (Figure 2). The output is three matrices X_{mo}, Y_{mo} and Z_{mo}, which represent the coordinates of the measuring path points along the X, Y and Z axes, respectively. As can be seen, the path is defined for the three axis of CMM. The model can easily include a simulation of more than three axes.

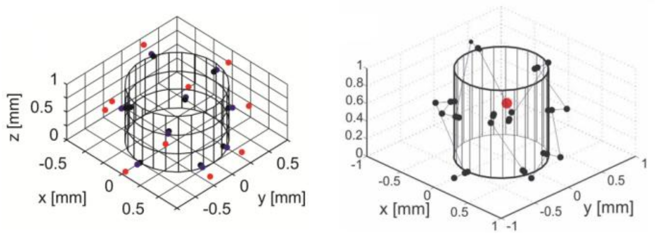


Fig. 2 *The distributed measuring points and simulation frames in MatLab software for cylinder inspection*

The simulation in *PTC Creo* environment is based on the already created CAD model measuring system consisting of PW, fixture clamps and CMM. The software offers the option of using its CMM so that the CAD model CMM does not have to be created except in cases of visualization of the existing one. The modeling and simulation procedure is as follows:

- Modeling of the 3D PW;
- Import of the modeled 3D PW into the CMM module (Manufacturing module);
- Setting up the CMM process, includes three processes:
    - Defining CMM workcell;
    - Defining probes or measuring heads;
    - Defining fixtures.
- Setting operations: defined the initial coordinate system of CMM;
- Defining steps of the operations or more specific operations;
- Creating DMIS (.ncl) code and post processing.

In addition to the distributed measuring points by features, in order to create a collision-free path, it is necessary to define node points. In the PTC Creo software as node points use so-called APN points. These points represent collision free points when moving from one feature to another.

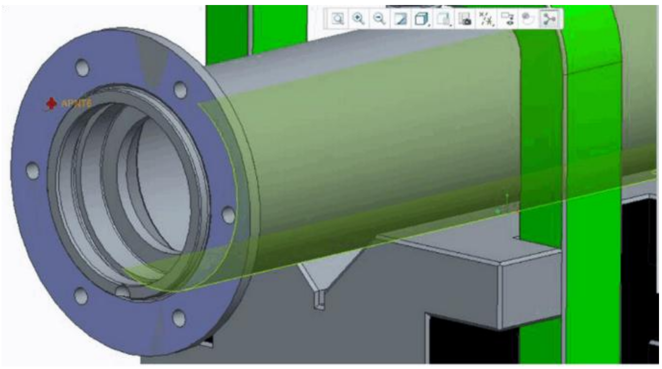


Fig. 3 *The selection of "APN" points as the start and end points of the measuring probe*

As can be seen from the described simulation procedure, the creation of DMIS (Figure 4) code is the last operation aimed at preparing data for input into the CMM control unit. Probe Path is a command used to display the path of the measuring sensor and generate DMIS code. This code contains information on the movement along the CMM axes, the coordinates of the measuring path points and other necessary information. Specifically, this code was generated for CMM DEA-IOTA 2203. For real measurement on this machine, it was necessary to correct the code and adjust it to the conditions of PW alignment on the CMM table, i.e. determining the position and orientation of the PW coordinate system in relation to the CMM coordinate system.

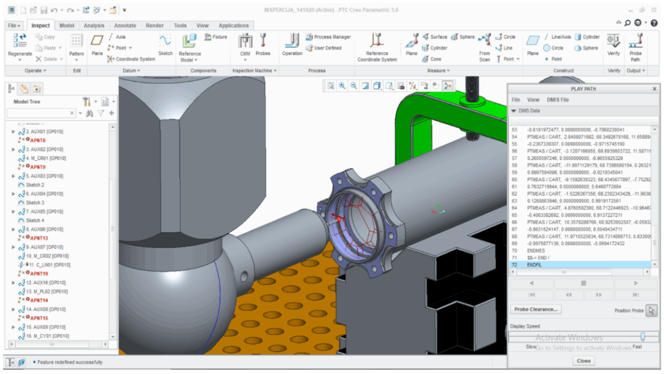


Fig. 4 *The defining the measuring path of the cylinder with the written DMIS code*

PC-DMIS software enables simulation and real time measurement, i.e. communication with CMM. Also, the software performs statistical data processing based on the acquisition of measuring points and thus generates measurement results. Part of the DMIS code, as well as a graphical representation of the measurement results is given in Figure 5.

