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PATH PLANNING FOR INSPECTION PRISMATIC PARTS ON CMM AS A PART OF CYBER – PHYSICAL MANUFACTURING METROLOGY MODEL

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Abstract: *Cyber-Physical System (CPS) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet. The essence of this research is development Intelligent Model for Inspection Planning (IMIP) on CMM as support of Cyber-Physical Manufacturing Metrology Model and its metrology integration into coordinate measuring machine (CMM) inspection process planning for prismatic parts. Presented model is advanced feature-based inspection approach, whose advantage is in reduction the total measurement time by reducing the time needed for the preparation of the measurements and allowed opportunities for its optimization using one of the methods such as swarm theory. Needed geometrical information for feature description is taken from files IGES and STL. Output from the IMIP is point-to-point measuring path without collision between measurement probe and prismatic part. Distribution of measurement points for basic geometrical features is performed on the base modifies Hamersley principle. The results of the inspection of both PPs show that all tolerances are within the specified limits. This confirms the efficiency of the proposed feature-based model in IMIP of PPs. The model is especially suitable for use in case of measuring path planning for geometrically complex PPs with large numbers of tolerances.*

Key words: *Cyber-Physical Manufacturing, Digital Quality, Path Planning, Prismatic Parts, CMM.*

1. INTRODUCTION

Today's business structure is much more complex and dynamic ever before because the market demands of the industry's rapid changes in new products, which is directly reflected in the factory. Digitalization and information technology (IT) provide new, unimagined possibilities, engineers in the field of design and planning. According [1–6] two approaches have led to two concepts since emerged:

- digital factory and,
- digital manufacturing.

The goals that are put in front of digital factories are improve manufacturing technology, reduce costs, improve quality of products and processes, and, increase the adaptability to the emerging requirements of customers and market [7].

Developing and implement "advanced manufacturing" are a base for Cyber − Physical Manufacturing Systems (CPMSs), will be to evolve along five paths [8]:

- **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. This will only be achievable through flexible automation and effective collaboration between suppliers and customers;
- **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 and take-back models;
- **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. Future factories have to be more accommodating towards the needs of the workforce and facilitate real-time manufacturing based on machine data and simulation;
- **Innovative**: from laboratory prototype to full scale production – thereby giving competitors a chance to overtake enterprises through speed;
- **Green**: manufacturing 2020 needs focused initiatives to reduce energy footprints on shop floors and increase awareness of end-of-life (EoL) product use.

The digital manufacturing concept could address majority of the mentioned challenges, and it focuses on the improved automation and digitalization of the planning,

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design, manufacturing, inspection, management, and other activities in production system in a wider context. The digital model of a product could be used to simulate and analyze the manufacturing processes, production planning scenarios, as well as machining/tool path, inspection and resource utilization scenarios.

For a manufacturing system with typical machining operations factory-wide knowledge integration requires an integrated CAD-CAPP-CAM-CNC-CAI and integration with other production-related information systems such as:

- enterprise resource planning (ERP),
- manufacturing execution system (MES),
- advanced planning and scheduling (APS), etc.

The essence of this research is development Intelligent Model for Inspection Planning (IMIP) on CMM as support of Cyber-Physical Manufacturing Metrology Model and its metrology integration into coordinate measuring machine (CMM) inspection process planning for prismatic parts. Presented model is advanced feature – based inspection approach, whose advantage is in reduction the total measurement time by reducing the time needed for the preparation of the measurements and allowed opportunities for its optimization using one of the methods swarm theory. Output from the IMIP is point-to-point measuring path without collision between measurement probe and prismatic part.

The results of the inspection of both PPs by IMIP show that all tolerances are within the specified limits. This confirms the efficiency of the proposed feature – based model. The model is especially suitable for use in case of measuring path planning for geometrically complex PPs with large numbers of tolerances.

2. SMART MANUFACTURING THROUGH CPMS

2.1. Cyber-Physical Manufacturing Systems (CPMSs)

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 [9]. 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 [10, 11].

