

Task-oriented temperature compensation as an instrument for reduction of uncertainty in Shop Floor CMM

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Abstract. The significance of Shop Floor CMM in inspecting mechanical parts in modern industries, such as automotive and aerospace, has been increasing in recent years, making it an integral part of the inspection process. However, a major issue that remains is the uncertainty, particularly caused by changes in environmental conditions, such as ambient temperature, in shop floor conditions. Task-oriented temperature compensation software can solve these problems. Its effectiveness can be evaluated through uncertainty analysis.

Keywords: Shop Floor Coordinate Measuring Machine, uncertainty, ambient temperature compensation.

I. INTRODUCTION

Trends in the development of high-tech industries have given a central place to coordinate metrology, Coordinate Measuring Machines (CMM) is the most common and fundamental measurement technology in the automotive industry, Modern geometric tolerances are becoming increasingly narrow, so the industry needs more accurate measuring instruments and more sophisticated measurement systems.[1] In the automotive industry, there are specific technical requirements for position tolerance such as true position and profile and surface measurement. These specifications and the combination of different materials with complex geometries make the CMM best suited for this task.

The development of the automotive industry and the need for high measurement reliability combined with near 100% control is leading to a change in the development of measurement and control. These requirements lead to the need for measurements close to the point of manufacture, for which shop floor CMMs are best suited.

The use of Shop floor CMM in production allows strong measurement versatility, great flexibility, adaptability and universality with the ability to perform complex metrological tasks without a real equivalent. The

resultant measurement quality of CMM is limited by deviations and some uncertainties. The measurement deviations in coordinate metrology can be related to the operator performance quality, environmental interaction, work piece finishing, and CMM accuracy. It can be assumed that some influence factors of operator behaviour and CMM software accuracy have effective reactions on the measurement quality factors. [2]

II. UNCERTAINTY IN SHOP FLOOR CMM

During CMM measurement, all relevant factors may have an impact on the measurement results. The sources of uncertainty in the coordinate measuring system can be divided into five categories according to the analysis method of “personnel, machine, object, method and environment” commonly used in product quality management as shown in Figure 1: Uncertainty caused by CMM instrument’s own errors, measured work piece, surveyors, measuring method, and external environment (Fig. 1).[1]

1. Uncertainty caused by the subject of the measurement - the operator is caused from his level of professional qualities and self-responsibilities. In conventional CMM the uncertainty caused by operator is mainly characterized by the differences of the measurement strategies but for 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 pre-set CNC programs.

2. Uncertainty caused by the instrumental errors which could be represent by deviation of the CMM’s own metering characteristics from the ideal characteristics, including the uncertainty caused by design, standard quantity, detection system, dynamic characteristics, fitting and evaluation algorithm, probe system errors, datum stylus errors and other factors. These instrumented CMM errors on the shop floor are reflected in the impact of the residual system errors after correction and calibration

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introduced by the "error map". In order to ensure accuracy, it is necessary to carry out repeat accuracy checks and recalibrations according to the manufacturer's requirements or international standards. [3]

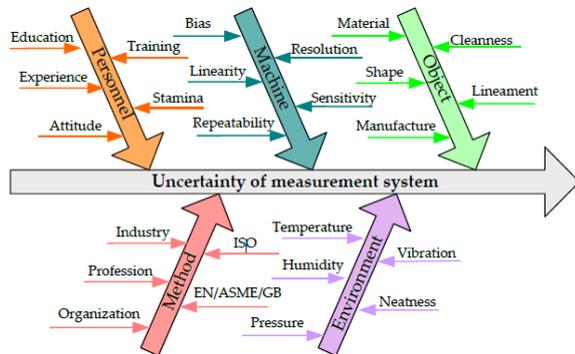


Fig. 1. Cause and effects diagram for uncertainty source of Shop Floor CMM. [1].

In the GPS ISO 10360 series standards [4] the CMM performance evaluation has been defined and relevant performance parameters and evaluation methods of the measuring instrument have been given. [5] There are some parameters influencing measurements with Shop Floor CMMs such as the indication and detection errors of the dimensional measurement as well as the dimensional and geometrical errors of the universal detection system. In practical measurement, the Maximum Permissible Indication Error (EMPE,L) is mainly related to the errors of the distance and other dimensional elements, and the MPEP indicates the error of the whole measurement system in a very small test space, generally affecting the form measurement. [1]

3. The uncertainty caused by the workpiece being measured can be represented by the geometric shape and dimensions, the measurement method and algorithm of the characteristics, the materials, with a large difference in thermal expansion, the elastic deformation of the workpiece due to the measurement force, and the clamping method.

