SPC as an instrument for implementation and MSA as an instrument for evaluation of non-linear object based temperature compensation into Shop Floor CMM

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Abstract— **Trends for the application of Shop Floor Coordinate Measuring Machines (CMMs) in a changing ambient environment are driving new requirements for them. This necessitates the outcome of proven methods to provide improvement to enhance the metrological and performance characteristics of Shop Floor CMMs. To evaluate the stability of the measurement process we use SPC through which we implement nonlinear temperature compensation of the objects with complex form and multi material combination. To evaluate the result, we use an adapted MSA methodology applied before and after the introduction of temperature.**

Keywords— Coordinate Measuring Machine (CMM), Measuring system analyze (MSA), temperature compensation, SPC (statistical process control), OBTC (object based temperature compensation)

I. INTRODUCTION

Coordinate metrology takes center place in high-tech industries. Coordinate Measuring Machines (CMMs) are now an integral and fundamental part of the entire product development life cycle - the design, manufacture, control and maintenance of precision products. The close relationship with aerospace and automotive industry necessitates the need to follow standard GPS and ISO standards. New trends give Shop-floor CMM an important role as they allow control to be moved to the machine tool directly in production and processes can be monitored and adjusted online. This is in direct relation to modern quality management systems such as Six Sigma & Lean manufacturing.

Modern quality control systems are associated with the use of various tools for statistical control (SPC - Statistical process control) and analysis of measurement systems (MSA). In combination with current geometric tolerances that were getting lower and lower, advance automotive materials and GD&T methods, the industry needs more accurate and more reliable CMM which continue to improve day by day.

To improve the metrological and operational characteristics of Shop-Floor CMM we will use previous studies on the term: Object Based Temperature Compensation for “Shop floor” CMM, Journal of Mechanical Engineering Research and Developments, ISSN: 1024-1752 Published Year 2021., as we will apply SPC as an instrument for implementation and MSA as an instrument for evaluation of non-linear object based temperature compensation.

II. PARAMETERS INFLUENCING THE RESULTS OF COORDINATE MEASUREMENTS

To ensure that the accuracy of the CMM conforms to requirements, it is usually necessary to perform acceptance checks and verify the measurement characteristics of the CMM through measurement calibration procedures. The GPS ISO10360-2 series of standards defines the evaluation of CMM performance and gives the relevant performance parameters and methods for evaluating the measuring instrument. The technical parameters corresponding to the operational parameters are normally presented by the maximum tolerance errors. In practical measurements, the maximum permissible error of the readings (EL, MPE) is mainly related to the errors of the distance and other dimensional elements, and the MPEP indicates the error of the whole measuring system in a small test space, usually affecting the measurement of the shape [23]

Control results with the shop-floor CMM are limited by outliers and some uncertainties. Measurement deviations in coordinate metrology can be related to various influencing factors that represent the professional qualities and concentration of the operator, changes in the environment, and specifics of the workpiece manufacturing technology and the accuracy of the CMM. [17]

CMMs are widely used highly accurate and reliable systems for controlling the geometric dimensions and characteristics of the object being inspected. They can be operated manually by an operator, but the priority is to be automated and computer controlled based on a previously made or generated program.. [21] For Shop Floor CMM there are “Fixed” CNC programs for eliminating the operator's direct influence on the result and reducing uncertainty. For the aim of current study we ignore this uncertainty.

There are many parameters that affect the results of coordinate measurements. Some of these parameters, just like ambient temperature and complex form of measured part, have a greater influence on the shop floor CMMs than on the laboratory CMMs. We could modify the measurement strategy specifically oriented to the CMM in the workshop to reduce the influence of the object and the environment in the part of the shape deviation caused by the used materials and complex surfaces as well as by temperature fluctuations. The specificity of the workshop CMMs is related to the operation in automatic mode, which reduces the influence of the

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operator to the level of placing the measured object in the fixture and to visual inspection for contaminations. The measurement strategy remains constant and does not affect the CMM parameters over time. As far as the technical specification of the CMM is concerned, we believe that accuracy and reliability remain constant over time under constant or slightly changing conditions as a function of the environment.

III. SHOP FLOOR CMM UNCERTANTY REDUCTION BY OBTC

The developments in CMM should be progressive in order to thrive in ever expanding competitive market. Last decade, the development expectations for CMM were that they should be more flexible, efficient and intelligent enough to meet fluctuating demands of customers. [18] Nowadays CMMs should become more massive used out of laboratory and to provide flexibility. For this possibilities CMM should meet requirements of industries. As an improvement goal, we can use the reduction of uncertainty induced by measuring object and environmental condition as a part of factors responsible for uncertainties associated with CMM measurement (Figure 1. Factors responsible for uncertainties associated with CMM measurement) and in particular that related to Shop Floor CMMs.

When taking into account whether a CMM meets its specification, the uncertainty of measurement needs to be considered and ISO 14253 decision making rules applied. Most important is the uncertainty to be calculated. The recommended equation for the standard uncertainty of the probing error, u(P) is[10]:

$$u(P) = \sqrt{\left(\frac{F}{2}\right)^2 + u^2(F)} \qquad (1)$$

Where F is the form error reported on the calibration certificate of the test sphere and u(F) is the standard uncertainty of the form error stated on the certificate. The recommended equation for the standard uncertainty of the error of indication, u(E), is[10]:

$$u(E) = \sqrt{u^2(\varepsilon_{cal}) + u^2(\varepsilon_\alpha) + u^2(\varepsilon_t) + u^2(\varepsilon_{align}) + u^2(\varepsilon_{fixt})} \qquad (2)$$

Where ε_{cal} is the calibration error of the slip gauges; ε_α is the error due to the input of the CTE of the slip gauges; ε_t is the error of the temperature of the slip gauges; ε_{align} is the error due to the misalignment and ε_{fixt} is the error due to the fixturing of slip gauges.

These standard uncertainty calculation methods can be adapted to Shop Floor CMMs requirements by adopting the uncertainty components as follows: ε_{align} = RMS (Root Mean Squared) error of the difference between the datum features from the CAD model and the measured features, which reflects alignment. At the beginning, reference elements (features) must be defined and linked to the model. We then calculate the RMS to determine how well the real elements (features) match the CAD model; ε_α - is the error due to the input of the CTE (coefficient of thermal expansion) of the material of object as a function of temperature fluctuation and inseparable part from Δ_t:

$$\Delta_t = \varepsilon_\alpha + \varepsilon_\varphi + \varepsilon_t \qquad (3)$$

Where: ε_φ - is error caused of form and material of object as a function of temperature fluctuation; ε_τ - temperature measuring device error (0,3÷0,5℃), which for the purposes of the study can be neglected because it does not significantly affect the measurement result for relatively small object sizes (Ø200mm or less)

$$\Delta_t = \varepsilon_\alpha + \varepsilon_\varphi \qquad (4)$$

We could represent OBTC as a length measurement according to Length tests from calibrated artefacts: [3]

$$L_m = L + bias \pm E_{L,MPE} \qquad (5)$$

We could adapt this mathematical model from prospect of Shop Floor CMMs, non standard length object and error between point A (at temperature 20°C) and point A(t) (at temperature different from 20°C):