2.2. Smart factory

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 [11].

Smart factory manufacture brings with it numerous advantages over conventional manufacture, as example [9–11]: (i) CPS – optimized manufacturing processes: smart factory “units” are able to determine and identify their field(s) of activity, configuration options and manufacture conditions as well as communicate independently and wirelessly with other units; (ii) Optimized individual customer product manufacturing via intelligent compilation of ideal production system which factors account product properties, costs, logistics, security, reliability, time, and sustainability considerations; (iii) Resource efficient production; and (iv) Tailored adjustments to the human workforce so that the machine adapts to the human work cycle.

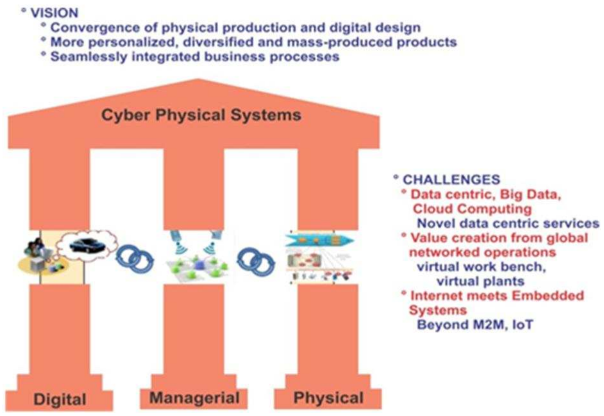


Fig. 1. CPSs – Basic facts [9].

This approach as a manufacturing revolution in terms of both innovation and cost and time savings and the creation of a “bottom-up” manufacturing value creation model whose networking capacity creates new and more market opportunities.

CPM insists upon adaptability, flexibility, self-adaptability and learning characteristics, fault tolerance, and risk management. 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.

3. INTELLIGENT MODEL FOR INSPECTION PLANNING ON CMM AS PART OF CPM CONCEPT

The essence of this research is development Intelligent Model for Inspection Planning (IMIP) on CMM as support of Cyber-Physical Manufacturing Metrology Model.

The development IMIP for prismatic parts involve following activities: (i) development ontological knowledge base presented in [12, 13]; (ii) local and global inspection plan, and (iii) optimize path of measuring sensor [14]. 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 basic geometric features and second element define the principle for collision avoidance between workpiece and measured probe. Both of the elements are base on proposed feature model.

3.1. Proposed feature – based model

The elements of feature – based model for path planing are CAD modul, knowledge base, local and global plan of inspection. Metrological recognition is based on the IGES file and the parametric defining of geometric features [12]. The knowledge base defined link between tolerance and geometric features by metrological features [15, 16]. The local plan of inspection represents the distribution of measuring points per geometric features. The global inspection plan is the plan of path sensors, presented with the local plan and algorithm for collision avoidance based on STL model of PP.

3.2. Path planning for prismatic parts

Sampling strategy

Sampling strategy is based on Hamersley's sequences [17] for the calculation of coordinates for two axes of a feature. By modifying the Hamersley's sequences, we define the distribution of measuring points for basic geometric features such as, plane, circle, cylinder, cone, hemisphere, truncated cone and truncated hemisphere. Most often, these features are involved in creation of PP tolerances.

To define the distribution of measuring points for a feature, the Descartes coordinates system O_F, X_F, Y_F, Z_F is needed. The coordinates are denoted by $P_i(s_i, t_i, w_i)$. For example the equations for calculation of measuring point coordinates for cylinder are:

$$s_i = R\cos\left(-\frac{\pi}{2}-\frac{2\pi}{N}\cdot i\right) \qquad (1)$$

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

$$w_i = \left(\sum_{j=0}^{k-1}\left(\left[\frac{i}{2^j}\right]\mathrm{Mod}2\right)\cdot 2^{-(j+1)}\right)\cdot h\,, \qquad (3)$$

where, s_i, t_i, w_i correspond x_i, y_i, z_i respectively, $h[\mathrm{mm}]$ – height of a cylinder, $R[\mathrm{mm}]$ – radius of a cylinder and N – number of measuring points.

