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DIGITAL MEASURING SYSTEMS IN SMART MANUFACTURING CONTEXT

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Abstract: *Smart manufacturing represents a new concept which creates new requirements in manufacturing and manufacturing metrology area such as flexibility, mass customization, quality of product, digital twin, optimization, internet of things, big data etc. all of them towards real time control and monitoring all manufacturing processes including and metrological processes. Smart manufacturing an extremely expressed requirement for better control, monitoring and data mining. This paper presents new approach of development smart manufacturing – smart metrology concept on the example an digital measuring system (DMS) based on coordinate measuring machine (CMM) and digital measuring twin (DMT). The framework DMS, are based on integration of digital product metrology information through metrological identification, application artificial intelligence techniques and generation of inspection protocol for CMM. The system is based on the application of three AI techniques such as engineering ontology, genetics algorithm and ants colony optimization. The developed system consists of: the ontological knowledge base; the mathematical model for generating strategy of initial measuring path; the model of analysis and optimization of workpiece setups and probe configuration; the path simulation model in MatLab, PTC Creo and PC-DMIS software as well, the model of optimization measuring path by applying ants colony optimization. After simulation of the measurement path and visual checks of collisions, the path sequences are generated in the control data list and measuring protocol for appropriate CMM. The advantage of the DMS is its suitability for monitoring and digitalization of the measurement process planning, simulation carried out and measurement verification based on CMM, reduction of the overall measurement time and minimizing human involvement or human errors through intelligent planning, which directly influences increased production efficiency, competitiveness, and productivity of enterprises. The simulation enables DMT and monitoring the measuring operation of a real CMM based on a virtual one.*

Key words: *Digital system, Measuring system, Smart manufacturing, Digital Twin, CMM.*

1. INTRODUCTION

In today's rapidly changing world, globalization, products customized to customer requirements and automation play a decisive role in the development of the industry, especially mechanical engineering. Introducing advanced technologies and techniques that will change products, processes and supply chains this industry is at the top of Industry 4.0. This industry also enables even greater connectivity through IC technologies, enabling producers to maintain their competitive benefit and respond flexibly and quickly to customer requirements [1].

Industry 4.0 in manufacturing plays a key role in three areas [2, 3]: (a) smart supply chains – greater coordination and flow of information in real time, enabling better tracking of goods and raw materials in an integrated business planning model and production. This provides new models for coordination and collaboration between supply chains; (b) smart manufacturing – the use of data analytics and new manufacturing techniques and technologies (such as autonomous robots, multi-purpose production lines and augmented reality) helps to improve quality and accelerate production. This enables new business models such as mass customization, and (c) smart products – rapid innovation and faster delivery times to the market are made possible by data acquisition about the product, along with user feedback, collected through social networks on the Internet. This data also enables remote diagnostics and predictive maintenance.
Industry 4.0 is an intensive digital transformation of producing and other industries in a connected environment of data, people, processes, services, systems and the Internet of Things (IoT) – industrial resources assets with the generation, use and reuse of information that can be applied as a way and means to accomplish smart industries and ecosystems, based on industrial innovation and collaboration.

Industry 4.0, as a German strategic initiative, aims to create intelligent (smart) factories where manufacturing technologies are upgraded and transformed into SFS, IoT and cloud computing [4–6]. Such factories, in addition to the key roles mentioned above consist of components such as smart production, smart metrology and smart machine tools.

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Generating of detail model from the quality measurements process in manufacturing requires the development of dedicated framework, like to the example cyber physical manufacturing metrology model (CP3M). Based on testing model of CP3M, we have encountered the generation of a number of huge data sets that required processing, finding of correlations between data and extraction of useful information to be shared between CP3M modules [7].

The contribution of this paper refers to development digital measuring systems in smart manufacturing context and application of AI techniques such as EO, ACO, and GA to optimize the measurement path, the number of measuring part setups, as well the configuration of the measuring probes.

2. DATA MODELING

The data for digital measuring systems in smart manufacturing context includes all data from the request for measurement i.e. tolerance until the generation of the measurement report for three type of inspection, preprocess, process and postprocess inspection. Smart manufacturing from metrological aspect in this paper is presented with digital measuring twin. Smart metrology and digital measuring systems take part in that mediation chain. Figure 1 shows the hierarchy of constituent components or terms.

The emphasis is on the data needed to plan the measurement process on the CMM. Namely, it is generally known that the CMM measurement process consists of planning, preparation and execution of measurement processes. The measurement preparation process also includes the measurement programming process. Since it requires knowledge of different CMM software due to different CMM manufacturers, it will be discussed using an example of DMIS code. Figure 1 shows data flow inside of the presented digital measuring twin.

2.1. Engineering ontology

In order to develop one DMS it is necessary to create the necessary set of data. Since this is a measurement of one class of mechanical parts, which are prismatic, the primary data set is the geometry of these parts. Engineering ontology (EO) is used to modeling this type of data. As one of the techniques of artificial intelligence, it goes far beyond the framework needed to model geometry data, so it is also used to classify and reuse knowledge in one area. All three possibilities of application (modeling, classification and reuse) are used for the domain of coordinate metrology, i.e. virtual measurement on CMM.

