Usage of I++ Simulator to Program Coordinate Measuring Machines when Common Programming Methods are difficult to apply

A. Gąska, D. Szewczyk, P. Gąska, M. Gruza, J. Sładek

Laboratory of Coordinate Metrology, Cracow University of Technology, al. Jana Pawla II 37, 31-864 Cracow, Poland

Nowadays, simulators facilitate tasks performed daily by the engineers of different branches, including coordinate metrologists. Sometimes it is difficult or almost impossible to program a Coordinate Measuring Machine (CMM) using standard methods. This happens, for example, during measurements of nano elements or in cases when measurements are performed on high-precision (accurate) measuring machines which work in strictly air-conditioned spaces and the presence of the operator in such room during the programming of CMM could cause an increase in temperature, which in turn could make it necessary to wait some time until conditions stabilize. This article describes functioning of a simulator and its usage during Coordinate Measuring Machine programming in the latter situation. Article also describes a general process of programming CMMs which ensures the correct machine performance after starting the program on a real machine. As an example proving the presented considerations, measurement of exemplary workpiece, which was performed on the machine working in the strictly air-conditioned room, was described.

Keywords: CMM, simulator, I++ protocol, coordinate metrology.

1. INTRODUCTION

FOR DECADES simulators have been successfully used in various areas of human activities, such as medicine [1], aviation, military, astronautics, robotics, logistics [2], mechanical systems [3], production engineering [4] and other types of industry [5]. Thanks to simulators it is possible to safely train aircraft pilots, industry robot operators, etc. [6]. Metrological software very often allows simulating: measuring path, positioning of measuring object and motion of CMM's probe head, however, there was no software that offered simulation of CMM working in on-line mode and access to virtual model of CMM which represents construction and workings of real CMM. The solution for this problem has been brought lately by the company Messtechnik Wetzlar. Their project uses universal protocol called I++ DME and allows to program a virtual model of CMM, implemented in EasyRob environment, in metrological software which cooperates with the mentioned protocol (QUINDOS, PC-Dmis, Modus, Calypso, PowerTrain) [7].

With this solution it is now possible to train CMM operators without a number of measuring stations and also to train students studying at technical universities [7, 8]. But benefits of this approach are not only of educational kind. It is more than possible that this type of solution will find a widespread application in industry and science.

Coordinate Measuring Machines, as well as the range of their applications, are still evolving. Today they can be used in both nano- and large-sized measurements. Still, in some cases programming of CMM using the machine itself can be difficult or almost impossible. For example, in measurements of nano elements it is a common situation when one or more dimensions are not visible to the eye. In such circumstances vision systems are used to provide zoom on probe head, measured element and their position. However, this method is cumbersome and it is leaving an operator too much space for making mistakes which can result in the damage of the relatively expensive stylus. I++ simulator can be also useful when measurements are performed on high-precision (accurate) measuring machines which work in strictly air-conditioned spaces. The presence of the operator in such room during the programming of CMM could cause an increase in temperature, which in turn could make it necessary to wait some time until conditions stabilize. Any pause during measurements is a waste of money and I++ simulator can be very helpful in preventing it in these situations. This article describes functioning of the simulator and its usage during Coordinate Measuring Machine programming. Article also describes a general process of programming CMM which ensures the correct machine performance after starting the program on the real machine. As an example proving the presented considerations, measurement of exemplary workpiece from automotive industry, which was performed on PMM 12106 machine, working in the air-conditioned room that meets the rigorous requirements for temperature variation, was described.

2. I++ SIMULATOR

I++ working group was created in 1999 inspired by the idea of metrological software unification. Group members were mostly recruited from automotive industry (VW, Audi, Volvo, DaimlerChrysler, and BMW). Their collaboration resulted in the creation of I++ DME protocol (Dimensional Measuring Equipment), which in modern times has become the standard for most popular metrological programs (QUINDOS, PC-Dmis, Modus, Calypso, PowerTrain, etc.). [7].

I++ Simulator connection protocol is also based on I++ DME protocol. This allows the cooperation between simulator and the mentioned programs.

In practice, the simulator works on two screens. One monitor shows Virtual model of CMM, while the second one displays metrological software. Movement of the virtual machine is controlled by a gamepad, the same as is used in game consoles (Fig.1.).