The distributions of measuring points based on sampling strategy method for parameters of cylinder (Fig. 2,*a*) are presented in Fig. 2,*b*).

Principle for collision avoidance

Based on STL model of PP geometry, the tolerances of PP, the coordinates of the last point $P_{(N_{F1})1}$ of the feature F1 and the coordinates of the first point $P_{(N_{F2})1}$ of the feature F2, the simplified principle of collision avoidance is presented in Fig. 3.

Algorithm for distribution of measuring points

Algorithm for distributions of measuring points is presented across 13 (A13) steps and shown in Fig. 4**.**

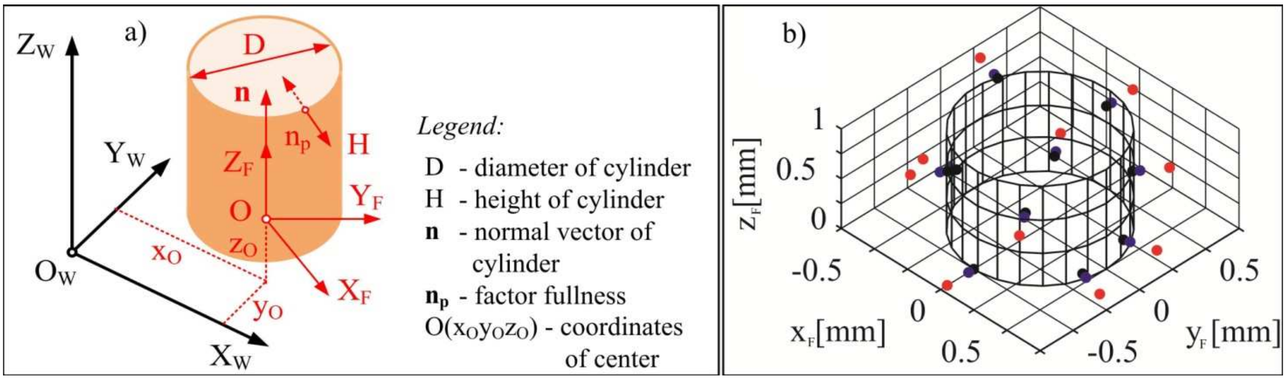


Fig. 2. Cylinder: *a* – geometric parameters; *b* – distributions of measuring points.

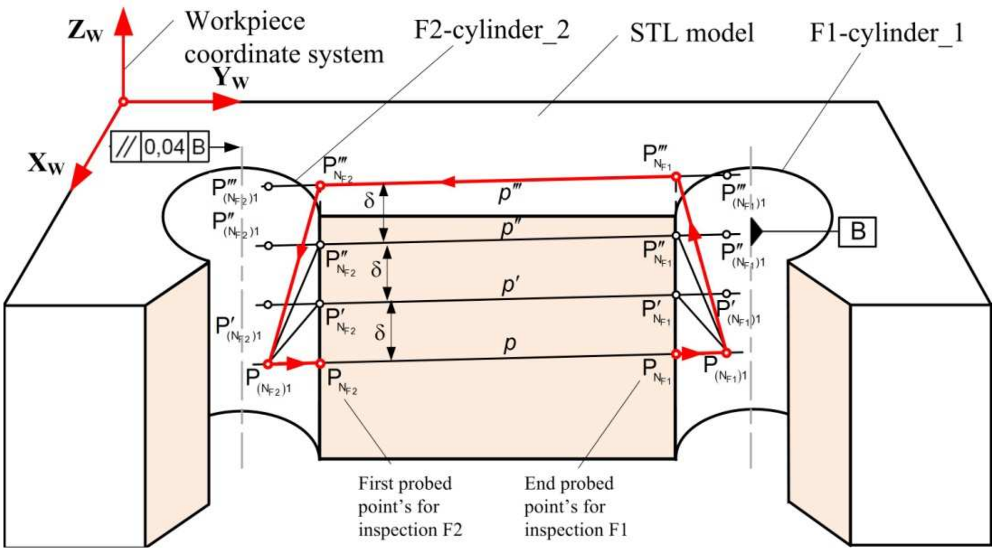


Fig. 3. The principle of collision avoidance.

