ISSN 1392 - 1207. MECHANIKA. 2009. Nr.1(75)

Limited accuracy reference free angular position determination

D. Bručas*, J. Sužiedelytė-Vysockienė**
**Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania, E-mail: domka@ktv.lt*
***Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania,*
E-mail: j_visockiene@hotmail.com

1. Introduction

Testing and calibration of angle measuring instruments was important ever since angle measurements were started to implement. These tasks are still of an extreme importance today since lots of angle measurement devices are being implemented in many branches of industry, such as machine engineering, construction works, geodesy, etc. Generally, there are several groups of plane angle measurement methods which could be implemented for the mentioned task [1].

1. Solid angular gauge method:
   - polygons (multiangular prisms);
   - angle gauges, etc.
2. Trigonometric method (angle determination by means of linear measurements).
3. Goniometric method (plane angle determination by means of a circular scale):
   - full circle (limb, circular scales, etc.);
   - nonfull circle (sector scales).

Usually the calibration of angle measuring instruments (calibration of the entire device) is performed by means of the comparison of the tested device with the reference one. Several technical decisions for the angle determination can be implemented in order to create a reference measure. The most significant means used for this purpose are [2].

1. Polygon/autocollimator.
2. Moore's Precision Index.
3. Circular scale/microscope(s).
4. Angular encoders.
5. Ring laser (laser gyro).
6. Interferometric angle generator.

In case of the implementation of the mentioned devices for the comparation of angle measurements there is a need of expensive and complicated device creating reference measures itself (one of the mentioned), also the precise alignment (centering and leveling) of the reference measure is needed [2]. Additionally, in some cases (as with polygon/autocollimator) only a limited number of angular positions could be tested or (as with Moore's Precision Index) the entire process of calibration can hardly be automated, or the calibration devices (as Interferometric angle generator) can not be implemented in industrial conditions.

In case of the calibration (or testing) of the low accuracy angle measuring instruments (turn tables in mechanical industry, construction site geodetic instruments, etc.) some robust, uncomplicated (in terms of adjusting) and less sensible for the environmental conditions system is needed [3, 4].

2. Principle of the new angle testing/calibration method

As was mentioned before adjusting of the calibrating device to the tested instrument is one of the most complicated and time consuming procedures of the entire calibration process. Precise alignment of the axis (centering and leveling) of the angle measuring instrument and reference mean is needed.

The proposed here method of angle testing or calibration is based on photogrammetric determination of the 3D points. Photogrammetry is a method of determination of the coordinates spatial points by means of two (or more) overlapping images of the object. Therefore by means of the two properly calibrated and positioned cameras (or single camera from different positions) and a special photogrammetric software coordinates of the selected point(s) (visible on both images) can be determined.

Principal geometry for coordinate determination of the photogrammetric system with two cameras is shown in Fig. 1 [5].

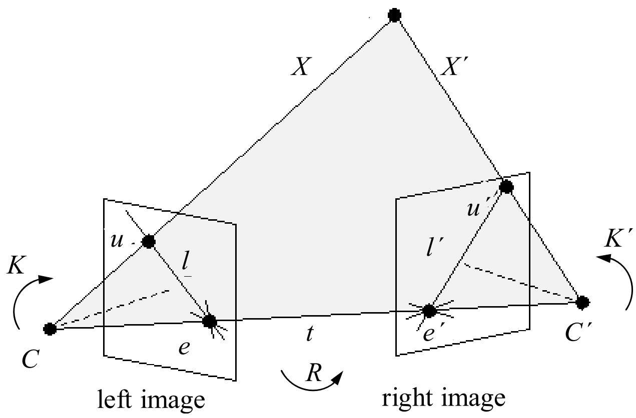

Fig. 1 Geometry of overlapping image

In Fig. 1:

- the line connecting optical centers C and C' of the camera is called the baseline – t;
- scene point X observed by the two cameras and the two corresponding rays from optical centers C, C' define an epipolar plane. This plane intersects the image planes in epipolar lines l, l'. When object point X moves in space, all epipolar lines pass through epipoles e, e' - epipoles are the intersections of the baseline with the respective image planes;
- u, u' are projections of the scene point X in the left and right images respectively;
- the ray CX represents all possible projections of the point X to the left image, and is also projected into the epipolar line l' in the right image;

- the point u' in the right image that corresponds to the projected point u in the left image must lie on the epipolar line l' in the right image;
- K and K' are rotation of the camera, with R being the flip of the cameras position.