Fig.1. Gamepad used for controlling of virtual machine in the I++ simulator [9].

Wide database of CMM models is attached to the simulator. Apart from the existing models of machines, manufactured by leading producers, it is possible to add new models to the database. These models can be constructed by the user using the 3D design software. As can be seen, there is a possibility to simulate any type of machine. There are also no problems with adding other elements, such as the measured objects and a variety of metrological accessories like probe changers, probe heads, styli, etc., to the database. The only limitation here is the necessity of having a 3D model of the object being added.

Working with simulator begins with the loading of proper models of: machine, measuring head, probe changers and set of styli, used in simulated measurement. Then, the functions assigned to each button of the gamepad need to be defined. CAD model of measured workpiece is loaded when all previous components are ready (Fig.2.). The object can be placed anywhere in the machine working area. Next, metrological software, in which the machine will be programmed, should be opened. From that point, work with the simulator is identical as work with the actual CMM. As the object of virtual measurement, any model constructed in 3D modeling program and saved in IGP format can be taken.
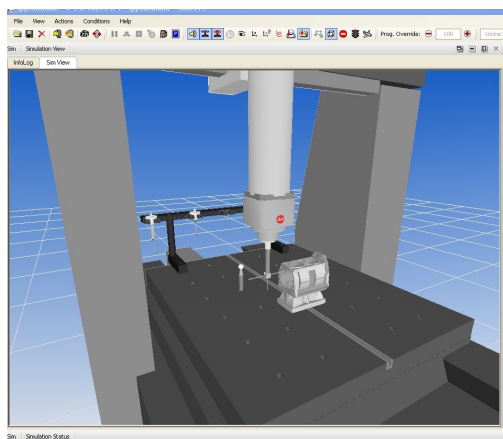

Fig.2. Simulation of motor housing measurement performed with I++ Simulator. Loaded machine model is Leitz PMM 12106.

The main benefit of the simulator is the possibility to train CMM operators without exploitation of real machines. Moreover, the simulator gives the ability to customize, optimize and test the existing measuring programs in order to avoid possible collisions [10]. As mentioned in the introduction, I++ Simulator may also turn out to be a useful device for programming CMMs in severe conditions when machine programming using the real system is difficult.

3. USAGE OF I++ SIMULATOR FOR PROGRAMMING THE COORDINATE MEASURING MACHINES

The possibility of implementation of the measuring program created using the simulator on a real machine was shown using the Leitz PMM 12106 machine located in the Cracow University of Technology in the Laboratory of Coordinate Metrology (LCM). This machine is a very accurate measuring system, its maximum permissible errors are given by equation: MPE = $0.8 + 2.5*1000/L$ μm, where L is measured length given in mm. The machine's measuring range is equal to 1200x1000x600 mm. It is located in a strictly air-conditioned room (temperature variation in the measuring volume of the machine is ± 0.05° C, providing there is no person in the room) (Fig.3.). Each operator intervention which takes place in the vicinity of the machine entails the possibility of temperature rise above the declared values. In that case it is not possible to achieve the best measurement accuracy until the temperature stabilizes again in the declared range of variation. Therefore, it is a great convenience to program a machine using the I++ Simulator, and then transfer the finished measuring program to the actual machine. In this situation, the operator activity in close proximity to the machine can be easily reduced only to the installation of the measured workpiece on the machine table.

Fig.3. Leitz PMM 12106 machine placed in the laboratory air-conditioned using water panels and controlled air flow.

The exemplary measured object is shown in Fig.4. Characteristics such as the distance between the elements, radius, diameter, tilting angle, parallelism deviation and radial run-out were evaluated.

It is important to develop an algorithm of preparation activities preceding the object measurement (proper orientation, mounting of the workpiece on the machine) and measurement strategy before the machine is programmed.

