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Contribution to the development of a digital twin based on CMM to support the inspection process

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ABSTRACT

Digital twin (DT) based on CMMs acting as a mirror between the physical and virtual measuring system and process. The inspection planning process performed on the virtual components of DT, and execution of measurement on the physical components. In this paper the measurement system with the DEA-IOTA-2203 was used as a physical twin, and a virtual machine, generated after modeling and configuring in PTC Creo software. Also, a simulation process was performed in order to check the collision and generate a measuring path for one example prismatic part. The information flow is unidirectional and flowing from the virtual to the physical inspection system based on CMM. In this way, a data format or a list of instructions for the physical machine and its movements per axes is provided. Virtual measurement system is developed for inspection of the standard types of tolerances and family of prismatic mechanical parts. The result of this paper is a new contribution to the development of the digital twin for CMM based on unidirectional information flow by.ncl (DMIS) file. The application of the results of DT development is especially pronounced when planning the inspection of prismatic parts with a large number of tolerances in industrial conditions.

1. Introduction

Beginning of the 21st century, production engineering became a type of symbiosis of computer and machine technology and the basis for the development of modern CNC machines. This type of symbiosis didn't bypass a very important field of mechanical engineering, a scientific field known as production metrology. The trend of technology integration, development and design of such systems, in this field is spreading in the area of their application, especially on coordinate measuring machines (CMMs). Advances in information and communication technologies have greatly improved the development of manufacturing. Computer-aided technologies are rapidly evolving in the industry, including the development others CAx, FEA and PDM systems. Large amounts of data, internet data, artificial intelligence, fifth generation (5G) cellular network, wireless sensor networks are developing rapidly and show great potential in all aspects of the industrial field. All these technologies provide opportunities for the integration of the physical world into the digital world and vice versa, while setting a high trend in terms of complexity, which also affects the high demands of the market. However, the advantage of this integration has not been strategically exploited to the full. The process of that integration is very long and the latest achievements in that integration will be focused on digital twins [1]. The digital twin consists of a virtual display of a production system that is able to work in different simulation disciplines, which are typical for the synchronization between virtual and physical system thanks to data read from sensors and connected to smart devices, mathematical models and real-time data processing. The main role of production systems in Industry 4.0 as a new paradigm is to use all the above characteristics to predict and optimize the behavior of the production system at each stage of the cycle in real time [2].

The novelty of the paper is today's trend of Industry 4.0, its production and production metrology, based on the development of the DT model and its further research. Also, the novelty of the work is that in an efficient, dynamic and intelligent way it integrates the entire production into one compact whole and thus solves the problem of production costs with maximum efficiency.

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

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prismatic parts and fixture clamps, was employed as a digital twin.

The measured piece and the development model of the simulation on a virtual measuring machine are described in the software PTC Creo. PTC Creo is a three-dimensional computer program for computer design or technical construction. The program is widely used in production engineering, especially for manufacturing and CMM inspection.

Another software used in this paper is the PC-DMIS. Within this program, an on-line and off-line inspection planning procedure was performed on a real measuring machine DEA-IOTA 2203 supported by a DEA computer unit and the PC-DMIS software package. Digitally simulates measurement in a virtual work environment. PC-DMIS is available as an upgrade package for most other CMM manufacturers [3].

The basis for the development of this approach is the intelligent system [4] and the applied artificial intelligence techniques presented in Refs. [5,6].

1.1. Literature review

The term Digital Twin was brought to the general public for the first time in NASA's integrated technology roadmap under the technology area 11: Modeling, Simulation, Information Technology & Processing (NASA Technology Roadmap, 2010 and 2012) [7].

Faster reply of optimization algorithms, increased computer power and amount of available data, can leverage the area of simulation towards real-time control and optimization of products and production systems. This concept – often referred to as Digital Twin – enables real-time geometry assurance and allows moving from mass production to more individualized production [8].

Geometric variation is a problem in all complex, assembled products. Recently the digital twin concept is a tool for the improving geometrical quality and reduces costs by using real time control and optimization of products and production systems. The digital twin concept is depending on high quality input data [9]. One of the problems in creating digital twins is the need for integration and joint processing of a large amount of heterogeneous information [10].

A recent Gartner survey reveals that 75% of organizations implementing Internet of Things (IoT) already use digital twins or plan to within a year. By 2022, over two-thirds of these companies are anticipated to have deployed at least one digital twin in production [11].