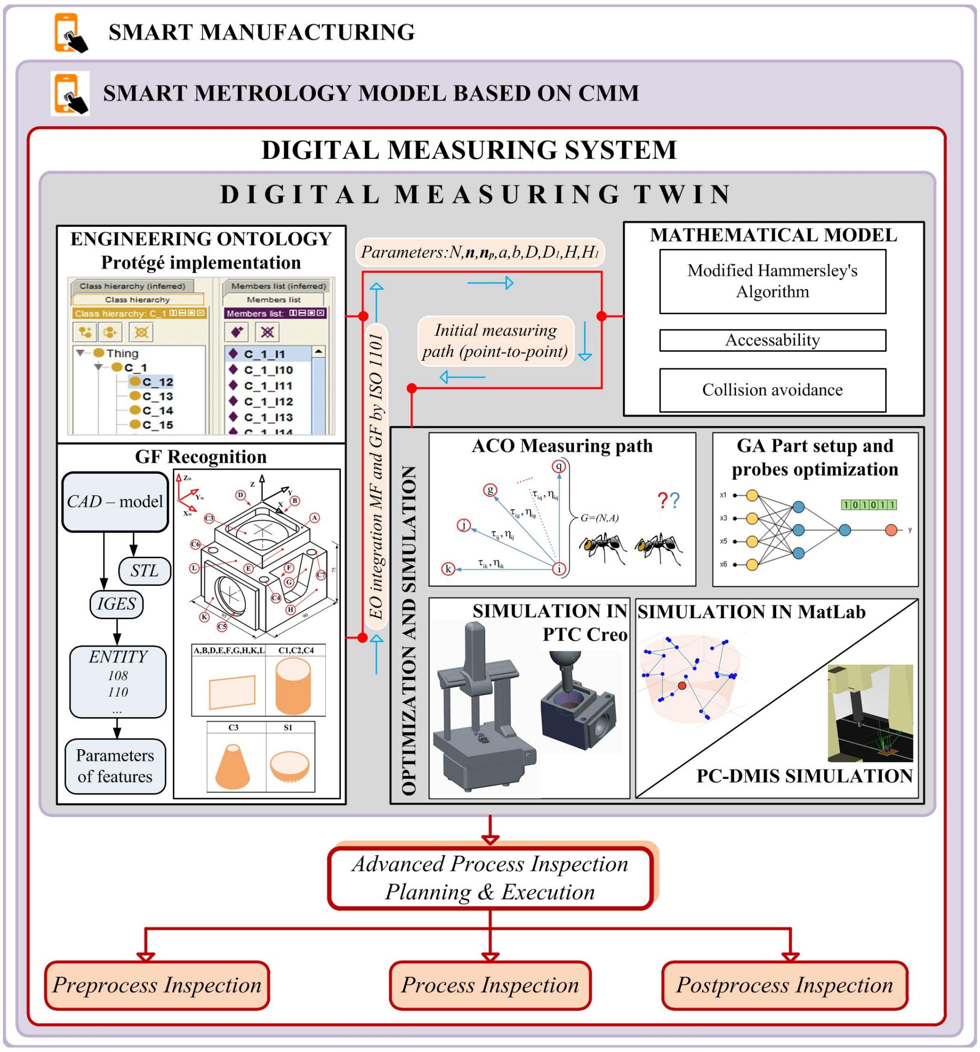

Fig. 1. Data flow inside of the digital measurement system.

According [8] the term ontology is known in philosophy where is "defined as a branch of metaphysics that studies the nature of being" [9], or of the "species kinds of things that exist" [10]. In engineering this term have a different meaning and is primarily designed for knowledge representation some area for example manufacturing metrology. Research in artificial intelligence and knowledge representation, the term ontology is link for the possibility of reuse knowledge and of sharing knowledge a field, pointing that is the main purpose of EO the transfer and exchange of knowledge [8]. On the other hand, one number of the authors the ontology connects to the knowledge base, arguing that it is the basic logical structure around which will build a knowledge base [9]. However, one thing is certainly, "the ontology has found its place in areas where is the semantics of the base of communication between people and systems" [11].

The proposed ontological development in engineering can be categorized according for what is intended. According to [12] have three purposes: a high level of specification of knowledge domains, system interoperability, and exchange of knowledge as well as its reuse of knowledge. The developed ontology is implemented in Protégé software. Software is a free, open source ontology editor and knowledge – based framework, based on Java. At its core, Protégé implements a set of knowledge – modeling structures and actions that support the creation, visualization, and manipulation of ontology in various representations formats [13]. The OWL editor that supports the Web Ontology Language is used, as most recent development in standard ontology language. OWL ontology includes description of classes, properties and instances.