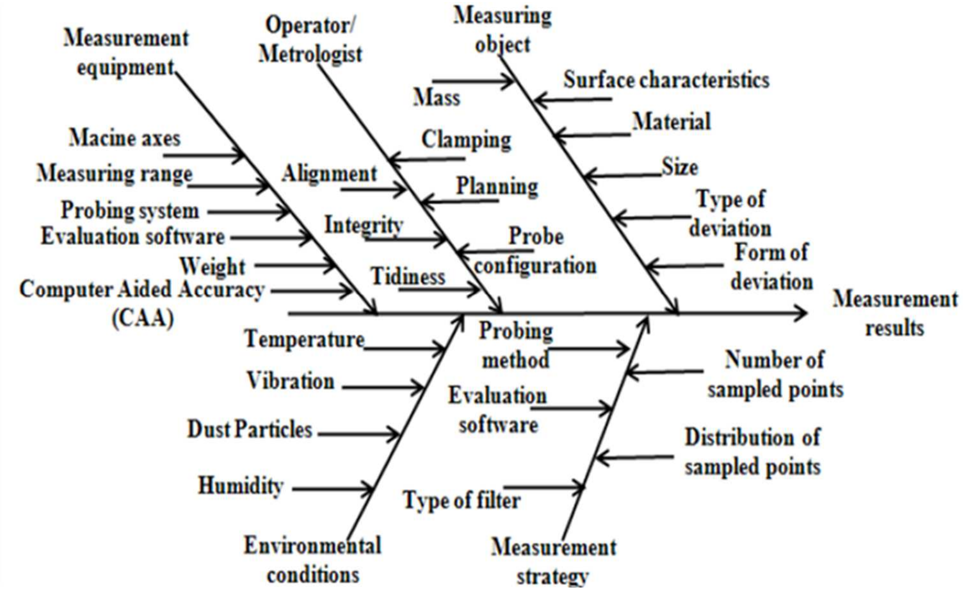


Fig. 1. Factors responsible for uncertainties associated with CMM measurement [18]

$$L_A = L_0 + bias \pm E_{L,MPE} \quad (6)$$

Where: L_0=real (unknown) position; Bias – deviation of the results from measured object; $E_{L,MPE}$ is length maximum permissible error.

Position of point A as a function of temperature fluctuation is:

$$L_{A(t)} = L_A \pm \Delta_t \quad (7)$$

And could also be calculated from temperature error caused by CTE and the form of the object:

$$L_{A(t)} = L_A \pm (\varepsilon_\alpha + \varepsilon_\varphi) \quad (8)$$

$$L_{A(t)} = L_0 + bias \pm E_{L,MPE} + \Delta_t = L_0 + bias \pm E_{L,MPE} \pm (\varepsilon_\alpha + \varepsilon_\varphi) \quad (9)$$

The differential change of the position:

$$\delta L_{A(t)} = L_{A(t)} - L_A = L_0 + bias \pm E_{L,MPE} + \Delta_t - L_0 - bias \pm E_{L,MPE} = \theta \pm (\varepsilon_\alpha + \varepsilon_\varphi) \quad (10)$$

Where: Θ- Coefficient of correction function of $E_{L,MPE}$

For an object of more than one material $\varepsilon_\alpha \neq$const. is nonsystematic error and couldn't be compensate by linear temperature compensation for CTE

For an object of one material ε_α=const. is systematic error corrected because the software of modern CMMs there are linear temperature compensation for CTE

$$L_{A(t)} = \theta \pm \varepsilon_\varphi \quad (11)$$

The expanded uncertainty U(P) from serial repeated measurements could be easily present as standard deviation σ of the results which are not include in mathematical model:

$$\sigma = \sqrt{\frac{\sum_{i=n}^{n}(L_{A(t)_i} + \overline{L_{A(t)}})}{n}} \quad (12)$$

Where: $\overline{L_{A(t)}}$ is average from n measurement [2]

$$L_{A(t)} = \theta \pm \varepsilon_\varphi \pm \sigma \quad (13)$$

Object based temperature compensation could be calculated as a coefficient of correction (Θ) and error caused of form and material of object (ε_φ) as a function of temperature fluctuation.

IV. TEMPERATURE ORIENTATED SPC

The SPC is a basic statistical tool for verifying the conformity of technical requirements of products. Even in robust manufacturing processes, quality characteristics are associated with randomness due to the presence of uncontrollable (or difficult/costly to control) input variables. Common cause variability is considered an inherent part of the production process and cannot be changed without changing the process itself. [16] SPC implies application of statistical methods for identification and control of special causes of variation in the process via observed significant factors and indicate process behavior changes in order to eliminate the potential problem on time, before it occurs [20]. The application of SPC can help us identify and report the root cause of measurement process disturbances in the shop floor CMM as a function of time.

Temperature is the most critical of all the environmental factors. The effect of ambient temperature changes should not be underestimated because it has a large influence on the result and is a major component of the uncertainty. Deformation, caused by temperature fluctuations and spatial temperature gradients over time, is very difficult to predict or to simulate quantitatively. [12] Deviations from the reference temperature of 20°C (ISO 1:2016 [4]) results in variations of length, form and position of measured features and cause uncertainty of the Shop Floor CMM. Due to the fact that the advance automotive materials have big difference in coefficients of thermal expansion and the new trends in the construction of the parts combined with the trends in control according to GD&T cause unexpected temperature deformations in wide range of fluctuation of ambient temperature.

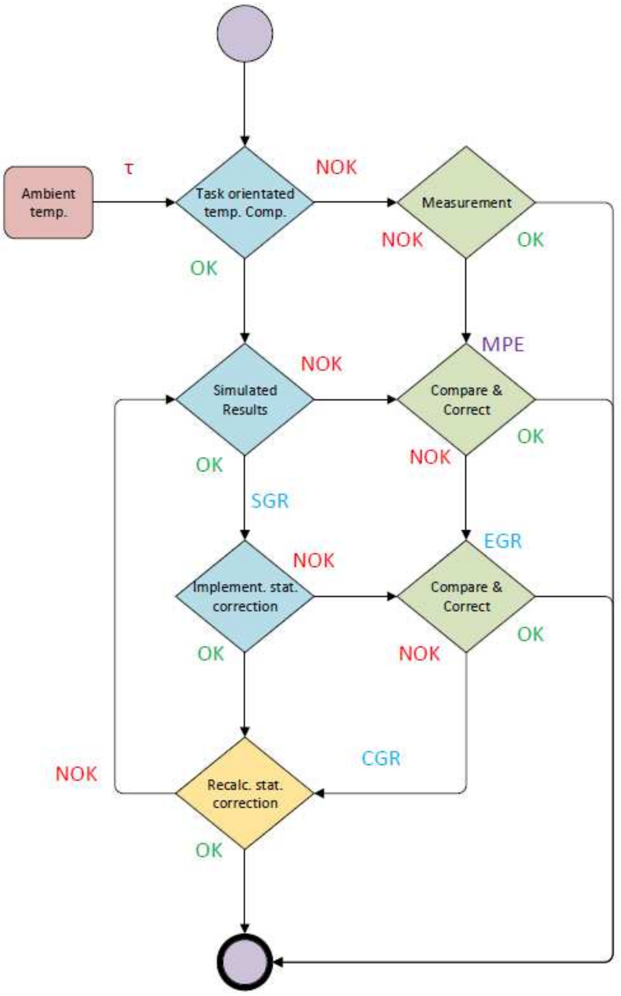


Fig. 2. Block diagram for the application of SPC as a tool for implementation of OBTC

For improvement of Shop Floor CMM we could use “Object based temperature compensation (OBTC)”. For implementation of methodology. We would use fluctuation of temperature as adjusting parameter for adapting SPC to shop floor ambience.

The main purpose of using SPC is to reduce the influence of temperature Δt (temperature error cause by fluctuation from t0 (reference temperature of 20°C), therefore the method itself can be adapted to given specific requirements and in case it is used to compare analytical (simulated) results SGR (simulated geometrical results) with experimental ones EGR (experimental geometrical results). This helps us to exclude the error MPE (Maximum permissible error of measurement) of CMM from the application of Object based temperature compensation – CGR (corrected geometry results.).