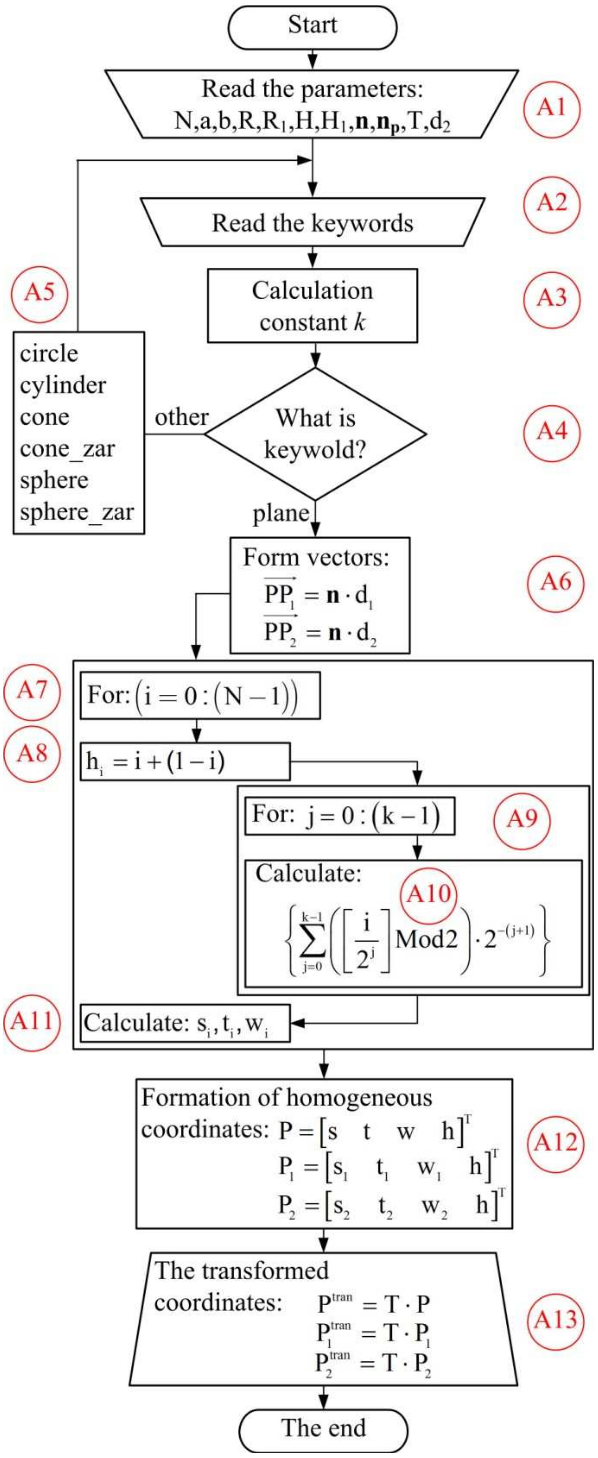


Fig. 4. Algorithm for distribution of measuring points.

Algorithm for collision avoidance

Algorithm for collision avoidance is presented across 12 (A12) steps and shown in Fig. 5.

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:

$$Ax + By + Cz + D = 0 \tag{4}$$

and it begins with the formation of a normal vector

$$\vec{n} = \overrightarrow{T_1T_2} \times \overrightarrow{T_1T_3} = A\vec{i} + B\vec{j} + C\vec{k}\,, \tag{5}$$

wherefrom the constants A, B, C and D could be identified. 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:

$$\overrightarrow{M} = \vec{P} + t \cdot \vec{p}\,, \tag{6}$$

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

If an intersection between the line (6) and the plane (4) exists, then it is a point $P_j(x_j, y_j, z_j)$, where *j* is the number of intersection points.

