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Publication IV

B. Hemming, A. Fagerholm, and A. Lassila, "High-accuracy Automatic Machine Vision Based Calibration of Micrometers", *Meas. Sci. Technol.* **18**, 1655-1660 (2007).

http://www.iop.org/EJ/abstract/0957-0233/18/5/058/

Meas. Sci. Technol. **18** (2007) 1655–1660 doi:10.1088/0957-0233/18/5/058

High-accuracy automatic machine vision based calibration of micrometers

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Received 12 December 2006, in final form 7 March 2007
Published 13 April 2007
Online at stacks.iop.org/MST/18/1655

Abstract
The calibration of simple handheld instruments is often more expensive than the price of a new device. Therefore, the amount of manual labour is kept at a minimum in order to keep the price of calibration at a tolerable level. This also means that only a few points of e.g. a length scale can be checked. By using automatic machine vision based systems, the calibration of measurement instruments can be done faster and more thoroughly. In order to study the possibilities of machine vision automation for volume calibration tasks a set-up for micrometer calibration was constructed at Centre for Metrology and Accreditation (MIKES). With the developed automated machine vision system it is possible to check hundreds of points on the scale of a micrometer, giving new insight into error sources of the micrometer screw. The attained uncertainty is at the same level as calibration with gauge blocks according to ISO 3611.

Keywords: metology, calibration, micrometer, machine vision

1. Introduction

The manual calibration of a micrometer calliper according to IS0 3611 is done by using ten gauge blocks [1]. This gives only a rough figure of the accuracy of the instrument and is not a complete check of the scale. To reveal the error sources of a typical micrometer, many more points should be checked. Possible error sources are zero setting error, form error on the measuring faces, pitch error and nonlinearities in the screw, location errors or bad quality of graduation lines on the thimble and variations in the measuring force.

During recent years many measurement tasks both in industry and in laboratories have been automated using machine vision. With automatic machine vision based systems the calibration can be extended to several hundred points, giving a more complete picture of the errors.

Two important matters in measurements and calibrations are traceability and measurement uncertainty. The complexity of measurement uncertainty increases along with the complexity of the measurement equipment. Accuracy and measurement uncertainty in machine vision were previously discussed thoroughly in papers [2–4], but the presentation differs from the approach in the *Guide to the Expression of Uncertainty in Measurement* (GUM) [5].

In a previous paper the author has presented equipment for automatic calibration of dial indictors [6]. In this paper the updating of that equipment into a calibration device for micrometers is described. Detailed uncertainty analysis following recommendations of GUM is also given.

2. The developed instrument

The calibration of a micrometer according to ISO 3611 includes flatness and parallellity inspection of the measurement surfaces, measurement of the measurement force of the micrometer, checking the zero adjustment and measurement of the micrometer scale. The measurement of micrometer screw errors and measurement of force can be done with the developed instrument.

The instrument consists of two motorized stages, a length transducer and a red LED ring light together with a CCD camera (figures 1 and 2). The rotation of the micrometer thimble is motorized through a flexible coupling. A plate is fastened to the measurement stage (motorized stage 1) and the micrometer is run against a ball attached to this plate. A force transducer can also be placed between this plate and the measurement surface of the micrometer. The position of the measurement stage is measured by a length