The projections of the scene point X in fundamental matrix of geometry of the system with two cameras are [5]:

$$u = \left[K|O|\right]\begin{bmatrix} X \\ 1 \end{bmatrix} = KX \quad (1)$$

$$u' = \left[K'R - K'R\,t\right]\begin{bmatrix} X \\ 1 \end{bmatrix} = K'\left(RX - R\,t\right) = K'X' \quad (2)$$

Relative 2D coordinates of certain point in the images are obtained and since u, u' provides a strong epipolar constraint that reduces the dimensionality of the search space for a correspondence between u and u' in the right image from 2D to 1D; general 3D coordinates of the point can be calculated.

Therefore, using the photogrammetric principles it is possible to determine the point cloud of some kind of a flat plane attached to the tested instrument and rotating together with it. Some photos of the plate at different (calibrating) positions of the angle measurement instrument can be made. Using these photo images the point clouds of the plates at different angular positions can be obtained. Having these point clouds flat surfaces can be drawn through these clouds (Fig. 2).

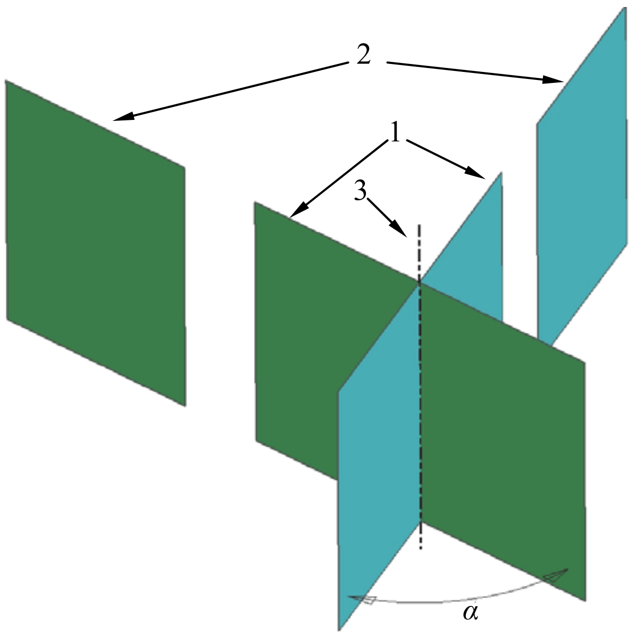

Fig. 2 Angle between the planes: *1* - planes, *2* - the same planes at certain distance, *3* - axis of rotation (planes intersection line)

After the planes *1* (Fig. 2) are obtained, it is possible to determine the spatial angle between them (α). An important thing in that case is that despite the position of the plate mounted on the tested instrument (therefore the position of the point cloud *1* or *2*) there will always be a single intersection line of these planes *3*, that is axis of rotation of the tested/calibrated instrument. Rotation angle (α) is measured by comparing it with the reference one created in the computer program used for that application. So, the measurements can be considered as reference-free (with the virtual reference created inside PC).

Therefore there is no difference how the plate (the point cloud of which should be obtained) is positioned, the only limitation is stability of the plate on the tested instrument and its visibility for cameras. Consequently, there is no need in precise positioning neither calibration plate nor the cameras (since the spatial angle is calculated between two obtained planes), which makes the preparation for the calibration considerably easier.

Some examples of application of such testing/calibration arrangements are shown in Figs. 3 and 4.

