Calibration of precision polygon/autocollimator measurement system

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Abstract. Measuring system of polygon/autocollimator is considered the most accurate widely available means of angle measurement, therefore its accuracy researches are of high importance. In this paper we describe the experiments of both autocollimators and polygon calibration implementing the equipment of average accuracy. The calibration data analysis given allows determining the errors of equipment without implementation of high accuracy reference means of measurement. The results of calibration of both autocollimators and precision polygon are also given in the paper.

1. Introduction
Precision polygons (miltiangular prisms) are by now considered to be the most accurate relatively widely available mean of angle measurement. Polygon/autocollimator measurement system is implemented for various tasks such as accuracy testing and calibration of angle measuring instruments, rotary tables etc. Therefore determination of accuracy and calibration of polygons and autocollimators is an important task analysed and performed at most of the high level metrology laboratories worldwide. Calibration of the measuring system (polygon/autocollimator) could be divided into two relatively independent branches – calibration and accuracy determination of polygon and calibration of autocollimator. Both tasks are extremely important, since both instruments influence the final accuracy of measurements, and both are complicated due to the needed high accuracy of measurements.

2. Calibration of autocollimators
Calibration of autocollimators has always been a complicated task since small angle steps must be generated with a very high angular precision. At Vilnius Gediminas Technical University two modified autocollimators modified by fitting the CCD matrixes to the optical units are used for the angular measurements [1].

2.1. Calibration procedure
For the calibration of the autocollimators a rotary table constructed by Wild Heerbrugg company and having the experimental standard deviation in no case exceeding 0.32” was used [2, 3]. Two mirrors
Figure 1 were placed on the rotary table and two autocollimators (1 and 4) were placed opposite each other and pointed to each mirror. Therefore the rotary table in this case acts as a small angle generator and the reference mean of angle measurement (and angular positioning).

![Image of Figure 1 showing layout of measuring equipment for experiment: 1 – autocollimator II, 2 – Wild rotary table, 3 – mirrors, 4 – autocollimator I.]

Placement of the mirrors which is shown in Figure 1 is not very typical since moving the mirror reflecting surface from the centre of rotation of the table may produce some additional errors, nonetheless for the experimental purposes and additional control of the measurements (described further) the presented scheme of mirrors placement was chosen.

Autocollimators under research give the position of the reflected mark in form of the number of the pixel, therefore the device needs to be calibrated to attribute the pixels values to arc seconds.

During the experiment the rotary table (with the mirrors) was rotated with the steps of 9° in the full range of the autocollimators measurements (approx. 250°). After four series of measurements the rotary table was turned 180°, so that the autocollimators faced different mirrors and the process of measurements was repeated.

After performing eight test series in the full range of autocollimators measurements the results were obtained (Figure 2).

![Image of Figure 2 showing dependency of autocollimator measurements deviation on the reflected mark position on CCD matrix.]

As can be seen from Figure 2, random errors of autocollimator measurements are quite small and standard deviations are 0.0587” for Autocollimator I and 0.04757” for Autocollimator II.

After further analysis of the received measurement data, it was determined that in case of both autocollimators their measurement deviation mean curves correspond to the 3rd order polynomial curves quite well. In case of Autocollimator I the best-fit polynomial curve can be expressed by the equation (disregarding the constant constituent):

\[ y = -1.084 \cdot 10^{-3} x^3 + 1.57 \cdot 10^{-3} x^2 - 6.27 \cdot 10^{-3} x \]  

(1)
and in case of Autocollimator II:

\[ y_d = 1.048 \times 10^{-4} x^3 - 1.2 \times 10^{-5} x^2 + 3.588 \times 10^{-3} x. \]  

(2)

where \( x \) is autocollimator measure in pixels, and \( y \) value of determined angular position in arc seconds.

These determined polynomial curves could be stated as the typical curves of the tested autocollimators (Figure 2).

The standard deviations of the best-fit 3rd order polynomial curve (typical curve) for Autocollimator I and II are respectively 0.113” and 0.142”. Having the stated practical standard deviation of the rotary table (0.32”), a general standard deviation of determined typical curves can be calculated, and for Autocollimator I and II it is respectively 0.339” and 0.350”.

2.2. Review of the possible measurement errors

Generally the sources of systematic errors of the measurements performed by autocollimators are:

- Influence of the non-parallelism of beams (autocollimator is not focused to the infinity);
- Flatness deviations of the mirror;
- Systematic errors of the CCD matrix;
- Errors caused by the optical system of autocollimator;
- Errors caused by the CCD orientation (CCD matrix not perpendicular to the beams).

As can be seen from Figure 2, typical curves both in case of Autocollimator I and II are of quite unusual (compared to the calibration data of other autocollimators) shape [5]. Some above mentioned factors can cause the systematic errors that produce such shape of deviations.

Influence of the non-parallelism of the beams is one of the major factors determining the accuracy of the autocollimator measurements. Nonetheless the character of the systematic errors (calibration curve) is quite different from the ones caused by the non-parallelism of the beams (especially in case of Autocollimator I) [5].