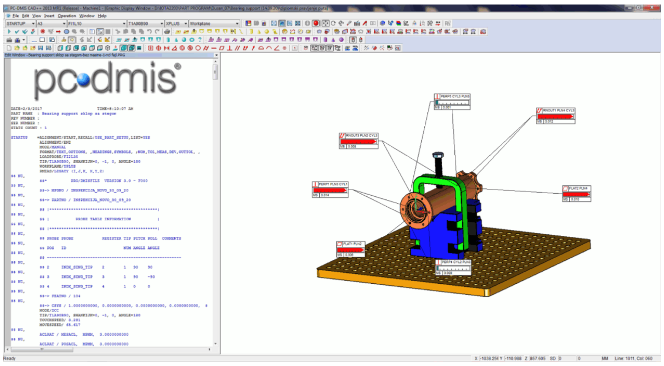
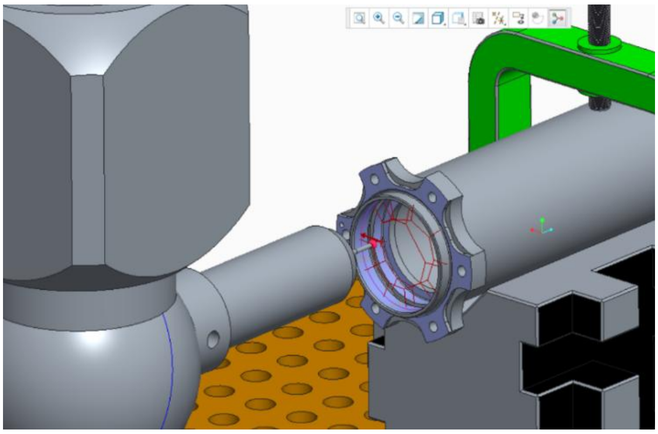


Fig.5 *Measurement protocol: a – original code of the program PC-DMIS; b – generated *ncl code Creo Parametric.*

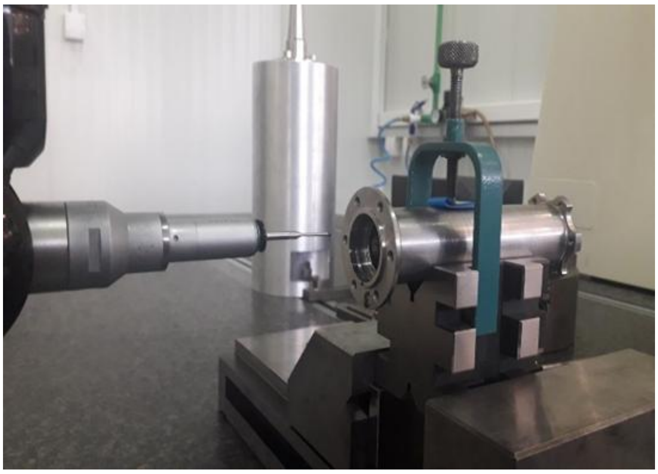
4. Digital Inspection Twin Based on CMM

As it is known DT consists of physical twin and its digital replica virtual twin. In this paper, the DEA-IOTA 2203 machine was used as a physical twin, while the machine model created in PTC Creo and PC-DMIS software was used as a virtual twin. The created DT is shown in Figure 6. Figure 6a) shows the virtual twin in PTC Creo software, while the real process is shown in Figure 6b). It is noted that the developed DT has a one-way flow of information from the virtual to the physical CMM model. As a result, it is impossible to update the data in the opposite direction, i.e. from physical to virtual twin. Given that inspection planning is a one-way process (unrepeatable once completed) this is considered acceptable, and therefore a two-way flow of information within the two basic components of DT is not necessary.

In order to realize DT, it is necessary to harmonize the output-input. The PC-DMIS software allows the import of a .ncl (DMIS) file, previously generated and tested in the PTC Creo software using the standard import → DMIS command block. Previously, a .ncl (DMIS) file was generated in *PTC Creo* to verify the inspection plan procedure on the virtual CMM. The machine in the functional sense completely coincides with the real measuring machine DEA-IOTA 2203, and on which the plan of inspection of the PW was performed.



a)



b)

Fig. 6 DIT based on CMM: a) PTC Creo measuring path simulation view; b) Display of the assembly of models and clamping accessories on the real CMM DEA-IOTA 2203 [15].

5. Conclusion

The paper presents an approach to the development of DT, whose role is increasingly important today within digital measuring systems. From the aspect of production metrology, the role of the DT is to monitor the measurement process, to improve the quality of processing, accuracy of dimensions and roughness of processed surfaces, and thus to reduce production costs in an efficient and dynamic way.

Research in this paper generates knowledge for the functioning of the process of inspection of measuring parts in modern flexible technological systems and environments, where the need for quality control is extremely important for the production and production metrology as a special scientific discipline.

The result of this paper is a new approach of the conceptual development of the digital inspection twin, based on CMMs - towards off-line DT based on CMM by virtue of the .ncl (DMIS) file. The measurement system based on CMM DEA-IOTA-2203 was used as a physical twin, and a virtual machine, generated after modeling and configuring in *PTC Creo* software of both the machine itself and the prismatic parts and fixture clamps, was employed as a digital twin. The paper also includes the verification of measurements on a virtual measuring machine and a physical measuring machine with a defined information exchange protocol. The novelty of the research is application into today's trend of industry 4.0 of its production and production metrology. Also, the novelty of the work is that in an efficient, dynamic and automatic way it integrates the entire production into one compact whole and thus solves the problem of production costs with maximum efficiency.

Besides the to-date developed off-line DT, future research will also include DT development with bi-directional data flow between physical and virtual CMMs. One of the future development directions will be extension of this concept to CMMs of various manufacturers (software). Also, on the basis of proposed methodology, the directions of future research would embrace extension to non-prismatic machine parts and development of digital thread for measurements on a CMM.

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