2013 XXIV International Conference on
Information, Communication and Automation Technologies (ICAT)
October 30 – November 01, 2013, Sarajevo, Bosnia and Herzegovina

Robotic manipulation in dimensional measurement

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***Abstract*—Three dimensional measurement of complex geometry with Coordinate measuring machines (CMMs) requires multiple clamping and fixturing of measured object. In order to speed-up this process and to reduce the number of fixturing operations, a robotic arm can be used to manipulate the measured object. This paper describes measurement uncertainty analysis of an improved complex measurement system consisting of robotic arm and the coordinate measuring machine.**

***Keywords*—dimensional measurement; robot; coordinate measuring machine (CMM); measurement uncertainty**

I. INTRODUCTION

Dimensional measurement in product testing by means of three-dimensional Coordinate Measuring Machine (CMM) is a requirement imposed to any manufacturer of automotive parts in today's global market. In order to have reliable and traceable test results, all measurements should be performed by sophisticated measurement systems. Automotive parts often have very complex geometry, and their measurements can be complex and time-consuming. CMMs with touch-probes can be reconfigured to access any surface of measured object's geometry, but object's shape can require multiple measurement phases, with separate fixturing. Any fixturing process slows down the measurement process, and it would be desirable to have the possibility of measured object manipulation. Some specialized measurement machines already have simple manipulation capabilities (i.e. roundness testers have rotating table to manipulate measured object - see Fig.1), but this manipulation is still limited.

CMM is an automated measuring device for dimensional measurements. Positioning of the measured object is performed manually, and various clamping accessories are used to fixture the measured objectin proper position. The dimensions of measured object are controlled from several different sides, and its geometry can require changing positions of the measured object. The measured object has to be positioned relative to measuring device, which requires complex and time-consuming actions. Each time when position change is required, the local coordinate system should be redefined. That causes increase of costs of product testing. In order to simplify testing procedure and to reduce costs, several options for positioning measured object inside working area of CMM using industrial robot were considered.

Fig. 1. Marform roundness tester has rotating table with limited capabilities of measured object manipulation (source: www.mahr.de)

The idea in this research is to use a robot to manipulate measured object, in order to be able to reach any geometrical feature, when CMM with touch-probes is used. The main purpose of such system is to extend measurement capabilities, while keeping the measurement reliability within allowable limits. The similar analysis was presented in [1], where we showed that it is possible to use an industrial robot to extend the manipulation capabilities of a coordinate measuring machine. We also pointed out some important aspects which should be taken in consideration, such as: conditions of university laboratory, the bonding of CMM and the robot, vibrations caused by robots instability, limited reach of the robots arm due to its position relative to CMM, and mechanical impacts on CMM. The major drawbacks of research presented in [1] were excessive vibrations, due to poorly realized bond between CMM and robot. Experiment presented in this paper was improved by different configuration which avoided unwanted vibrations of robot induced by CMM touch-probe movement.

The first similar research was conducted by Santolaria and Aguilar [2]. They presented the survey about the development of kinematic modeling of robotic manipulator and AACMM (Articulated Arm Coordinate Measurement Machine). They analyzed the influences of chosen model onto procedure

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parameters. Their optimization algorithm was based on presented accuracy and repeatability of the procedure. They developed the algorithm which followed the simple data optimization scheme, and they obtained the input data by measuring several spheres placed on various positions within the working area of both systems.

The integration of robot and CMM was performed for the first time in 2003 by Mitutoyo Company [3]. They developed special software module in order to adjust the actions of CMM and robotic handling machine used for manipulation of measured objects. Mitutoyo has released the source code with the hope that third party software vendors will develop products based on it. As of our knowledge, no accomplishments in this field were published until now.

Hansen et al. in [4] estimated measurement uncertainty of hybrid system consisting of Atomic force microscope attached to coordinate measuring machine, using linear combination of these two components. Although their system is also combination of two devices, their approach differs from ours; we used one system to position the measured object, and they used two-component system to perform the measurement.