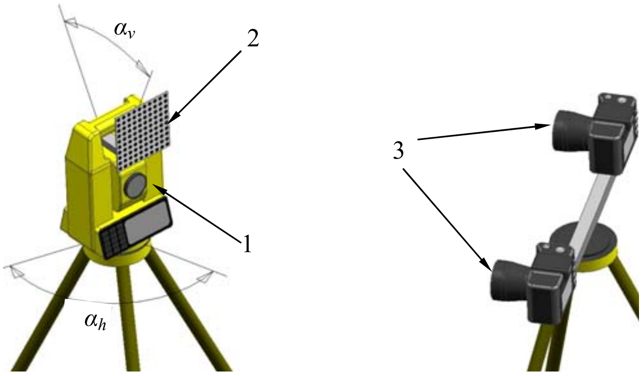

Fig. 3 Testing/calibration of angle measuring geodetic instrument: *1* - geodetic instrument (tacheometer), *2* - measurement plate, *3* - fotogrammetric calibration instrument (two cameras)

In Fig. 3 an arrangement for testing or calibration of angle measuring geodetic instrument (tacheometer) *1* is shown. Here the calibration plate with marks *2* for better photogrammetric points acquisition is attached to the spyglass of the geodetic instrument. The arrangement of two cameras on a tripod *3* is placed at some distance (so that the plate was visible at calibrated angular positions), there can also be a single camera used but its position should be changed to obtain the images of single angular position but from different camera positions. Such arrangement allows calibrating both horizontal (α_h) (with the vertical movement of the spyglass being fixed) and vertical (α_v) (with the horizontal movement being fixed) angle positioning. After series of angular movements has been done (and their images made) the results of angular positioning from the geodetic instrument can be compared to the results obtained from the photogrammetric software after processing of the images.

Obviously the calibration with single calibration plate can not be performed at the entire range of tacheometer angular measurements (360°) since the plate will not be visible on the images. To perform the full circle calibration the plate or the instrument or the cameras should be repositioned or there should be some special shape of the calibration plate used (there can be used a three or four angle object instead of the plate). The plate can also be positioned on any part of the geodetic instrument where the suitable attachment points are available. Obviously there is also no limitations in size of the plate and its distance to the axis of rotation (the larger the plate or its distance to the axis of rotation the larger linear movement, detected by the photogrammetry, of the plate and its points will be obtained) therefore the higher accuracy can be achieved with the only limitation in visibility of the plates by cameras.

Another example of the application of testing/calibration method on industrial milling machine is shown in Fig. 4.

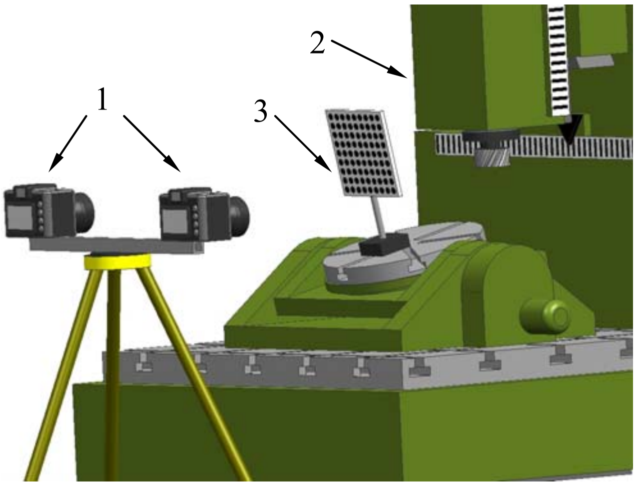

Fig. 4 Example of testing/calibration of rotary table of industrial milling machine: *1* - fotogrammetric calibration instrument (two cameras), *2* - milling machine, *3* - turn table (4th and 5th coordinate)

In case shown in Fig. 4 angular positioning of the turn table (4th and 5th coordinate) of five-coordinate milling centre is presented. The calibration plate with marks *3* (same as used in Fig. 2) is firmly (for example by magnetic holder) placed on the turn table of the milling machine *2* at any position. The arrangement of two cameras *1* is positioned next to the turn table (so that the plate is visible in the images), the entire process of calibration is identical to the one of the geodetic instrument. That way both the 4th and the 5th coordinate rotations of the table can be calibrated using the mentioned instruments in industrial conditions (workshop).

