CYBER-PHYSICAL MANUFACTURING METROLOGY MODEL (CPM^3)

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Abstract: *The paper shows the concept of Serbian Industry 4.0 Model based on cyber-physical manufacturing metrology model (CPM^3) and an integrated approach to manufacturing quality. The paper presents two directions of research: Virtual optimization of CAI process parameters for the sculptured surface inspection and Intelligent model for Inspection Planning on CMM.*

Keywords: INDUSTRY 4.0, MANUFACTURING, ICT, MODELING, MANUFACTURING METROLOGY, QUALITY

1. Introduction

Today's business structure is more complex and dynamic than ever before. The market requires rapid changes in the industry with new products, which directly reflects on the work of the factory. On the other hand, digitization and information technology (IT) provide new, unimagined possibilities, engineers in the design and planning. These two approaches have led to two concepts that have since emerged: the digital factory and digital manufacturing [1, 2].

Cyber-physical systems (CPSs) are enabling technologies which bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other [3]. Together with the internet and the data and services available online, embedded systems join to form cyber physical systems. CPSs also are a paradigm from existing business and market models, as revolutionary new applications, service providers and value chains become possible [2].

High levels of automation come as standard in the smart factory: this being made possible by a flexible network of CPSs - based manufacturing systems which, to a large extent, automatically supervise manufacturing processes. Flexible manufacturing systems which are able to respond in almost real-time conditions allow in-house manufacturing processes to be radically optimized [4]. Manufacturing advantages are not limited solely to one-off manufacturing conditions, but can also be optimized according to a global network of adaptive and self-organizing manufacturing units belonging to more than one operator.

2. Cyber Physical Manufacturing Systems (CPMSs) - Basic Concept

Developed and implement "advanced manufacturing concept" as a base for Cyber - Physical Manufacturing Systems (CPMSs), will be to evolve along five directions [4,5]: (i) on – demand manufacturing: Fast change demand from internet based customers requires mass-customized products. The increasing trend to last-minute purchases and online deals requires from manufactures to be able to deliver products rapidly and on-demand to customers; (ii) optimal and sustainable manufacturing: Producing products with superior quality, environmental consciousness, high security and durability, competitively priced. Envisaging product lifecycle management for optimal and interoperable product design, including value added after-sales services; (iii) human - centric manufacturing: Moving away from a production-centric towards a human-centric activity with great emphasis on generating core value for humans and better integration with life, e.g. production and cites; (iv) innovative products: From laboratory prototype to full scale production – thereby giving competitors a chance to overtake enterprises' through speed, and (v) green products: for example Manufacturing Strategy 2020/30 [1, 2] needs focused initiatives to reduce energy footprints on shop floors and increase awareness of end-of-life (*EoL*) product use, and there are framework for CPMSs. The merging of the virtual and the physical worlds through CPSs and the resulting fusion of manufacturing processes and business processes are leading the way to a new industrial age best defined by the INDUSTRIE 4.0 project's "smart factory" concept [4].

Smart factory products, resources and processes are characterized by CPSs; providing significant real-time quality, time, resource, and cost advantages in comparison with classic manufacturing systems [3]. The smart factory is designed according to sustainable and service-oriented business practices. These insist upon adaptability, flexibility, self-adaptability and learning characteristics, fault tolerance, and risk management.

3. Our Research in the Field of Cyber Physical Manufacturing Metrology Model (CPM^3)

In our Laboratory for Production Metrology and TQM on Mechanical Engineering Faculty, Belgrade, now we have following researches areas: (i) Digital Manufacturing – Towards Cloud Manufacturing (base for CPMs), (ii) Intelligent model for Inspection Planning on CMM as part of CPM concept (IMIP), and (iii) CPMS – CPQM our approach. In this paper we shall show some research results for third direction.