Conformity quality planning and management, as an essential part of the Computer Integrated Quality (CIQ) model, is based on different classes of metrological processes. Metrological processes in classical technological systems are performed according to the requirements of the discrete production process, while in the new generations of these systems such as digital measuring systems based on DT this process is performed as a continuous model of measurement [12].

In order to realize the project vision of smart Assembly 4.0, the paper [8] specifies and highlights the infrastructure, components and data flows necessary in the Digital Twin.

A chapter of the book [13] focuses on the simulation aspects of the Digital twin, in this sense simulation merges the physical and virtual world in all lifecycle phases.

The paper [12] gives a review of digital twin applications in manufacturing where special focus is on the degree of integration of the proposed DT with the Manufacturing Execution Systems (MES) and practical implementation of a DT in a MES equipped assembly laboratory line.

> "Digital twin, a new emerging and fast growing technology which connects the physical and virtual world, has attracted much attention worldwide recently" [14].

The paper [15] presents a virtual replica to work parallel to an integrated inspection system (IIS) for inspection of freeform and complex surfaces based on a metric of their geometric complexity.

Manufacturers have to accept small-scale orders due to the limited profit margins and huge costs caused by the vacancy of production lines [16]. For this reason, it is necessary to develop a DIT that would enable the monitoring of an extremely diversified measurement needs.

The paper [1] analyzed the status of digital twin research and reviewed the digital twin from the perspective of concepts, key technologies, and industrial applications. From the viewpoint of manufacturing, these authors point out that the role of digital twin is essentially to improve processing quality and reduce production cost in an efficient, dynamic, and intelligent manner, which is not available in the traditional method, as well as that the problems of data integration and complex phenomena modeling remain to be solved in future works.

From a simulation point of view, the Digital Twin approach is the next wave in modeling, simulation and optimization technology [7].

According to Ref. [11], many ways have been proposed to differentiate the digital twin from more traditional notions of modeling and simulation, such as real-time visualization as a key innovation with digital twins, while other research has focused on the digital twin as a virtual duplicate of a physical system.

The paper [17] specifies and highlights functionality and data models necessary for real-time geometry assurance.

Generation of inspection data as support to digital twin for geometry assurance, as well as an inspection strategy serving the Digital twin is given in Ref. [9].

As can be seen from literature review, DIT belongs to the field of measurement in production and its development is crucial for this field and its future development in era digitalization technologies. The basis for the development of this approach is the intelligent system [4] and the applied artificial intelligence techniques presented in Refs. [5,6].

The result of this paper is a new approach of the conceptual development of the digital inspection twin, based on CMMs - towards off-line DIT based on CMM by virtue of the.ncl (DMIS) file.

2. Outline of the concept

This method starts from modeling of the prismatic workpiece (PW) with predefined tolerances, modeling of the CMM DEA-IOTA-2203 components, fixture clamps, as well as probe design in CAD system. By setting the coordinate systems and selecting the corresponding kinematic links of the machine CAD components, virtual CMM was configured in a software system PTC Creo.

Presented approach for development of DT in this paper refers to already machined PW (post-processing measurements), that is to say, 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 work, ends by generating.ncl (DMIS) code for DEA-IOTA-2203.

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.

3. Simulation models

3.1. PTC Creo inspection model

In order to perform the inspection planning process on the CMM, it is necessary to modeling the 3D CAD PW, machine and fixtures, as well as creates a measurement program for simulation on a virtual CMM in CAD environment. Modeling of the 3D PW, machine and fixtures was performed in the PTC Creo software (CMM module). By those CAD models, a virtual measuring system based on a real measuring machine DEA-IOTA-2203 – virtual twin is modeled and simulated.

Programming of the CMM implies a series of activities that need to be implemented, in order to obtain the control unit sequences based on will be measurement performed. For the measurement program, it is necessary to define in advance: (i) inspection features and position tolerances; (ii) position or clamping plan; (iii) configuration of measuring