Similar angular position calibrations can be performed on many kinds of machines as, for example, spindles of turning machines (in case the turning was interpolated), turning tables of different machines, etc. The measurements can be performed very fast with extremely short time needed for the attachment of calibration instruments and high rate of measurements (1-2 seconds to take the images of a single angular position). The measurements can be performed at any indoor environment (only avoiding direct sunlight, heat radiation and other sources of optical distortions of the surrounding air), with further processing of the images performed by computer software at any suitable facility. The entire computer results processing can also be quite easily automated with the automated marks recognition performed by the photogrammetric software (which is widely implemented).

3. Testing of the accuracy of calibration

To test the suggested calibration method practically a special measurement arrangement was composed (Fig. 5).

The calibration plate with the marks attached to it *1* (Fig. 5) was placed on a precise turn table *2* produced by

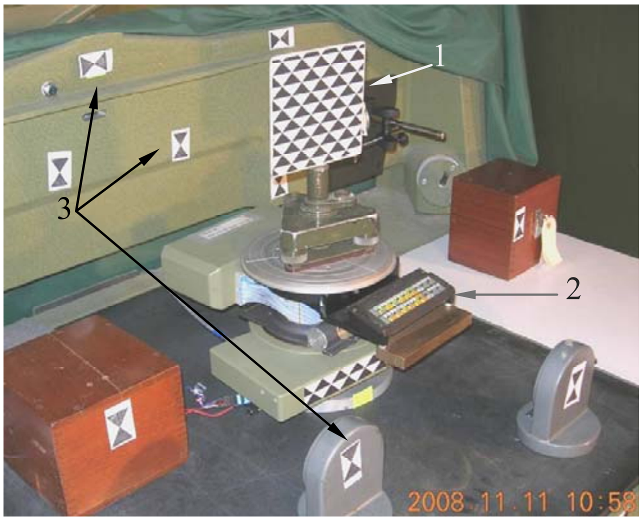

Fig. 5 Measurement equipment arrangement for testing of the suggested calibration method

Wild Heerbrugg company (its angular accuracy of 0.3″ [6, 7]). Large number of marks was used to decrease the random errors of the photogrammetric coordinates determination of a single point by obtaining the number of points and calculating the average best fit plane. A professional digital camera *Canon EOS 350D* (8 mega pixel) calibrated at the University of Technology of Bonn by *TCC* software was used for the experiment (with camera position changes for each measurement step). Special tie points *3* were used for later camera photogrammetric orientation.

The turn table (with the calibration plate attached) was turned with a step of 15° starting and ending at the positions where the marks were no longer visible by the camera and the measurement cycle repeated after that. Several photos (from different points) were taken at each measurement step and coordinates of the calibration plate marks for each step were calculated using *PhotoMod* photogrammetric software in manual mode (since no special software was prepared for the initial preliminary test).

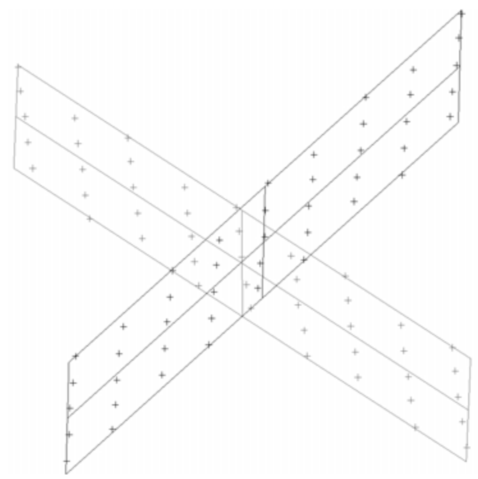

Fig. 6 Point clouds of several angular positions with the best fit planes attached

After obtaining the point clouds (for each step) the best fit plane for each measurement step was created using Imageware software. Angles between the plates were later calculated by the Unigraphics CAD software (Fig. 6).The results of tests comparation of angular position generated by the turn table, precisely determined by its encoder and considered as reference are shown in Table. The deviations of angular position determination by the suggested calibration method are shown in Fig. 7.