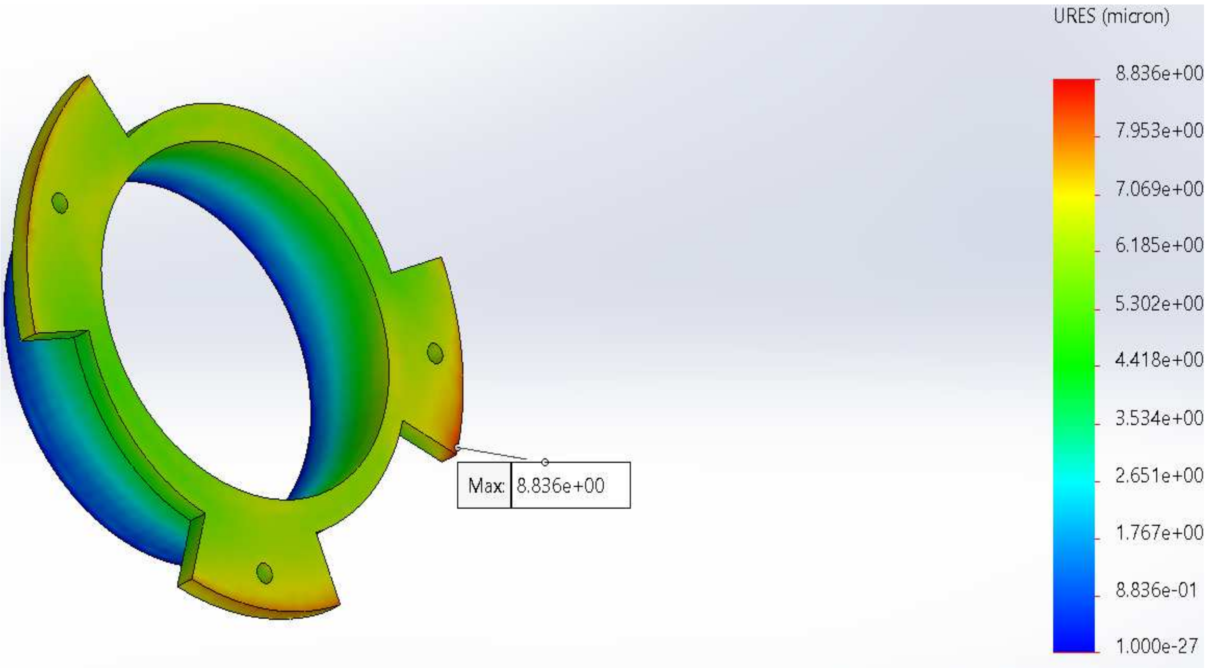
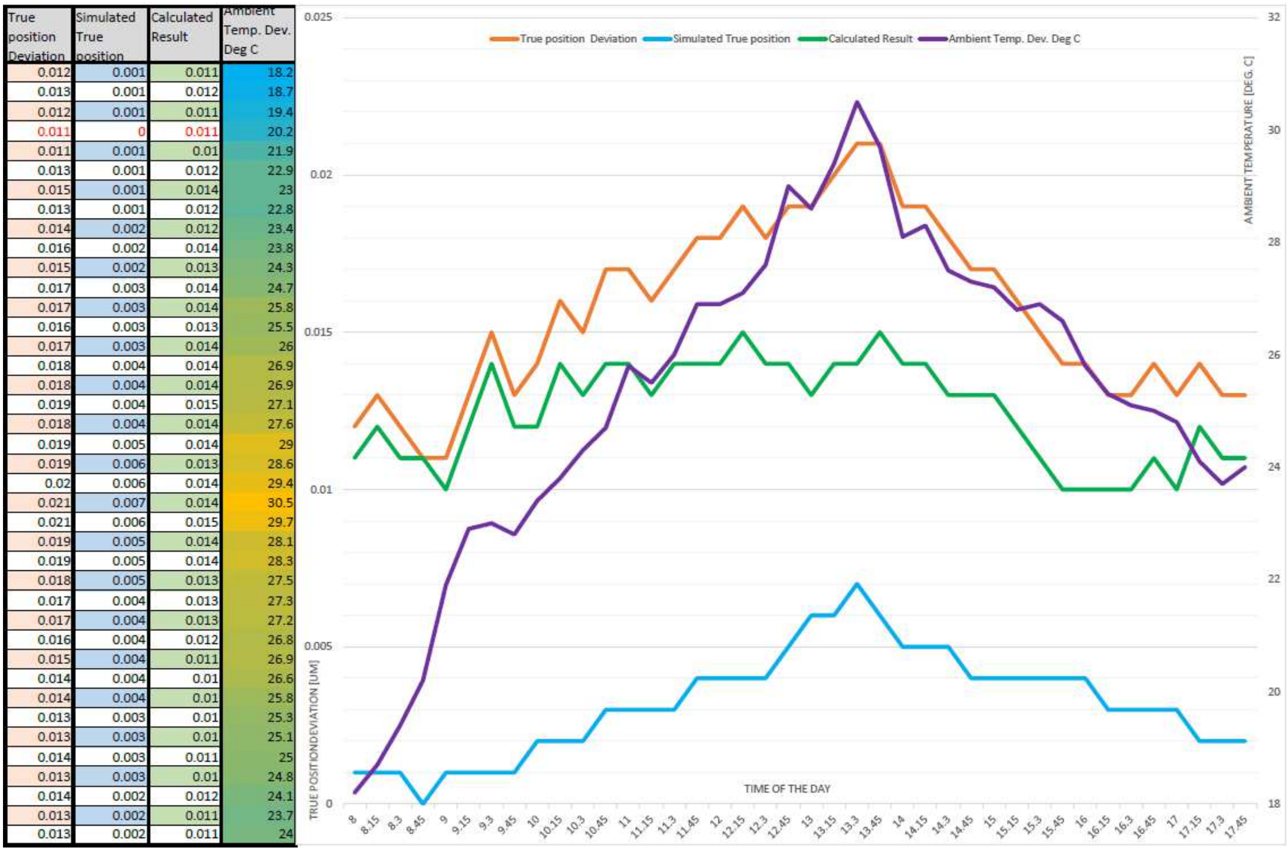


Fig. 3. Temperature simulation of CAD model by SOLIDWORKS Simulation

For the implementation of Block diagram for the application of SPC as a tool for implementation of OBTC (Fig. 2. Block diagram for the application of SPC as a tool for implementation of OBTC), it is necessary to obtain simulated results of an "ideal part" represented by a CAD model and to calculate temperature deformation by suitable software with a finite element method (FEM) as a popular numerical method for solving problem in areas of structural analysis, heat transfer, fluid flow etc. [11]

Temperature in Shop floor ambience widely fluctuate by various reasons, for whose we consider a range of 15°C for the purpose of the study. We compare results from computer simulation by Solidworks (Fig. 3. Temperature simulation of CAD model by SOLIDWORKS Simulation) with those



True position Deviation	Simulated True position	Calculated Result	Ambient Temp. Dev. Deg C
0.012	0.001	0.011	18.2
0.013	0.001	0.012	18.7
0.012	0.001	0.011	19.4
0.011	0	0.011	20.2
0.011	0.001	0.01	21.9
0.013	0.001	0.012	22.9
0.015	0.001	0.014	23
0.013	0.001	0.012	22.8
0.014	0.002	0.012	23.4
0.016	0.002	0.014	23.8
0.015	0.002	0.013	24.3
0.017	0.003	0.014	24.7
0.017	0.003	0.014	25.8
0.016	0.003	0.013	25.5
0.017	0.003	0.014	26
0.018	0.004	0.014	26.9
0.018	0.004	0.014	26.9
0.019	0.004	0.015	27.1
0.018	0.004	0.014	27.6
0.019	0.005	0.014	29
0.019	0.006	0.013	28.6
0.02	0.006	0.014	29.4
0.021	0.007	0.014	30.5
0.021	0.006	0.015	29.7
0.019	0.005	0.014	28.1
0.019	0.005	0.014	28.3
0.018	0.005	0.013	27.5
0.017	0.004	0.013	27.3
0.017	0.004	0.013	27.2
0.016	0.004	0.012	26.8
0.015	0.004	0.011	26.9
0.014	0.004	0.01	26.6
0.014	0.004	0.01	25.8
0.013	0.003	0.01	25.3
0.013	0.003	0.01	25.1
0.014	0.003	0.011	25
0.013	0.003	0.01	24.8
0.014	0.002	0.012	24.1
0.013	0.002	0.011	23.7
0.013	0.002	0.011	24

Fig. 4. Control Chart to compare EGR, SGR and ΔC as a function of Δτ

obtained after measuring an actual detail (with real geometric errors under normal conditions) with Shop floor CMM Aberlink Extol.