Digital quality, as a key technology for CPMs represents virtual simulation of digital inspection in digital company, based on a global model of interoperable products (GMIP). GMIP represents the integration CAD-CAM-CAI models in the digital environment. The essence of this research is solved the concept of metrology integration into GIMP for the CMM inspection planning [5,6], based on Cyber-Physical Manufacturing Metrology Model (CPM^3).

Feature-based technology and STEP standard could be considered as a main integrator in terms of linking the engineering and manufacturing domain within various CAx systems. To specify the part data representation for a specific application, STEP (ISO 10303) uses Application Protocols (AP) [7,8]. Beside STEP APs, the following standards and interfaces are important for CAI. A vendor-independent Dimensional Measuring Interface Standard (DMIS) provides the bidirectional communication of inspection data between systems and inspection equipment, and is frequently used with CMMs. It is intermediate format between a CAD system and a CMM's native proprietary language.

Fig.1. *CMM interoperability model* [7]

Dimensional Markup Language (DML) translates the measurement data from CMMs into a standardized file that could be used for data analysis and reporting. I++ DME-Interface provides communications protocol, syntax and semantics for command and response across the interface, providing low level inspection instructions for driving CMMs [4], Fig. 1.

3.1. Virtual optimization of CAI process parameters for the sculptured surface inspection

Fig. 3. shows the working process with the integration of design, production and coordinate inspections. Master Assembly represents the mechanical assembly with all associated parts. This assembly consists upper and lower tools and wind turbine. The experiment was done on the lower side of the Mold Turbine Blade (MTB, shown in Fig. 2.

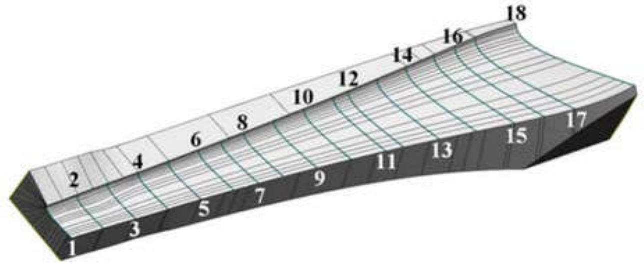

Fig.2 *Nominal geometry of Mold Turbine Blade* [8]

Computer aided manufacturing (CAM) or Computer aided inspection (CAI) is executed in a separate part-file that consists the original geometry of the part. Only this way it is possible to make changes on the original geometry that can reflect on some of the engineering activities.

Part file CAD/CAM is usually obtained as STEP AP203 or AP214. It represents the basis for the preparation of manufacturing technology. At the same time a geometry inspection is being prepared so that when a part is manufactured, its inspection can be implemented on the coordinate measurement machine (CMM).

As an output from CAD/CAM, STEP AP203/214 is obtained which is the input for PC-DMIS Wilcox. S/W Wilcox PC-DMIS uses its integrated translator to convert it into DMIS format. At this stage GD&T and the motion of measurement probe are defined. Based on the acquired measurements, DMIS output was generated which can be a printed report or STEP too, but now with measured geometry. This STEP can be loaded again into a CAD/CAM system or some other coordinate system for inspection, and contents for the same part of DMIS file give procedure CMM inspection.

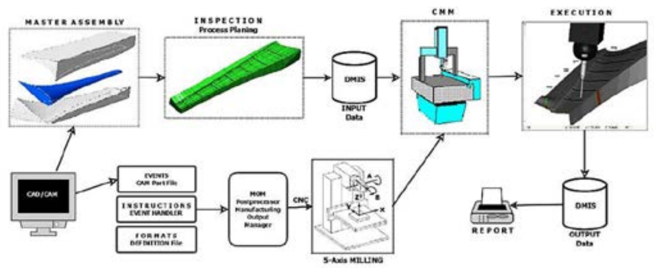

Fig.3. *Process with the integration of design, production and coordinate inspections for Turbine Blade Mold* [7]

Our research [8] aims to contribute to the development of a virtual inspection of freeform surfaces, in terms of the investigation of CAI parameters' effects on the quality of the inspection process.