The implementation of metrology primitives according [14, 15] in Protégé includes modeling:

- classes,
- of class hierarchy,
- of the individual,
- properties of classes and individuals.

According [16] classes are represented metrological features, which are organized in a hierarchy and individuals are represented in Protégé as a specific class. The notation for the classes is K_i, where i = 1, 2, 3,…, 9 and denotes the ordinal number of features such as point, line, cylinder, etc. The notation for subclasses is K_ij, where j = 1, 2, 3,…, 9 and indicates the ordinal number of the subclass. Finally, the notation for an individual is K_ij_Ik, where k = 1, 2, 3,… and denotes the ordinal number of the individual that makes up the subscript within a given class. As can be seen the place of the subclass to the class, as well as the individual subclass is described by the underscore (_). For example, K_5 class consists of subclasses K_53, K_54, K_55, K_57, K_58 K_59 and as a result of the fact that individuals plane (K_5j_Ik) take part in the description of other classes such as K_3, K_4, K_5, K_7, K_8 and xK_9.

The advantage of defined class hierarchy, for the case to describing the geometry which consists of basic metrology features, is that the methodology same for all PW [16].

2.2. Mathematical model

The indirect role of the mathematical model is to eliminate the collision between the measuring sensor (star probe configuration and head) and the measuring part. In other words, its role is to define a collision-free point-to-point path. Its primary role is to establish links between coordinate systems and generate an initial (point-to-point) measurement path that will be later optimized in purpose to shorten length of path and traveling time of the measurement probe [17–19]. According to Fig. 2,*a*), basic equation of the model is:

$$^{M}\mathbf{r}_{P_i} = {}^{M}\mathbf{r}_{W} + {}^{W}\mathbf{r}_{F} + {}^{F}\mathbf{r}_{P_i} = {}^{M}\mathbf{r}_{F} + {}^{F}\mathbf{r}_{P_i}$$

According to [18, 19] generating point-to-point measurement path defines distribution of two sets of points: (i) set of measuring points and (ii) set of nodes points.

Distribution of measuring points for different geometric features such as plane, circle, hemisphere, cylinder, etc. is obtained by modifying Hamersley [20] sequences. An example of formulas for calculation of measuring points coordinates $P_i(s_i, t_i, w_i)$ in *Cartesian* coordinate system for a plane according [18, 19] is given as follows:

$$s_i = \frac{i}{N}\cdot a$$

$$t_i = \left(\sum_{j=0}^{k-1}\left(\left[\frac{i}{2^j}\right]\mathrm{Mod}2\right)\cdot 2^{-(j+1)}\right)\cdot b$$

$$w_i = 0$$

where is: $a[\mathrm{mm}]$ – x-axis constraint value; $b[\mathrm{mm}]$ – y-axis constraint value.

According to [18, 19] and Fig. 2,*b*) set of node points implies two sets $P_{i1}(s_{i1}, t_{i1}, w_{i1})$ and $P_{i2}(s_{i2}, t_{i2}, w_{i2})$, where is $i = 0,1,2,...,(N-1)$ and N – number of measuring points. Sub-set $P_{i1}(x_{i1}, y_{i1}, z_{i1})$ presents points for the transition from fast to slow feed. The distance between points $P_{i1}(x_{i1}, y_{i1}, z_{i1})$ and $P_i(x_i, y_i, z_i)$ is presented (Fig. 2,*b* and 2,*d*) by d_1 – slow feed probe path, and the distance between points $P_{i2}(x_{i2}, y_{i2}, z_{i2})$ and $P_{i1}(x_{i1}, y_{i1}, z_{i1})$ is d_2 – rapid feed probe path.

According to [18, 19], coordinates of the nodal points $P_{i1}(x_{i1}, y_{i1}, z_{i1})$ and $P_{i2}(x_{i2}, y_{i2}, z_{i2})$ are defined from:

$$x_{i1} = x_{P_iP_{i1}} + x_i,\ y_{i1} = y_{P_iP_{i1}} + y_i,\ z_{i1} = z_{P_iP_{i1}} + z_i,$$

$$x_{i2} = x_{P_iP_{i2}} + x_i,\ y_{i2} = y_{P_iP_{i2}} + y_i,\ z_{i2} = z_{P_iP_{i2}} + z_i.$$

where coordinates $x_i = s$, $y_i = t$, $z_i = w_i$ are actually coordinates of the measuring point $P_{i1}(s_{i1}, t_{i1}, w_{i1})$, while other unknown coordinates are determined from the expression:

$$\overrightarrow{P_iP_{i1}} = \overrightarrow{n_{pi}}\cdot d_1 = x_{P_iP_{i1}}\vec{i} + y_{P_iP_{i1}}\vec{j} + z_{P_iP_{i1}}\vec{k},$$

$$\overrightarrow{P_iP_{i2}} = \overrightarrow{n_{pi}}\cdot(d_2 + d_1) = x_{P_iP_{i2}}\vec{i} + y_{P_iP_{i2}}\vec{j} + z_{P_iP_{i2}}\vec{k}$$

where $\overrightarrow{n_{pi}}$ is the vector of fullness of GF.