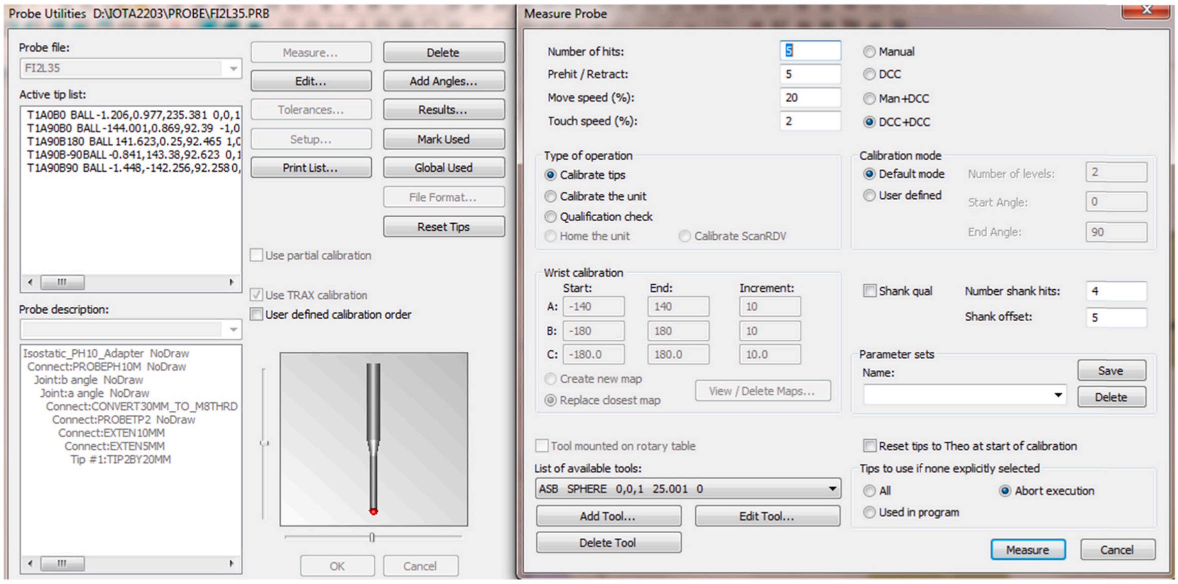

Fig. 1. Measure probe parameters settings.

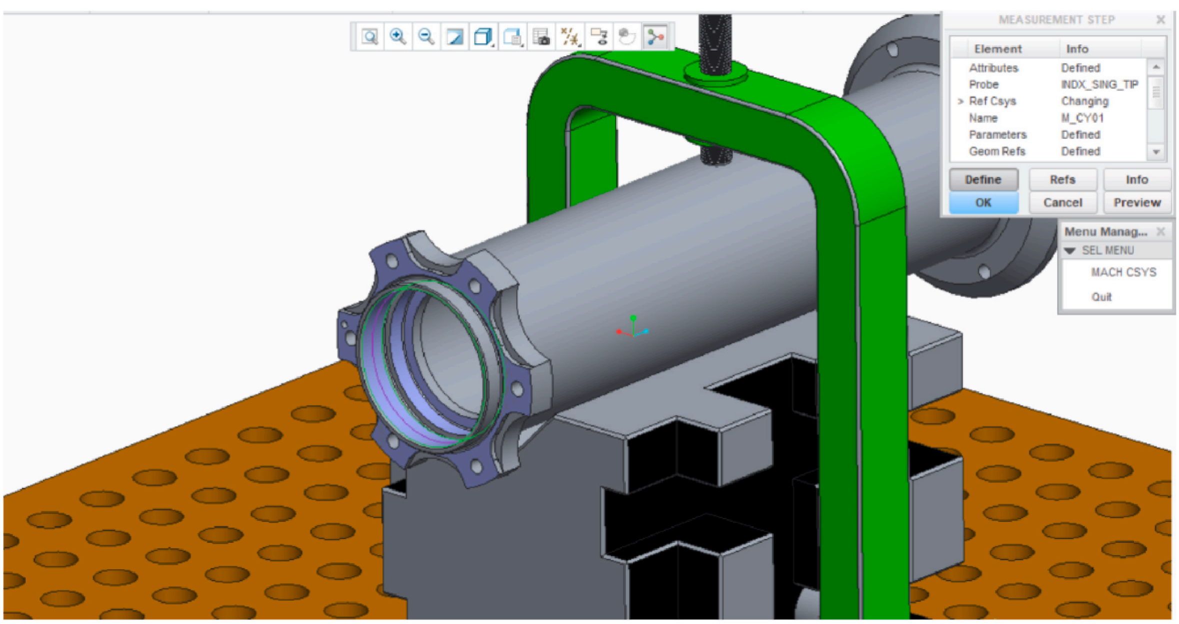

Fig. 2. Defining motion parameters per axis (speed and acceleration) for cylinder inspection.

probes and coordinate systems of alignment and measurement. The program uses the digital twin model data with a parallel simulation of the measurement inspection plan in the PTC Creo and PC-Dmis programs, which is generated as.ncl code. This code is exported as a DMIS file in the PC-Dmis software..