Since $\Delta T_1T_2T_3$ is represented by a plane, and a line segment $\overline{P_{(N_{F1})1}P_{(N_{F2})1}}$ is represented as a part of a line *p*, it is necessary to check whether the intersection point P_j is placed at the line segment $\overline{P_{(N_{F1})1}P_{(N_{F2})1}}$ and whether it belongs to the part of the plane limited by $\Delta T_1T_2T_3$. In that case, to check whether the intersection point is placed in the surface part that is limited by a triangle.

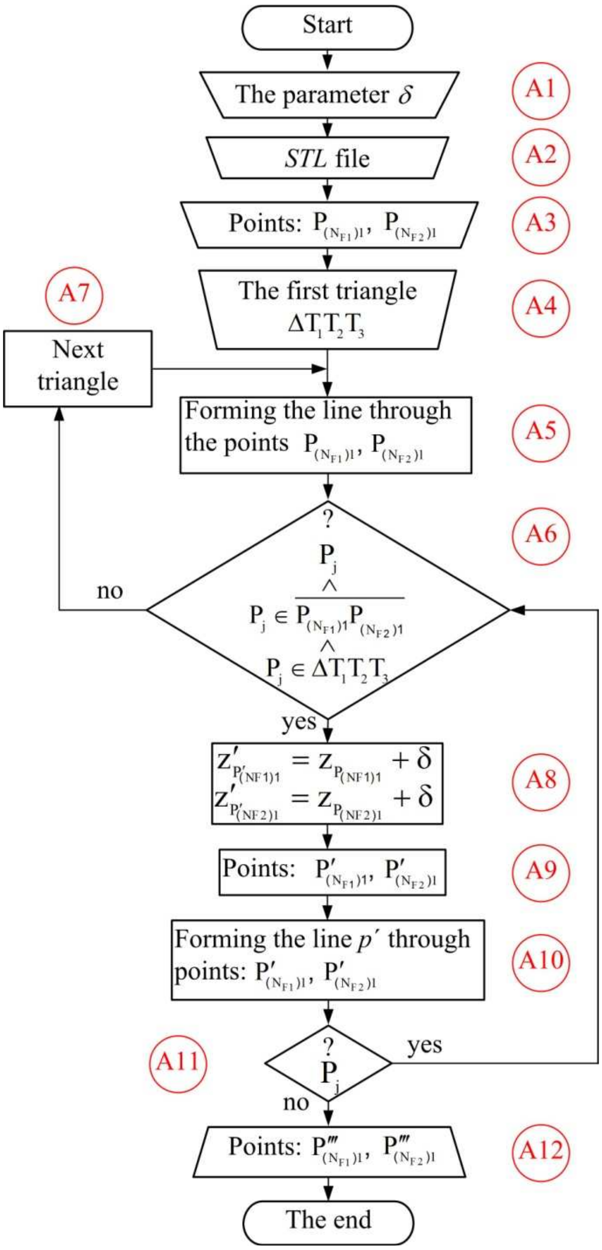


Fig. 5. Algorithm for collision avoidance.

If an intersection between a line *p* and any of the triangles from STL model exists, then using iterative procedure the points $P_{N_{F1}}, P_{N_{F2}};...;P^{j}_{N_{F1}}, P^{j}_{N_{F2}}$ are determined. The difference between the next point $P'_{N_{F1}}$ and the previous point $P_{N_{F1}}$ is in the value of z-axis, i.e. the value of the correction parameter $\delta[\text{mm}]$. The correction parameter is a constant for one PP. The procedure is repeated until there are no remaining intersections between a line and triangles from STL model. The last points $P'''_{N_{F1}}$ and $P'''_{N_{F2}}$ of this iterative procedure are the points for which there is no collision during the measuring probe crossover.

For the example shown in Fig. 3, the algorithm for collision avoidance (Fig. 5) performed three corrections of z-coordinates and the points $P'''_{(N_{F1})1}$ and $P'''_{(N_{F2})1}$ are adopted.