The most common indicator of measurement quality and reliability of measurement results is standardized as measurement uncertainty. A number of researchers analyzed the measurement uncertainty of a CMM.

Aggogeri et al. in [5] used simulation and planned experimentation to assess the measurement uncertainty of CMM. They identified and analyzed five influence factors, and showed that the simulation can successfully be used to estimate the CMM uncertainty.

Weckenmann et al. in [6] investigated how measurement strategy affects the uncertainty of CMM results. They defined the measuring strategy as "operator influence" which was neglected in other researches. They have shown that measuring strategy influences CMM's uncertainty, and that significantly larger number of touch points can overcome this influence.

Wilhelm et al. in [7] also investigated the influence of measurement strategy. They defined it as the "task specific uncertainty". They also showed that virtual CMM, using Monte Carlo simulation, can be used to estimate uncertainty. Although they mentioned that part fixture could influence the uncertainty, they avoided to analyze it thoroughly.

Feng et al. in [8] applied the factorial design of experiments (DOE) to examine the measurement uncertainty of a CMM. They also studied the effect of 5 factors and their interaction, and showed that there is statistically significant interaction of speed and probe ratio. They also gave some recommendations , showing that uncertainty is minimized when the speed is highest, stylus length is shortest, probe ratio is largest, and the number of pitch points is largest.

Piratelli-Filho and Giacomo in [9] proposed the approach based on a performance test using a ball bar gauge and a factorial design technique to estimate CMM uncertainty. They investigated the effect of length, position, and orientation in work volume on CMM measurement errors. The analysis of variance results showed a strong interaction between the orientation and measured length.

Unlike abovementioned researches, the goal of this research was to estimate if robot can be used to position the measured object in complex measuring system CMM-robot. For this purpose, the measurement uncertainty analysis according to GUM (Guide to the expression of uncertainty in measurement) [10] was used.

II. MOTIVATION FOR RESEARCH

Fig. 2 shows an example of an assembly used to clamp the measured object in a CMM. During measurements, this system requires multiple clamping operations between measurements, especially if the part's geometry is complex and some surfaces are inaccessible by CMM touch-probes. Products with complex geometry (Fig. 3) can only be measured in multiple steps, with repositioning of measured object. That requires further actions, such as local coordinate system redefinition.

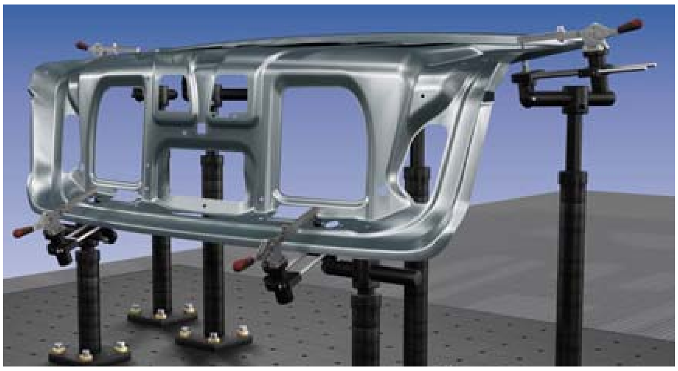

Fig. 2. An example of fixturing assembly for CMM measurements of automotive components (source: www.zeiss.de)

Fig. 3. Complex geometry is difficult to measure by CMM without multiple time-consuming repositioning and reconfiguration (source: www.zeiss.de)

The chosen position of the measured object and the optimal combination of touch-probe stylii often prevent the CMM's touch-probes from coming into contact with the measured object. The obscured surfaces can be difficult to reach without repositioning the measured object.

We analyzed the measurement uncertainty when robot is used to reposition the measured object. We performed the measurements with two different configurations:

1. Measuring object fixed to CMM table;

2. Measuring object manipulated by robot, in various positions of robot arm.

In order to quantify the quality of the measurement process, we estimated the measurement uncertainty for these two systems, and compared them with the uncertainty of the robot and the CMM as stated by the manufacturers.