Table

Results of the angle measurement tests

Test set	Test Nr.	Angular position, deg	Determined angle, deg	Deviation of angle determination, arc min	RMS of camera orientation in images, mm
1	1	0.0000	0.0028	0.17	2
	2	14.9909	15.0053	0.87	2
	3	29.9840	29.9427	-2.48	5
	4	44.9789	44.9650	-0.84	2
	5	59.9767	59.9922	0.93	1
	6	74.9773	74.9351	-2.53	4
	7	89.9809	89.9950	0.85	3
	8	104.9866	104.9839	-0.16	1
2	9	14.9912	14.9747	-0.99	2
	10	29.9848	29.9965	0.70	4
	11	44.9790	45.0094	1.83	5
	12	59.9766	59.9904	0.82	4
	13	74.9770	74.9812	0.25	2
	14	89.9813	89.9911	0.59	2

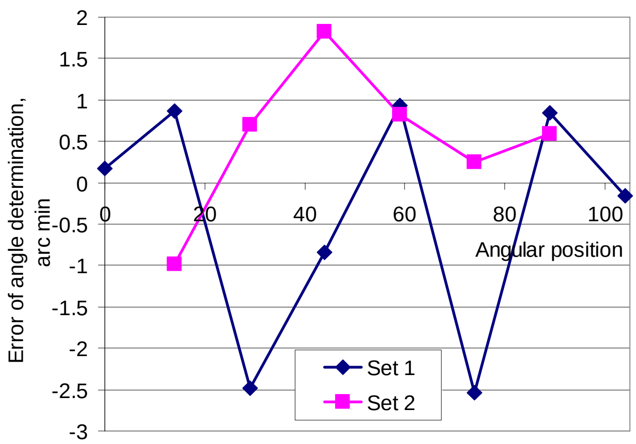

Fig. 7 Deviations of angular position determination

As can be seen according to the results of experiment the maximal deviation of angular position determination by means of the suggested photogrammetrical method does not exceed 2.53′ (test Nr. 6). Standard deviation of the tests performed is 0.89′ (with the standard deviation of the rotary table positioning neglected due to its small value).

It should be noted that the results are quite good for initial tests with high potential for further improvement of the measurement accuracy.

4. Possible sources of errors and higher accuracy achievement

Since the described experiment was only the initial trial to adopt the described method of calibration of angle measuring devices, there are plenty possible sources of errors with huge possibilities of the accuracy increase. Among the many possible the main sources of errors in case of that particular experiment could be named [8, 9]:

- errors of camera orientation;
- errors of camera calibration (lens and CCD matrix distortions);
- errors of photogrammetric point position determination;
- optical distortions of the air;
- limited resolution of the camera.

Since the measurements were performed using a single camera, some tie points had to be used to determine camera position in several images (perform camera orientation inside the photogrammetric software). Accuracy of such orientation is absolutely essential for further point position determination. The results of deviation of angular position determination in comparison with the root mean square (RMS) of photogrammetric camera orientation are shown in Fig. 8.

As can be seen from Fig 8, the largest deviations of angular position determination (tests 3, 6, 11) correspond well to the largest RMS of the cameras orientation. It should be possible to decrease mentioned errors by using an arrangement of two cameras (Figs. 3 and 4), since in that case the position of the cameras would be predetermined in all images.