In order to assess the effect of CAI control factors (Number of Control Section, Number of Measured Points, Uniform distribution and distribution with Geometric progression) on the quality of measuring process (measuring accuracy and measuring time), a virtual experiment has been performed for a sculptured surface part in PLM software environment. The measuring accuracy is presented by the distance error and the angle error, and the measuring time is presented by the measuring path length. The results of analysis performed using RSM (Response Surface Methodology) are: Number of Control Section and its square term are significant for the distance error; all three control factors and/or their square terms and interactions are significant for the angle error; for the measuring path length only Distribution Method (Uniform and Geometric Progression) is insignificant. Finally, the optimal CAI factors setting was obtained for the observed freeform surface part. Although the analysis has been performed for the selected part (MTB) that was taken as a reference, these findings could serve as guidelines for the setting of CAI parameters in inspecting sculptured surface parts. Besides, in this approach, the inspection curves were fitted using a cubic spline.

3.2. Intelligent model for Inspection Planning on CMM

The development Intelligent model for Inspection Planning on CMM (IMIP) for prismatic parts involve following activities: (i) development ontological knowledge base presented in [9]; (ii) local and global inspection plan, and (iii) optimize path of measuring sensor. Output from the local and global inspection plan (LGIP) is initial measuring path. The first element LGIP's is sampling strategy or model for the distribution of measuring points for features, and second element define the principle for collision avoidance between work piece and measured probe. By modifying the *Hemmersly* sequences, we define the distribution of measuring points for basic geometric features such as plane, circle, cylinder, cone, hemisphere, truncated hemisphere and truncated cone presented in figure 4.

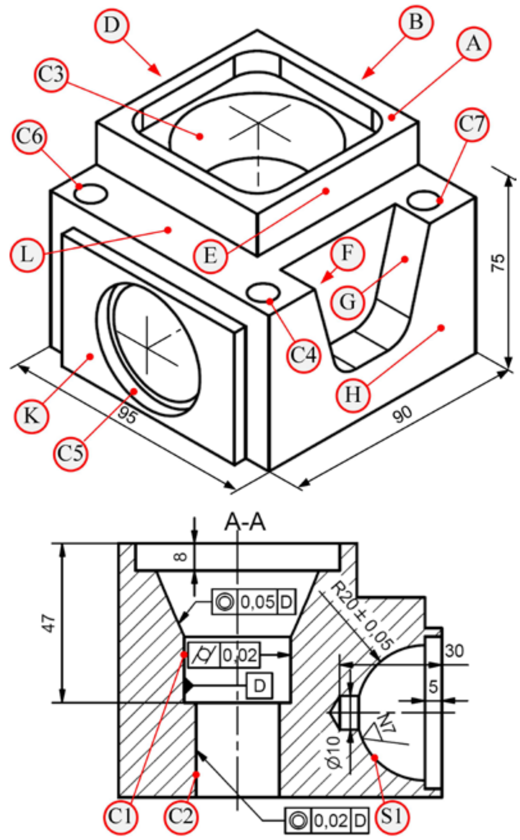

Fig.4 *The features of the real part: plane - A,B,D,E,F,G,H,K,L; cylinder – C1,C2,C4; cone – C3; sphere – S1*

Each geometric feature is uniquely determined by the local coordinate system O_F, X_F, Y_F, Z_F and a set of corresponding parameters. These parameters could belong to the following types: diameter (D, D_1), height (H, H_1), width (a), length (b), normal vector of a feature (**n**), fullness vector of a feature ($\mathbf{n_p}$). The vector **n** determines the orientation of a feature in the space. The fullness parameter is defined by a unit vector of the X-axis of a feature. The fullness vector and the normal vector define the direction of a measuring probe access in generating the probe path.