4. The current development of CMM does not provide specific standards, procedures or specifications for the selection of strategy, measuring tips, relative coordinate system, sequence of actions for unambiguous definition of the measured parameters, which is the reason for the ambiguity of the results and source of uncertainty.

5. Uncertainty caused by environmental factors has higher impact on Shop Floor CMM than on standard CMM works in Laboratory environment. The temperature, humidity temporal gradient, vibration, dust, and other environmental has a very large fluctuation within one work shift. During CMM dimensional measurement, temperature compensation is usually needed and is "Task orientated"

The evaluation of measurement uncertainty should consider all factors that may affect the measurement results but focus must fall on the specific measurement tasks. Task-oriented measurement uncertainty must represent results from actions taken to improve the quality of results. This makes it appropriate to concentrate efforts on a small

number of factors that reflect part-to-part variation which represent close correlation between sources of uncertainty and measurement tasks.

III. ADVANCED MATERIALS IN WORKPIECE WITH COMPLEX FORM AND CONSTRUCTION

The development of technology allows the production of new materials and the use of different combinations between them. Materials have specific requirements (customer and legislative) to meet the demands of the automotive industry. [6] Advanced materials help us create lighter, stronger and more flexible parts. With new types of steels, such as high strength steels (HSS), (UHSS) and (AHSS), which are specifically developed for the automotive industry, we get durability, strength and hardness combined with low production costs in large quantities and the ability to recycle. [7]

Aluminium and magnesium alloys are increasingly used in mechanical engineering and in particular in the automotive and aviation industry. Aluminium castings are used for various automotive parts, resulting in significant weight reduction. [8]. On the other hand, magnesium is lighter than aluminium and SS with higher corrosion resistance. Due to specific mechanical and physical properties, magnesium components require a unique more complex design. [6]. Titanium alloys has a principal advantages likes their low density, high strength to density ratio, excellent corrosion resistance and superior strength retention at elevated temperatures. The major drawback of titanium is its high cost [9]

Polymers, plastics and composites such as polyamide (PA), acrylonitrile/butadiene/styrene (ABS), polyvinyl chloride (PVC), polypropylene (PP), polyoxymethylene (POM), acrylic (PMMA), polybutylene terephthalate (PBT), etc. have revolutionized many industries. Parts made of plastics are corrosion resistant, offer flexibility and elasticity for added safety, have very good thermal insulation. Plastics are helping to reduce the cost of vehicle production, and polymers are improving vehicle design. [10]

Carbon fibers are widely used in parts that need to be stable and lightweight, resistant to torsion, corrosion and abrupt changes in operating conditions. Carbon fibre reinforced plastics (CFRP) are highly desirable materials in automotive and aerospace applications due to their specific stiffness, good strength and fatigue properties compared to conventional metals. [11]

Hybrid composites are made of several layers of composite and other materials. Their undoubted advantages are the basis of their increasing prevalence at the expense of specific design features and complicating component control. [12]

All of these materials and the combinations between them in the design and construction of complex parts and assemblies comes with specific design, construction, form and configuration requirements. The main problem with all these materials is the big difference in their Thermal expansion coefficients (α) which varies from $\alpha=7$ [10-6 m/m°C] to $\alpha=300$ [10-6 m/m°C] and makes the measurement of details with complex construction difficult

in the shop floor ambient environment and imposes a task-oriented metrological mission.

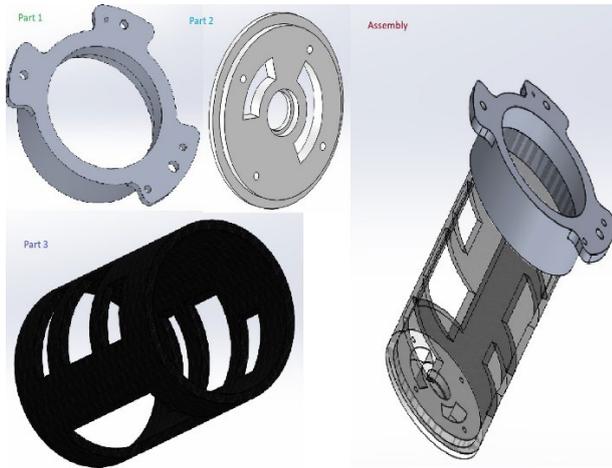


Fig. 2. Assembly of three parts made from different materials with complex requirements for form and position control.

