New artifacts for calibration of large CMMs

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Abstract

Especially in car and aircraft industry large coordinate measuring machines (CMMs) are widely used. The calibration of these CMMs with conventional tools like lasers, level meters or straight edges is costly and scarcely practical. This paper deals with new 2D artifact-based techniques for the error mapping for large CMMs. This work is part of the European Standards, Measurements and Testing Programme[1]. Participants are Physikalisch-Technische Bundesanstalt PTB (Germany), Istituto di Metrologia “G. Colonnetti” IMGC (Italy), Brown & Sharpe DEA (Italy), Carl Zeiss (Germany), Trimek (Spain), Volkswagen Navarra (Spain) and Czech Metrological Institute CMI (Czech Republic).

Introduction

Calibration and numerical error correction of CMMs require a mathematical model of the error behavior and methods to assess the errors. While for small and medium-sized portal-type CMMs the rigid-body error model fits well with the real behavior, this is not so for large CMMs. Large horizontal arm CMMs and to some extent also large bridge type CMMs show elastic errors which cannot be properly modeled up to now. The assessment of the CMM error map for smaller CMMs can be performed by measuring calibrated ball or hole plates (up to 960 mm x 960 mm in size) in defined positions [1]. This method is time- and cost-effective compared to the use of lasers and other dedicated tools like levels and straight edges. Unfortunately ball plates cannot be simply upscaled for the error mapping for large CMMs because of among other things weight, elasticity and thermal problems. Hence the model and the error assessment have to be adapted to large CMMs.

Error model adapted to large horizontal arm CMMs

The rigid-body model is a good starting point for an effective model of large CMMs. It provides a clear idea of the error nature. Additionally, numerical correction algorithms based on the rigid-body model have been implemented in most CNC-driven CMMs. Therefore it suggests itself to keep this model as a basis and to expand single rigid-body error functions by additive elastic error terms. As elastic effects of horizontal-arm CMMs are related to the column, three elastic functions are found to be significant [2, 3]: the elastic roll error $xrx(x,z)$ of the x-slide, the elastic straightness error of the vertical axis $ytz(y,z)$ and the related pitch error $yrx(y,z)$. All elastic effects are proportional to the ram extension z:

elastic roll of x-slide	$xrx(x,z)$	$= C(x)\cdot z$	(column tilt)
elastic column straightness	$ytz(y,z)$	$= B(y)\cdot z$	(column bending)
elastic pitch	$yrx(y,z)$	$= A(y)\cdot z$	(column bending)

The designation of axes x, y, z follows the kinematic chain (cf. Fig. 1). The model is extended here to cover column tilt errors of horizontal arm CMMs with a long x-stroke [4]. Therefore the model parameter C is not treated as a constant [2, 3] but as an x-dependent function $C(x)$. All elastic model functions $A(y)$, $B(y)$, $C(x)$ (designation according to [2]) are specific to the design of the CMM. CMMs of the gantry type show different elastic errors and have to be treated separately.

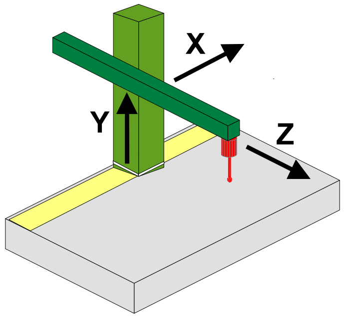

Fig.1: Designation of CMM axes according to the kinematic chain

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[1] SMT4-CT97-2183: “MESTRAL”

New artifacts adapted for the error mapping of large horizontal arm CMMs

Design

The error mapping of large CMMs up to a certain size should be performed by calibrated material measures such as ball or hole plates as these present obvious advantages. The artifacts must be adapted in size to the large CMMs.

To overcome problems due to the required size, large artifacts should have certain features: They should be dismountable to overcome transport problems. Main components should be built from simple geometry elements to allow effective manufacture. Therefore L-shaped dismountable 2D artifacts [3] have been manufactured. They include two main tube components (Fig. 2, 3 m and 1,5 m), which carry precision spheres. Calibrated sphere positions provide length and straightness reference. The spheres are probed by the CMM in defined artifact positions for rigid-body and elastic error mapping [3]. The tubes of the 2D artifact can also be applied for CMM verification using only the given length information.