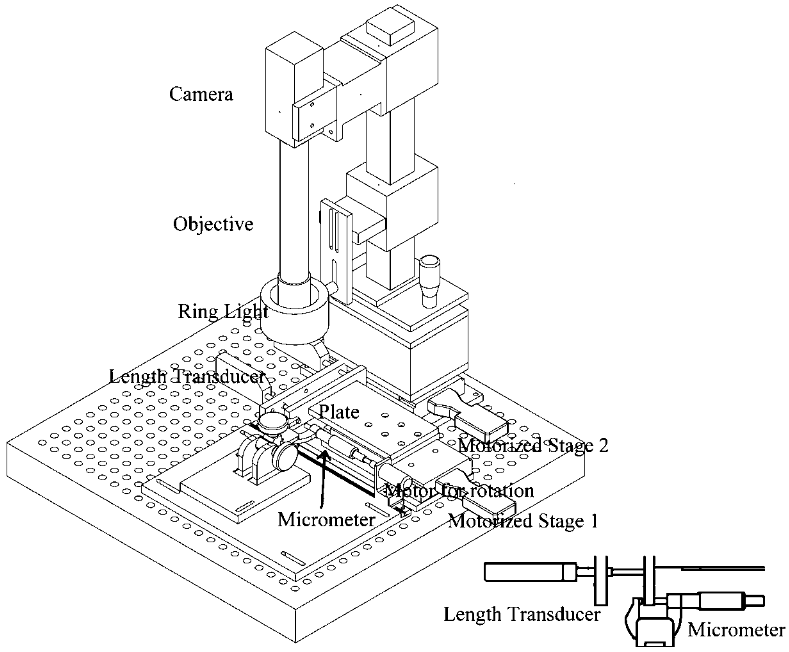

Figure 1. Drawing of the developed instrument.

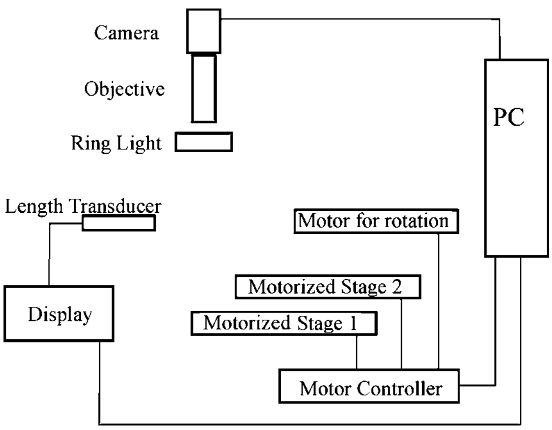

Figure 2. Schematic of the developed instrument.

transducer. A CCIR standard camera with resolution 752 × 582 is installed with a variable zoom objective. In order to achieve high accuracy, the field of view is small; therefore, another motorized stage (motorized stage 2) is needed to move the camera. The software was written using Visual Basic 6.

3. Image processing

At the frame grabber (Matrox Meteor II) the image is digitized to a resolution of 768 × 576. Although a zoom objective was used, the magnification is locked to a fixed magnification. The field of view is 4 mm × 6 mm and a typical image is shown in figure 3. The position of the division lines on the micrometer thimble is found using the pattern-matching function in the Matrox Mil library. The pattern matching in MIL is a speed optimized greyscale cross-correlation peak detection algorithm [7]. The accuracy of the algorithm is about 1/8 pixel, verified by using Matlab.

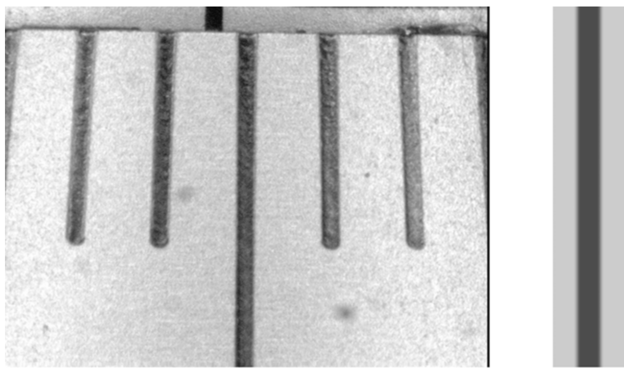

Figure 3. Typical image (left) and target (right).