For example, the equations for calculation of measuring point coordinates for cylinder are:

$$s_i = R\cos\left(-\frac{\pi}{2} - \frac{2\pi}{N}\cdot i\right)$$

$$t_i = R\sin\left(-\frac{\pi}{2} - \frac{2\pi}{N}\cdot i\right)$$

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

where, s_i, t_i, w_i correspond x_i, y_i, z_i respectively and $h[\text{mm}]$ is the height of a cylinder.

In Figure 5 are presented distribution points, windows of simulation for plane and cylinder and optimizing path by solving TSP using ants colony.

The simulation is based on three algorithms: Algorithm for Measurement Points Distribution (AMPD), Algorithm for Collision Avoidance (ACA), and Algorithm for Probe Path Planning (APPP).

Application of ACO in a coordinate metrology is based on the solution of TSP, where the set of cities that the salesman should pass through with the shortest possible path corresponds to the set of points of a minimal measuring path length [10]. Precisely, the set of cities corresponds to the set of points, and the salesman corresponds to the measuring probe. Since it is necessary to avoid collision between the workpiece and a measuring probe during measurements on CMM, the mathematical model must be developed to present distribution of points for basic geometric primitives and for their unique description.

The model is based on the following equation for calculation of the measuring probe path during the measurement on N measuring points:

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

In order to obtain a measuring path, a module 'Manufacturing' and its sub-module 'CMM' in Pro/ENGINEER® (version Wildfire 4.0) was used. The coordinate system of a workpiece during the inspection corresponds to the workpiece coordinate system used for the inspection on CMM. Figure 4 shows the measuring path for the inspection of a hemisphere diameter, as well as a part of the generated CL file.

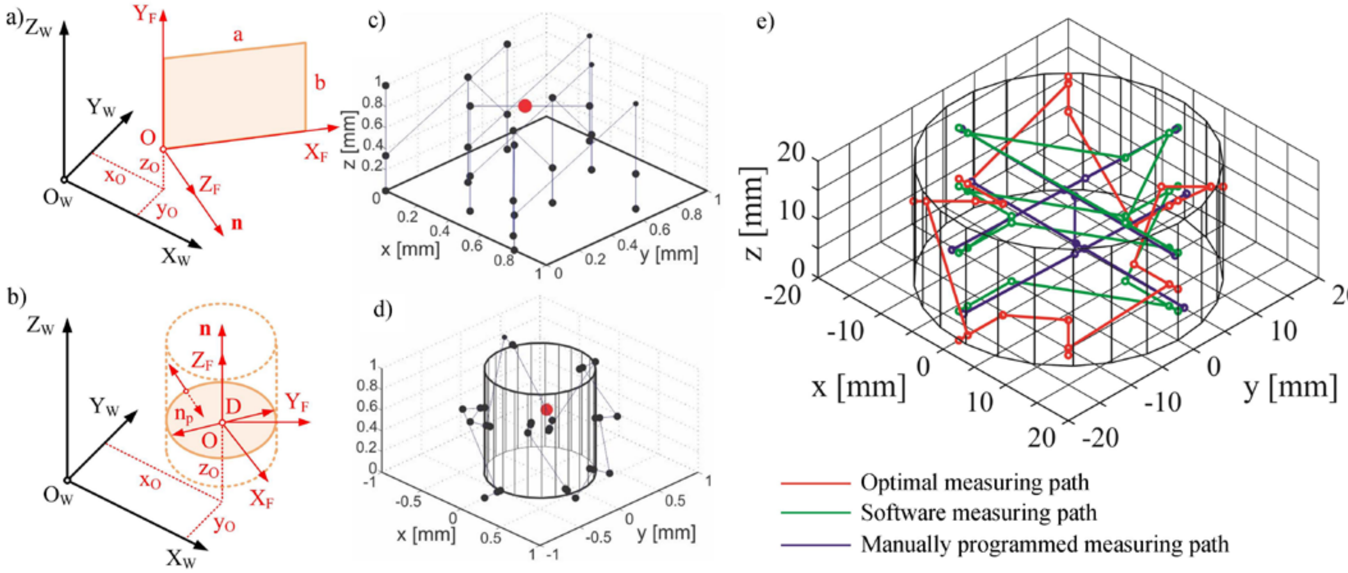

Fig.5 *The features of the real part: plane - A,B,D,E,F,G,H,K,L; cylinder – C1,C2,C4; cone – C3; sphere – S1*