The reduction of a number of triangles in the algorithm for collision avoidance results in a fast response, i.e. the coordinates of points without collision, and it does not significantly affect the processing time.

3.3. Optimization measuring path by ACO

The optimization model is based on: (i) the mathematical model that establishes an initial path presented by the set of points with defined sequence of measuring probe passes without collision, and (ii) the solution of travelling salesman problem (TSP) obtained using ant colony optimization (ACO) [14].

In order to solve TSP, ACO algorithm that aims to find the shortest path of ant colony movement (i.e. the optimized path) is applied. Then, the optimized path is compared with the executed path obtained by on-line programming on CMM ZEISS UMM500 and with the measuring path obtained in CMM module for inspection in software Pro/ENGINEER® (Fig. 6). Results of comparison between the optimized path and the other two generated pats show that the optimized path is minimum 20% shorter than the path obtained by on-line programming on CMM ZEISS UMM500, and minimum 10% shorter than the path obtained using CMM module in Pro/ENGINEER®.

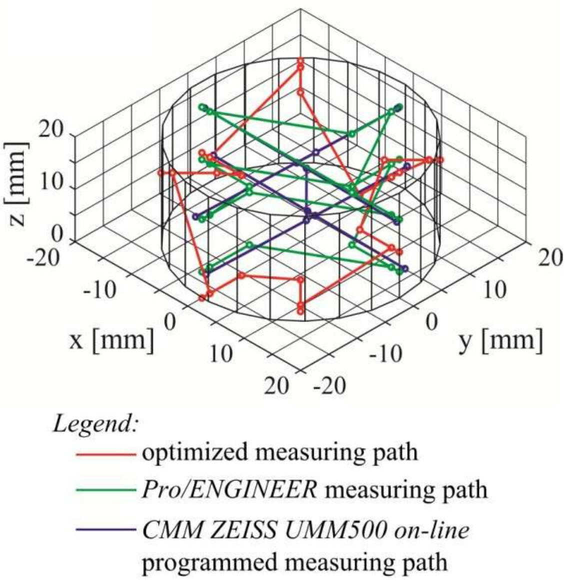


Fig. 6. The comparisons three paths on the example of cylinder.

4. EXPERIMENT

Experiment involves measurement of two PPs that are produced for this research (Fig. 7). Testing of the presented model is initially performed using the simpler workpiece, i.e. prismatic part 1 (PP1). After the successfully performed experiment on PP1, testing of the model is performed on the second, more complex workpiece – prismatic part 2 (PP2).

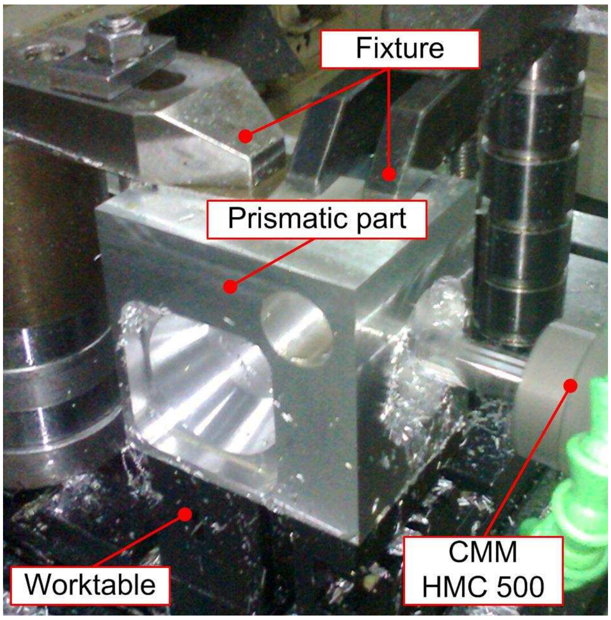
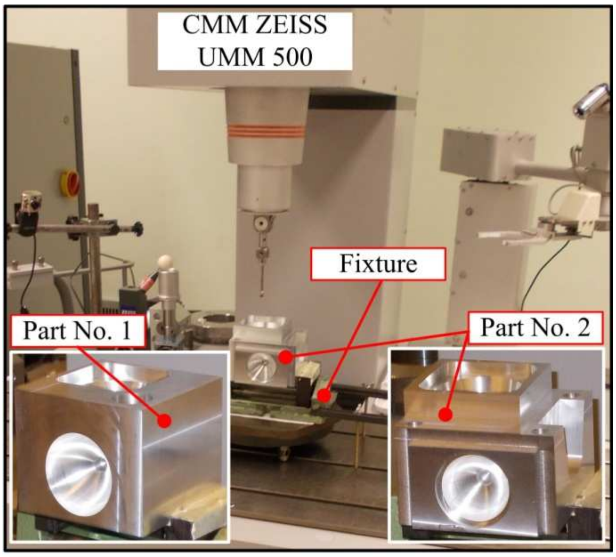