The use of materials like CFRP, aluminium, PA, PEEK, ABS, and brass in the automotive industry is leading to changes in structural elements. These changes include more complex geometries, asymmetric shapes, and narrower tolerance limits. Specific requirements for true position, datum features, profile, and surface are also necessary based on datum features. Lightening structures to improve physical characteristics can have drawbacks in controllability, especially in the Shop Floor environment. This requires new approaches and the use of CMM as the primary measuring tool in the automotive and other modern industries. The spatial deformations caused by unpredictable shapeshifting due to ambient temperature are non-linear in nature. Thermal expansion coefficients α cannot universally recalculate these deformations. Additional research and mathematical models are necessary to reduce the non-linearity based on task-oriented temperature compensation.

To ensure the necessary accuracy of the assembled unit, it may be necessary to perform some processing while it is assembled. Therefore, it is important to check not only the individual elements but also the assembled unit. This presents challenges in controlling positional deviation, profile deviations, and surface deviations in workshop conditions due to the varying coefficient of linear temperature deformation of the different materials used. Additional calculations are necessary to ensure accurate measurements comparable to those made under normal conditions (ISO 1:2016). [13]

Fig. 2 presents an isometric image of a complex body part composed of parts made of different materials: Part 1 (material: Aluminium), Part 2 (material: ABS), and Part 3 (material: Hexcel AS4C). This serves as an example of an assembly made of different materials. The primary metrological issue concerns the regulation of concentricity (EPC) between the central holes of Part 1 and Part 2, deviations from roundness (EFK), and true position (EPP) in relation to the datum's (Fig. 3). [14]

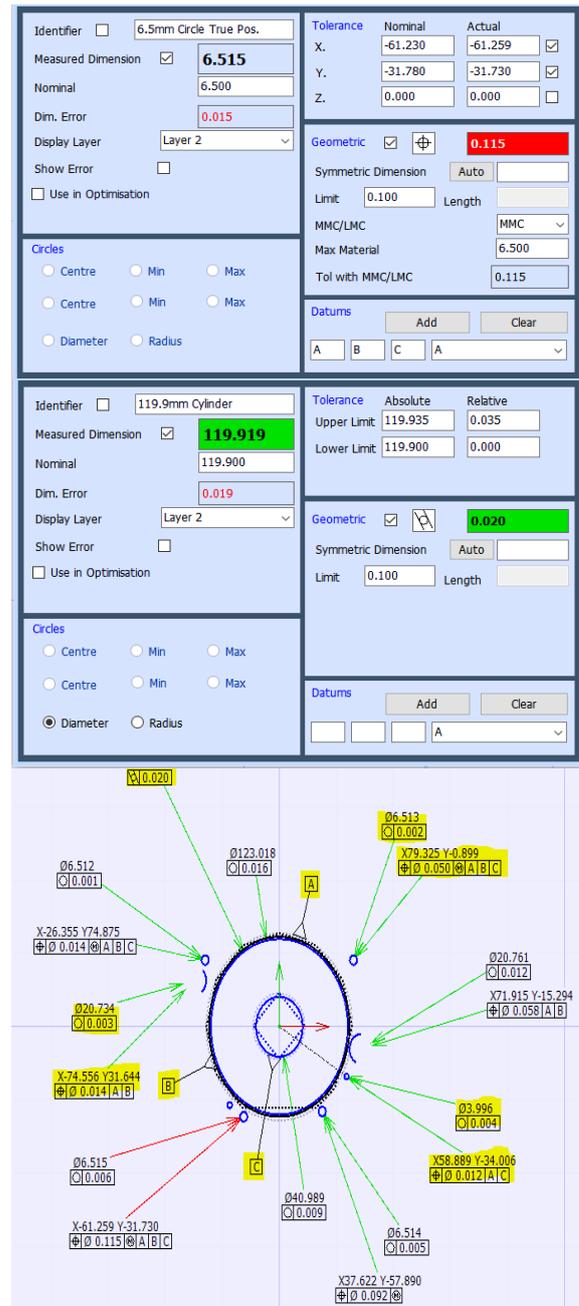


Fig. 3. This is a fragment of a program for controlling all-part assembled unit using Aberlink 3Dv4 software.