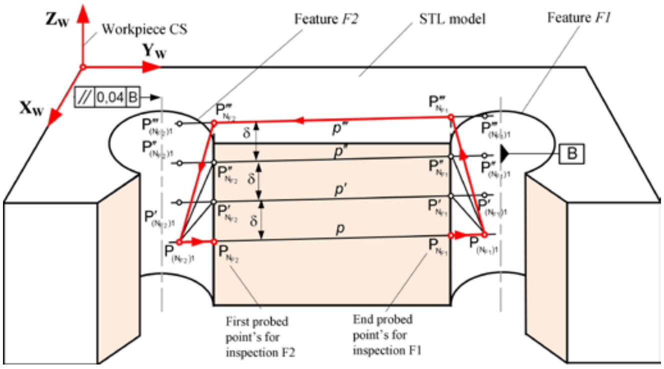

Fig.6 *The principle collision avoidance*

Based on STL model for the presentation of PP geometry, the tolerances of PP, the coordinates of the last point $P_{(N_{F1})1}$ of a feature F1 and the coordinates of the first point $P_{(N_{F2})1}$ of a feature F2, the simplified principle of collision avoidance between work piece and probe at parallelism tolerance inspection is presented in Figure 6.

For each triangle in STL file, the belonging plane equitation is formulated. If triangle vertexes are T_1, T_2, T_3, the procedure of formation of the plane is described by the following equitation:

$Ax + By + Cz + D = 0$

and it begins with the formation of a normal vector

$\vec{n} = \overrightarrow{T_1T_2} \times \overrightarrow{T_1T_3} = A\vec{i} + B\vec{j} + C\vec{k}$

wherefrom the constants A, B and C could be identified. The constant D is calculated using the scalar multiplication $D = -\vec{n}\cdot\vec{r_1}$ where $\vec{r_1} = \overrightarrow{OT_1}$. The next step is the formation of line equitation through two points $P_{(N_{F1})1}$ and, $P_{(N_{F2})1}$, based on the vector form of line equitation:

$\overrightarrow{M} = \vec{P} + t\cdot\vec{p}$

where $\vec{p} = \overrightarrow{P_1P_2}$, $\vec{P} = \overrightarrow{OP_1}$.

The principle is iterative and consists from moving line *p* for distance δ until line became collision free (line segment p''').

The planning of an inspection of PP on CMM is performed with regard to three orthogonal directions. This fact is used for the definition of direction of a measuring probe access to PP.

