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CALIBRATION OF MEASURING INSTRUMENTS ON A COORDINATE MEASURING MACHINE

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Abstract:
In order to perform a calibration, a traceable standard of measurement shall be available. In addition, we need instrumentation for transferring the measure from the standard to the calibration object. Co-ordinate measuring machines (CMMs) can be used as such instrument for variety of calibrations. Since measuring processes can be programmed in advance, calibration procedures can be made easy and fast and a large number of simple standards and instruments can be calibrated at a time. Two different approaches can be applied when using a CMM as a calibration instrument - a CMM is calibrated for special tasks, using special calibration procedures and standards, or a laser interferometer (LI) is used as a standard. The first approach is used when calibrating standards with simple shapes, for which traceable standards of similar sizes and shapes are available. The second approach is used for simple measurands like internal and external diameters and linear distances. In this case we are not limited by size. In our laboratory we have some positive experiences regarding this kind of calibrations and they are presented in this article.

Key Words: Calibration, Traceability, Co-ordinate measuring machine, Laser interferometer, Uncertainty of measurement

1. INTRODUCTION

Calibration tasks often require flexible instrumentation for transferring dimensions from a standard of measurement to an object of calibration. Standards of measurements can be rigid like e.g. a gauge block or multidimensional like laser interferometer. In both cases we need in instrument to take the metrological data from the standard and transfer it to the calibration object. A good solution is to use a co-ordinate measuring device (CMM) for such task. CMMs are universal and flexible measuring devices used for solving a wide range of measuring tasks in industry. A great advance of such machines is also automatic calculation of measuring results and programmability for repeatable measurement tasks [1-4]. All these advances can also be used in calibration of measuring standards and instruments. However, it is very hard to calibrate a CMM for universal purposes and therefore we can hardly speak of traceability. In industrial use we are almost always happy with some functional performance checks [2-4], which are of course not enough when applying CMMs for calibration tasks. In cases of using a CMM as a calibration device, it shall be applied in combination with some standards of measurement like gauge blocks or gauge rings, which are easy to calibrate, or with laser interferometer serving as traceable linear measuring system. In such way CMMs are used as calibration devices in many European national laboratories in their original or adopted shape. The Laboratory for Production Measurement (LTM) at the University of Maribor, which is also nominated and financed by the Metrology Institute of Republic of Slovenia (MIRS) as a National Standard Laboratory, is applying a Zeiss UMC 850 CMM as a calibration device since many years as well. The laboratory is very well experienced in the comparator approach, which is used for calibrating screw thread rings, long calipers, setting rods for micrometers and different special gauges that can not be calibrated by standard methods. A new field of research is concerned with introducing methods for calibrating standards and instruments with laser interferometer by using the CMM as an instrument for metrological data transformation.

2. CALIBRATION APPROACHES

2.1 Comparison approach

The comparison approach, called also "comparator principle" [2, 4], is used for calibrating CMMs for special measuring tasks. The method uses calibrated standards (e.g. gauge blocks, gauge rings) that are similar to the measuring objects as regards shape and dimension. The measure of the calibrated object is compared with the measure of the standard by using the CMM as a comparator. The procedure is described in Figure 1. The main weakness of this principle is that a calibrated standard of similar size as the calibration item (allowed difference is up to 15 %) is needed for each calibration.