The objective of this research was to improve the capabilities of CMM machine, by shortening the measurement procedure and reducing the measurement cycle duration. Simultaneously, we intended to quantify the measurement quality through uncertainty analysis of two different systems used in this experiment.

III. EXPERIMENTAL SETUP

A. *Equipment used in experiment*

The three-dimensional coordinate measuring machine Zeiss Contura G2 700 Aktiv with tactile probing system was used in this research (measurement range: 700 x 1000 x 600 mm, measurement uncertainty estimated according to ISO 10360-2 is MPE_E = 1.8+L/300 μm, MPE_P = 1.8 μm).

The positioning and rotating of the measured object was performed manually, inside the CMM’s workspace, with an educational robot having five degrees of freedom, Robot RV-2AJ, manufactured by Mitsubishi Electric–Melfa robots, Japan. The measurement uncertainty of this robot is not stated by the manufacturer; the only comparable parameter is repeatability, stated to be ±0.04 mm. The robot is a stationary robotic system, with programmed motion path and automatic determination of the target.

B. *Experiment environmental conditions*

All measurements were performed with the conditions and capacities available at the laboratory for dimensional measurements at the Mechanical Engineering Faculty, University of Zenica. The temperature during the experiment was 21°C. The workpiece and CMM measuring elements were cleaned prior to measurement in order to remove possible contaminants. There were no other machines in the vicinity of the CMM; nor were there any other vibration sources (except the CMM’s and robot's own vibrations). Prior to measurement, the calibration of the measuring tools and measuring system was performed using 25 mm ceramic reference sphere manufactured by Zeiss, using the calibration procedure defined by CMM software Calypso (Fig. 4).

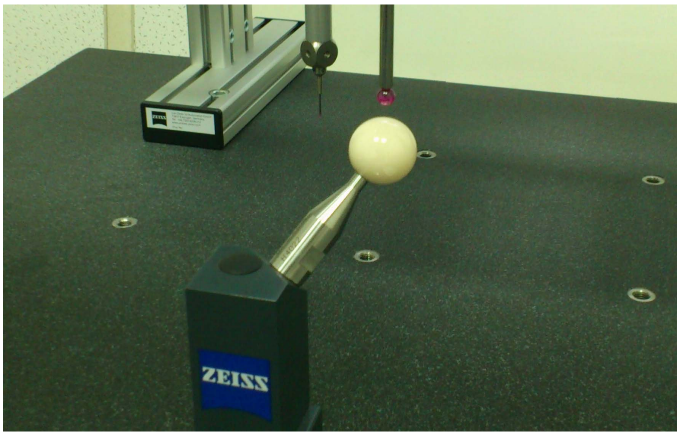

Fig. 4. Calibration with ceramic reference sphere

C. *Measured object description*

The measured object in previous experiment (Fig. 5) was selected to have geometrical features typically found in coordinate measurements: planes, cones, and cylinders.

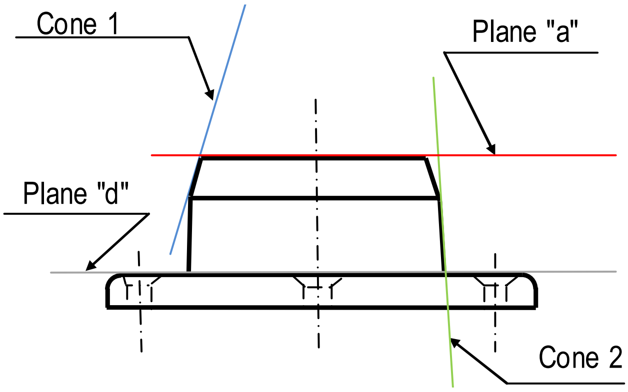

Fig. 5. Geometric features measured by CMM in previous experiment [1]

In order to minimize errors induced by manufacturing technology or other product deviations, a measuring gauge was used in this experiment (Fig. 6). Only one dimension was measured (internal diameter D) in different configurations of measurement system.