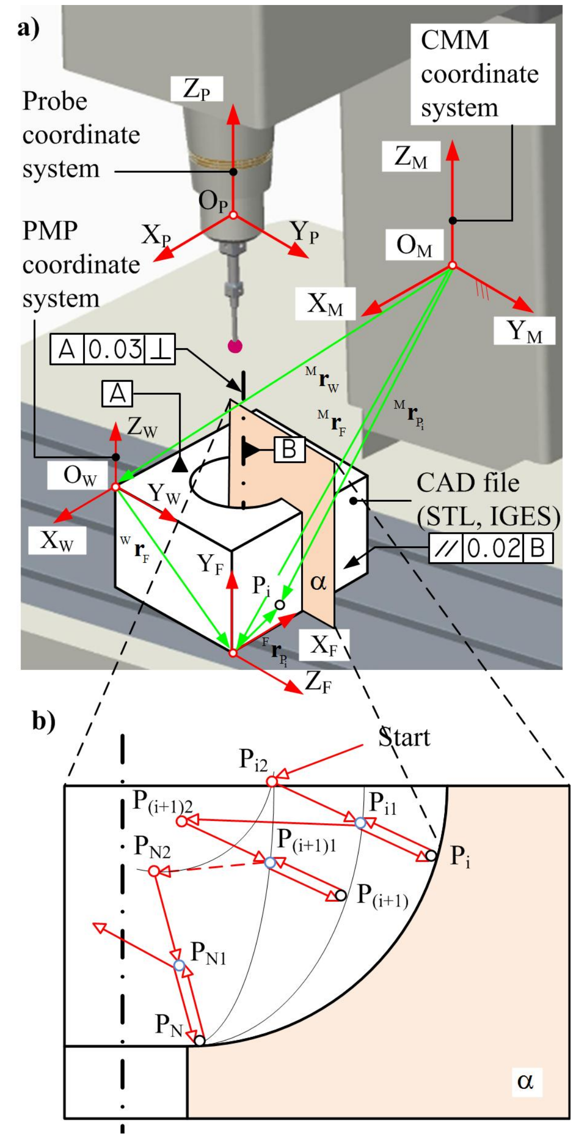

Fig. 2. Mathematical model: *a* – a PW and its tolerances; *b* – initial measuring path for truncated sphere [17].

Based on STL model for the presentation of WP geometry, the tolerances of WP, the coordinates of the last point $P_{(N_{F1})l}$ of a feature truncated hemisphere and the coordinates of the first point $P_{(N_{F2})1}$ of a feature plane, the simplified principle of collision avoidance between PW and probe at parallelism tolerance inspection is developed. The principle is iterative and consists of moving line p for distance δ until the line became collision free (line segment p).

Overall travelled path by a measuring probe in the inspection in N measuring points represents an initial measuring path of a measuring sensor and can be calculated as

$$D_{tot} = \sum_{i=0}^{N-1}\left(\left|\overrightarrow{P_{i2}P_{i1}}\right| + 2\cdot\left|\overrightarrow{P_{i1}P_{i}}\right| + \left|\overrightarrow{P_{i1}P_{(i+1)2}}\right|\right) +$$

$$+\sum_{i=1}^{P}\left(\left|\overrightarrow{P_{NF_1}P_{(NF_1)l}}\right| + \left|\overrightarrow{P_{(NF_1)l}P'''_{NF_1}}\right| + \left|\overrightarrow{P'''_{NF_1}P'''_{NF_2}}\right| + \left|\overrightarrow{P_{(NF_2)1}P_{NF_2}}\right|\right)$$

where is: P – number of obstacles (transitions from one feature to another), $\left|\overrightarrow{P_{i2}P_{i1}}\right|$ rapid feed rate and $2\cdot\left|\overrightarrow{P_{i1}P_{i}}\right|$ double travelled slow feed rate for the *i*-th point, and $\left|\overrightarrow{P_{i1}P_{(i+1)2}}\right|$ length of distance in probe's transition from previous *i*-th point to the next *(i+1)* nodal point.

2.3. Inspection features model

As is known, the generation of the measurement path on the CMM is achieved by direct contact with touch objects, i.e. inspection features (IFs). Thus, the measuring sensor touching the IF at certain points, as well as passing through the collision avoidance points during the inspection of one IF and moving from one to another IF generates a measuring path for a form of tolerance. An IF consists from one or more geometrical features. In order to plan the inspection of PWs, it is necessary to define a limited set of these IFs as well as their parameters that uniquely determine them (Table 1).

As we have said, each IFs is unambiguously determined by a set of parameters relative to the local coordinate system (O_F, X_F, Y_F, Z_F) and global to the measurement coordinate system of the measurement part (O_W, X_W, Y_W, Z_W).