Digital Canon EOS 350D camera used in the experiment was calibrated (at Technical University of Bonn by *Tcc* software) with focusing to the eternity, unfortu-

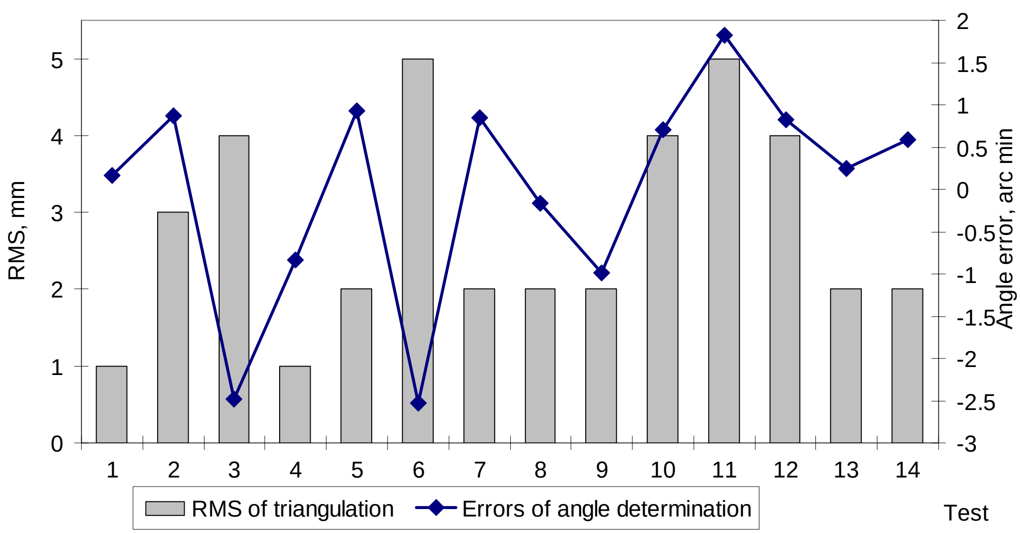

Fig. 8 Angular position determination deviation with the RMS of camera orientation

nately due to quite short distance from the camera to the rotating plate (1-2 meters) in case of the experiment described most of the images were quite blurry (with focusing to the eternity), and refocusing of the camera would lead to loss of the accuracy of measurement due to undetermined optical distortion of the lenses. Therefore it is necessary to perform the calibration with focusing at the shorter (work) distances suitable for the described task. Such camera calibration should increase the accuracy of measurements considerably.

Some errors of the photogrammetric points (on the plate) position determination could occur due to manual nature of the point collection in the experiment. Such influence was decreased by the use of a large number of points but errors could still influence the measurements. Automation of this process is possible and should increase the accuracy of point position determination and therefore the accuracy of measurements. Automation should also allow collection of the larger number of points (on the calibration plate) which should decrease random errors of specific point coordinates determination due to final approximation of the measurement results (creation of the single best fit plane through the point cloud).

Optical distortion of the surrounding air is always a great problem in case of optical measurements; therefore at the mentioned experiment it was tried to decrease the fluctuation of air, changes of temperature, etc., but still those influences definitely were present due to movements of the operator controlling the camera (since a single camera had to be moved from one place to another to obtain needed images). The errors of measurement caused by the distortion of images by air fluctuation should also be decreased by the implementation of the previously mentioned camera arrangement (Figs. 3 and 4).

Additionally higher accuracy of measurements could be achieved by the implementation of higher resolution (15-20 mega pixels) camera.

One of the possible sources of the errors of measurements was considered to be the angle of the calibration plate to the camera but according to the results of experiment (Fig. 7) there is no obviously noticeable influence of the rotation angle on the deviations of its determination. Nonetheless since the tests are only preliminary, the mentioned hypothesis could not be completely rejected till some further researches were done.

Generally in classical digital close range photogrammetry it is considered that achieving the accuracy of point coordinate determination of ±0.001% (or even ±0.0005%) from the distance to the object is quite possible (depending on various factors) [10]. Therefore theoretically it may be stated that in case of the described experiment (plate size 240x240 mm and distance to the camera 1.3 m) the accuracy of the points position determination could be around ±0.013 mm, which makes the angular accuracy of ±0.37′. Therefore accuracy of the measurements could be increased considerably even theoretically.