The CMM simulation steps in the PTC Creo are 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 postprocessing.

After the basic definition of the CMM process, the development and definition of the basic steps of the inspection plan in PTC Creo can begin. Next it is necessary to introduce the whole set of models and clamping fixtures as a whole. Then, with the assembly commands, the components are joined. In the *Inspect Tab* command palette, the *Reference Model* command is selected and the already made sample assembly and clamping fixtures are imported. It then performs an appropriate plane matching so that the whole assembly is accepted by the program as a fixed part. This is achieved in the command *Reference Model* under the command *Placement.*

Since the inspection plan was made in the PTC Creo program, next step is the inspection of the measuring machine in the PC-Dmis program. This means that corrections are required after the introduction of the *dmis* file in the form of changing the length of the probe to be inspected,

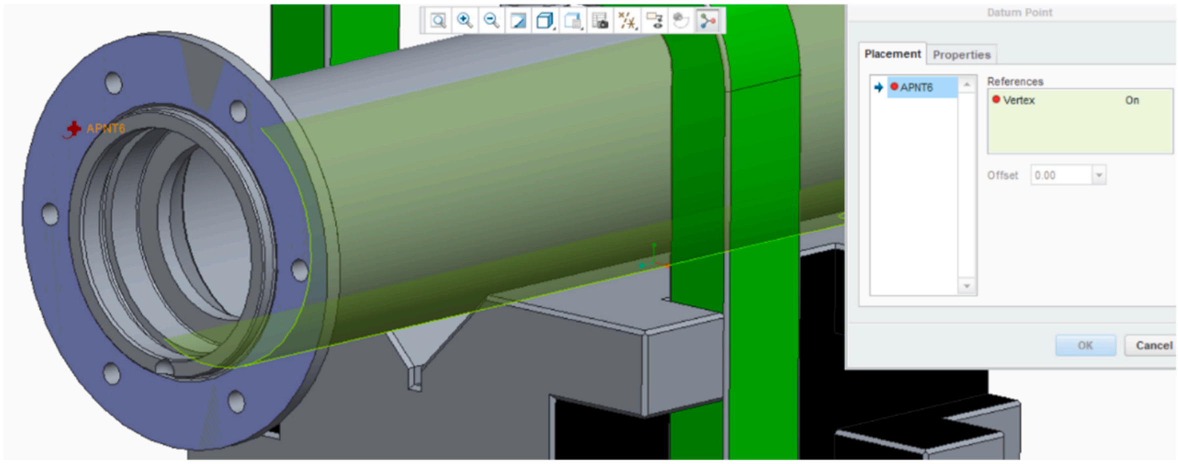

Fig. 3. Setting of APN points as the start and end points of the located measuring probe.