IV. SOFTWARE COMPENSATION FOR AMBIENT TEMPERATURE FLUCTUATION

Temperature is a critical environmental parameter affecting the uncertainty of the Shop Floor CMM measurement. On the one hand, temperature fluctuations over a wide range have a significant impact on the entire machine structure due to the deformations it causes. This deformation is very difficult to predict or simulate. In parallel, the ambient temperature has a significant influence on the dimensions and shape of complex workpieces of different materials. Spatial temperature gradients of the surrounding environment, draughts, and thermal radiation caused by surrounding machinery, walls, windows, luminaires or sunlight have a particular influence on dimensions and shape. For parts of simple single material construction, these influencing factors are

functionally dependent on the thermal expansion coefficients (α) of the materials. [15]

Shop-floor production control has the undeniable advantages of eliminating the requirement to maintain a reference temperature, resulting in the elimination of the need for expensive air conditioning systems to maintain a temperature of around $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and $65\% \text{ RH} \pm 10\% \text{ HR}$, in accordance with the recommendations of the international standard ISO 1:2016 [13].

As a major disadvantage it should be noted the environmental uncertainty of the measurements and the assessment of the agreement between the results obtained in the laboratory and in the workshop. [16]

Based on the requirements of the market (consumers) for integration of the Shop Floor CMM in automated control, the ambient temperature can have the most impact on a CMM's accuracy and repeatability. Depending on the requirements of the specific industry and the design specifics of the items being controlled, specific "task-oriented" software temperature compensation can be used.

The CMM utilizes software temperature compensation as a standard to minimize the impact of temperature changes on its structure. Additionally, linear temperature compensation of objects is possible. To enhance the performance of the Shop Floor CMM, "task-oriented" software can be utilized to compensate for temperature and reduce environmental uncertainty. This is particularly effective in minimizing the impact of ambient temperature on form and position deviation.

A "task oriented" software temperature compensation can be performed in several steps. Firstly, we need to identify the critical control parameters (CCP_n) from the drawing according to the expected non-linear temperature deformation. The previous information from the control of the part will help in the identification. Then we need to simulate the temperature deformation using the Finite Element Method (FEM) [17] to determine each critical parameter as a theoretical deviation $d_{\text{SIMU,A}}(dt)$ (simulated nonlinear temperature deformation) for a given temperature change:

$$dt = t_0 - t_n, \quad (1)$$

where: t_0 - standard reference temperature [13] t_n - measured temperature.

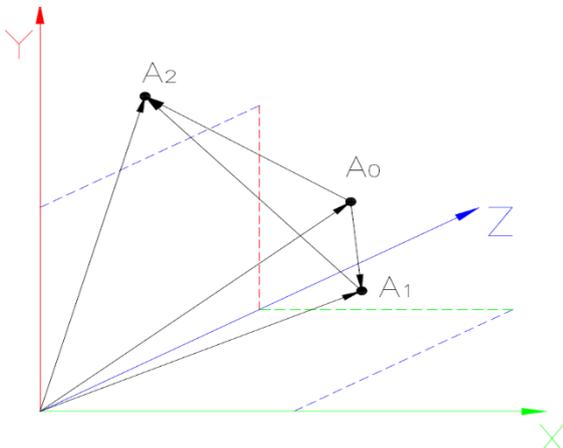


Fig. 4. Vector representation of SNTD as position of point A in Cartesian coordinate system.

The next step is to perform a vector analysis (Fig. 4) of the variation of CCP_n as point positions $A(x_a, y_a, z_a)$ and radius vectors $A(i_a, j_a, k_a)$ to the center of the relative coordinate system $OXYZ$ ($i=0, j=0, k=0$) of the workpiece. Vector $\overrightarrow{OA_0}$ represents the theoretically accurate position A_0 with confidence. The temperature compensation option integrated into the Shop Floor CMM software accurately calculates the linear deformation at temperature t_n and determines the position of point A_1 , represented by vector $\overrightarrow{OA_1}$:

$$\overrightarrow{OA_1} = \overrightarrow{OA_0} + \overrightarrow{A_0A_1}, \quad (2)$$

where:

$\overrightarrow{A_0A_1}$ is linear temperature compensation $t_n \neq 20^{\circ}\text{C}$. The actual position A_2 can be represented by a vector $\overrightarrow{OA_2}$ and analytically as the sum of the vectors:

$$\overrightarrow{OA_2} = \overrightarrow{OA_0} + \overrightarrow{A_0A_2}, \quad (3)$$

where $\overrightarrow{A_0A_2}$ is a vector that determines the actual position of A_2 after simulation of non-linear temperature deformation and is analytically equal to:

$$\overrightarrow{A_0A_2} = \overrightarrow{A_0A_1} + \overrightarrow{A_1A_2}, \quad (4)$$

where $\overrightarrow{A_1A_2}$ is a vector representing the change in position A_0 after application of linear compensation $\overrightarrow{A_0A_1}$ and simulated non-linear temperature deformation $\overrightarrow{A_0A_2}$.