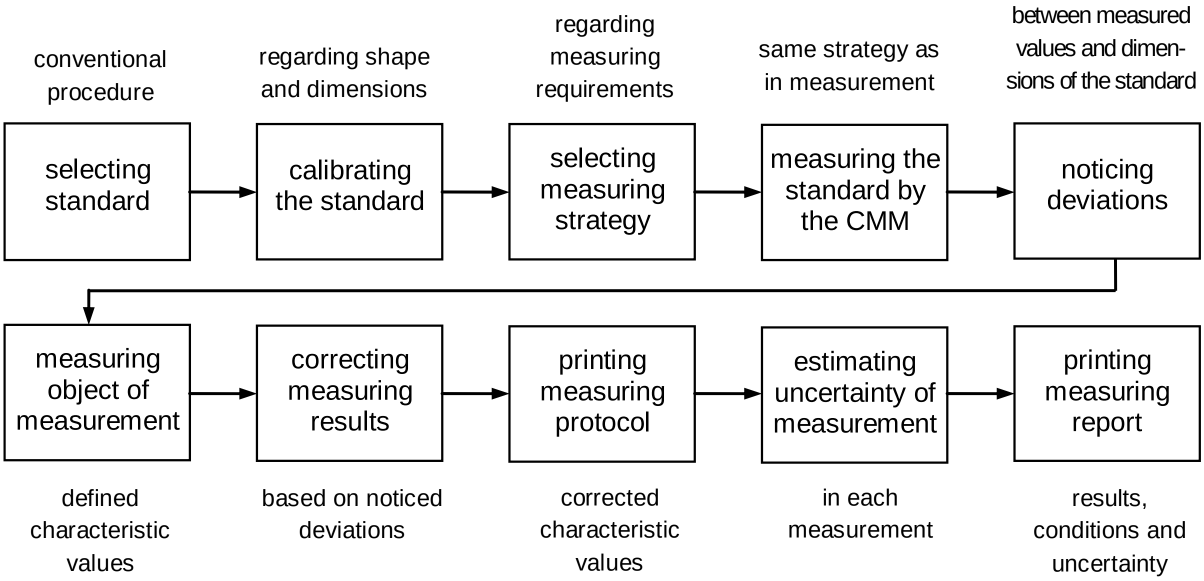


Figure 1: Calibration of a CMM using the comparison approach.

2.2 Direct measurement approach

In this approach we use a laser interferometer (LI) as traceable measuring system and the CMM serves only as fixing table and probing system (Fig. 2) [3,4]. This approach is very appropriate for calibrating different types and sizes of measuring standards and instruments and is often used in high-level calibration laboratories. A combination of a top-level accurate measuring system (LI) and very flexible probing system is of a great advance when high accuracy absolute measurements are needed. Standards LI optics shall be replaced with linear optics consisting of linear reflector and linear interferometer. Such optics allows movements also in a direction perpendicular to the measurement direction.

When laser interferometer is used as linear measuring system, it is very important to fix it on the measuring table. In this case we have no relative movements between the calibrated item and the laser beam source. This is especially important for devices with floating table. It is also important to fix the reflector into the probing head together with the probe(s). In this way the movement of the probes is exactly the same as the movement of the reflector, which is measured by the laser interferometer.

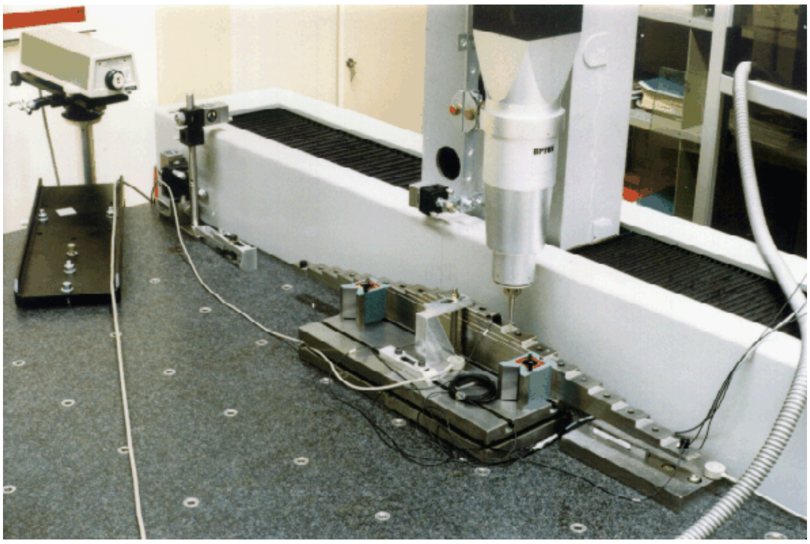


Figure 2: Combination of a CMM and a laser interferometer.