On the thimble of a micrometer there are ten long division lines, and one revolution corresponds usually to 0.5 mm. The target for pattern matching is similar to the 0.05 mm division line of the thimble and it is generated by a Matlab script. Because the 0.05 mm division line of the thimble is longer than the 0.01 mm division line, only the 0.05 mm division line is found by the algorithm at the required score level. Typically the error of a small micrometer is below 5 μm. If there is a hypothetical error of 50 μm in the micrometer the software would give zero error as result. On most micrometers the thimble is bevelled and therefore the division line is parallel with the fiducial line only when the reading is zero, otherwise the division line will be tilted from vertical in the image. If the error of the micrometer exceeds 15 μm, the division line appears tilted, and the score of pattern matching is low and the user is notified.

4. Calibration procedure

First the zero setting of the micrometer is checked together with a manual measurement of a 5.1 mm gauge block. Then

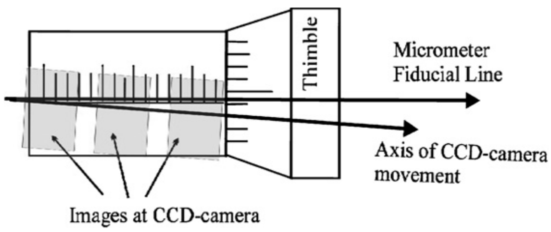

Figure 4. Measurement of the alignment error between the micrometer and the direction of movement of the camera.

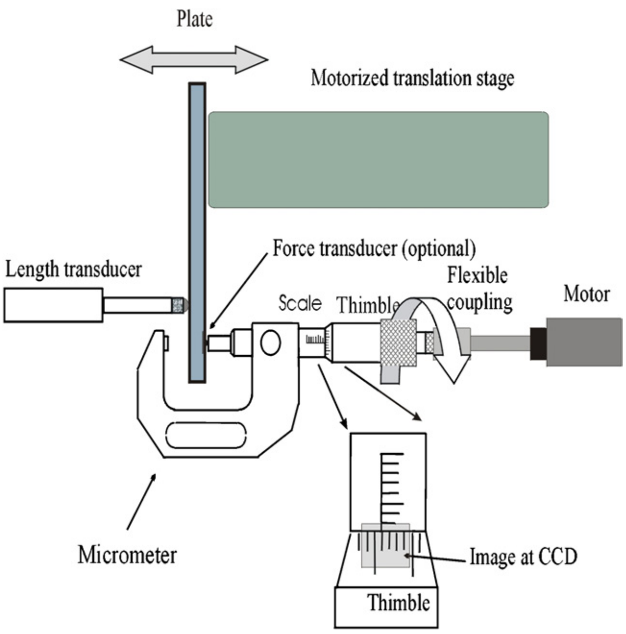

Figure 5. The operating principle of the instrument in an automatic calibration.

the micrometer is fastened to the clamp and aligned parallel to the length transducer using a dial indicator.

Then, the alignment error between the micrometer and the direction of the movement of the camera is measured (figure 4). This alignment error, which is smaller than 1°, is calculated from 15 images along the 5–25 mm range of the micrometer. The position of the fiducial line is found using the above-mentioned pattern-matching method. Using a least-squares line fit on the found positions of the micrometer fiducial line, an offset and a slope are obtained. This result is used to define the fiducial line in the camera coordinate system.

The next step is the automatic measurement of the micrometer screw errors where the length transducer is used as reference (figure 5). The calibration is done at 0.05 mm intervals but the operator can also specify a longer step length. The position of the division line in the image is measured (see figure 3) and the reading of the micrometer is the distance between the division line and the fiducial line, defined and measured earlier (see figure 4).

The time needed for setting up the micrometer is about 15 min and the duration of the automatic calibration of 400 points with 0.05 mm intervals is about 2 h. The time needed for the automatic measurement of one point is 18 s. The sequence for one point involves rotation of the thimble, movement of the measurement stage (motorized stage 1), movement of the camera (motorized stage 2), rotation of the thimble into contact, reading of the reference value and processing of the captured image. Each mechanical movement is allowed to take 3–4 s. A speed optimization and tuning of the written software would probably shorten the measurement time considerably. The manual ISO 3611 calibration of the micrometer screw using ten gauge blocks would take about 10 min, but the interval step is 2.1–2.6 mm. For a manual calibration the uncertainty is typically 2 μm ($k = 2$), and roughly half of this uncertainty comes from reading the thimble.