The parameters can be of the following types: coordinates (X, Y, Z), diameter (D, D_1), height (H, H_1), width (a), length (b), feature vector (**n**), feature fullness vector (**n**$_p$). Example of the parameters for truncated hemisphere is shows on Fig. 3.

Vector **n** determines feature orientation across space. Feature position is determined by coordinates(X_0,Y_0, Z_0). Fullness vector and feature vector define approach direction of the measurement sensor probe, whereas $\mathbf{n}_G$ and $\mathbf{n}_L$, respectively, represent the global approach direction for the feature and the local approach direction for the measuring point.

Table 1

Parammeters of the IFs

No	IFs name	Parameters										
		Coordinates [mm]			Dimensions [mm]						Normal vector	Fullness vector
		X	**Y**	**Z**	**a**	**b**	**D**	**H**	**D₁**	**H₁**	**n**	**n**$_p$
1	Point P	X_P	Y_P	Z_P								
2	Plane α	$X_α$	$Y_α$	$Z_α$	**a**$_α$	**b**$_α$					**n**$_α$	
3	Circle C	X_C	Y_C	Z_C			**D**$_C$				**n**$_C$	**n**$_{pC}$
4	Cylinder	X_{CY}	Y_{CY}	Z_{CY}			**D**$_{CY}$	**H**$_{CY}$			**n**$_{CY}$	**n**$_{pCY}$
5	Truncated cone	X_{TC}	Y_{TC}	Z_{TC}			**D**$_{TC}$	**H**$_{TC}$	**D**$_{1TC}$	**H**$_{1TC}$	**n**$_{TC}$	**n**$_{pTC}$
6	Truncated hemisphere	X_{TH}	Y_{TH}	Z_{TH}			**D**$_{TH}$	**H**$_{TH}$	**D**$_{1TH}$	**H**$_{1TH}$	**n**$_{TH}$	**n**$_{pTH}$

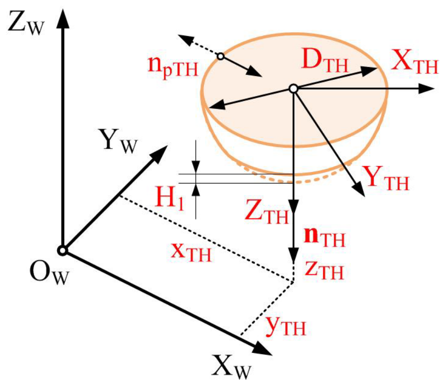

Fig. 3. Example of the parameters for truncated hemisphere: workpiece coordinate system (O_WX_W,Y_W,Z_W), feature coordinate system ($O_{TH}X_{TH},Y_{TH},Z_{TH}$), coordinates ($X_{TH},Y_{TH},Z_{TH}$), diameter ($D_{TH}$), high ($H_{1TH}$), normal vector (**n**$_{TH}$**)**, fullness vector (**n**$_p$).

Vectors **n** and **n**$_p$, as well as newly introduced vectors **n**$_G$ and **n**$_L$ define a feature from the viewpoint of PMP setup and probe configuration.

3. OPTIMIZATION METHODS

In the PW inspection planning process, three processes are dominant from the aspect of decision-making and optimization. The first is the process of generating the optimal path of the measuring sensor; the second is deciding on the placement of the part and third is configuration of the measuring sensor. All these three decision processes can be optimized by applying the appropriate artificial intelligence technique. For the measurement path, it turns out that the Ants Colony Optimization (ACO) method should be used, while genetic algorithms (GA) are used for setting the PW and configuring the measurement sensors. The selected methods of artificial intelligence are not binding for application (others can be used), however, they provide a number of facilities for application and good results at the output.

3.1. Measuring path

As stated, the ACO method is used to optimize the measurement path. The input data are potential paths generated in the form of point-to-point, i.e. the initial measurement path described in the 2.2 subchapter.

The application of ACO in a coordinate metrology is based on solution of travelling salesmen problem (TSP), where the set of cities corresponds to the set of points of a minimal measuring path length.

According to [21–23], "TSP can be represented by a complete weighted graph $G=(N,A)$ with N being the set of nodes representing the cities, and A being the set of arcs. Each arc $(i,j)\in A$ is assigned a parameter of length d_{ij} and weight parameters such as η_{ij}, τ_{ij}, with $i,j\in N$,,. "The goal in TSP is to find a minimum length of Hamiltonian circuit of the graph where a Hamiltonian circuit is a closed path visiting each of the $n=|N|$ nodes of G exactly once" [21, 22], so that an optimal solution to the TSP is a permutation π of the node indices {1, 2, …, n}.