EGR is arithmetic mean value (mean) from n=5 consecutive measurements of True position error ε_{TP}.

$$EGR = \bar{\varepsilon}_{TP} = \frac{1}{n}\sum_{i=1}^{n}\varepsilon_{TP_i} = \frac{1}{5}\sum_{1}^{5}\varepsilon_{TP_i} \qquad (14)$$

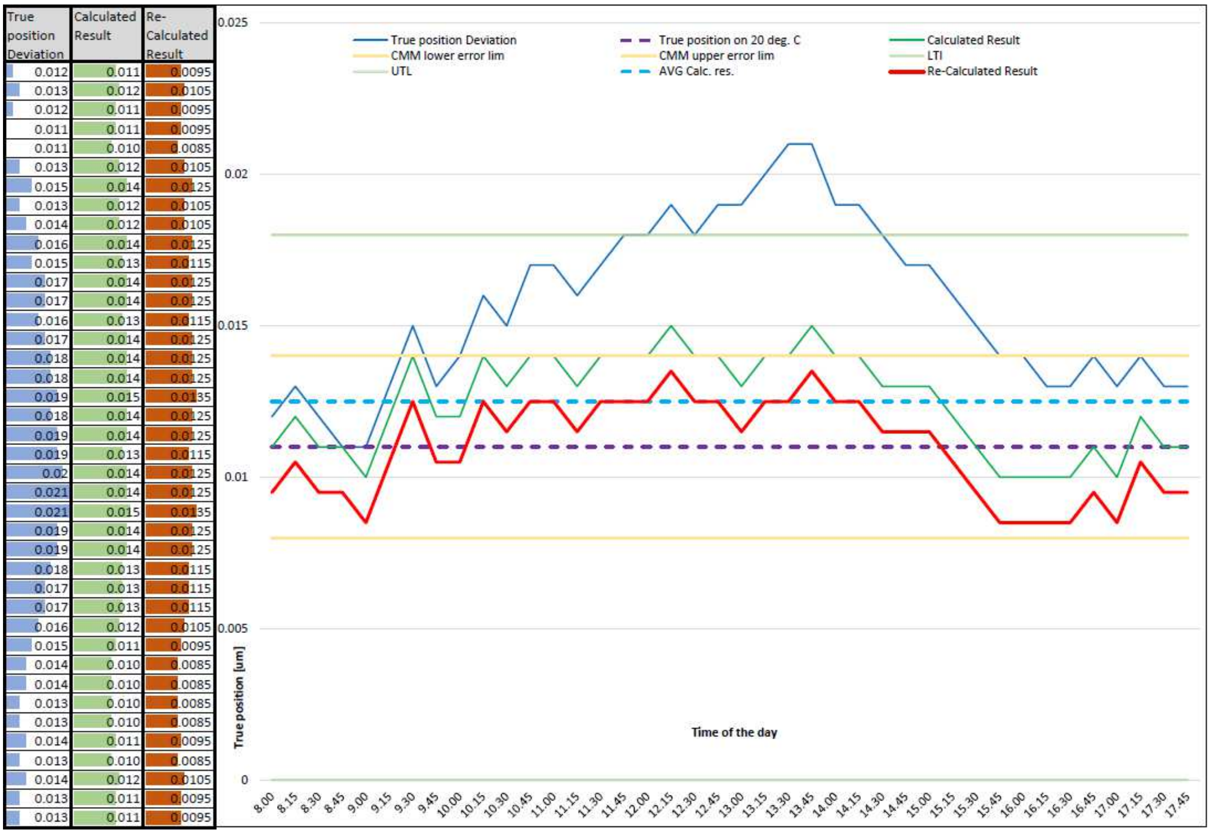
Calculated geometric results Δ_C could be presented as function of temperature fluctuation Δ_τ:

$$\Delta_C = EGR(\Delta_\tau) - SGR(\Delta_\tau) = \bar{\varepsilon}_{TP} - SGR(\Delta_\tau) \qquad (15)$$

SGR as a function of temperature fluctuation are results from computer simulation applied to ideal CAD model and compared to real one included ε_{TP} for unknown value of True position (Fig 4. - Control Chart to compare EGR, SGR and Δ_C as a function of $\Delta\tau$) We could use Control charts as one of the most powerful instrument for implementation of SPC, because there are easy visualization of tendency of process represented as a function of disturbing factors influencing the process (ambient temperature). This allows us to compare and correct values that represent systematic Shop floor CMMs error.

Coefficient of correction function (Θ) can be calculated as the difference between the average calculated geometric results (Δ_C) and true position error δt_0 at temperature t_0 (reference temperature of 20°C):

$$\theta = \bar{\Delta}_c - \delta t_0 = \frac{1}{n}\sum_{i=1}^{n}\Delta_{c_i} = \left(\frac{1}{n}\sum_{i=1}^{n} EGR(\Delta_\tau)_i - SGR(\Delta_\tau)_i\right) - \delta t_0 = \left(\frac{1}{40}\sum_{1}^{40} EGR(\Delta_\tau)_i - SGR(\Delta_\tau)_i\right) - \delta t_0 \qquad (16)$$



True position Deviation	Calculated Result	Re-Calculated Result
0.012	0.011	0.0095
0.013	0.012	0.0105
0.012	0.011	0.0095
0.011	0.011	0.0095
0.011	0.010	0.0085
0.013	0.012	0.0105
0.015	0.014	0.0125
0.013	0.012	0.0105
0.014	0.012	0.0105
0.016	0.014	0.0125
0.015	0.013	0.0115
0.017	0.014	0.0125
0.017	0.014	0.0125
0.016	0.013	0.0115
0.017	0.014	0.0125
0.018	0.014	0.0125
0.018	0.014	0.0125
0.019	0.015	0.0135
0.018	0.014	0.0125
0.019	0.014	0.0125
0.019	0.013	0.0115
0.02	0.014	0.0125
0.021	0.014	0.0125
0.021	0.015	0.0135
0.019	0.014	0.0125
0.019	0.014	0.0125
0.018	0.013	0.0115
0.017	0.013	0.0115
0.017	0.013	0.0115
0.016	0.012	0.0105
0.015	0.011	0.0095
0.014	0.010	0.0085
0.014	0.010	0.0085
0.013	0.010	0.0085
0.013	0.010	0.0085
0.014	0.011	0.0095
0.013	0.010	0.0085
0.014	0.012	0.0105
0.013	0.011	0.0095
0.013	0.011	0.0095

Fig. 5. Control Chart to compare true position error before and after application of OBTC

This allows us to calculate the CGD: of CMM from the application of Object based temperature compensation – CGR (corrected geometry results.).

$$CGR = \Delta_C - \theta = \Delta_C - \bar{\Delta}_c - \delta t_0 = \bar{\varepsilon}_{TP} - SGR(\Delta_\tau) - \bar{\Delta}_c - \delta t_0 = EGR(\Delta_\tau) - SGR(\Delta_\tau) - \bar{\Delta}_c - \delta t_0 \qquad (17)$$

Graphical visualization through a control chart allows us to evaluate the effect of applying object based temperature compensation and the deviation of the results within the MPE tolerances defined in the CMM technical specification.