Basic measuring principle is shown in Figure 3. It is necessary to apply flat mirror and flat mirror interferometer, because it is not possible to avoid movements in different directions. In the example on Figure 3 it is necessary to lift the probe (and the mirror) in order to travel from the left probing point to the right one. Classical prism reflector does not allow such movements. The CMM probing head position shall be almost perfectly perpendicular to the measurement direction and the mirror shall be perfectly flat in order to assure that the beam returns to the interferometer.

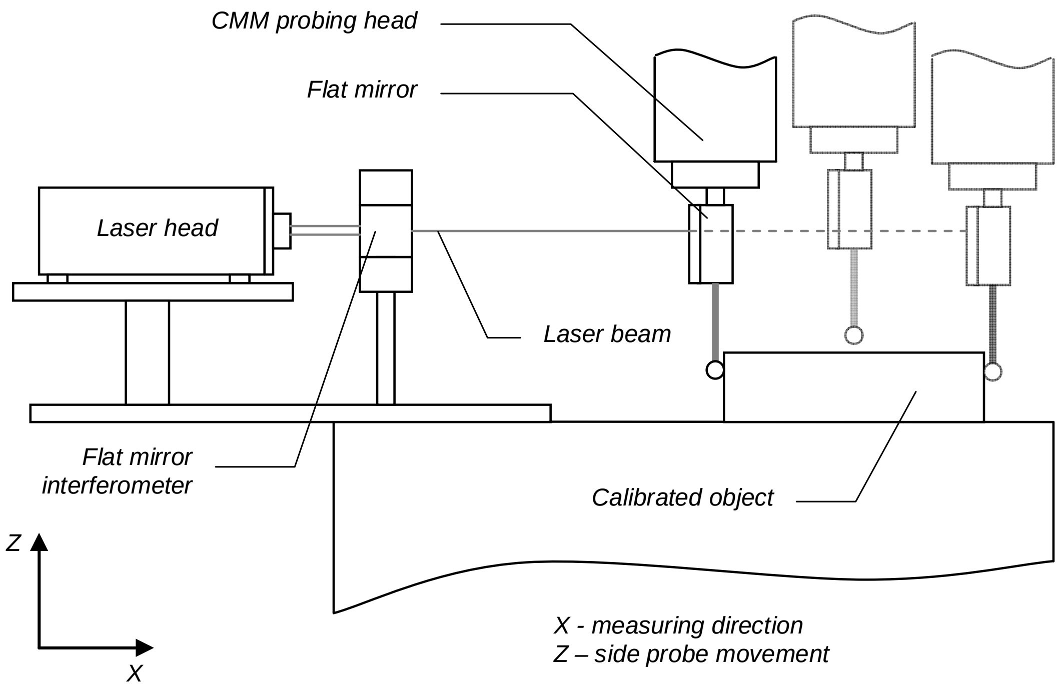


Figure 3: Measuring setup for calibrating external distance on CMM by using laser interferometer.

3. CALIBRATION ITEMS

Typical measurands to be calibrated on a CMM are the following [1,3]:

- Internal distance,
- External distance,
- Internal diameter,
- Step height,
- External diameter,
- Internal thread pitch diameter,
- External thread pitch diameter
- Thread pitch.

Standards and instruments in a wide range of shape and sizes can be calibrated on a CMM (Fig. 4). Maximum size depends however on the size of the applied CMM. Most frequent calibration items are the following [1]:

- Setting rings,
- Setting rods,
- Thread rings,
- Thread plugs,
- Long vernier callipers,
- Step gauges,
- Ball gauges,
- Taper gauges,
- Gauges with parallel surfaces …