At the beginning, CAD model of the workpiece was uploaded to the simulator and its position on the machine table was determined. In order to be able to determine whether the collision with mounting elements is possible, they should also be modeled in 3D CAD software and uploaded to the simulator. This model should dimensionally correspond to the actual mounting elements that are being used.
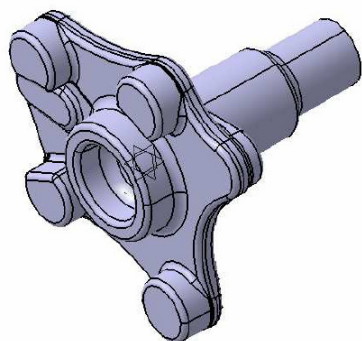

Fig.4. 3D view of measured object

For measurement simulation two styli were used. Parts of workpiece which could be measured with the stylus directed vertically were measured using a stylus shown in Fig.5.a). Elements which could not be reached with the mentioned stylus were measured using a star probe (Fig.5.b)). Dimensions of the styli selected in the simulator were identical to the dimensions of probes used for the actual measurements.
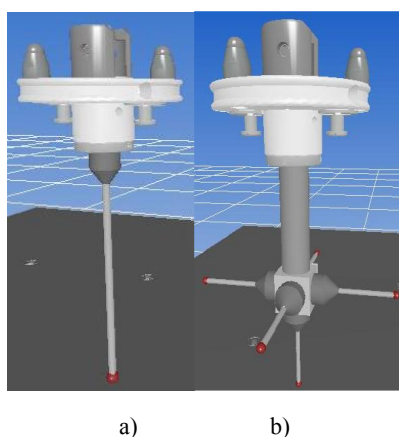

a)   b)

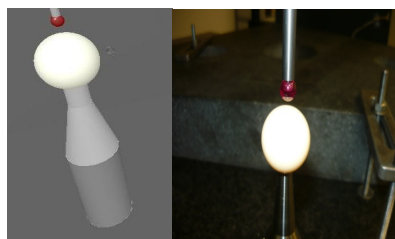Fig.5. Styli used for measurement

Fig.6. Qualification done in I++ simulator (left picture) and on the actual machine (right picture).

In the next stage, probe qualification was performed using a standard sphere of 25 mm diameter (Fig.6.). This step has no practical purpose in simulator as it uses virtual measuring balls that have no errors; it is done here just to include this activity in the measuring program as it is necessary in a real measurement.

In the following step, the manual coordinate system was built using the simulator environment. This measurement will be reproduced on a real coordinate machine in exactly the same way. After the coordinate system has been recreated in automatic mode, measurement of selected elements was programmed along with the definition of required evaluations. In case of the simulator, the results of these evaluations are just results of simulations and they mainly depend on values of probe head errors, whose range of variation was set at simulator properties. Evaluations also depend on errors arising from digitization of the CAD model. Without a module which is simulating real errors of considered CMM, this result has a purely random character. In case of running the created program on a real machine the results of evaluation are replaced by the results that were given by a real measurement.

Program created in this way was implemented at a real CMM. After the workpiece had been mounted on the machine, the manual coordinate system was built. The rest of the program was performed completely automatically. Measurements performed both on the simulator and on a real machine are illustrated in Fig.7. Except for workpiece installation and coordinate system reproduction, the operator had no other influence on the functioning of the machine. Program was executed to the very end without any obstacles, which proves that if the specified conditions between virtual model and real system are met, simulator could be used to program CMM in virtual environment.
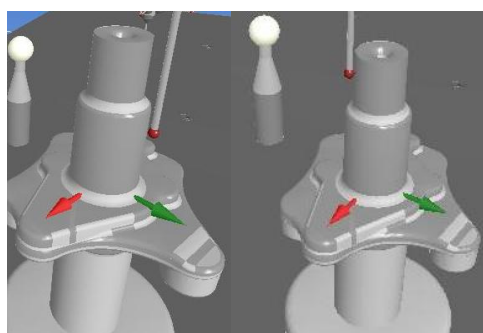

Fig.7. Measurements performed on: simulator and Leitz PMM 12106 machine.

4. GENERAL PROCESS OF CMM PROGRAMMING WITH USE OF I++ SIMULATOR

Researches described above contributed to the development of the general process of CMM programming using I++ Simulator (Fig.8.):

• Determination of the place and method of mounting of the workpiece on the machine table.

The position of the workpiece should provide easy access to all geometrical features that are going to be measured. Space around measured workpiece should be obstacle free in order to avoid collisions during approaches and retracts at measuring points. Workpiece mounting should be reliable to prevent accidental changes of workpiece position. If it is possible to measure object in specified position using I++ Simulator with defined probe configuration and certain machine model, it would be also possible to measure it on real machine with the same settings.