5. Conclusions

1. A new method of the calibration of angle measuring instruments allowing rapid settlement of simple calibration equipment and fast calibration process at the instruments work environment was suggested by the authors of the paper.

2. The experiment of implementation of the mentioned calibration method showed accuracy of the measurements not exceeding ±2.53′ (standard deviation 0.89′), which allows implementation of the method "as is" for the calibration of less accurate angle measuring instruments.

3. A huge amount of the improvements could be made to the mentioned method allowing increasing the accuracy of measurements considerably.

4. Further tests should be performed both in the field of accuracy increasing of measurements and practical implementation of the method.

Acknowledgments

This work has been funded by the Lithuanian State Science and Studies Foundation, Project No B-32/2008.

References

1. **Eidinov, V.J.** Angle Measurements in Machine Building.-Moscow. Gosudarstvenoe izdatelstvo standartov, 1963.- 413p (in Russian).
2. **Giniotis, V.** Measurements of Position and Displacement. -Vilnius: Technika, 2005.-215p. (in Lithuanian).
3. **Spruogis, B., Turla, V., Jakštas, A.** Investigation of radial misalignment influence on dynamics of precise rotor system. -Mechanika. -Kaunas: Technologija, 2007, Nr.1(63), p.45-49.
4. **Marcinkevičius, A.H.,** Automatic control of longitudinal form accuracy of a shaft at grinding. -Mechanika. -Kaunas: Technologija, 2008, Nr.1(69), p.63-68.
5. **Sonka, M., Hlavac, V., Boyle, R.** Image Processing, Analysis, and Machine Vision. -Iowa: PWS, 1998. -260p.
6. **Ingensand, H.** A new method of theodolite calibration. -XIX International Congress, Helsinki, Finland, 1990, p.91-100.
7. **Katowski, O., Salzmann, W.** The angle-measurement system in the Wild Theomat T2000. Wild Heerbrugg Ltd. -Precision Engineering, Optics, Electronics. -Heerbrugg, Switzerland, 1983, p.1-10.
8. **Karara, H.M.,** Handbook of Non-Topographic Photogrammetry.-North Virginia Ave., Falls Church, VA: American Society of Photogrammetry, 1997.-206p.
9. **Atkinson, K.B.,** Development of Photogrammetry and Surveying.-London: Applied Science Publishers LTD, 1980.-222p.
10. **Atkinson, K.B.,** Close Range Photogrammetry and Machine Vision. -Roseleigh House, Latheronwhel, Caithness, KW5 6DW, Scotland UK: Whitteles Publications, 2001.-371p.

D. Bručas, J. Sužiedelytė-Visockienė

RIBOTO TIKSLUMO BEETALONIS KAMPŲ MATAVIMAS

R e z i u m ė

Kampų matavimo prietaisų patikra ir kalibravimas yra labai svarbūs geodezijoje, mašinų gamyboje ir kitose srityse. Daugeliu atvejų kampų matavimo prietaisams tik-