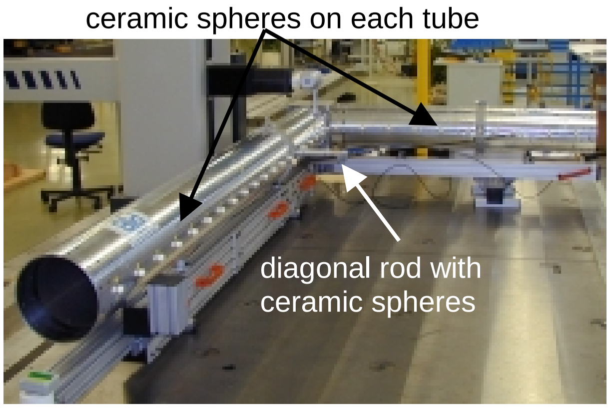

Fig. 2: L-shaped dismountable 2D artifact 3 m x 1,5 m with mounting equipment

Material

Due to the weight, the use of an artifact is limited by practical handling aspects and by the induced bending. Therefore carbon fiber reinforced plastics (CFRP) as a light weight material has been used for the artifact’s main tube components. CFRP tubes can be manufactured by the fiber winding process, which is an industry-proven, cost-effective and variable process. Additionally, it allows the use of high modulus (HM)-fibers to make the structure as stiff as possible. CFRP components have been protected by aluminum foil to avoid air humidity-induced changes in the artifact dimensions [3]. The analysis of the length measurements shows that the stability of the CFRP material is sufficient for use as large CMM calibration artifacts (constancy over half a year: 5 µm over 3 m length). For measurements in facilities without air-condition, the CFRP length expansion coefficient of $+0.9 \cdot 10^{-6}\,K^{-1}$ has to be taken into account.

Mounting

The use of dimensional artifacts always requires stable mounting. Absolute minimization of bending and bending changes can be achieved by multiple-point mounting. Here a quite uncommon but most effective method is applied, which is both flexible and stable: a coupled passive hydraulic system provides the same force for every supporting point of the artifact (Fig. 3).

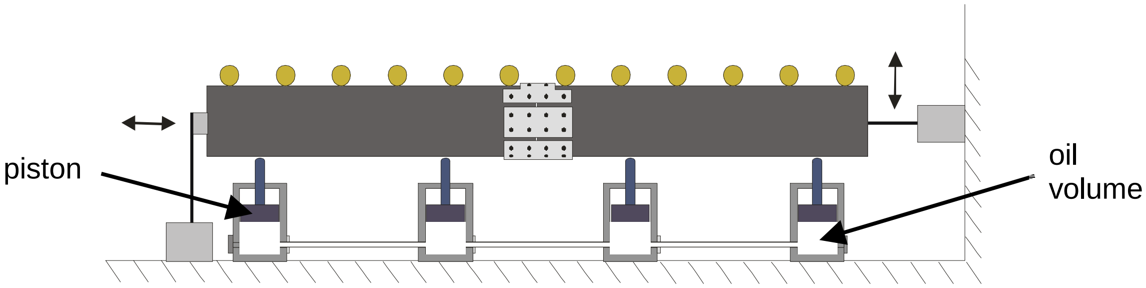

Fig. 3: Scheme of the hydraulic mounting system (here e.g. 4 point mounting)

Calibration

The calibration of larger artifacts is a difficult task. For handling and transport reasons, artifacts are not allowed to be extremely heavy, which itself might provide long-term calibration stability. Therefore environmental and transport effects can strongly influence large artifacts of reasonable dimensions and weight. One solution to this dilemma is to calibrate artifacts at the customer's site just before use (in-situ calibration). 2D artifacts embody length and straightness reference. Therefore we use a two-step calibration procedure: comparison of the 2D artifact sphere distances against a length standard with a mobile comparator (Fig. 4 and 5) and a reference-free straightness calibration on the CMM. The calibration data show that a procedure with a four-position reversal about both artifact sides yields best results. Three additional horizontal positions are required here, which is a reasonable effort considering the advantages of the in-situ calibration.