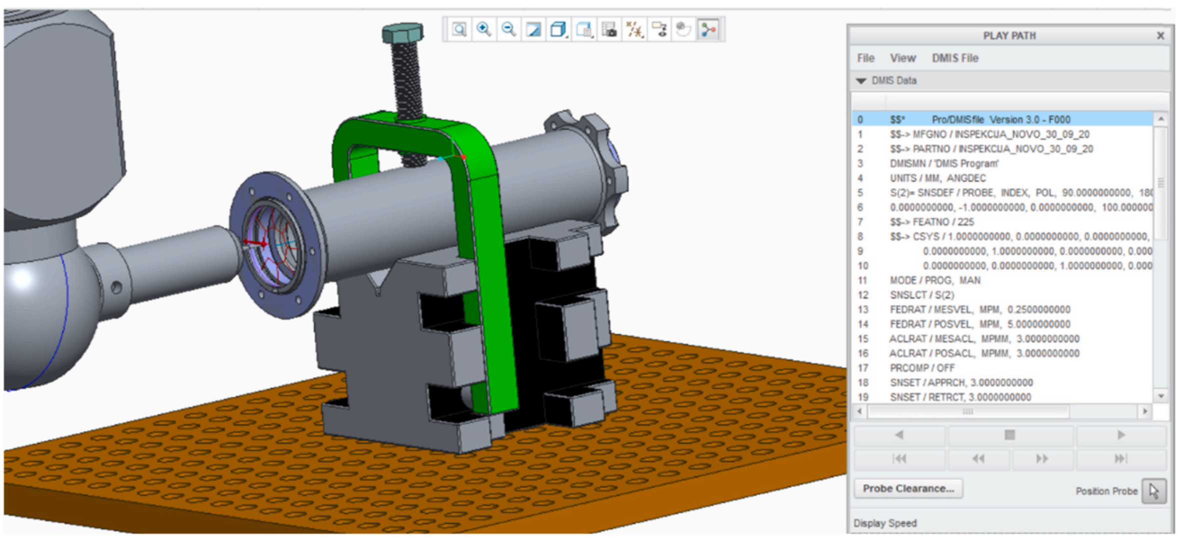

Fig. 4. A PTC Creo simulation view: defining the probe path with the DMIS code printed.

the overall dimensions of the machine along the X, Y and Z axes, as well as the positioning of the clamping fixture and the PW. *Probes open* command use for selecting and loading measuring heads. In the program palette, there is already measuring heads called *indx_sing_tip_modified.asm* (Fig. 1).

The command for selects the coordinate system is also very important for defining the initial coordinate system of the PW, for easier positioning or centering on the table of CMM. After activating some of these groups of the commands, it is necessary to adjust the speeds and accelerations (Fig. 2) of the measuring and auxiliary (safe) movements, the distances of approach and departure during the measuring and auxiliary movements. Using the *Ptc* and *Path* option defines the number and layout of control points. The simulations are performed, among other things, to protect the CMM from the unwanted position of the working elements and to avoid additional unnecessary costs. In order to avoid collisions, it is necessary to connect the measuring steps with the help of (Auxiliary) auxiliary movement (Fig. 3).

For the end, all that remains is to generate a *dmis* file. After generation, the.ncl file required to generate the path (Fig. 4) in the on-line mode for the PC-DMIS program is obtained.

3.2. *PC-DMIS inspection model*

After the created model and its inspection plan in the PTC Creo program, it is necessary to perform the verification of measurements on a real CMM. This is achieved in online mode after the generated.ncl (Dmis) file.

3.2.1. *Probe calibration and PW leveling*

In order to perform the calibration of the selected probe, it is necessary to use *Measure* option for shows the speed of approaching the calibration and the diameter of the beam used for calibration. Modeled CMM performs measurements in 3 dimensions X, Y and Z, thus centering is performed in 3 steps and it is strictly important that they are performed in the given order: (i) leveling, (ii) rotation around the three axes, and (iii) laying the foundation.

Part leveling is the measurement of a plane on a part to obtain a unit vector that will define whether that plane is parallel or vertical to the axes of the machine. Centering in the software PC-Dmis is achieved by the command *Alignment* in the drop-down menu *Insert*.

3.2.2. *Measurement protocol*

The main difference between the PC-Dmis program and the inspection in the PTC Creo is the measurement protocol record, more precisely

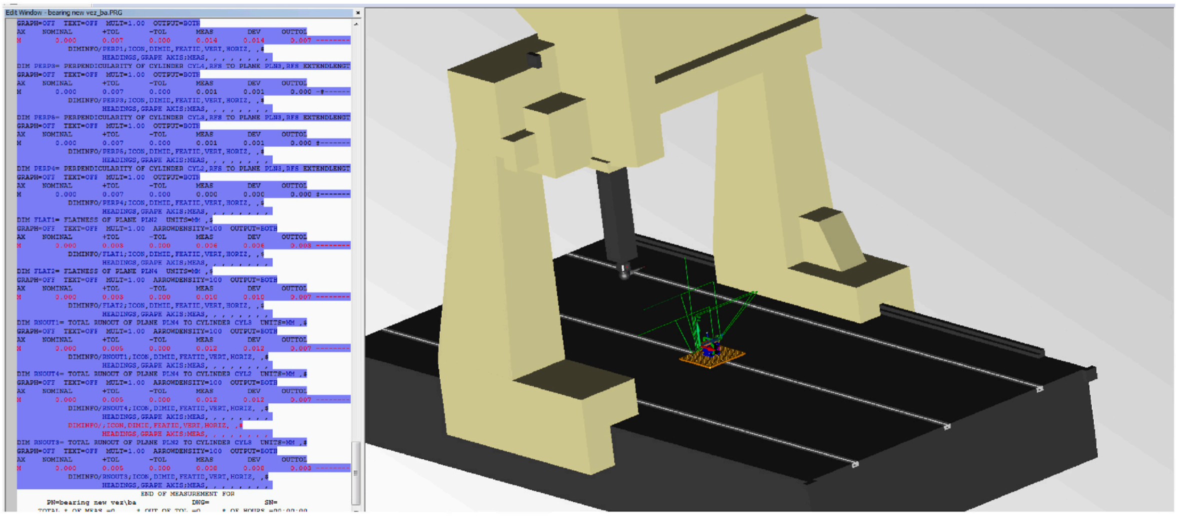

Fig. 5. PC-DMIS simulation view.