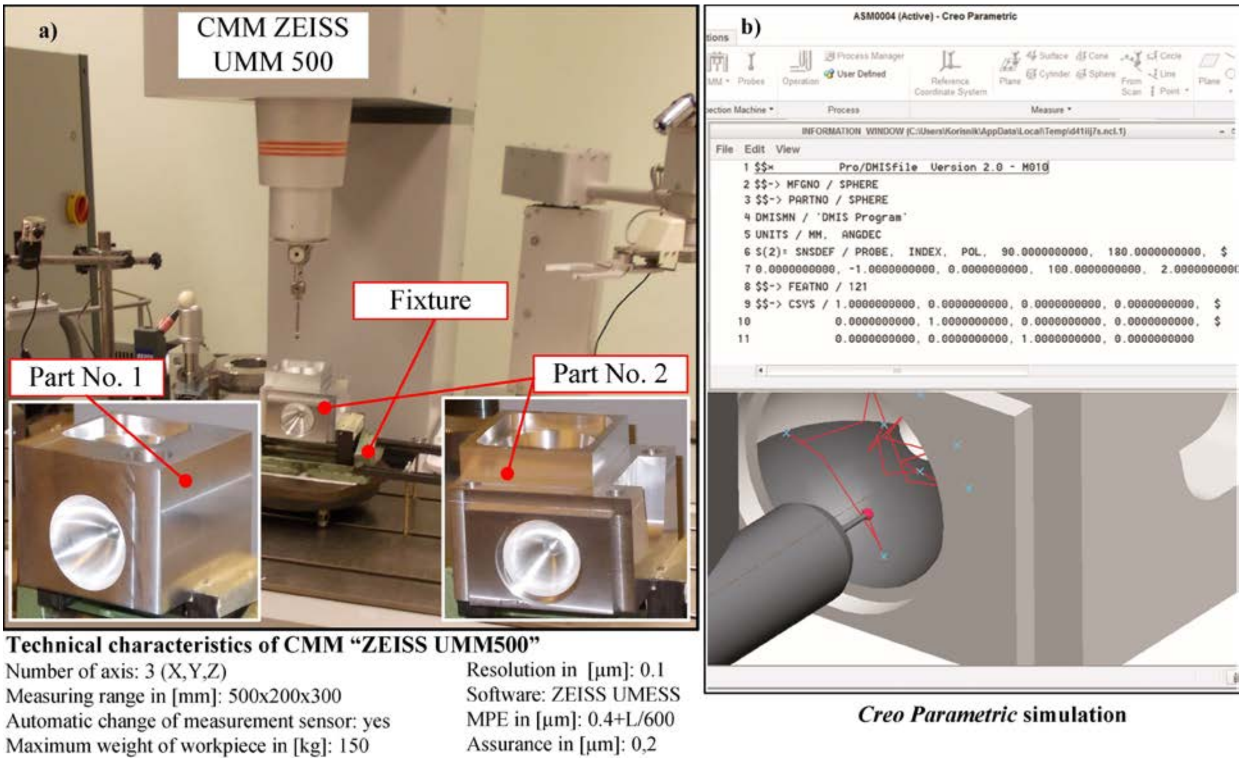

Fig.7 *The principle collision avoidance*

Experiment involves measurement of two PPs that are produced for this research. In comparison to the simpler workpiece PP1 and more complex workpiece PP2 contains new types of tolerances that should be tested. Experimental setups for the measurement of PP1 and PP2 are shown in Figure 7. The measurement of both parts is performed in a single clamp, and the measuring probe configurations are shown at the figures. Experiment is performed on the coordinated measuring machine ZEISS UMM 500.

4. Conclusion

In the above presented of SPMSs for quality as a CAI model, it is important to consider the newly developed AP242 that is designed to improve the interoperability in STEP, support model-based GD&T and allows for CMM programming based on the inspection features. AP242 enables 3D product manufacturing information (PMI) with semantic representation and 3D model-based design and data sharing on service-oriented architecture (SOA).

Future research of virtual optimization of CAI process parameters for the sculptured surface inspection could include the usage of higher order splines and comparison of their performances with a cubic spline, for the observed problem. As a general outcome, RSM indicated quite promising results when applied to a CAM environment and more experiments will be conducted for multi axis surface machining in the near future.

The complex geometry of the PP by IMIP changes to the set of points whose sequence defines the measuring path of sensors without collision with work piece. Presenting measuring path by set of points with a defined order is optimizing by solving TSP with ants colony. Finding the shortest measuring path, the main criteria for optimization, influence to the reduction of the total measurement time, which is one of the goals of this research. The ISIP is especially suitable for use in case of measuring path planning for geometrically complex PPs with large numbers of tolerances. The simulation provides a visual check of the measuring path.

CPM^3 will integrated in CPMSs model in our future researches.

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