In the application of vector analysis to the calculation of shape and position deviation, it is necessary to represent the vectors as projections in an XY datum feature plane by the errors they generate:

$$E_{A,t} = \varepsilon_\alpha - \varepsilon_\phi \pm E_{MPE,L}, \quad (5)$$

where the linear temperature deformation error ε_α is equal to the projection of the vector $\overrightarrow{A_0A_1}$ in the XY datum feature plane and the non-linear temperature deformation error ε_ϕ is equal to the projection of the vector $\overrightarrow{A_0A_2}$ in the XY datum feature plane.

V. UNCERTAINTY EVALUATION IN SHOP FLOOR CMM WITH TASK-ORIENTED TEMPERATURE COMPENSATION

Shop-floor CMMs are highly effective in inspecting complex surfaces, including multiplex surfaces (free-form surfaces), which are considered one of the most challenging measurement tasks due to the critical factor of measurement uncertainty. [18]

The measurement uncertainty of Shop-floor CMMs is affected by various factors. The ISO 15530 series of standards [5] offers several methods for determining the measurement uncertainty of a specific measurement task. Multiple measurement strategies are available, with or without calibrated workpieces, and computer simulation can also be used. Measuring complex surfaces at Shop-floor CMM poses a challenge for uncertainty estimation, but with careful attention, it can be done confidently. Inspection of complex parts using CMM is challenging due to the limitations of existing standards and recommendations. Assessing uncertainty of CMM measurements for complex shapes is mainly challenged by ensuring traceability of measurements. [2],[18]

Various methods exist for estimating uncertainty when measuring complex surfaces with shop floor CMM. A simplified methodology can account for some of the components contributing to uncertainty. In this study, we will use a simplified model to project a point onto a plane and estimate the change in coordinates resulting from ambient temperature changes. Our focus will be on the uncertainty caused by nonlinear temperature deformations. One of the main issues is the inability to make comparisons with a reference due to variations in materials and combinations, as well as the complex shapes of the parts.

To estimate the uncertainty of the Shop Floor CMM, use a combination of Type A and Type B uncertainties [19], along with computer simulation methods for temperature deformations. [20]

Type A evaluations assess the repeatability or randomness of a measurement process. The standard deviation is used to calculate the Type A uncertainty [21]:

$$\sigma_x = \sqrt{\frac{1}{n-1} \sum_{k=1}^n (x_k - \bar{x})^2}, \quad (6)$$

where:

$$\bar{x} = \frac{1}{n} \sum_{k=1}^n x_k \quad (7)$$

where x_k are the individual measurements and n is the number of measurements.

To evaluate all uncertainties associated with input estimates that have not been obtained from repeated observations, scientific judgement must be used. The metrologist should draw on all possible sources of information, their experience, and general knowledge about the processes to make reliable decisions about Type B uncertainties. [21], [22]

For the purpose of the study we use a Shop Floor CMM Aberlink Extol 370 [23] which is placed in conditions of ambient temperature change over a wide range (approximately 15 degrees within 8 hours). The aluminium workpiece being tested has complex shapes that require specific form and position requirements.

The measurement uncertainty can be represented by 5 components which have a different performance compared to spatial CMMs.

$$u_c = \sqrt{u_{ES}^2 + u_{EI}^2 + u_{EO}^2 + u_{EM}^2 + u_{ET}^2} \quad (8)$$

The uncertainty caused by the measurement person (subject) u_{ES} depends on placing the measured object on a jig (fixture device) u_{ESF} , because Shop Floor CMM works with a pre-set CNC inspection program that is not affected by changes in ambient temperature. To evaluate u_{ESF} , we could perform uncertainty Type A with two series of 10 repeated measurements of datum features. The first series would involve measuring the object without replacing it (u_{NF10}^2), while the second series would involve replacing the object after each measurement (u_{F10}^2).

$$u_{ES} = u_{ESF} = \sqrt{(u_{NF10}^2 - u_{F10}^2)} \quad (9)$$

Type B uncertainty allows the Repeatability error E_R stated in the technical specification by the manufacturer to represent the u_{ESF} :

$$u_{ESF} = E_R \quad (10)$$

The instrumental uncertainty u_{EI} is represented as a Type B uncertainty with two components: - Reading uncertainty u_{EIR} on the Shop Floor CMM, represented by the measurement error from the ISO 10 360 [12] length calibration certificate $E_{MPE,L}$; - Probe uncertainty u_{EIP} , represented by the measurement error declared by the manufacturer $E_{MPE,P}$:

$$u_{EI} = \sqrt{u_{EIR}^2 + u_{EIP}^2} = \sqrt{E_{MPE,L}^2 + E_{MPE,P}^2} \quad (11)$$

The Repeatability error (E_R) is an integral component of the $E_{MPE,L}$.