• Probe selection.

Chosen probes should be able to reach all measuring points gathered on the surface of measured object. Workpiece position on machine table as well as relative position of geometrical elements being measured should be considered in this step.

• Determination of the measurement sequence.

The purpose of defining a proper measurement sequence is to reduce total measurement time. It is reasonable to measure features that are located closely to each other, so that the time of probe head travel between them is as short as possible. In turn, a well-written measurement program can provide the minimum number of probe changes.

• Construction of manual coordinate system.

Appropriate construction of manual coordinate system is the most important phase of preparation for CMM programming. Properly created, it allows transferring the measuring program between various types of machines (in this case between simulator and Leitz PMM 12106). Manual coordinate system reproduced on another CMM allows proceeding with the rest of the program in automatic mode. No operator interference is necessary after this reconstruction.

• Construction of automatic coordinate system.

In this step, usually the automatic measurement of elements which were used to build manual coordinate system is programmed. Reproduction of coordinate system in automatic mode ensures better accuracy of measurement. However, manual and automatic system does not always have to be the same.

• Carrying out measurements.

Measurement points of selected geometrical elements have to be collected in accordance with the developed measurement procedure. It is also important to program the clearance points that are needed to move the machine around the workpiece without collisions.

• Evaluation of measurement results.

When the measurement is done, the set of features and relations which have to be evaluated should be chosen. The most of programs allow generation of report that gives in the graphical way a clear answer whether the measured object is consistent or not with the construction assumptions.
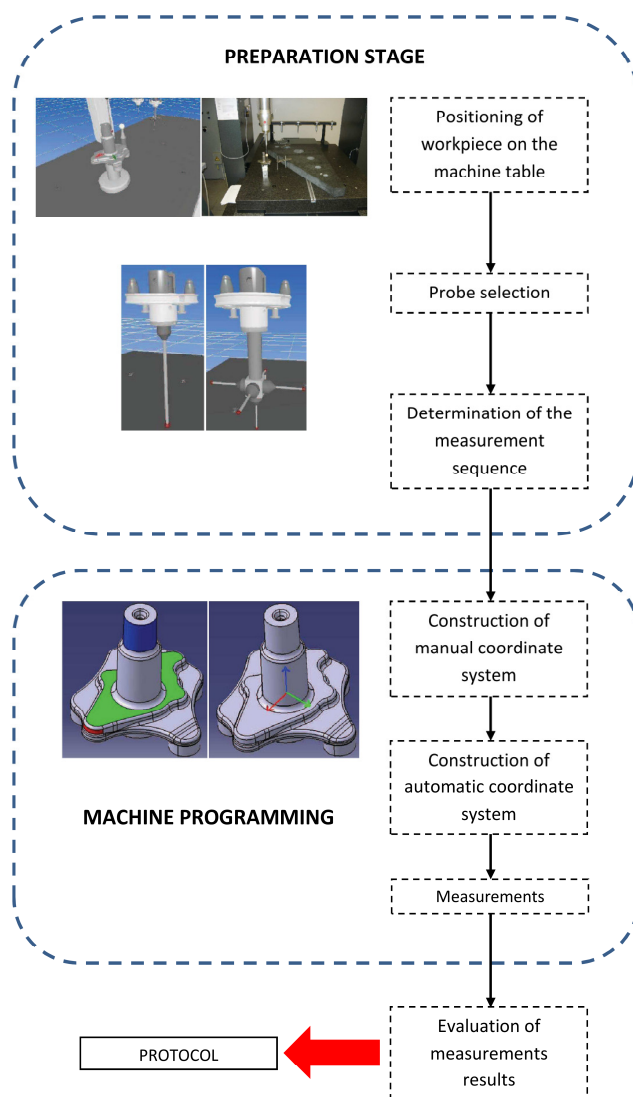

Fig.8. General process of CMM programming.

5. DIRECTION FOR FURTHER DEVELOPMENT - ENHANCING SIMULATOR BY THE ACCURACY MODEL

The biggest drawback of I++ Simulator is its rudimentary system of measurement accuracy reproduction. In its present form, the program does not take into account the real machine errors and errors introduced by probe head. Variability of the results obtained from measurement simulations depends only on inaccuracy of the creation of CAD models (limited resolution with which they could be saved in digital format) and the accuracy of the point acquisition parameter, which can be defined by the user.