With the developed instrument it would be possible to measure also the measurement force during the automatic measurement of the micrometer scale. However, the deflections of the used force transducer were about ten times bigger (about 10 μm) than expected typical errors (about 1 μm) of the micrometer. Therefore, the measurement of force would influence the length measurements, which therefore have to be done with the force transducer removed.

To keep the measuring force stable throughout a measurement, the motorized thimble of the micrometer is turned making two clicks. This is a benefit compared to a manual calibration, because different human operators can cause large variations in force and measurement result, depending on the handling. With small changes the equipment is also ready to calibrate a dial indicator (see [6]).

5. Measurement uncertainty for an automatic calibration

A complete calculation of measurement uncertainty according to GUM includes a mathematical measurement model together with thorough description of each uncertainty component. The error sources were evaluated from measurements, experiment, data sheets or experience. The first step of an uncertainty analysis was formulating the model of the measurement. The measurement model is basically the expression used in the actual measurement software together with error sources named as corrections.

In the calibration of the micrometer only the position of the thimble is measured and the reading l_{ix} of the micrometer is

$$l_{ix} = c_x(x_i - x_0 - a \cdot L) + L \qquad (1)$$

where c_x is the magnification factor, x_i is the found position of the 0.05 mm division line of the thimble, x_0 is the position of the fiducial line at $L = 0$, a is the slope of the micrometer fiducial line in relation to the camera movement and L is the nominal length.

The magnification factor c_x is the relation between camera pixels and scale division lines at the thimble. By multiplying the slope a (pixel mm^{-1}) in equation (1) by the movement L (mm) the result is a correction for the alignment error (in pixels). The corrected position of the thimble (in pixels), relative to the fiducial line, is then multiplied by the scale factor c_x (μm/pixel).

The error E_x of a micrometer is obtained from the relationship

$$E_x = l_{ix} - l_s + \delta l_{ap} + \delta l_{ay} + \delta l_c + \delta l_p + \delta l_m + \alpha L \Delta t \qquad (2)$$

where E_x is the error of the micrometer; l_{ix} is the micrometer reading; l_s is the reference position; δl_{ap}, δl_{ay} are corrections for the Abbe error, due to offset between the measurement axis of the micrometer and the length transducer, with angular errors of translation stage; δl_c is the correction for cosine error between the micrometer and the length transducer; δl_p is the correction for flatness of the measuring surface of the micrometer; δl_m is the correction for repeatability errors (includes for example variations in measuring force and temperature); α is the thermal expansion coefficient of steel; L is the nominal length and Δt is the temperature difference of the micrometer from 20 °C.

Cosine error, δl_c

The alignment error or cosine error δl_c between the micrometer and the length transducer is tested to be easily adjustable within $\pm 0.4°$. Most of the error sources are assumed to have a rectangular distribution and the standard uncertainty is calculated by dividing the variation by $\sqrt{3}$. The standard uncertainty for alignment is

$$\frac{0.4°}{\sqrt{3}} = 0.23° = 4 \text{ mrad}.$$

Magnification factor, c_x

The scale factor is calibrated using an interferometrically calibrated line-scale [8] the uncertainty of which is less than 0.1 μm/50 mm. The result of the calibration is a scale factor of 7.24 μm/pixel and a standard error of 0.03 μm/pixel. Here the main error source is in the focusing and vertical position adjustment of the lens. When a typical micrometer thimble is slightly turned an angle matching one 10 μm scale line the camera sees it as a displacement in the image of roughly 1 mm (see figure 3). This magnification increases the sensitivity of the above scale parameters by the factor 100. Therefore the 'micrometer-reading to pixel' magnification factor c_x is 0.0724 μm/pixel.