Fig. 7. Machining *PP* No. 1 on CNC LOLA HMC 500.



Technical characteristics of CMM “ZEISS UMM500”

Number of axis: 3 (X,Y,Z)	Resolution in [µm]: 0.1
Measuring range in [mm]: 500x200x300	Software: ZEISS UMESS
Automatic change of measur. sensor: yes	MPE in [µm]: 0.4+L/600
Max. weight of workpiece in [kg]: 150	Assurance in [µm]: 0,2

Fig. 8. Experimental setup for the measurement of prismatic part No. 1 and part No. 2.

Table 1

The results of measurement workpiece No. 1 and workpiece No. 2 [18]

Part	**No.**	**Tolerances**			**Measurements**					
		Name	Label	Value in mm	1.	2.	3.	4.	5.	Deviation in µm
No. 1	1	Flatness	⏥ 0,02	0,02	0,0005	0,0004	0,0005	0,0005	0,0004	0,1
	2	Diameter	**50**	±0,1	50,0851	50,0855	50,0852	50,0856	50,0855	0,2
	3	Perpendicularity	⊥ 0,03 A	0,03	0,0014	0,0024	0,0023	0,0022	0,0023	0,4
	4	Angle	**Cone: 39°**	±0,5	39,2991	39,2991	39,2995	39,2982	39,2991	0,5
	5	Parallelism	∥ 0,04 B	0,04	0,035	0,0346	0,035	0,0348	0,035	0,2
No. 2	6	Distance	**70**	±0,02	70,0111	70,0111	70,0112	70,0111	70,0106	0,2
	7	Cylindricity	⌭ 0,02	0,02	0,0042	0,0043	0,0041	0,004	0,0041	0,1
	8	Coaxiality	◎ 0,02 D	0,02	0,0068	0,008	0,008	0,0091	0,0092	1
	9	Roundness	○ 0,03	0,03	0,0094	0,0092	0,0092	0,0101	0,0096	0,4
	10	Position	⌖ 0,75 C B	0,75	0,6471	0,6483	0,6416	0,6481	0,6424	3,2

In comparison to PP1, PP2 contains new types of tolerances that should be tested. Experimental setups for the measurement of PP1 and PP2 are shown in Fig. 8. The measurement of both parts is performed in a single clamp, and the measuring probe configurations are shown at the Fig. 8.

Experiment is performed on the coordinated measuring machine ZEISS UMM 500.

In this experiment, the inspection process is composed of the preparation and measuring process.

The preparation process involves:

1) setting up the workpiece, with the analysis of fixture tools and accessories;

2) configuration of measuring probes;

3) calibration of measuring probes using calibration sphere;

4) alignment of PP.

The measuring results for both PPs are given in tables 1. As it could be seen, measurement was repeated five times and standard deviation was calculated.

5. CONCLUSIONS

The essence of this research is development IMIP on CMM as support of Cyber-Physical Manufacturing Metrology Model and its metrology integration into CMM inspection process planning for prismatic parts.

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 workpiece. 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 IMIP 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.

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