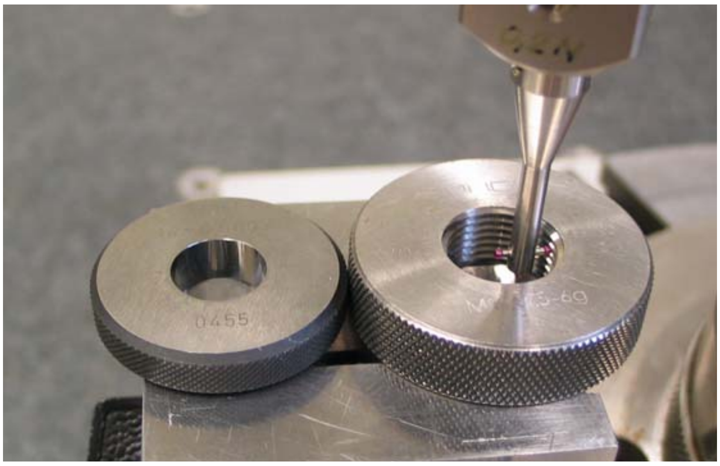


Figure 4: Calibration of a screw thread ring on a CMM.

4. TRACEABILITY

4.1. Traceability of comparative measurements

Traceability in this calibration approach is usually achieved very easily by calibrating standards of measurement used for comparison in accredited or national laboratories. In our laboratory we use only gauge rings and gauge blocks, which are calibrated in European national laboratories on the primary level. A little bit more complicated can be some complex task like calibration of pitch diameter on thread ring [5], where also probing ball shall be traceable, since the diameter serves for calculation of pitch diameter. This example is shown in Figure 5.

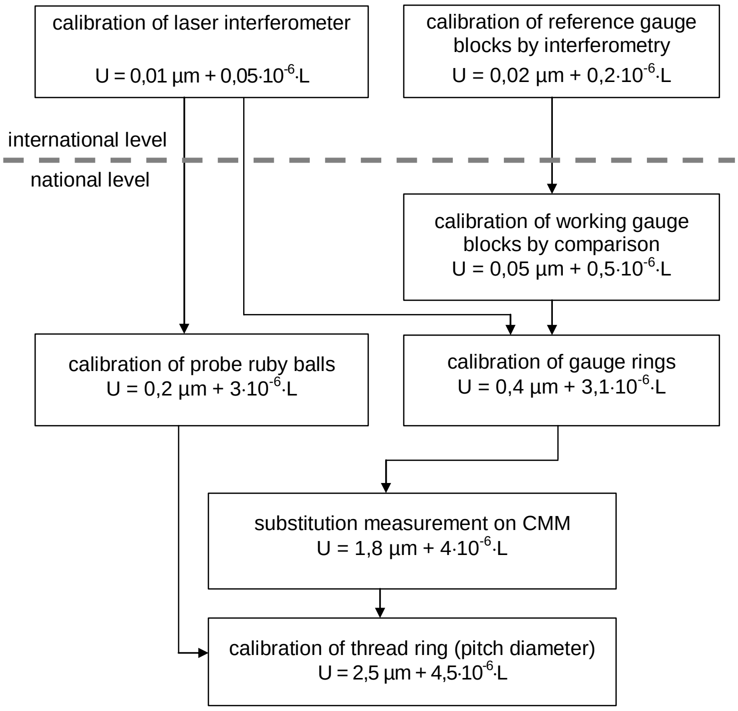


Figure 5: Traceability of thread ring pitch diameter calibration in LTM - MIRS.

4.2 Traceability of direct measurements

Laser interferometer as the main measuring system is usually calibrated directly by primary standard [6]. It is important to calibrate laser frequency and environmental (temperature and pressure) sensors. Environmental parameters are used for recalculating wavelength of the laser beam in the air and therefore directly influence the measurement result.

It is also important to calibrate the CMM probing ball diameter, because the final calibration result is calculated as a sum/difference of the distance measured by the LI and the probing ball diameter. The sum is applied when measuring internal dimensions and the difference for external dimensions. The principle is shown in Figure 6. Ball diameter is conventionally calibrated on the CMM ball standard, but this calibration is not good enough for calibration tasks. The ball shall be additionally calibrated in the actual direction of calibration. For external distance calibration we apply a gauge block of short dimension in order to eliminate measuring system influences. For internal distance calibration, the ball shall be calibrated on a special gap created from three gauge blocks. The gap shall be slide bigger than the ball diameter.