Found position, x_i

In machine vision systems used in laboratories the lens errors are typically about 0.1% of the field of view or roughly about ± 1 pixel. The errors of the pattern-matching algorithm are typically about 1/8 pixel. The errors in the developed machine vision system were evaluated using an accurate line-scale. Although lines of the glass scale are of better quality than the lines of a micrometer, the measurement is very similar to the measurement of the position of micrometer scale lines because the same algorithm is used. Now the typical error of a single scale line was ± 0.2 pixel in the image and assuming a rectangular distribution the corresponding standard uncertainty for x_i is 0.12 pixel.

Slope, a

The slope is determined from measurements of the fiducial line. The straightness of these measurements corresponds to errors in the movement of the translation stage of the camera. The standard uncertainty for the slope is estimated to be 0.008 pixel mm^{-1}.

Position of the fiducial line, x_o

The offset of the fiducial line is evaluated from linear regression together with the slope a. The standard uncertainty for this position is found to be typically 0.07 pixel.

Reference position, l_s

The accuracy of the length transducer is ± 0.5 μm, according to the manufacturer. However, the length transducer has been calibrated against a laser interferometer over several years and a systematic error, which is found to be stable, can be largely compensated. The remaining error is approximated to ± 0.2 μm, which corresponds to a standard uncertainty of 0.12 μm assuming a rectangular distribution.

Abbe error, δl_{ap}, δl_{ay}

Ideally when length scales are compared, they should be on the same axis. If the scales are not on the same axis, this offset multiplied by the sine of any angular deviation in the linear movement along the scale gives the Abbe error. The length transducer is vertically 6 mm and horizontally 18 mm from the centre of the micrometer screw axis (see figure 5). This gives an Abbe error δl_{ap} due to the pitch and δl_{ay} due to the yaw of the translation stage. The pitch is within ± 0.03 mrad and the yaw is within ± 0.02 mrad according to measurements made with an autocollimator. Assuming rectangular distributions the corresponding standard uncertainties are 0.0173 mrad for the pitch and 0.0115 mrad for the yaw.

Flatness of measuring faces, δl_p

The flatness of the measuring faces of a micrometer should be within ± 0.5 μm according to ISO 3611. Assuming a rectangular distribution the corresponding standard uncertainty would be 0.29 μm. In the developed equipment only the middle of the measuring surface is contacting the ball. Therefore, the standard uncertainty for the correction for flatness of the measuring surface is much smaller and it is approximated to be 0.1 μm.

Temperature difference, Δt

The equipment is operated in a temperature-controlled room. The temperature difference of the micrometer from 20 °C is estimated to be $\pm 1°$ under typical conditions when performing calibrations, and assuming a rectangular distribution the standard uncertainty is 0.58°. As effective length for thermal expansion 20 mm is assumed. The rest of the temperature related uncertainties sources are supposed to be seen at repeatability test.

Repeatability errors, δl_m

The pooled standard uncertainty for repeatability errors, such as variations in measurement force and temperature, is approximated to 0.2 μm based on repeatability tests.

In table 1 the standard uncertainties are combined. The estimates in the second column in table 1 are only shown as an example. The sensitivity factors are found in the fifth column. Because of the formulation of the measurement model, the

Table 1. Uncertainty budget for the calibration of a micrometer with the developed instrument.