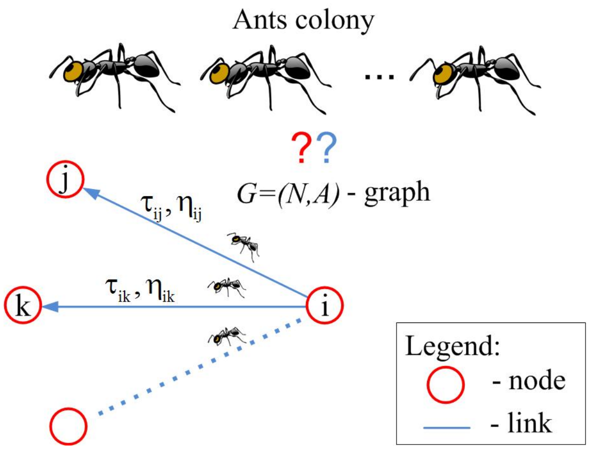

Fig. 4. ACO graph.

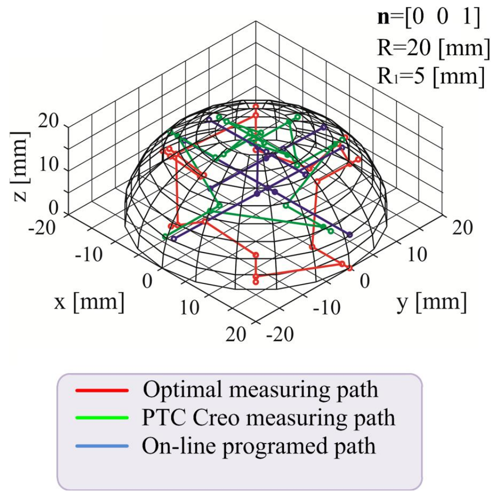

Fig. 5. Comparing of three type of measuring path for truncated hemisphere [19, 24].

In order to compare the optimal paths, two new paths are generated for the same feature types. The first path is generated on CMM by manual programming, and the second is automatically generated in Pro/ENGINEER software. Figure 5 shows a graphic representation of these three paths. The optimized path is given in red, the Pro/ENGINEER path in green and the manually programmed path in blue.

According to [17] comparison between the optimal path obtained by ACO and the PTC Creo programmed path shows improvement, i.e., reduction of the measuring path length per GFs minimum 10%. Also, the optimal path obtained by ACO is shorter per GFs minimum 20% compared with on-line programmed path, using the same parameter settings for both methods.

3.2. PW setup

The installation of PW is preceded by an analysis of the specified types of tolerances and part geometry, i.e. IF. Unlike PW processing, where the entire geometry of the part is analyzed because the surfaces are obtained by processing, when measuring on the CMM, only the geometry (IFs) that participate in the specified tolerances is analyzed. The rest of the geometry or volume of the part is important only from the aspect of avoiding collision between the measuring sensor PW as well as the analysis of the placement of the part.

Depending on the geometry of the part and the set tolerances, the number of axes of the CMM, etc. there may be more settings. In order to reach the optimal number of PW placements, the principle shown in Figure 6b) was defined. For a geometrically simplified PW, the placement possibilities are given. On the other hand, to take into account the number of CMM axes, Feature Approach Directions (FADs) and Boolean matrix S is defined according to [24]. The FADs (Fig. 6,*b*) define possible directions of access to the features.

In order to apply GA, it is necessary to define the Boolean matrices of setup S and configuration C. The elements of the matrix S links to the FADs and can be 0 or 1. For example, according to Figure 6c element of the matrix S (C,F#1) takes value 1 because to the cylinder C can be accessed from FAD#1. Similarly, the element of the matrix S (F,F#4) takes the value 0 because to the cylinder C cannot be accessed from the FAD # 4. The matrix S defines optimal setup direction F#6 (FAD#6) as it shown in Fig. 6,*c*).

3.3. Configuration of sensors

For the optimal number of placements of PW, determined in the previous subchapter, the optimal configuration of the measuring sensors is determined so that it enables the measurement of all forms of tolerances foreseen for that placement. The orientation of the primitive is the starting point for this analysis of the key parameter, which is the unit vector of the primitive. On the other hand, depending on the number of CMM axes, Probe Approach Directions (PADs) are defined according to [24].

According [24, 25] inspection on three-axis CMM can be performed from three orthogonal directions corresponding to the axes X, Y and Z or derived six directions (+X, -X, +Y, –Y, +Z and –Z).

From the standpoint probes it is introduced probe approach direction (PAD). PADs are shown in Fig. 6,*a*). They define the possible directions of access the probe and are oriented opposite to the FAD. Due to the setup of the measuring part at the working table of CMM, one of the PADs is lost, the maximum of the PADs can be 5.

Analogous to the filling of elements of the matrix S, the configuration matrix C is also filled to use PADs. It should be noted that the number of rows of both matrices is equal to the number of features which creating tolerances. In this case, it is two types of tolerance and three features. The matrix C defines optimal probe direction P#1 (PAD#1) as it shown in Fig. 6,*c*).

Optimal solutions for the case of measuring parts setup are obtained by GA model and are represented by zero-columns. Optimal solutions for the case of probe configuring (measuring heads) are also obtained by mentioned GA model, but represented by the unit-column.