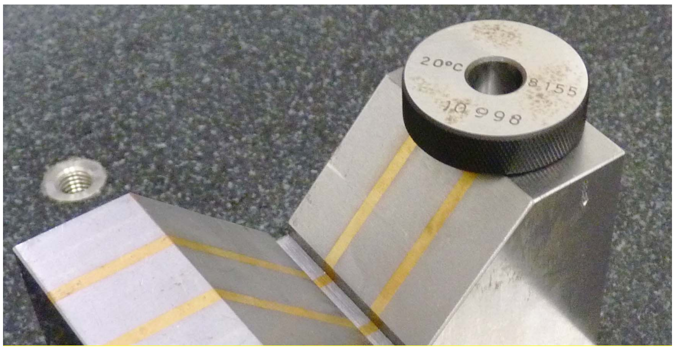

Fig. 6. The measurement gauge (internal diameter D = 10.998 mm) used as measured object, attached in fixed position by magnetic holder.

D. Positioning

The robot's position compared to CMM was limited by the robot's arm-reach limit or its workspace. Accordingly, the robot was positioned and fixed in an optimal position. This position was defined by relative angular rotation in the arm's joint, and the position and orientation of the grippers in the space, ensuring correct performance of the given assignment. In previous experiment [1], the robot was attached to the CMM's granite table using Z-shaped profile elements with firm screw connections. That lead to transfer of unwanted vibrations from CMM to robot, increasing uncertainty. To avoid that, we disengaged robot from CMM, providing fixed position of robot's stand without direct connection between the robot and the CMM.

Control of the robot was semiautomatic. The control program for piece positioning was followed with manual triggering of each measuring phase. After the robot trapped the measured object with the pneumatic gripper, it was then moved into a position enabling measurement with a single stylus system.

E. Measured geometry

Dimensional measurements were repeated 25 times, under the same conditions, in order to compensate random errors. The number of measurements (the size of the sample) was determined according to the significance level of the test $\alpha = 0.01$ and the probability of failing to detect a shift of one standard deviation $\beta = 0.01$ for a two-sided test, assuming normal distribution and known standard deviation [11].

The diameter D of cylindrical surface on measurement gauge was measured by set of 500 points distributed circularly. The measurement results were used to estimate the measurement uncertainty, as a measure of validity of the results. The first measuring cycle was performed on a CMM with the measuring object fixed on the CMM's granite table. The second cycle was measured by the complex CMM-robot system, in two positions of robot arm.

IV. MEASUREMENT UNCERTAINTY

A measurement result is complete only when accompanied by a quantitative statement of its uncertainty [12]. The uncertainty is required in order to decide if the result is adequate for its intended purpose and to ascertain if it is consistent with other similar results. To overcome the variation in approaches, the International Organization for Standardization (ISO) developed a detailed guide which provides rules on the expression of measurement uncertainty for use within standardization, calibration, laboratory accreditation, and metrology services. The Guide to the Expression of Uncertainty in Measurement (GUM) was published in 1993 (corrected and reprinted in 1995) by ISO, and approved as an European Standard in 1999 [10]. The newest published version is a standard JCGM 100:2008 produced by Working Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG 1). The focus of GUM is the establishment of general rules for evaluating and expressing uncertainty in measurement that can be followed at various levels of accuracy and in many fields - from factories to fundamental research.

Uncertainty of measurement, according to GUM, is the parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand [10]. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion. The measurement uncertainty can be either Type A or Type B. Type A evaluation of uncertainty is performed by the statistical analysis of series of observations. Type B evaluation of uncertainty is performed by means other than the statistical analysis of series of observations.

The coverage factor is a numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty. Expanded uncertainty is quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

The measurement uncertainty of Coordinate Measuring Machines was analyzed in a number of references. Lawford [13] compared the influence of software onto measurement results. Fang, Sung and Lui in [14] observed the influence of measurement uncertainty from CMM calibration and the importance of working environment temperature. Zhang et al. [15] described the error compensation on bridge-type CMM, which resulted in improvement of accuracy by the factor of 10.