Quantity	Estimate	Distribution	Standard uncertainty	Sensitivity factor	Uncertainty contribution
Independent of length					
x_i	400 pixels	Rectangular	0.115 pixel	0.072 μm/pixel	0.008 μm
x_o	390 pixels	Normal	0.070 pixel	0.072 μm/pixel	0.005 μm
c_x	0.072 μm/pixel	Normal	0.0003 μm/pixel	5 pixels	0.002 μm
l_s	24.9995 mm	Normal	0.115 μm	1	0.115 μm
δl_{ap}	0 mrad	Rectangular	0.017 mrad	6 mm	0.104 μm
δl_{ay}	0 mrad	Rectangular	0.012 mrad	18 mm	0.208 μm
δl_p	0 μm	Normal	0.100 μm	1	0.100 μm
δl_m	0 μm	Normal	0.200 μm	1	0.200 μm
Length dependent					
Δt	0 K	Rectangular	0.580 K	0.0115 1/K L[a]	0.007 μm L
a	0.25 pixel mm^{-1}	Normal	0.008 pixel mm^{-1}	0.072 1/pixel L	0.001 μm L
δl_c	0 mrad	Rectangular	4.000 mrad	0.002 1/mrad L	0.008 μm L
L	20 mm				
E_x	0.86 μm		Independent of length		0.343 μm
			Length dependent (uncertainty)		0.010 μm L
			Expanded uncertainty ($k = 2$)		Q [0.685; 0.021L] μm
			Expanded uncertainty, $L = 20$ mm ($k = 2$)		0.802 μm

[a] L is length in mm.

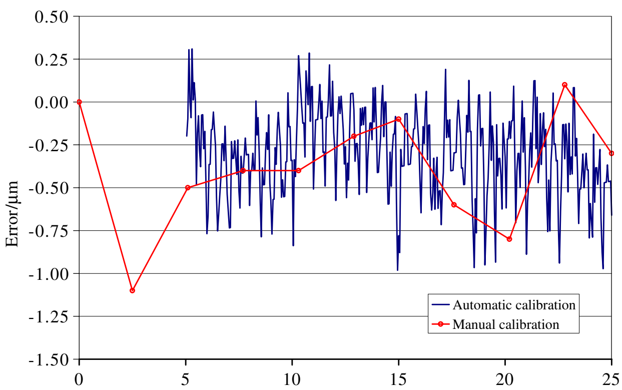

Figure 6. Calibration result using ten gauge blocks and using the automatic system.

(This figure is in colour only in the electronic version)

magnification factor c_x has a sensitivity factor which actually is the reading of the micrometer (see equation (1) and figure 3) and the value 5 pixels is shown as an example of a reading of 0.36 μm. The uncertainty budget shows that the error sources on the machine vision system are very small. The uncertainty contribution from the found position (x_i), magnification factor (c_x) and fiducial line (x_o and a) is only 0.05 μm ($k = 2$).

6. Results

Results from a manual calibration (ISO 3611) performed by an experienced technician together with results from an automatic calibration are shown in figure 6. The result from the automatic calibration gives a much more detailed picture of the errors of the micrometer than a manual calibration. In figure 6 there are fluctuations in the error curve which correspond to one revolution of the thimble, probably due to the flatness error in the measuring face of the micrometer. The slower fluctuation in the error curve might be due to the either pitch error in the screw or the Abbe error in the developed instrument. However, in this case the micrometer seems to be quite good with small errors of the screw. The agreement between different methods of calibration of a micrometer is acceptable. The differences can be explained by the uncertainties for each result.

7. Conclusion

Using machine vision in a normal routine calibration makes it possible to check hundreds of points on the scale of a micrometer. If a micrometer is used for quality checking at a production line in a factory measuring the same dimension thousands of times each year the result might be wear and errors at this single point of the scale of the micrometer. If manually calibrated this wear would probably not be revealed and the result would be quality problems when the micrometer gives wrong dimensions to the part at the production line.

The accuracy of the automatic calibration of a micrometer screw is better than the manual calibration because image processing works on a magnified image, and the variations in turning force are smaller than with a human operator. The purpose of this paper was to show the feasibility of traceable calibration of micrometers using machine vision. Although both machine vision methods and mechanical design of the equipment could be improved, the main conclusion is that the presented new approach has the potential to produce more than ten times more calibration results at an uncertainty which is less than 10% compared to the uncertainty of a manual calibration. In future improvements of the instrument the Abbe error should be minimized, more sophisticated machine vision methods could be used and the speed of the measurement program should be optimized.

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