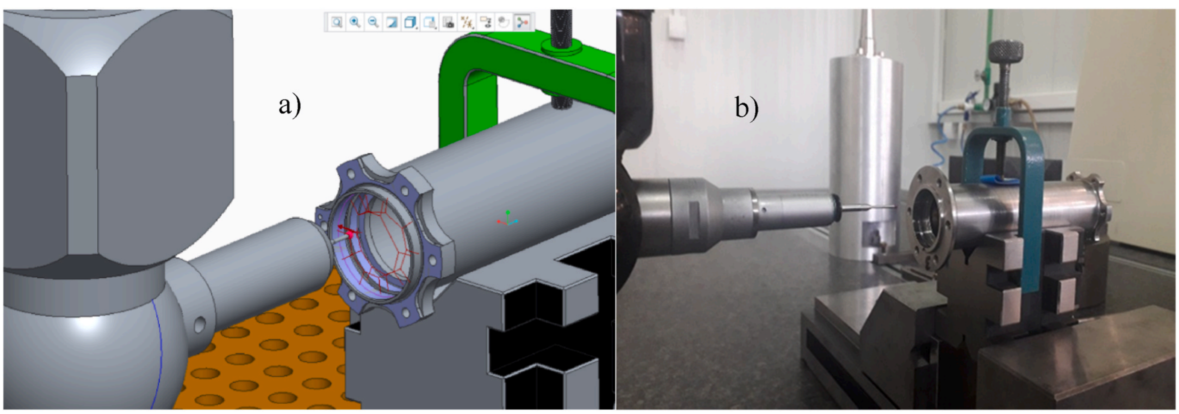

Fig. 6. DIT based on CMMs: a) PTC Creo measuring path simulation view; b) Display of the assembly of models and clamping accessories on the real CMM DEA-IOTA 2203.

the *Edit window*. In the same window, you can write the original measurement protocol from the program PC-DMIS, as well as the import of already created and generated.ncl code from the program PTC Creo. Each geometric feature that is examined (measured) in the program PC-DMIS is written as an abbreviated word. If it is a plane, circle, cylinder or some other geometric shapes, each of them will be written in the *Edit window* as PLN, CIR, CYL, LIN, etc.

Since the measurement protocol was made in the PTC Creo program and already exists it was used for further verification of the inspection on a real measuring machine by importing a file into the program itself.

3.2.3. Measurement compliance between PC-DMIS and PTC Creo

In purpose to realize the DT, it is necessary to harmonize the two programs. PC-DMIS allows the import of a.ncl (dmis) file previously generated and tested in the PTC Creo software using the import → dmis command block, in the file drop-down menu. The aim of the modeling and simulation in PTC Creo is to obtain the.ncl (dmis) file in order to verify the procedure of the inspection plan on the virtual CMM.

Fig. 5 shows the import of a virtual measuring machine into the PC-DMIS software. The machine shown in Fig. 5 coincides with the real measuring machine DEA-IOTA 2203 on which the inspection plan of the PW model was performed. In Figs. 5 and 6a it can be seen the difference between the original code in the PC-Dmis program and the code used for the measurement, obtained by virtual measurement in the PTC Creo program.

4. Proposed digital twin

A DT also encompasses the flow of data between physical and digital twin in one direction. From the standpoint manufacturing data the inspection process is specific because that consists from post-process and in - process inspection [18]. Therefore according [18], "the measurement data report for post-process inspection is a final-output document and no further return (bi-directional flow of information) to the manufacturing is required".

4.1. Physical twin and virtual twin

As physical twin it used CMMs DEA-IOTA-2203. As the data formats its use DMIS file. A measuring path was programmed, a virtual inspection systems based on a virtual CMM IOTA-2203 as virtual twin.