The application of SPC implemented by Control charts (Fig 5. Control Chart to compare true position error before and after application of OBTC) allows us to monitors process capability, and it is an indicator of the adequacy of the measuring process to meet customer requirements under routine operating conditions. In summary, SPC aims at maintaining a stable, capable and predictable process.

As an on-line statistical control method, SCP allows us to make a correction after any additional process information we receive and thus adjust the OBTC application parameters.

V. TEMPERATURE ORIENTATED MSA

Modern trends in coordinate measurements require the consideration of all influencing factors as well as their importance on the result. To evaluate the quality of the measurement process, the Measurement System Analysis (MSA) methodology is used, as an undivided part of the automotive industry.

The specifics of the Shop Floor CMM application, as well as the differences in operation when compared to traditional CMMs in a laboratory setting, requires adaptation of the MSA to obtain the most comprehensive measurement process information. When applying OBTC, it is necessary to prioritize certain variables at the expense of others (Fig. 6. Measurement System Variability Cause and Effect Diagram).

Compared to the standard application of MSA in which Workpiece (Part), Instrument (Gage) and Person (Appraiser) are considered through their variations: Part variation (PV), Equipment variation (EV), which is basically Repeatability, Appraiser variation (AP), which is basically Reproducibility. GRR is the variance of the internal and external disturbances for the system represented by the combined variance of repeatability and reproducibility. [13]

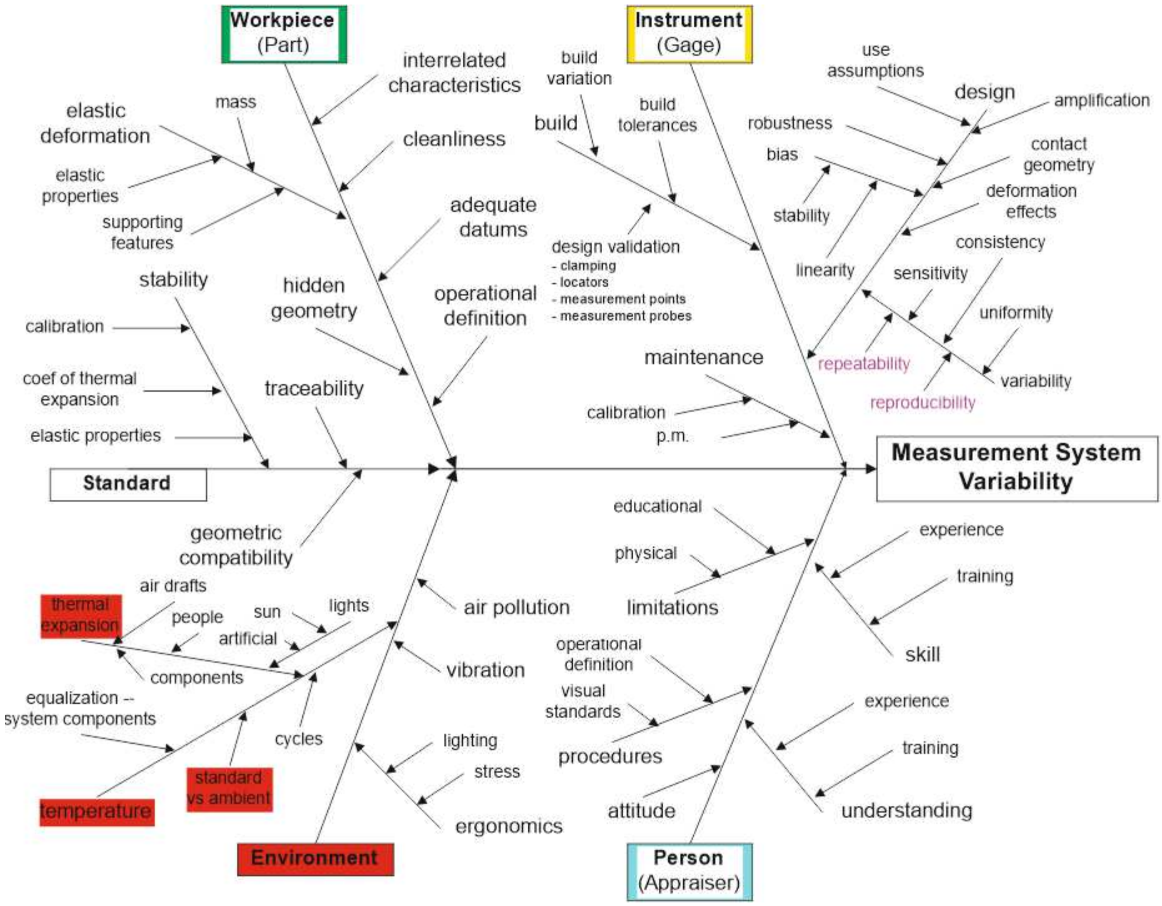


Fig. 6. Measurement System Variability Cause and Effect Diagram [13]

When no standard values are available the GRR should be used. The method presents “repeatability error” ($\varepsilon_{repeatability}$), “reproducibility error” ($\varepsilon_{reproducibility}$), “systematic errors” ($\varepsilon_{systematic}$) . Reproducibility, for the purpose of the study, is not considered a systematic error. Writing the measurement error as $\varepsilon_{measurement}$, the following equation follows directly from these definitions: [1]

$$\varepsilon_{\text{measurement}} = \varepsilon_{\text{reproducibility}} + \varepsilon_{\text{repeatability}} + \varepsilon_{\text{systematic}} \qquad (17)$$

This case is applicable when standard values are not available. We could use results from measurement at 20°C as a reference point for comparing.

Variation caused by the subject of the measurement (AV) is function of his level of professional qualities, measuring strategy and self-responsibilities. For the Shop Floor CMM the effect of operator is reduce to his influence caused by fixing of part on clamping positioning and defining of coordinate system, because operator used preset automated programs.

To implement an adapted MSA we adopt an approach related to the use of True position error (δ) at temperature T_j for reference Part (not standard one, but with known dimension (true position) at standard temperature t_0=20°C). We have calculated TV on the base of Part measured on 10 times in wide temperature range, so we simulate 10 different part, as a function of ambient temperature, and evaluate PV. This will give as possibility to compare AV to MPEE for Shop Floor CMMs

Measurements of the workpiece are performed at a random temperature $T_j(j=1\div10)$, with the temperature increasing with each consecutive trial ($T_j<T_{j+1}$). In order to obtain unambiguity of the results obtained for the position deviation $\delta(T_j)$, at temperature T_j we perform a recalculation with regard to reference values of temperatures Tr_j under the following conditions.

To facilitate visualization, we work with a constant increase in ambient temperature $T_j<T_{j+1}$, and a corresponding constant increase in reference temperature $Tr_j< Tr_{j+1}$ over 1℃.

Measurements started at $T_1=t_0\pm1\%=t_0\pm0.2°C$ with taking into account the scatter of the temperature values to neglect the thermometer error.