V. EXPERIMENT

In the first measuring cycle, the measured object was positioned and fixed to the CMM's measuring table (Fig. 6), and in the second cycle the position of the measured object was defined by the robot's arm position (i.e., auxiliary elements in the robot's arm were holding the measured object) inside the CMM's coordinate space. The robot's arm holding the measured object moved from one position to another and back again, between each two measurements.

The coordinates of the robot's arm in both positions were defined by the robot's off-line programming in such a way that the robot could be positioned manually and that position memorized. Figs. 7 and 8 show the first and the second robot arm positions, respectively.

Fig. 7. Robot arm position 1

The measured object (measurement gauge) was attached to robot's arm by pneumatic holder. The positions 1 and 2 were chosen to simulate the allowable position limits. In real application, robot's arm should be moved within these limits, taking different orientations with regard to touch-probe head of the CMM.

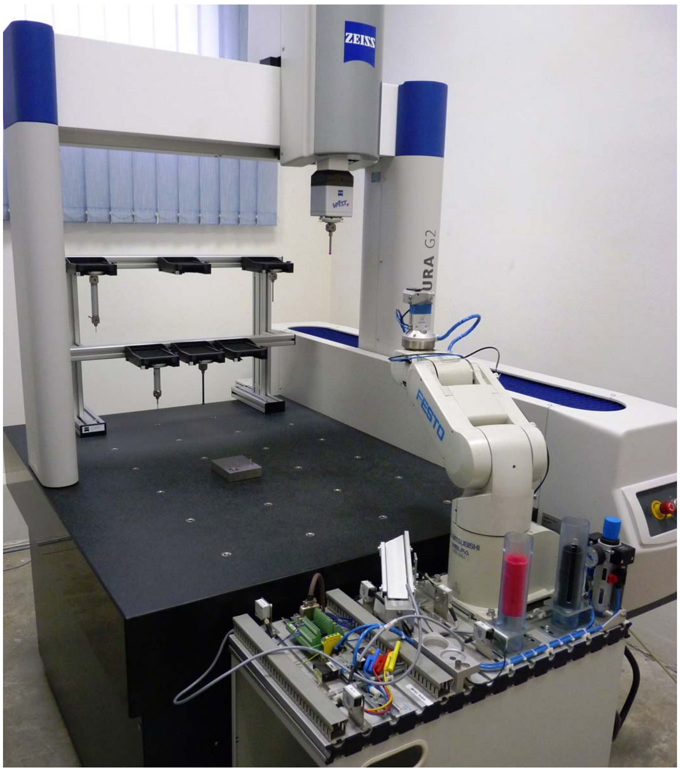

Fig. 8. Robot arm position 2

VI. MEASUREMENT RESULTS

Measurement results are shown in Table I.

TABLE I. PARTIAL MEASUREMENT RESULTS - THREE CASES OF MEASUREMENT SETUP WITH STATISTICAL PARAMETERS

Result No.	**Measured values (mm)**		
	Case 0 (CMM only)	***Case 1 (CMM-robot, leftmost position)***	***Case 2 (CMM-robot, rightmost position)***
1.	10.99921	10.99936	10.99893
2.	10.99925	10.99921	10.99895
3.	10.99921	10.99910	10.99904
...	...	...	...
23.	10.99930	10.99902	10.99913
24.	10.99923	10.99933	10.99931
25.	10.99925	10.99901	10.99910
Mean value	10.99923	10.99918	10.99911
Standard deviation	0.00004	0.00012	0.00014
Max.	10.99932	10.99939	10.99940
Min.	10.99917	10.99898	10.99893

A. *Measurement uncertainty*

The declared measurement uncertainty of the CMM used in this experiment is ±1.80 µm. In all three cases we assume only Type A standard measurement uncertainty, which equals standard deviation times coverage factor 2. The standard measurement uncertainties of three measurement cycles are shown in Fig. 9.