Since the mirrors were interchanged during the experiment, and it is practically impossible to point the autocollimators at the absolutely identical point on the mirror, the influence of the mirrors flatness deviations causing the obtained calibration curves could be rejected.

The other systematic error which could result in such calibration curves could be the systematic error of the rotary table itself (though theoretically due to the construction of table it should not exist). Nonetheless according to correlation analysis of measurement data (described further) and some further tests hypothesis of the rotary table systematic errors could also be rejected.

It is also doubtfully that the obtained errors could be caused purely by the errors of CCD matrixes (though their influence is obviously present). The most probable source of the deviations of such shape are the optics of the collimators itself, since in all cases the shape of the systematic errors was very similar (3rd degree polynomial) and in case of all autocollimators tested their optical systems were produced by a single company (“Hilger & Watts”).

The quality of mirrors used should be precisely tested. Determination of mirrors surfaces flatness deviations require special equipment, nonetheless approximate judgement of the mirrors quality could be done performing the correlation analysis of measurements at different combinations of instruments (autocollimators and mirrors), such analysis could be performed due to the use of multiple mirrors and autocollimators for the measurement simultaneously (two mirrors with two autocollimators) [6].

To analyze the data obtained by means of interchanging the mirrors and autocollimators (Figure 3) the correlation coefficients were calculated between each measurement consequently. The correlation calculation types are shown in Figure 4. As can be seen from Figure 4 the correlation coefficients were calculated between the measurement data obtained while Autocollimator I was pointed to mirror I and Autocollimator II to Mirror II (correlation coefficient \( C_{1} \)), Autocollimator I pointed to mirror II and Autocollimator II to Mirror I (correlation coefficient \( C_{2} \)), Autocollimator I pointed to mirror I and Autocollimator I to Mirror II after rotation of turn table 180° (correlation coefficient \( C_{3} \)) etc.
Finally the correlation coefficients of the measurement results obtained by means of same autocollimators pointed to the same mirrors (i.e. correlations between the multiple tests series) are assigned the numbers that are given in Table 1.

| Type of correlation                  | Given correlation number |
|--------------------------------------|--------------------------|
| Autocollimator I – Mirror I          | C₇                       |
| Autocollimator II – Mirror II        | C₈                       |
| Autocollimator I – Mirror II         | C₉                       |
| Autocollimator II – Mirror I         | C₁₀                      |

The estimates of correlation coefficients (according to Figure 4 and Table 1) are shown in Figure 5.

As can be seen from Figure 5 the highest correlation coefficient estimates belong to C₇, C₈, C₉ and C₁₀. These correlation coefficients were calculated between the repeated measurements performed by the same instrument at the same positions. Therefore they represent the accuracy (repeatability) of the angular positioning of rotary table in combination to the accuracy (repeatability) of the autocollimators. As can be seen the accuracy of rotary table positioning and autocollimators angular position determination is quite high, with correlation coefficients C₈ and C₁₀ for Autocollimator II being little lower which is normal due to slightly lower accuracy of Autocollimator II (2).
The estimate of correlation coefficient $C_1$ is high enough indicating that the accuracy of measurements of both autocollimators is high enough (both mirrors in that case move absolutely simultaneously and flatness deviations of mirrors has no influence on repeatability of measurements).

Correlation coefficients $C_2$, $C_3$ and $C_4$ have lower estimates which indicates the flatness deviations of one of the mirrors, which produces stable systematic errors every time the collimator is pointed to the different area of the mirror (since it is almost impossible to point the autocollimator exactly at the same point after the rotation of the turn table by 180 degrees).

The estimate of correlation coefficient $C_5$ is high again indicating that despite the change of autocollimators (high accuracy measurements of which was previously determined) the measurements shown no (or little) systematic constituent. This clearly indicates low flatness deviations of Mirror I.

Looking for the practical explanation of the results it can be stated that according to Figure 5 the estimate of correlation coefficient $C_6$ is very low, which clearly indicates the systematic errors of Mirror II most probably caused by the flatness deviations of the mentioned mirror surface. Therefore the use of the Mirror II for precise measurements should be avoided.

3. Calibration of precision polygon

There are various methods of calibration of precision polygons given in the literature; here we give the comparison test of two calibration methods – “simple” calibration and comparation, with the use of instrumentation available. “Simple” calibration is the calibration of precision polygon using to autocollimators and the rotary table of undetermined accuracy, the calibration is performed by repositioning the autocollimators (changing the angle between autocollimators so that they where pointed to different polygon faces) [7].

The calibrated Hilger&Watts 12 sided (having 12 reflective surfaces) precision polygon is very frequently used for the tasks in the calibration laboratory of the Vilnius Gediminas Technical University. The mentioned polygon was calibrated at PTB (Physikalische-Technische Bundesanstalt) National Metrology Institute in Braunschweig, Germany in 2007. In order to accomplish the time-span control of accuracy of the polygon the calibration of the same polygon was performed at VGTU.

A previously mentioned Wild rotary table was used as the base for polygon calibration.