The tests aiming at combining the I++ Simulator with one of the existing CMM accuracy models [11-15] are now performed at LCM.

The authors are implementing the accuracy model based on the Matrix Method (MM) conceived in LCM. The Matrix Method is based on the accuracy of measuring point reproduction, which was based and is consistent with the nature of coordinate measuring technique. For this purpose, the grid of reference points is constructed in the measuring volume of the considered machine, and the points located at

the nodes of this grid are described by the vector expressing the error of measuring point reproduction. In practice, the essence of this method is to measure the plate standard (hole plate or ball plate) placed in the measuring volume of CMM, in order to create a spatial grid of reference points, whose size and pitch correspond to those of used standard. The difference between the coordinates of centers of the shapes of individual components (holes or balls) obtained as a result of a standard calibration and those indicated by the tested CMM, gives a spatial grid of CMM errors (Fig.9.). It is a base for a matrix model of identification of CMM errors. Currently, due to the high development of laser tracking systems, the grid of reference points can be also built with their use.
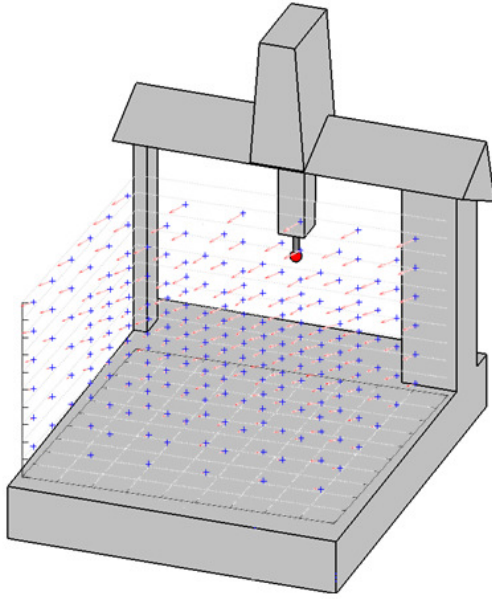

Fig.9. Spatial grid of measuring point reproduction error vectors.

Determination of the error of measuring point reproduction is associated with the vector character and presentation of error. As in the case of methods based on control length measurement the presentation of error consists of components derived from both the systematic and random errors [11].

First component is associated with the probing system - $\overline{p}_g$ while the second one comes from geometric errors of the machine - $\overline{p}_p$.

The source of the second error can be found in the 21 components of geometric errors pointed out in an analytical model of the machine. The vector of error of measuring point reproduction can be represented by (1):

$$\overline{p}_a = \overline{p}_g + \overline{p}_p \qquad (1)$$

At the same time, the vector of error of measuring point reproduction $\overline{p}_a$ can be characterized as vector starting between a real point of contact between the stylus and the measured object $\overline{p}_{rz}$, and the point indicated by the machine $\overline{p}_m$ - Fig.10. illustrates these two situations.
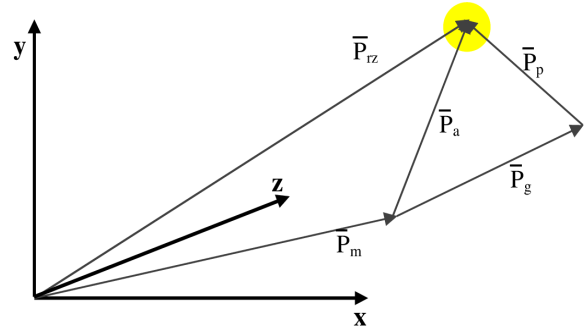

Fig.10. Error of measuring point reproduction $\overline{p}_a$.