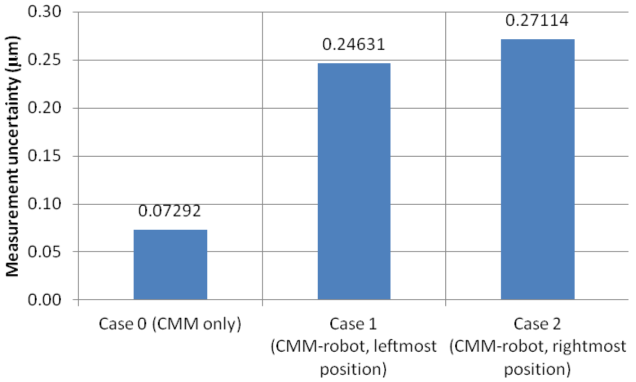

Fig. 9. The standard measurement uncertainties of three measurement cycles

We can conclude that all measurements expressed lower uncertainty than stated on the CMM’s calibration certificate, due to stable laboratory conditions. The measurement results in cases 1 (±0.25 µm) and 2 (±0.27 µm)show that measurement uncertainty of the system CMM-robot is significantly larger than the uncertainty of the case 0 (±0.07 µm), where object was fixed to CMM's granite table, but still below the machine's declared value (±1.80 µm).

B. *Statistical analysis*

The first step in statistical analysis was to question the normality of distribution of the measurement results. Kurtosis of all results was between -1.11 and 0.84, and the skewness ranged between 0.20 and 0.87. For 25 samples, the standard error of the skewness is 0.49 and standard error of the kurtosis is 0.98; therefore, both skewness and kurtosis are lower than twice the standard error, and we can assume normal distribution of measured data.

Statistical t-test (Paired Two Sample for Means) was used to check the correlation between results obtained in the case 0 (measurements performed on fixed measured object using only CMM) and in two positions of robot's arm (cases 1 and 2 of measurement obtained by the system robot-CMM). The results for statistical analysis are shown in Table II. These results lead to conclusion that Hypothesis 0 (Uncertainty of measurement for complex measuring system CMM-robot is within limits of allowed uncertainty of measurement of CMM) should be rejected, since P-values for both one-tail and two-tail are significantly lower than critical value of t-variable for sample size of 25.

The Pearson correlation factor for all cases is very small compared to critical values, and we can conclude that there is no statistically significant correlation between pairs of results measured by CMM with fixed part and results measured by the system CMM-robot.

TABLE II. THE RESULTS OF THE STATISTICAL T-TEST: PAIRED TWO SAMPLE FOR MEANS

	Case 0 - Case 1 (CMM-robot, leftmost position)	*Case 0 - Case 2 (CMM-robot, rightmost position)*
Pearson Correlation	-0.40	0.03
t Stat	1.93	4.51
P(T<=t) 1 tail	0.03	7.24E-05
t Critical 1 tail	1.71 (α<0.05)	
P(T<=t) 2 tail	0.07	1.45E-04
t Critical 2 tail	2.07 (α<0.05)	

In absence of linear relationship between the two variables, we also tested the Spearman's rank-order correlation between the cases 0 and 1, and cases 0 and 2.

TABLE III. THE RESULTS OF THE SPEARMAN'S CORRELATION TEST

	Case 0 - Case 1 (CMM-robot, leftmost position)	*Case 0 - Case 2 (CMM-robot, rightmost position)*
r_s	-0.4211	-0.0848
t (α<0.05)	-2.23	-0.41
P one-tailed	0.017897	0.3428
P two-tailed	0.035794	0.6856

As shown in Table III, the calculated Spearman correlation coefficient r_s is negligible in the rightmost position, and expresses weak negative association in the leftmost position. This is logical, since the leftmost position is closer to the fixed position of measured object, while the rightmost position, when the robot's arm is stretched to the maximum, causes increased uncertainty.