At a temperature equal to the reference (T_j=Tr_j) for the true position we obtain δ(Tr_j)= δ(T_j), and at a temperature different from the reference (T_j≠Tr_j) the following:

$$\delta(Tr_j) = \delta(T_j) - \left(\delta(T_j) - \delta(Tr_{j-1})\right) * (Tr_j - T_j) \tag{18}$$

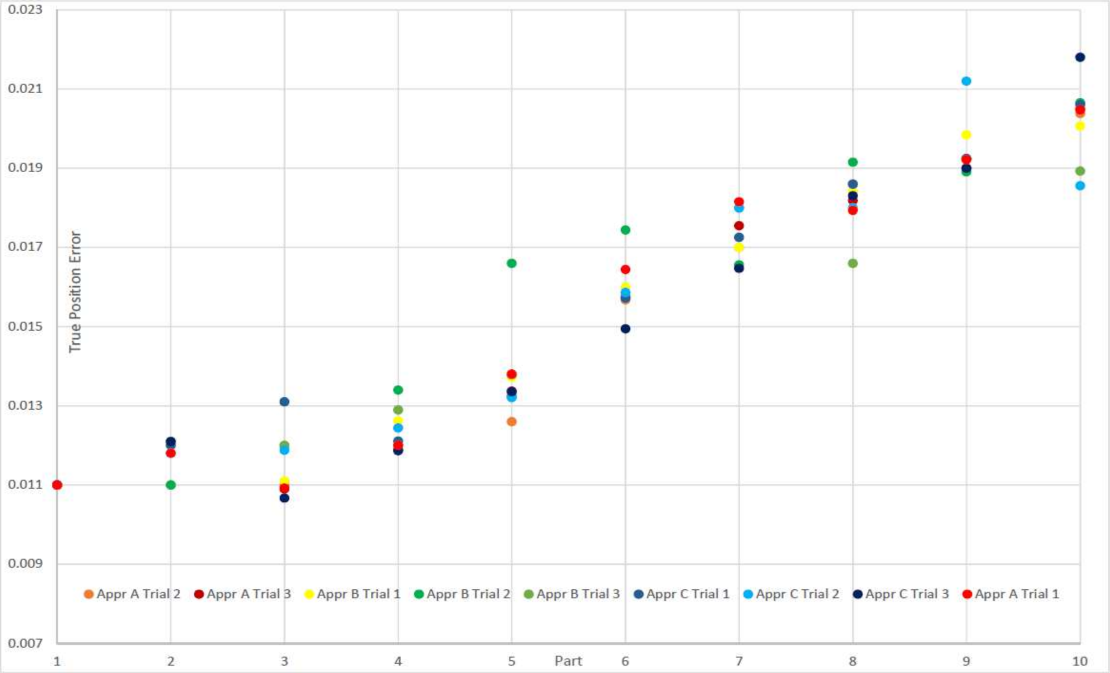
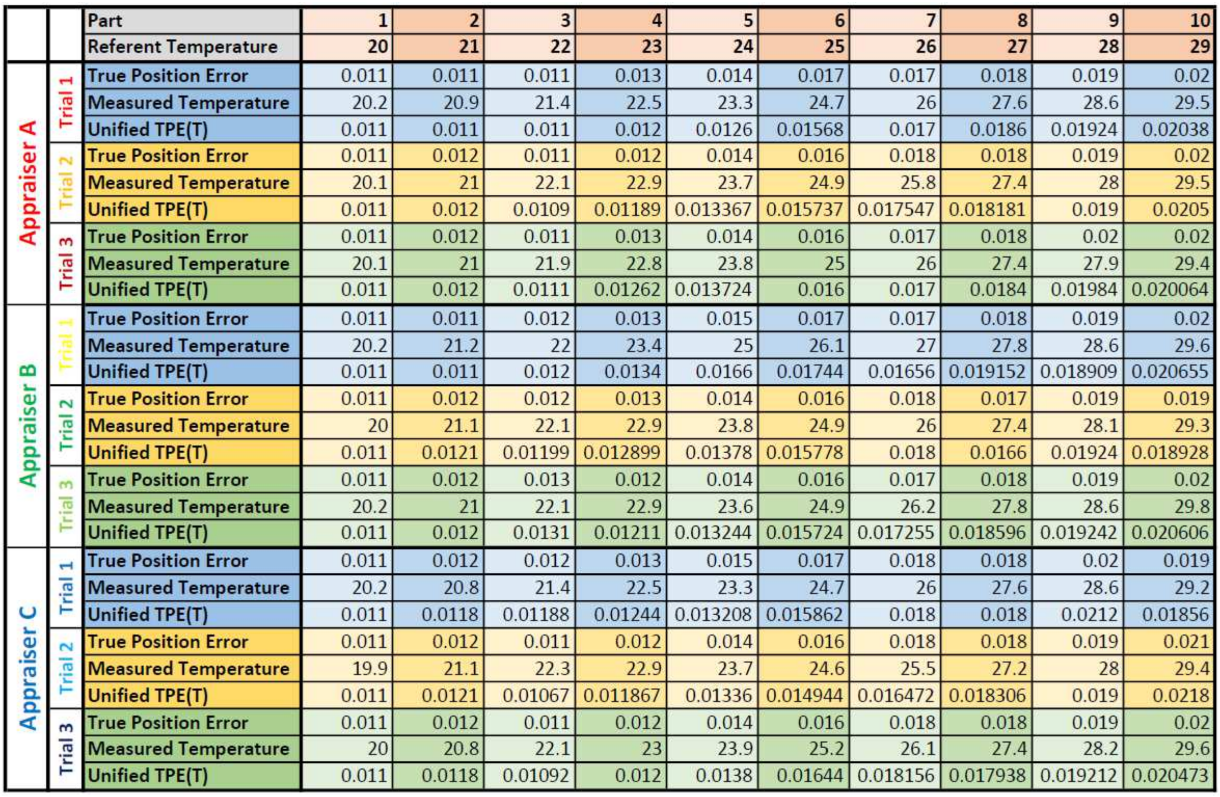


Fig. 8. Graph representing the scatter when measuring the reference part as a function of temperature change by three operators.



		Part	1	2	3	4	5	6	7	8	9	10
		Referent Temperature	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Appraiser A	Trial 1	**True Position Error**	0.011	0.011	0.011	0.013	0.014	0.017	0.017	0.018	0.019	0.02
		Measured Temperature	20.2	20.9	21.4	22.5	23.3	24.7	26	27.6	28.6	29.5
		Unified TPE(T)	0.011	0.011	0.011	0.012	0.0126	0.01568	0.017	0.0186	0.01924	0.02038
	Trial 2	**True Position Error**	0.011	0.012	0.011	0.012	0.014	0.016	0.018	0.018	0.019	0.02
		Measured Temperature	20.1	21	22.1	22.9	23.7	24.9	25.8	27.4	28	29.5
		Unified TPE(T)	0.011	0.012	0.0109	0.01189	0.013367	0.015737	0.017547	0.018181	0.019	0.0205
	Trial 3	**True Position Error**	0.011	0.012	0.011	0.013	0.014	0.016	0.017	0.018	0.02	0.02
		Measured Temperature	20.1	21	21.9	22.8	23.8	25	26	27.4	27.9	29.4
		Unified TPE(T)	0.011	0.012	0.0111	0.01262	0.013724	0.016	0.017	0.0184	0.01984	0.020064
Appraiser B	Trial 1	**True Position Error**	0.011	0.011	0.012	0.013	0.015	0.017	0.017	0.018	0.019	0.02
		Measured Temperature	20.2	21.2	22	23.4	25	26.1	27	27.8	28.6	29.6
		Unified TPE(T)	0.011	0.011	0.012	0.0134	0.0166	0.01744	0.01656	0.019152	0.018909	0.020655
	Trial 2	**True Position Error**	0.011	0.012	0.012	0.013	0.014	0.016	0.018	0.017	0.019	0.019
		Measured Temperature	20	21.1	22.1	22.9	23.8	24.9	26	27.4	28.1	29.3
		Unified TPE(T)	0.011	0.0121	0.01199	0.012899	0.01378	0.015778	0.018	0.0166	0.01924	0.018928
	Trial 3	**True Position Error**	0.011	0.012	0.013	0.012	0.014	0.016	0.017	0.018	0.019	0.02
		Measured Temperature	20.2	21	22.1	22.9	23.6	24.9	26.2	27.8	28.6	29.8
		Unified TPE(T)	0.011	0.012	0.0131	0.01211	0.013244	0.015724	0.017255	0.018596	0.019242	0.020606
Appraiser C	Trial 1	**True Position Error**	0.011	0.012	0.012	0.013	0.015	0.017	0.018	0.018	0.02	0.019
		Measured Temperature	20.2	20.8	21.4	22.5	23.3	24.7	26	27.6	28.6	29.2
		Unified TPE(T)	0.011	0.0118	0.01188	0.01244	0.013208	0.015862	0.018	0.018	0.0212	0.01856
	Trial 2	**True Position Error**	0.011	0.012	0.011	0.012	0.014	0.016	0.018	0.018	0.019	0.021
		Measured Temperature	19.9	21.1	22.3	22.9	23.7	24.6	25.5	27.2	28	29.4
		Unified TPE(T)	0.011	0.0121	0.01067	0.011867	0.01336	0.014944	0.016472	0.018306	0.019	0.0218
	Trial 3	**True Position Error**	0.011	0.012	0.011	0.012	0.014	0.016	0.018	0.018	0.019	0.02
		Measured Temperature	20	20.8	22.1	23	23.9	25.2	26.1	27.4	28.2	29.6
		Unified TPE(T)	0.011	0.0118	0.01092	0.012	0.0138	0.01644	0.018156	0.017938	0.019212	0.020473