This vector could be also given by (2):

$$\overline{p}_a = \overline{p}_{rz} - \overline{p}_m \qquad (2)$$

where:

$\overline{p}_a$ - vector of error of measuring point reproduction,

$\overline{p}_{rz}$ - position vector of the real contact point,

$\overline{p}_m$ - position vector of the point indicated by a machine

According to [11], full, defined for the whole measuring volume, model of accuracy of CMM can be adopted using the specified above $\overline{p}_a$ vector, applying it to the whole V space of dimensions R^3 in accordance with the machine's measuring range. Assuming that to each point $P (x, y, z) \in V \subset R^3$ the $\overline{p}_a$ vector is assigned, the vector field of errors takes the form described by (3):

$$\overline{p}_a(P) = \overline{i}\,p_{ax}(P) + \overline{j}\,p_{ay}(P) + \overline{k}\,p_{az}(P) \qquad (3)$$

where:
$\overline{p}_a(P)$ - vector of field of errors of reproducibility of the measuring point in P point of V space of given CMM,

p_{ax}, p_{ay}, p_{az} - the components of field of errors in Cartesian coordinate system of the CMM,

$\overline{i}, \overline{j}, \overline{k}$ - coordinate system axes versors.

In practice, it should be taken into account that, in fact, in addition to systematic factors, errors of reproducibility of the measuring point are also an outcome of other random factors. It is therefore necessary to further define the field of random errors.

If a coordinate system is specified in a three-dimensional space U, then a vector field of random errors $\overline{U}(p_a)$ can be written as (4):

$$\overline{U}(p_a) = \overline{i}\,U_x(p_a) + \overline{j}\,U_y(p_a) + \overline{k}\,U_z(p_a) \qquad (4)$$

where:
$U_x(pa),\ U_y(pa),\ U_z(pa)$ – uncertainty components in x,y,z coordinate system of error of measuring point reproduction
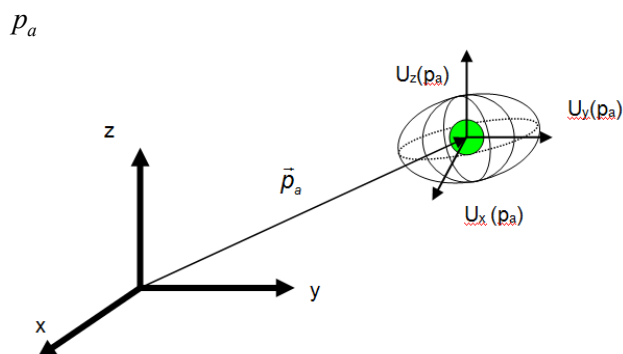
p_a

Fig.11. Three-dimensional random field of uncertainties of error of measuring point reproduction $\overline{U}(p_a)$ [11].

Taking into account the assumptions related to the same probability of occurrence of positive and negative random errors, and associated with a higher possibility of occurrence of smaller than large errors, it can be assumed that the random errors are normally distributed. According to [11], these errors in the measuring volume can be summarized as ellipsoid shown in Fig.11.

The $\overline{p}_a$ vectors are representations of systematic errors caused mainly by the kinematic errors of the machine. They can be estimated precisely using experiments mentioned above. The random errors are then the main contributors of uncertainty of point reproduction which is given using (4) and presented in Fig.11. as an ellipsoid. Considering the above facts, it can be assumed that the real points coordinates, that are included in the measurement, lay somewhere inside the ellipsoid presented in Fig.11. This area of coordinates reproduction constitutes the range of measuring point variability that can be used as a parameter describing kinematic accuracy of CMM and used along with the I++ Simulator.

Models based on descriptions given above were developed in LCM and described in [11] and [15]. Errors of kinematic system of the machine are determined using spatial standards or laser tracking systems, while probe head errors are determined in both cases by using spherical standards of relatively small diameter (less than 30 mm). In order to obtain the whole area of errors (the measurements aiming in determination of errors are conducted only in certain points, called the nods of reference points grid) the interpolation is needed. In the mentioned models it is done using the Monte Carlo Method or Neural Networks.

Model described in [15] was combined with the I++ Simulator and it passed through preliminary tests. Results showed that it is possible to simulate the whole measurement process, including the uncertainty evaluation using the created software. However, tests done so far were performed using simple communication algorithm that is based on the exchange of text files. In order to make the created system fully functional it is necessary to connect the I++ Simulator with accuracy model using the I++ DME Protocol. This work is in progress now and it will be described in future publications.