C. *Discussion*

When these results are compared with the results from previous experiment presented in [1], one can conclude that we obtained significantly better results. Most of the drawbacks questioned in [1] were eliminated, and we obtained the complex measurement system within declared measurement uncertainty limits of the machine itself. This experiment showed that it is possible to use an industrial robot to extend the manipulation capabilities of a coordinate measuring machine, and to stay within the uncertainty limits of the coordinate measuring machine.

The measurement setup presented in [1] had some drawbacks; the most significant drawback was the rigid bond between the robot and CMM's granite table. The bond transferred the vibration from CMM to robot, which increased the measurement uncertainty. Fig. 10 shows collections of 4 measured dimensions with assigned uncertainties. It is obvious that the worst case has unacceptable uncertainty, which is slightly improved when stabilizing mass is added to robotic arm. The measurement setup presented in this paper lead to significantly lower uncertainty, as seen in Fig. 9.

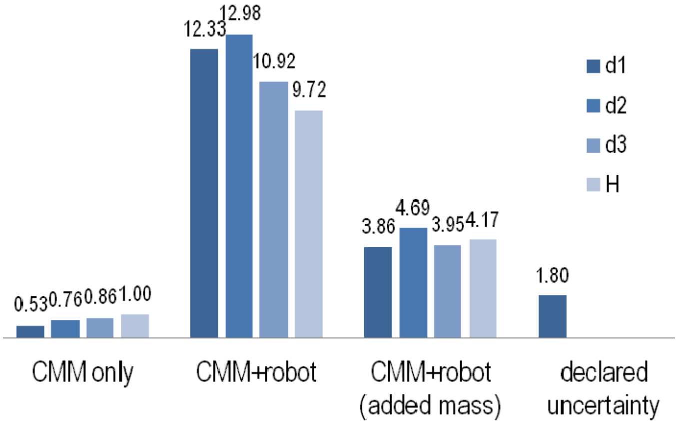

Fig. 10. The standard measurement uncertainties in previus experiment [1]

CMM's granite table provides vibration-free measurement system. However, when robot is physically attached to the table, vibrations increase uncertainty. The configuration where the robot is fixed to the ground, without a physical connection to the CMM granite table, drastically increased the measurement system's stability, reduced vibrations and lowered the measurement uncertainty.

One of drawbacks of both experiments is the limited reach of the robot's arm due to its position relative to the CMM. By using a different type of robot, it would be possible to increase the overlapping workspace zones of the robot and the CMM, thus increasing the robot's reach.

A deeper and more detailed measurement uncertainty analysis, using both Type A and Type B errors, and taking into consideration correlation of influence factors, should also be performed, in order to give a more general foundation for testing the complex measurement systems. It would also be desirable to compare this approach with the manually positioning of the measured object. In addition to measurement errors, it would be interesting to test the time required to complete the task and the variance between different operators.

VII. CONCLUSION

The principal idea of this paper was to extend the possibilities for automating the measurement process with coordinate measuring machines, and to reduce errors spotted in the previous research. The most often limitation of CMM measurements occurs due to measured object geometry. If the shape of the measured object is complex, that requires a number of measurement sequences, in order to reach obscured surfaces on the measured object. Measurements of such objects in CMM are possible, but they require manual repositioning of the measured object, including redefinition of the local coordinate system, which drastically slows down the process and prevents measurement process automation. The major goal is to keep the measurement uncertainty within allowable limits. The results of measurement performed on object manipulated by robot were compared with the results obtained by measuring the same object fixed in the CMM. The obtained measurement results have acceptable accuracy and precision, and they have met the criteria of the declared measurement uncertainty of a coordinate measurement machine.

ACKNOWLEDGMENT

This research was supported in part by the Ministry for Education and Science of the Federation of Bosnia and Herzegovina. It was realized as a part of a research project "Application of industrial robots for positioning of the measured object to the Coordinate measuring machine" at the Laboratory for measurements within the Chair for Automation and Metrology at the University of Zenica.

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