Fig. 7. Table with data for implemantation of MSA, GRR method

On Fig. 7. is presented table of True position error measured by 3 different appraiser, each by 3 trials. For realization we use 9 days data from Shop floor environment. Operator only place Part at jig and start preloaded automated program, so we have same measuring procedure. The measurement is carried out at a temperature (T_j) close to the reference (Tr_j) and a correction is made for unified results (δ(Tr_j)).

On Figure 8 there are graphical results of the obtained data representing the variation of true position error δ as a function of the variation of temperature (T_j) and scattering obtained from the MREE(including random errors) of the Shop Floor CMM.

Based on these data, we perform MSA using the GRR method according to the Reference Manual, 4th Edition [13], and obtain the following values:

Repeatability is equal to Equipment Variation:

$$EV = \bar{\bar{R}} * K_1 = 0.001 \tag{19}$$

(where all the coefficients are chosen from table according to Measurement systems analysis, Reference Manual [13])

Equipment Variation could be presented as %EV=100(EV/ Tolerance) = 20.94, where Tolerance is equal to difference between Upper Tolerance Limit (UTL) and Lower Tolerance Limit (LTL))

Reproducibility is equal to Appraiser Variation (AV):

$$AV = \sqrt{(\bar{X}_{DIFF} * K_2) - \frac{EV^2}{nr}} \approx 0 \tag{20}$$

(where all the coefficients are chosen from table according to Measurement systems analysis, Reference Manual [13])

(where all the coefficients are chosen from table according to Measurement systems analysis, Reference Manual [13])

Result could be presented as:

$$\%PV = 100(PV/Tol) = 96.67. \tag{24}$$

Part Variation (PV) represents the value of temperature deformations (TD)

$$PV = R_p * K_3 = TD \pm MPEE + \mu \tag{25}$$

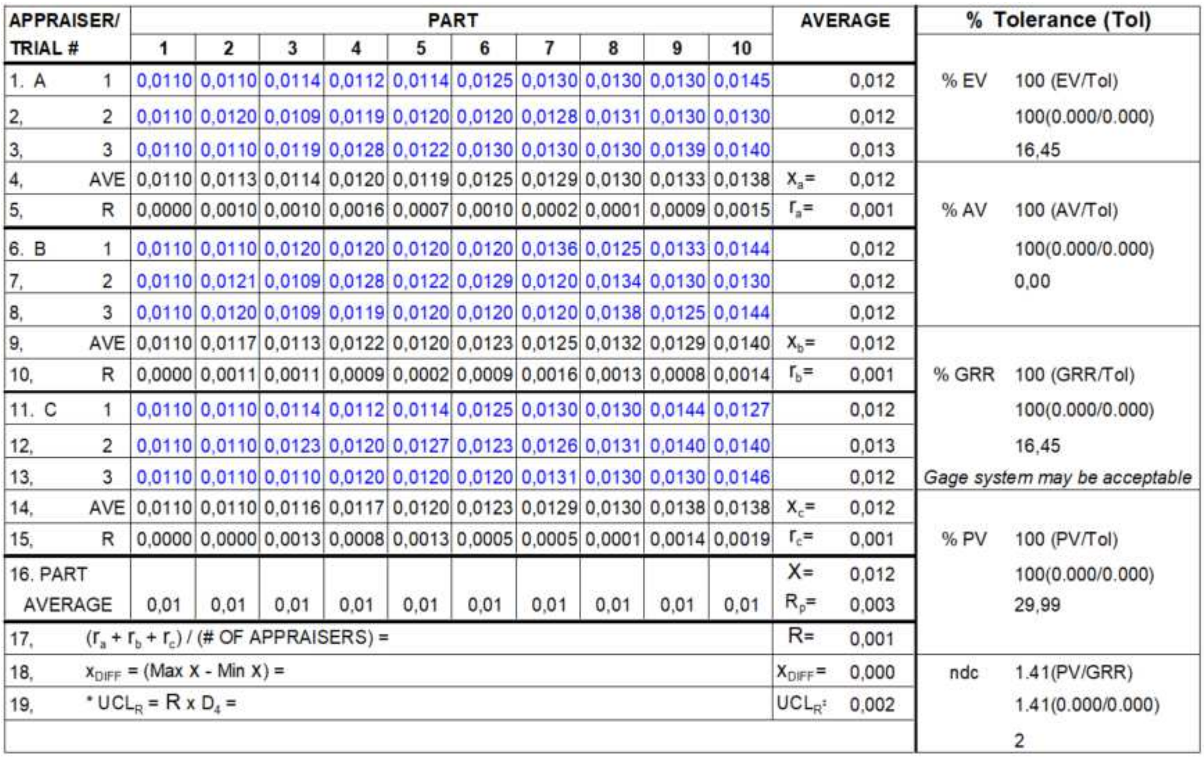
where μ - mathematical model error. To calculate μ we should use an ideal case in which $T_j=t_0$=const. and we measure the one part (as a reference) under the same conditions, therefore the temperature deformation TD=0, and in the worst case Rp=±MPEE, where:

$$\pm MPEE * K_3 = 0 \pm MPEE \pm \mu \tag{26}$$

When we apply OBTC we can use μ as a correction coefficient:

$$\pm\mu = MPEE * (K_3 - 1) \tag{27}$$

and then:



APPRAISER/		PART										AVERAGE		% Tolerance (Tol)	
TRIAL #		1	2	3	4	5	6	7	8	9	10				
1. A	1	0,0110	0,0110	0,0114	0,0112	0,0114	0,0125	0,0130	0,0130	0,0130	0,0145		0,012	% EV	100 (EV/Tol)
2,	2	0,0110	0,0120	0,0109	0,0119	0,0120	0,0120	0,0128	0,0131	0,0130	0,0130		0,012		100(0.000/0.000)
3,	3	0,0110	0,0110	0,0119	0,0128	0,0122	0,0130	0,0130	0,0130	0,0139	0,0140		0,013		16,45
4,	AVE	0,0110	0,0113	0,0114	0,0120	0,0119	0,0125	0,0129	0,0130	0,0133	0,0138	X_a=	0,012		
5,	R	0,0000	0,0010	0,0010	0,0016	0,0007	0,0010	0,0002	0,0001	0,0009	0,0015	r_a=	0,001	% AV	100 (AV/Tol)
6. B	1	0,0110	0,0110	0,0120	0,0120	0,0120	0,0120	0,0136	0,0125	0,0133	0,0144		0,012		100(0.000/0.000)
7,	2	0,0110	0,0121	0,0109	0,0128	0,0122	0,0129	0,0120	0,0134	0,0130	0,0130		0,012		0,00
8,	3	0,0110	0,0120	0,0109	0,0119	0,0120	0,0120	0,0120	0,0138	0,0125	0,0144		0,012		
9,	AVE	0,0110	0,0117	0,0113	0,0122	0,0120	0,0123	0,0125	0,0132	0,0129	0,0140	X_b=	0,012		
10,	R	0,0000	0,0011	0,0011	0,0009	0,0002	0,0009	0,0016	0,0013	0,0008	0,0014	r_b=	0,001	% GRR	100 (GRR/Tol)
11. C	1	0,0110	0,0110	0,0114	0,0112	0,0114	0,0125	0,0130	0,0130	0,0144	0,0127		0,012		100(0.000/0.000)
12,	2	0,0110	0,0110	0,0123	0,0120	0,0127	0,0123	0,0126	0,0131	0,0140	0,0140		0,013		16,45
13,	3	0,0110	0,0110	0,0110	0,0120	0,0120	0,0120	0,0131	0,0130	0,0130	0,0146		0,012	*Gage system may be acceptable*	
14,	AVE	0,0110	0,0110	0,0116	0,0117	0,0120	0,0123	0,0129	0,0130	0,0138	0,0138	X_c=	0,012		
15,	R	0,0000	0,0000	0,0013	0,0008	0,0013	0,0005	0,0005	0,0001	0,0014	0,0019	r_c=	0,001	% PV	100 (PV/Tol)
16. PART AVERAGE		0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	X= R_p=	0,012 0,003		100(0.000/0.000) 29,99
17,	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0,001		
18,	X_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0,000	ndc	1.41(PV/GRR)
19,	* UCL_R = R x D_4 =											UCL_R=	0,002		1.41(0.000/0.000)
															2