rinti ar kalibruoti būtina etaloninė matavimo priemonė, galinti matuoti kampinę padėtį daug tiksliau (komparatorius). Kiti patikros bei kalibravimo metodai, tokie kaip kryžminis kalibravimas ar tos pačios skalės naudojimas etalonui sukurti, yra gana sudėtingi ir ne visada gali būti pritaikomi. Be to, atliekant patikrą ar kalibravimą palyginimo (komparavimo) būdu, būtina tiksliai mechaniškai suderinti (centruoti, gulsčiuoti ir t.t.) kalibruojamąjį ir kalibruojantįjį (etaloninį) prietaisus, o tai ilgai trunka ir dažnai yra gan sunkiai pasiekiama. Šiame straipsnyje pateiktas riboto tikslumo kampų matavimo prietaisų patikros ar kalibravimo metodas (principas), kai paprastos kalibravimo plokštelės, pritvirtintos prie kalibruojamojo prietaiso sukamosios dalies trimatis paviršius yra identifikuojamas fotogrametriniais metodais ir išmatavus erdvinį kampą tarp plokštelės paviršių, esant skirtingoms kalibruojamojo prietaiso kampinėms padėtims, randamas tikrasis prietaiso pasukimo kampas. Tokiu būdu virtualus kampo etalonas yra sukuriamas kompiuterinės programos viduje. Jį naudojant, nereikia tiksliai mechaniškai derinti prietaisų, dažnai galima matuoti kalibruojamojo prietaiso darbo aplinkoje (ceche ir t.t.). Taip pat pateikti pirmieji šio principo eksperimentinio taikymo rezultatai ir pirminis matavimo tikslumo vertinimas. Remiantis eksperimentų rezultatais, pirminių bandymų metu pavyko pasiekti ne mažesnį kaip ±2,53′ kampų kalibravimo tikslumą.

D. Bručas, J. Sužiedelytė-Visockienė

LIMITED ACCURACY REFERENCE FREE ANGULAR POSITION DETERMINATION

S u m m a r y

Test and calibration of angle measuring instruments is an important issue in the areas of geodesy, machine engineering and maintenance, etc. In most of cases, to test or calibrate the instrument a reference device capable of producing the angular values of higher accuracy (comparator) is needed. Other methods of testing and calibration (as cross-calibration or using the same scale as reference) are quite complicated and not always can be implemented. Additionally, in case of testing or calibration by means of comparison, a precise mechanical adjusting (centering, levelling etc.) of the tested and reference devices is needed, that kind of adjustment is often very time consuming and hard to accomplish. In this paper a very principle of testing and calibration of angle measuring instruments by means of digital photogrammetry with limited accuracy but without the need of precise adjusting procedure and with a possibility of the method implementation at industrial facilities is described. In this method the angle of rotation of the calibrated instrument is determined by means of simple plate attached to the rotary part of instrument, the 3D surface of plate is obtained by photogrammetric means, thus the angle between the determined surfaces of plate at different angular positions can be determined. Virtual reference angle measure is created inside the computer software, therefore the method could be described as the “reference free”. First results of practical implementation of the method with the preliminary accuracy evaluations are presented, according to which the accuracy of calibration not exceeding ±2.53′ was reached during the initial tests.

Д. Бручас, Ю. Сужеделите-Высоцкиене

БЕЗЭТАЛОННЫЕ ИЗМЕРЕНИЯ УГЛОВ С УМЕРЕННОЙ ТОЧНОСТЬЮ

Р е з ю м е

Калиброване и проверка инструментов для угловых измерений очень важны в геодезии, машиностроении и других сферах производства. В большинстве случаев для проверки и калибрования угломерных инструментов необходима эталонная мера, измеряющая угловое положение с гораздо большей точностью (компаратор). Другие методы проверки и калибрования, такие как перекрёстное калибрование или использование той же шкалы в качестве эталона, довольно сложны и не всегда могут быть использованы. Кроме того, при проверке или калибровании методом сравнения (компарирования), необходима точная механическая установка (центровка, соосность и т.д.) калибруемого и калибрующего устройства, что в свою очередь сложно достигнуть. В данной публикации изложен принцип фотограмметрической проверки и калибрования угломерных инструментов невысокой точности, без необходимости прецизионной механической установки. В данном методе простая калибровочная пластина крепится к подвижной части калибруемого инструмента и фотограмметрически измерив трёхмерную поверхность пластины и измерив угол между поверхностями при разных угловых позициях калибруемого инструмента определяется реальный угол поворота. Таким образом, виртуальная эталонная угловая мера создаётся в специализированной компьютерной программе, поэтому метод можно называть „безэталонным“. Также приведены данные предварительных лабораторных испытаний данного метода, показывающие, что даже в первичных тестах была достигнута точность измерения углов не ниже ±2.53′.

Received December 12, 2008
Accepted February 05, 2009