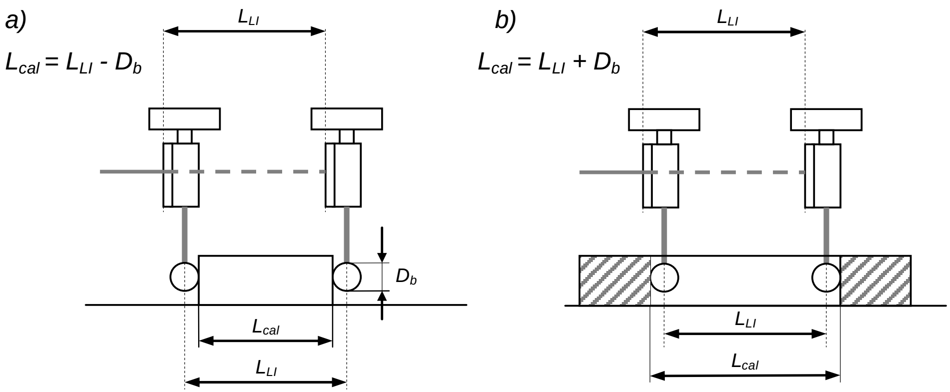
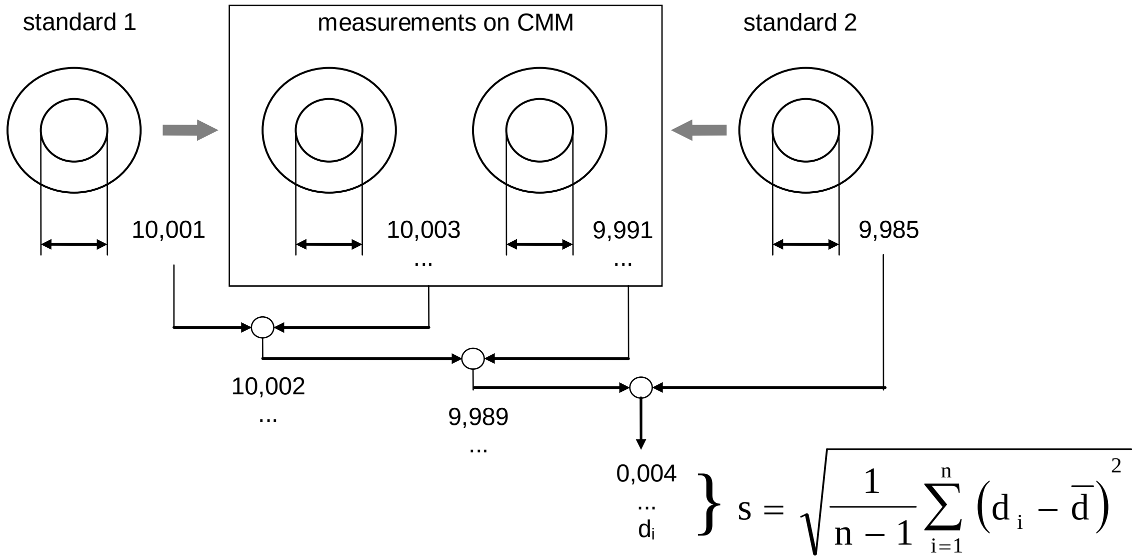


Figure 6: Calculation of calibrated length for external (a) and for internal (b) distances.

5. UNCERTAINTY OF MEASUREMENT

5.1 Uncertainty of comparative measurement

In this case the CMM is used as a comparator. The uncertainty of the comparative measurement should be determined and attached to the measurement result. Global principle of the calculation of uncertainty [7-13] is shown in Figure 7. In fact, measuring procedure is simulated with a known dimension of the measuring object (standard 2 in Fig. 7). Two slide different standards (or a standard and a measuring object of known dimension) are used for determining uncertainty at certain dimension. The uncertainty must be determined at approximately same place in the measuring volume as the measurement that follows (same plane - e. g. xy, same coordinates and the same orientation of standards). Temperature influences are not considered. It is assumed that both standards have same temperature.



$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2}$$

Figure 7: Uncertainty calculation for the comparison approach.