4. CAD MODELING AND SIMULATION

Modeling and simulation, has an aim to visualization, verification of measurement path and collision, as well as generation of output files for further use and real measurements, primarily in the DMS in smart manufacturing concept. Additionally simulation in MatLab software aims to calculate different types of measurement paths and comparisons, as well as the input for parsing the data and creating a control list of data for the control unit of some of the CMMs.

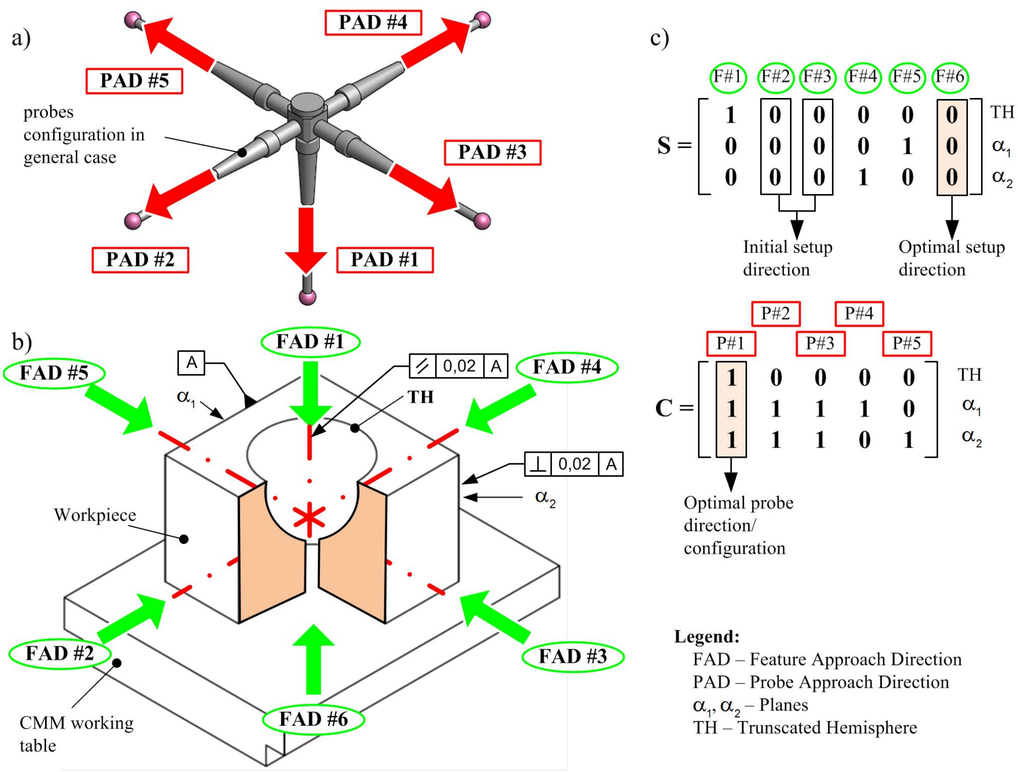

Fig. 6. Defining of PADs and FADs [26].

4.1. PTC Creo

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. According [27-29] the modeling and simulation procedure is as follows:

- modeling of the 3D PW;
- importing the modeled 3D PW into the CMM module (Manufacturing module);
- setting up the CMM processes.
- 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 auxiliary points. These points represent collision free points when moving from one feature to another.

As can be seen from the described simulation procedure, the creation of DMIS 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 (Fig. 7).

According [29] 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 [29].

4.2. MatLab

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 (Fig. 8). 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.

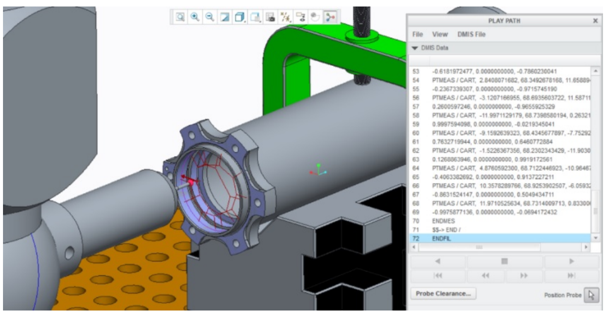

Fig. 7. Defining of measuring path for cylinder with generate DMIS code in PTC Creo [29].

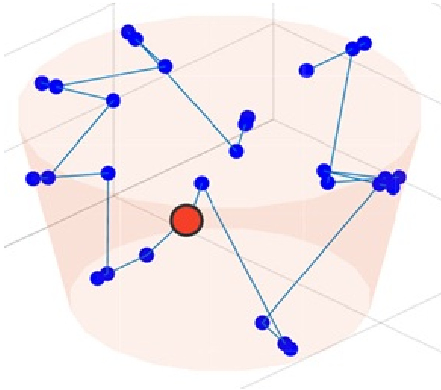

Fig. 8. A view of simulation in MatLab environment.

4.3. PC-DMIS

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 Fig. 9.