Fig. 9. Table with application of MSA(GRR) after implementation of OBTC

Appraiser Variation could be presented as %AV=100(AV/Tol) = 4.01. The influence of the operator can be disregarded because it has an insignificant impact on the outcome provided that he performs his duties conscientiously.

Gage Repeatability & Reproducibility:

$$GRR = \sqrt{EV^2 + AV^2} = 0.001 \tag{21}$$

and

$$\%GRR = 100(GRR/Tol) = 21.32 \tag{22}$$

Part Variation:

$$PV = R_p * K_3 \tag{23}$$

$$PV = R_p * K_3 + \mu$$

We re-perform the MSA approach using the GRR method after applying OBTC, and obtain results where the influence of ambient temperature fluctuations is compensated. This results in a reduction of temperature deformations (TD) from 0.011 um to only 0.004, which is a 63% improvement. This deviation is of the order of MPEE and results in the application of GRR expressed in close values of EV 20.94 to 16.45, AV 4.01 to 0, GRR 21.32 to 16.45, and a very large improvement in PV which decreases three times from 96.67 to 29.99 (Fig. 9. Table with application of MSA (GRR) after implementation of OBTC.).

VI. CONCLUSION

The research made it possible to implement Object Based Temperature Compensation (OBTC) to improve the metrological and operational characteristics of the Shop Floor CMM. As a result of the statistical control, we obtain data adaptive to the conditions allowing the implementation of OBTC. To evaluate the results, we use an adapted MSA methodology that shows the improvements achieved in relation to the reduction of non- linear temperature deformations in Shop Floor CMM.

ACKNOWLEDGMENT

The authors would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support.

BIBLIOGRAPHY & REFERENCE

[1] Allen T., Introduction to Engineering Statistics and Lean Six Sigma, Statistical Quality Control and Design of Experiments and Systems, Third Edition Springer-Verlag London Limited 2006, ISBN 978-1-4471-7420-2 (eBook), https://doi.org/10.1007/978-1-4471-7420-2

[2] Bird J., Basic Engineering Mathematics, Fifth edition Published by Elsevier Ltd. 2010, ISBN-13: 978-1-85-617697-2

[3] Calvo R., D'Amato R., Gómez E., Domingo R., Integration of Error Compensation of Coordinate Measuring Machines into Feature Measurement: Part II—Experimental Implementation, Sensors 2016, 16, 1705; doi:10.3390/s16101705, www.mdpi.com/journal/sensors

[4] ISO 1:2016 Geometrical product specifications (GPS) — Standard reference temperature for the specification of geometrical and dimensional properties

[5] ISO 10360-2:2009 - Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions

[6] ISO 1101:2017, Geometrical Product Specifications (GPS), Geometrical Tolerancing—Tolerances of Form, Orientation, Location and Run-Out

[7] ISO 14253-1:2017 - Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for verifying conformity or nonconformity with specifications

[8] ISO/TS 15530-1: 2013 - Geometrical Product Specifications (GPS)— Coordinate Measuring Machines (CMM): Technique for Determining the Uncertainty of Measurement—Part 1: Overview and Metrological Characteristics

[9] ISO 15530-3: 2011 - Geometrical Product Specifications (GPS)— Coordinate Measuring Machines (CMM): Technique for Determining the Uncertainty of Measurement—Part 3: Use of Calibrated Workpieces or Standards

[10] Flack D., Measurement Good Practice Guide No. 42 - CMM Verification, Queen's Printer and controller of HMSO, July 2001, National Physical Laboratory, ISSN 1368-6550

[11] Madenci E., Guven I., The Finite Element Method and Applications in Engineering Using ANSYS, Second Edition, Springer I. P. 2015, ISBN 978-1-4899-7550-8

[12] Mantel M. R., Coordinate measuring machines: A modern inspection tool in Manufacturing, (1993). Theses. 1246. https://digitalcommons.njit.edu/theses/1246

[13] Measurement systems analysis (MSA), Reference Manual, Fourth Edition, Copyright 2010 Chrysler Group LLC, Ford Motor Company, General Motors Corporation, ISBN#: 978-1-60-534211-5

[14] Montgomery D. C., Introduction to Statistical Quality Control, Sixth Edition, Copyright 2009 by John Wiley & Sons, Inc., ISBN 978-0-470-16992-6

[15] Qiu P., Introduction to Statistical Process Control, 2014 by Taylor & Francis Group, LLC, ISBN-13: 978-1-4822-2041-4 (eBook - PDF)

[16] S. C. N. Topfer, G. Linss, M. Rosenberger, U. Nehse, and K. Weissensee, Automatic Execution of Inspection Plans with the I++DME Interface for Industrial Coordinate Measurements, M&MS Journal, vol. XIV, no. 1 pp. 71–88, Poland, 2007

[17] S. Hammad Mian, A. Al-Ahmari, New developments in coordinate measuring machines for manufacturing industries, International Journal of Metrology and Quality Engineering 5, 101 (2014) EDP Sciences 2014, DOI: 10.1051/ijmqe/2014001

[18] Salah H. R. Ali, Automotive Engine Metrology, Copyright © 2017 Pan Stanford Publishing Pte. Ltd., ISBN 978-1-315-36484-1 (eBook)

[19] Šibalija T. V., Majstorović V. D., SPC and process capability analysis– case study, International Journal ''Total Quality Management & Excellence'', Vol. 37, No. 1-2, 2009.

[20] Smith G. T., Machine Tool Metrology an Industrial Handbook, Springer International Publishing Switzerland 2016, ISBN 978-3-319-25109-7 (eBook)]

[21] Statistical process control (SPC), Reference manual, Copyright 1992, Chrysler Corporation, Ford Motor Company, and General Motors Corporation

[22] Yinbao C., Zhongyu W., Xiaohuai C., Yaru Li, Hongyang Li, Hongli Li, Hanbin W., Evaluation and Optimization of Task-oriented Machines Based on Geometrical Product Specifications, Appl. Sci. 2019, 9, 6; www.mdpi.com/journal/applsci, ISSN: 2076-3417

[23] Stadek J. A., Coordinate Metrology, Springer 2020, ISBN 978-3-662-48465-4

[24] https://www.aberlink.com/, Aberlink 3D Mk4 Measurement Software, User Manual, Issue 24, Date: 20.02.2019

[25] https://www.aiag.org/

[26] https://www.solidworks.com/