The uncertainty caused by the measured object u_{EO} can be confidently simulated using the finite element method (FEM) [17] in SolidWorks. This uncertainty is comprised of two inseparable components: the uncertainty from the type of material/the combination of different materials u_{EOM} , and the uncertainty caused by the complex shape of the object u_{EOF} :

$$u_{EO} = \sqrt{u_{EOM}^2 + u_{EOF}^2} = dt_{SIMU} \quad (12)$$

where dt_{SIMU} is simulated non-linear temperature compensation.

The object uncertainty u_{EO} can be viewed as a modified software emulated Type B uncertainty.

Shop floor CMMs operate using a pre-set CNC program, which results in a high level of method uncertainty u_{EM} . The uncertainty observed when utilizing a CAD model is due to a mismatch between the datum features of the model and the actual workpiece (u_{EMDF}). The uncertainty is equal to the E_{RMS} error, which is calculated as the difference between the real and ideal object by the software Aberlink 3D MK4 [23]:

$$u_{EMDF} = E_{RMS} \quad (13)$$

The method uncertainty u_{EM} can be viewed as a modified software emulated Type B uncertainty.

The change in ambient temperature is the main factor that influences environmental uncertainty u_{ET} . This uncertainty is the result of the sum of Machine uncertainty u_{ETM} caused by temperature fluctuation and Part uncertainty u_{ETP} caused by temperature fluctuation:

$$u_{ET} = \sqrt{u_{ETM}^2 + u_{ETP}^2} \quad (14)$$

The Machine Uncertainty can be represented by a Type A uncertainty based on MSA (Measurement System Analysis) [23] calculations for Equipment Variation (EV), but at the same time it is software compensated and can be assumed to be zero:

$$u_{ETM} = EV = 0 \quad (15)$$

The Part uncertainty u_{ETP} is represented by a Type A uncertainty based on Measuring System Analysis (MSA) [24] calculations for Part Variation (PV). Additionally, the Part uncertainty has been previously calculated through software simulation as non-linear temperature compensation dt_{SIMU}

$$u_{ET} = \sqrt{EV^2 + PV^2} = u_{ETP} = dt_{SIMU} \quad (16)$$

The environmental uncertainty u_{ET} . can be viewed as a modified software emulated Type B uncertainty.

$$u_c = \sqrt{E_{MPE,L}^2 + E_{MPE,P}^2 + 2dt_{SIMU}^2 + E_{RPS}^2} \quad (17)$$

This study aims to determine how uncertainty varies with changes in environmental conditions, specifically ambient temperature:

$$u_c = \frac{d}{dt} f(u_c) \quad (18)$$

$E_{MPE,L}$ and $E_{MPE,P}$ are constant and not function of ambient temperature fluctuation:

$$\frac{d}{dt} E_{MPE,L} = \frac{d}{dt} E_{MPE,P} = 0 \quad (19)$$

The variation of uncertainty as a function of fluctuating ambient temperature is:

$$u_{\frac{d}{dt}} = \sqrt{2dt_{SIMU}^2 + E_{RMS}^2} \quad (20)$$

Introducing task-oriented temperature compensation results in an uncertainty $u_{d/dt}$ that is analytically equal to:

$$u_{\frac{d}{dt}} = E_{RMS} \quad (21)$$

The presented equation demonstrates how to estimate uncertainty as a function of ambient temperature variation using the E_{RMS} error. A task-oriented systematic software correction can be confidently introduced for each temperature value to effectively minimize uncertainty.

VI. CONCLUSION

Shop-floor CMMs are becoming increasingly popular due to their flexibility in automated high-tech manufacturing. Although they have specific applications, shop-floor CMMs are constantly evolving to reduce control uncertainty. The use of task-oriented temperature compensation can greatly reduce uncertainty and make results comparable to those obtained in laboratory conditions.

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