5. DIGITAL TWIN

As it is known DMT consists of physical twin and its digital replica virtual twin. In this paper, UMM 500 and IOTA 2203 machine was used as a physical twin, while the machines model created in PTC Creo software was used as a virtual twin.

The created DMT is shown in Fig. 10. Figure 10,*a* shows the virtual twin in PTC Creo software, while the real process is shown in Fig. 10,*b*. The developed DMT 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. Thus, 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 DMT is not necessary.

In order to realize DT, it is necessary to harmonize the output-input files. The machine in the functional sense completely coincides with the real measuring machine UMM 500 and IOTA 2203, as well as plan of inspection of the PW was performed.

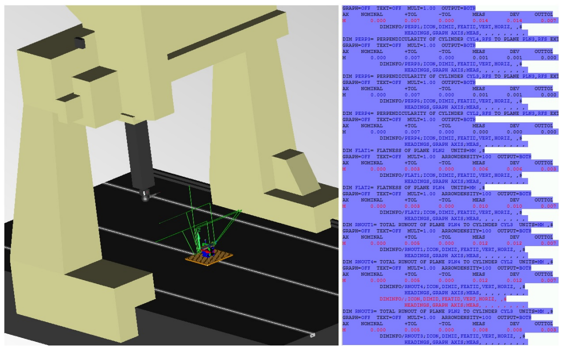

Fig. 9. PC-DMIS simulation view [29].

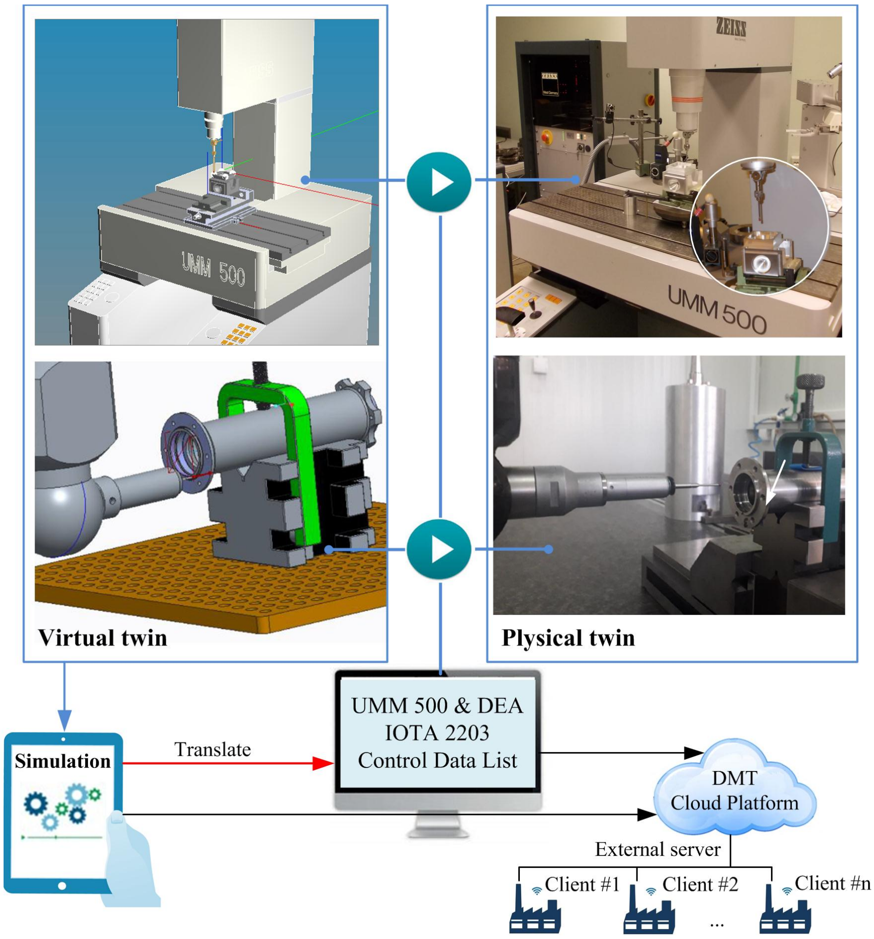

Fig. 10. DMT based on CMMs.

6. CONCLUSIONS

The paper presents an approach to the development of DMS and DMT for smart manufacturing, whose role is increasingly important today. From the aspect of production metrology, the role DMS and DMT is to monitor the measurement process, to improve the quality of processing, accuracy of the geometrical characteristics 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.

The result of this paper is a new approach of the development of the DMT, based on CMMs - towards off-line DT based on CMM. The measurement system based on CMM UMM 500 and IOTA 2203 was used as a physical twin, and a virtual machines, 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 and a physical CMM with a defined information exchange protocol. The novelty of the research is application into today's trend of smart manufacturing and smart metrology. Also, the novelty of this paper is that in an efficient, dynamic and automatic way it integrates DMS and DMT into smart manufacturing and thus solves the problem of production costs with maximum efficiency.

Besides the to-date developed off-line DMT, future research will also include DMT 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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