Matching the coordinate system of PW and coordinate system on working table enables the setting of the PW on the configured virtual twin based on CMM during the measuring simulation. Also, during the path simulation on virtual CMM, Fig. 6a, besides PW and probe that moves through measuring path, it is possible to create and load fixture that is of importance in verification of measuring path and detection of the possible collisions [18].

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

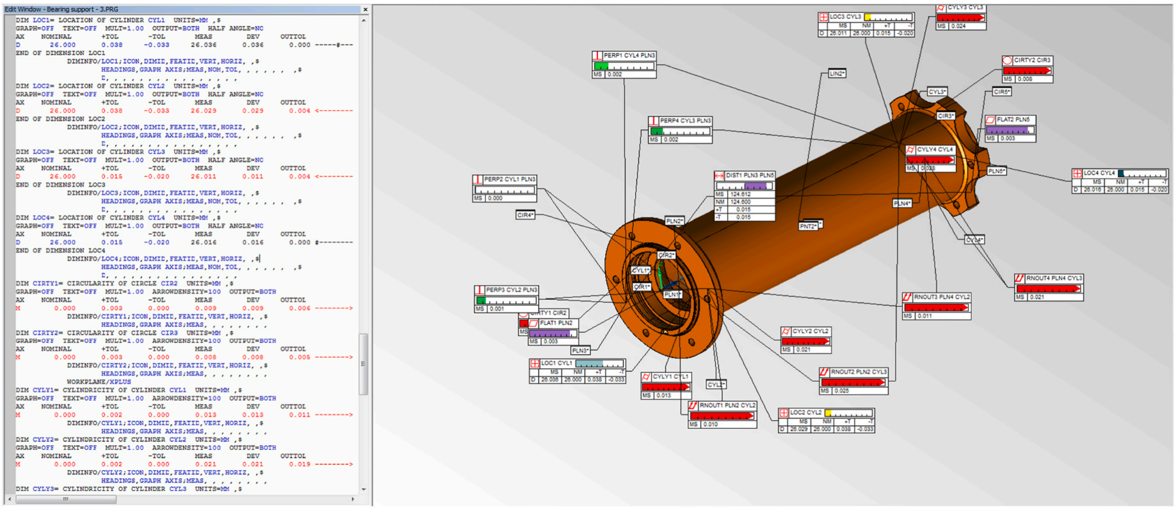

Fig. 7. Graphical display of the measured values on the model in PC-DMIS software.

→ dmis command block. Previously, a.ncl (dmis) file was generated in PTC Creo to verify the inspection plan procedure on the virtual CMM. Fig. 5 shows an illustration of an imported virtual measuring machine in the PC-DMIS program. 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.

The final representation of the developed DIT is shown in Fig. 6. Communication between physical (Fig. 6b) and digital twin (Fig. 6a) and is done with unidirectional data flow via a CDL and.ncl (dmis) file.

4.2. Results of measurement

The subject of this chapter is the verification of the created program on CMM DEA – IOTA 2203. The real measurement was done on the measuring machine DEA IOTA-2203, which uses PC-DMIS as software. The machine can operate in two modes, manual and automatic mode. It has a portal structure with spherical calibration accessories. It is connected to a computer for on-line programming mode. The measuring head is made by Renishow, connected to the postprocessor of the same manufacturer because of the measuring head itself, which contains a sensor for reading measuring points on geometric features when testing a sample. The working space of the machine is XYZ = 1320 x 970 × 970 mm. The temperature in the working room is 18–22 °C.

After the measurement, the graphical measurement report is generated as Fig. 7, which unambiguously gives an insight into the true condition of the measured part for pre-set tolerances. Based on its analysis, the operator together with the constructor makes a decision on whether the measured part is completely correct or whether it needs to be finished.

In Fig. 7, the symbols represent the tolerances that were previously defined by the requirement as the required values. There are: location of circles, direction, straightness and total throw. Also Fig. 7, entitled: NOMINAL - presents the nominal (theoretical) value; + TOL/−TOL - preents the values of the tolerance; MEAS - field shows the actual measured value; DEV - field represents the difference between the measured value and its nominal value.

5. Conclusions

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, dynamic and intelligent 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. In other words, this paper presents the tendency of digital twin CMM programming as a realistic application. Also, this approach of the development DT presents indirect programming method or off-line DT with one-direction of data flow.

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 real measuring machine with a defined information exchange protocol. The novelty of the work is 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 intelligent 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 other manufacturers, and thereby harmonization of STEP-NC in the application for programming 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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