The main influence on the uncertainty is repeatability of the CMM probing sensor [10]. Therefore we are talking of type A uncertainty [9,11], which is determined statistically. In our laboratory standard deviation s (Fig. 7) is typically evaluated from 30 to 50 repeated measurements. Different pairs of standards are chosen in order to cover the whole calibration range. Normally the range is covered by three to four pairs of standards. The uncertainty varies from case to case but an average of U = 0,5 μm can be stated for illustration.

5.2. Uncertainty of direct measurement by using laser interferometer

The uncertainty comprises the following components:

- Uncertainty of laser interferometer indication,
- Uncertainty of the CMM ball calibration,
- Uncertainty of the CMM probing sensor zero position,
- Uncertainty of thermal expansion correction for the calibrated object.

The uncertainty of the deformation due to the probing force [14-16] is hidden in the CMM ball calibration and is therefore not treated separately.

A simplified mathematical model of measurement [9,11] is presented in equation (1):

$$L_c = L_{LI} \pm D_b - O_{PS0} + O_{PSL} - L\cdot(1+\alpha_{co}\cdot\theta_{co}) \qquad (1)$$

where:

L_c - calibrated length at 20°C
L_{LI} - laser indication (reading)
D_b - CMM probe ball diameter
O_{PS0} - CMM probing sensor offset in zero point (assumed to be 0)
O_{PSL} - CMM probing sensor offset in end point (assumed to be 0)
L - nominal length to be calibrated
α_{co} - thermal expansion coefficient of the calibrated object
θ_{co} - deviation of the temperature of the calliper gauge

Uncertainty of laser indication

Contributions to the uncertainty of measured length for the system used in our laboratory are presented in Table I.

Table I: Characteristics of several types of used cartons.

Source of uncertainty	Standard uncertainty, expressed as length contribution $u(x_i)$
Frequency	$0{,}022\cdot10^{-6}\cdot L$
Counting system	$0{,}005 + 0{,}025\cdot10^{-6}\cdot L$
Environmental sensors	$0{,}08\cdot10^{-6}\cdot L$
Wavelength correction (environmental)	$0{,}105\cdot10^{-6}\cdot L$
Drifting of zero indication	0,005 μm
Total	$0{,}007\mu m + 0{,}14\cdot10^{-6}\cdot L$

Uncertainty of the CMM ball calibration

The ball is calibrated by measuring a gauge block. The main contributions are uncertainty of the gauge block calibration [17] and repeatability of the CMM probing sensor. The total standard uncertainty for a ball with 5 mm diameter on our machine was evaluated to be:

u = 0,08 μm

Uncertainty of the CMM probing sensor zero position

This uncertainty component [16,18,19] is typical type A uncertainty and is evaluated as standard deviation of repeated probing in one point. For the conditions in our laboratory it was evaluated to be:

u = 0,13 μm

Uncertainty of thermal expansion correction for the calibrated object

For steel objects and temperature deviation in the limits of ±1 °C this component is estimated to be:

$U = 0{,}58\cdot10^{-6}\cdot L$

Total uncertainty

Linearized total standard uncertainty for the whole CMM measuring range is:

$U = 0{,}15\ \mu m + 0{,}60\cdot10^{-6}\cdot L$

It is quite obvious that the LI contribution is almost negligible.

6. CONCLUSION

Extended research and practical application have shown that CMMs can be very powerful tool for calibrating measuring standards and instruments. They shall be, however, always used together with calibrated standards of measurement. The most universal traceable high precision standard for such use is laser interferometer. Application possibilities have been tested but not yet fully applied in our laboratory. Some uncertainty estimation models have already been developed and environmental conditions put fully under control. However, many research possibilities, especially those related to the uncertainty of measurement, are still open. Further work will be focused into development of measuring setups for laser application including special flat mirror optics. Additional probing systems with better repeatability will be tested, too. It is also planned to develop measuring software for calibrating lots of measuring standards - especially setting rings. One of the most important standards to be calibrated on the CMM is step gauge, which is widely used in industry and calibration laboratories.

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