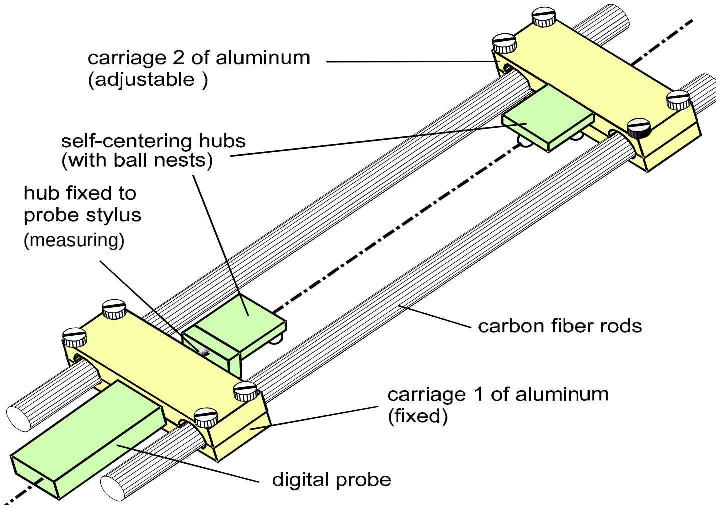

Fig. 4: Scheme of length comparator

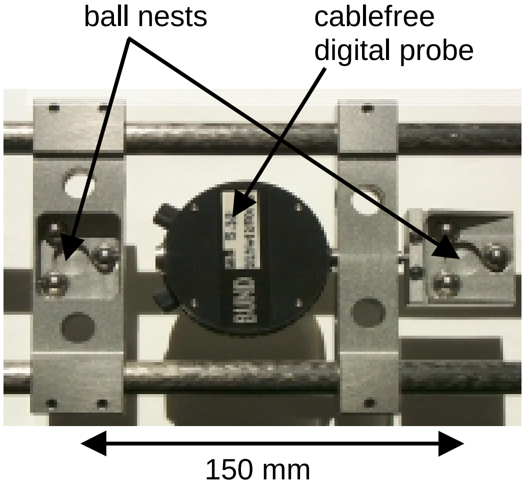

Fig. 5: Built up length comparator

Measurements

Measurements on large horizontal arm CMMs have been performed with the new L-shaped 2D artifact (Fig. 2) to test the handling, the error assessment procedures and the performance. Tests have been carried out in industrial environments to obtain realistic results.

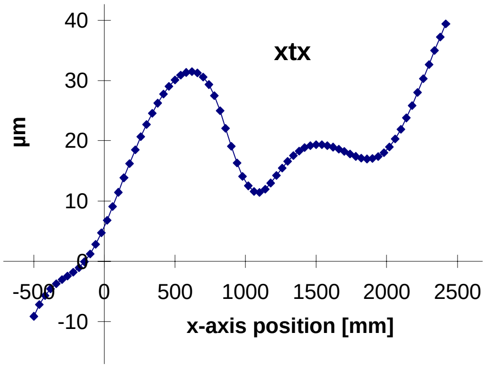

Fig. 6: Positional error xtx of horizontal arm CMM assessed with the new L-shaped 2D artifact

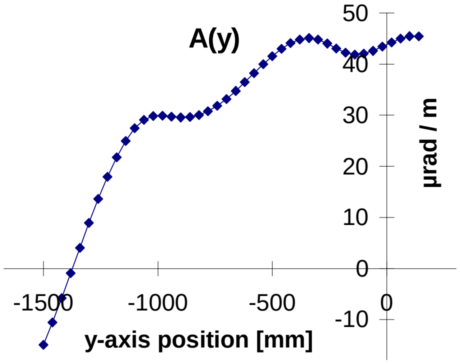

Fig. 7: Elastic model function A(y) of the elastic pitch $yrx(y,z) = A(y)\cdot z$ of horizontal arm CMM assessed with the new L-shaped 2D artifact

PTB developed analysis software (KALKOM) to assess CMM errors. The program features a graphical interface enabling the industrial use of the ball plate method with various 2D artifacts. KALKOM was extended to additionally extract the three horizontal arm CMM elastic errors from measurements with

L-shaped 2D artifacts. Fig. 6 and 7 show as an example the positional error *xtx* and the elastic model function *A(y)* [part of elastic pitch error *yrx(y,z)*] of a horizontal arm CMM. The evaluated error components can be directly used for the error correction of CMMs.

In order to prove the consistency of measurements, a test was performed to analyze the inconsistencies between the calibrated and the measured values. In this test KALKOM calculates the correction of the CMM using the 24 single error components just evaluated. The correction is applied to the original point measurement data for the error assessment (virtual correction). Differences between these values so corrected and the calibration values of the 2D artifact give an estimation of the contradictions in the measurements. Reasons for these discrepancies are the repeatability of the CMM itself, the stability of the artifact and its mounting and potential imperfection of the underlying kinematic model.

As a measure of the contradictions, the analysis of the length measurements is statistically evaluated. From this the standard deviation of the spread of all measured lengths amounts to 18 µm for the horizontal arm CMM under test. (Remark: It is to be noted that this standard deviation is calculated over all measured lengths up to 3200 mm!). In order to assess this value the repeatability of the sphere positions on the artifact has been used. This repeatability amounts to 12 µm (standard deviation). Assuming that the intrinsic repeatability of this CMM is not much below this value as further tests with other 2D artifacts have shown, the insufficiency of the error assessment with the new L-shaped 2D artifact is of the order of 10 µm.

From these results it can be derived that the mounting and the stability of artifacts have to be further optimized. Moreover, the experiments show how important it is to measure the temperatures of CMM scales during the CMM error assessment. Practical experience shows that the application of L-shaped 2D artifacts is limited in size for handling reasons. The authors estimate the artifact size limit for the use of L-shaped 2D artifacts to 3 m × 1,5 m. CMMs with one axis up to twice the greatest artifact length can be reasonably covered with these 2D artifacts.

Conclusion and outlook

This paper presents a new calibration set for making large horizontal arm CMMs traceable. The set consists of a new type of L-shaped 2D artifact, of error assessment procedures and of adapted error assessment software. Up to now tests have been performed at three industrial facilities. Handling experience with the new L-shaped 2D artifacts shows that full error assessment for a horizontal arm CMM with a 3 m x-stroke can be performed in two days, with the perspective of carrying out the procedure in nearly one day. First results will be cross-checked with CMMs of higher accuracy. Independent tests of the new artifacts with step gages or ball bars will validate the new system in the end. Final project results will be available in early spring 2001.

Acknowledgement

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