During experiment the calibrated polygon was placed on the rotary table and two autocollimators were pointed to different mirror faces. Initially autocollimator I was pointed to 0° and autocollimator II to 30° mirror surface (Figure 6). After the full circle measurement (with the measurement stops at every 30°) autocollimator II was pointed to 60° mirror face of polygon and measurements were repeated. Therefore autocollimator II was consequently moved each time to another polygon face. That way the accuracy of polygon could be determined in two almost independent ways – direct comparison (comparation) of polygon/autocollimator I (or II) measures to the ones obtained by the encoder of rotary table (i.e. angular position of polygon); and “simple” calibration by means of two autocollimators (Autocollimator I/Autocollimator II) [8].

Figure 6. Instruments arrangement for calibration: 1 – rotary table, 2 – Autocollimator I, 3 – Autocollimator II, 4 – Autocollimator II after repositioning.
After processing of the experiment data (including autocollimators calibration data) the results were obtained. It was determined that standard deviation of measurements performed by autocollimators (in this case, since the position of polygon was determined by rotary table encoder, standard deviation could be considered as combined one of the table encoder/polygon/autocollimator) were for Autocollimator I – 0.127” and for Autocollimator II – 0.381”. Its obvious that standard deviation of Autocollimator II measurements is much higher (thus accuracy lower) which could be explained by the lower resolution of Autocollimator II and probably due to the influence of repositioning of the autocollimator along the circle.

The direct comparison of measurements of Autocollimator I and Autocollimator II (with sequential shift of data by 30°) to the rotary table angular position (measured by the table encoder) are shown in Figure 7. After the calculation of “simple” polygon calibration the deviations of the polygon mirror faces were determined disregarding the rotary table positioning errors (Figure 7).

![Figure 7](image1.png)  
*Figure 7. Polygon mirror face angular deviations determined by different means.*

As it can be seen from Figure 5 polygon face angular deviation determined by different means is very similar.

Considering that the polygon calibration data determined by PTB was reference (since the equipment of much higher stated accuracy was used) the deviations of all types of calibration measurements performed were calculated (Figure 8).

As can be seen from Figure 8 the highest deviations from the reference values (PTB data) are of the measurements performed by Autocollimator II/rotary table (standard deviation – 0.116”), the most accurate measurements being by Autocollimator I/rotary table (standard deviation – 0.245”) and “simple” calibration influenced by both autocollimator measurements (standard deviation – 0.125”).

According to the results both rotary table encoder and Autocollimator I showed quite high accuracy (which was predictable for Autocollimator I), the deviations from reference values being not larger than 0.17”. Since Autocollimator II showed quite poor results (largest deviation 0.438”) the results of “simple” calibration (Autocollimator I/Autocollimator II) are also of quite low accuracy (largest deviation – 0.236”).

It should be noted that constant moving of the Autocollimator II by the operator could cause unpredictable fluctuations of air masses of different temperature thus causing instabilities of measurements (such effect was observed during other measurements) [3]. The instabilities of the placement of Autocollimator II due to its constant movements could also influence the accuracy. Thus avoiding of all of the mentioned factors – automated moving of the autocollimator without physical interruption of operator and remote control of equipment should influence the increasing of general measurements accuracy.

Having in mind that standard deviation of polygon calibration is stated 0.1”, calibration performed by Autocollimator I/rotary table can be evaluated as having total standard deviation of 0.151”, Autocollimator II/rotary table – 0.161”, “simple” calibration (Autocollimator I/Autocollimator II) – 0.287”.
According to the results of calibration it might be stated that the best results at present conditions can be obtained implementing Autocollimator I and rotary table. “Simple” calibration procedure can not be straigthly implemented (despite quite high accuracy) since it depends on Autocollimator II measurements results of which are quite unpredictable.

It should be also noted that it is quite difficult to check the results of experiment since there are very few laboratories capable of performing measurements of high angular accuracy in the world.

4. Conclusions

- Two autocollimators were calibrated using precise automated rotary table which allowed increasing the accuracy and decreasing the time of the calibration considerably. According to the calibration data typical curves for Autocollimator I and Autocollimator II were determined with the general standard deviations 0.339” and 0.350” respectively.
- Method of evaluation of accuracy of the measuring instruments applying the correlation analysis without implementation of reference means was proposed.
- Evaluating the experimental results by means of correlation analysis angle measurement errors of Mirror II were identified. It might be assumed that such errors are caused by the flatness deviations of the surface of mentioned mirror.
- Two methods of precision polygon (multiangular prism) calibration were tested – “simple” calibration and direct comparation using high accuracy rotary table and an autocollimator;
- The experimental total standard deviation of the calibration was Autocollimator I/rotary table – 0.151”, Autocollimator II/rotary table – 0.161”, “simple” calibration (Autocollimator I/Autocollimator II) – 0.287”.
- The results of the highest accuracy were obtained by simple comparison between the autocollimator (Autocollimators I) measurements and the angular position of rotary table. This method of polygon calibration can be implemented “as is” at present conditions.

5. References

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