6. CONCLUSION

Coordinate measuring machines are now an indispensable tool of quality control systems. CMMs allow quick verification of an object compliance with geometric specifications contained in the technical documentation. Due to the high measurement accuracy and a wide range of possible applications, CMMs are becoming an increasingly popular solution. In some cases, the operator interaction with the machine during its programming may be difficult. In this situation, the I++ Simulator can provide invaluable assistance. This fact is confirmed by the experiment described in this article. With adequate conditions of compatibility between the virtual model of measurement and the real measurement, concerning mounting and orientation of the workpiece, the selection of the proper probes as well as the order of performed tasks, it is possible to transfer the measuring program created using the I++ Simulator to the real CMM. General process of CMM programming using simulator allows transferring the measuring program on the real machine. Results of the performed experiment give considerably high probability of obtaining good results in programming of micro and nano coordinate measuring machines and machines of high precision using the I++ Simulator.

The great advantage of the I++ Simulator is also its ability to connect with the majority of popular metrological systems by the I++ Protocol. It allows to program machines using a variety of metrological software types. In addition, the I++ Simulator combined with functionality of this software becomes a suitable tool used to train new operators of CMM without the necessity of wearing out the real machines.

As mentioned in the previous section, the direction for further development should be linking of the I++ Simulator with one of existing CMM accuracy models using the I++ Protocol. In this case, the results of simulated measurements will not only be the random values sampled from the range defined by the user but they will become results containing accuracy of measurements, which can be obtained during measurements performed on the real machines. Software created in this way will allow defining the optimal measurement strategy and optimal location of measured workpiece in measuring volume, so that the best possible measurement accuracy could be achieved.

REFERENCES

[1] Choi, K.S., Soo, S., Chung, F.L. (2009). A virtual training simulator for learning cataract surgery with phacoemulsification. *Computers in Biology and Medicine*, 39 (11), 1020-1031.

[2] Longo, F., Massei, M., Nicoletti, L. (2012). An application of modeling and simulation to support industrial plants design. *International Journal of Modeling, Simulation, and Scientific Computing*, 3, 1240001.

[3] Zheng, W., Zhenyu, L., Jianrong, T., Yun, F., Changjiang, W. (2006). A virtual environment simulator for mechanical system dynamics with online interactive control. *Advances in Engineering Software*, 37 (10), 631-642.

[4] Klingstam, P., Gullander, P. (1999). Overview of simulation tools for computer-aided production engineering. *Computers in Industry*, 38 (2), 173-186.

[5] Fowler, J.W., Rose, O. (2004). Grand challenges in modeling and simulation of complex manufacturing systems. *Simulation*, 80 (9), 469-476.

[6] Banks, J. (1998). *Handbook of Simulation: Principles, Methodology, Advances, Applications and Practice*. Wiley.

[7] Sładek, J., Szewczyk, D. (2012). Usage of I++ Simulator for didactic and research activities. *Measurements Automation Robotics [Pomiary Automatyka Robotyka]*, 4, 66-70.

[8] Gómez, E., Maresca, P., Caja, J., Barajas, C., Berzal, M. (2011). Developing a new interactive simulation environment with Macromedia Director for teaching applied dimensional metrology. *Measurement*, 44 (9), 1730-1746.

[9] Messtechnik Wetzlar GmbH. *I++ Simulator Manual*.

[10] Hong, S., Jung, M., Lee, K. (2006). An analytic method for detecting collisions to develop simulator of coordinate measuring machine. In *IJCC Workshop 2006 on Digital Engineering*, February 8-9, 2006. South Korea.

[11] Sładek, J. (2011). *Accuracy of coordinate measurement*. Cracow University of Technology.

[12] Ramu, P., Yagüe, J.A., Hocken, R.J., Miller, J. (2011). Development of a parametric model and virtual machine to estimate task specific measurement uncertainty for a five-axis multi-sensor coordinate measuring machine. *Precision Engineering*, 35 (3), 431-439.

[13] Wilhelm, R.G., Hocken, R., Schwenke, H. (2001). Task specific uncertainty in coordinate measurement. *CIRP Annals – Manufacturing Technology*, 50 (2), 553-563.

[14] Trapet, E. et al. (1999). *Traceability of coordinate measuring machines according to the method of the virtual measuring machine*. PTB-Bericht F-35, Braunschweig, Germany.

[15] Sładek, J., Gąska, A. (2012). Evaluation of coordinate measurement uncertainty with use of virtual machine model based on Monte Carlo method. *Measurement*, 45 (6), 1564-1575.