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INVESTIGATION OF ERROR SOURCES MEASURING DEFORMATIONS OF ENGINEERING STRUCTURES BY GEODETIC METHODS

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Abstract. Modern bridges and road structures are characterized by large-size objects, the complexity of engineering structures and a high precision of joints and knots of structural elements. Due to the above characteristics and an extremely increased mechanization degree, construction technology and nature of the structural engineering equipment has changed, while demand for high accuracy increased. In order to carry out the measurements as accurately as possible, digital surveying devices are used. The main part of the geodetic work in structures is leveling. Using digital leveling instruments for the precise leveling, the methodology of measurements changes due to the occurrence of the specific sources of error that affect the structural engineering measurements and observations of deformations of engineering structures. For this purpose, it is necessary to perform digital precision investigations of digital levels and coded staffs of specific models, precision of digital leveling, and technical, geometric and metrological parameters of instruments.

Keywords: coded staff, digital leveling, leveling error.

1. Introduction

Many highway bridges were designed and built years ago for smaller vehicular loads, those incorporated in the existing codes and standards. Therefore, the behavior of structural members of these bridges should be inspected and controlled more carefully (Kudzys 2009).

Construction work starts and finishes with geodetic measurements, therefore geodetic measurements and labeling are the most important components of mounting and installation work in construction.

The digital levels represent a breakthrough in leveling techniques using the innovative concept of reading a bar coded staff. Optical readings are no longer needed. Experience shows (Fig. 1) that with digital levels there is up to 50% time saving when compared with conventional levels. The main reasons are the faster data capture as well as the shorter time and safer means of data processing, due to the possibility of saving measured data on storage devices. Digital levels measure and save the height and the distance to the staff at the press of a button, and calculate the height of the point. Advantages are that no readings are required, no copying or writing down and no calculation by hand (Ingensand 1999).

Digital automatic levels are precise instruments used for precise leveling. Operation of digital levels is based on the digital processing of video information from the coded staff. At the beginning of measurement a visual pointing of the instrument to the surface of leveling staff is performed. After that the instrument automatically points the focus of its optical system on the staff surface and then a rough correlation calculation is performed followed by the precise correlation. According to the data

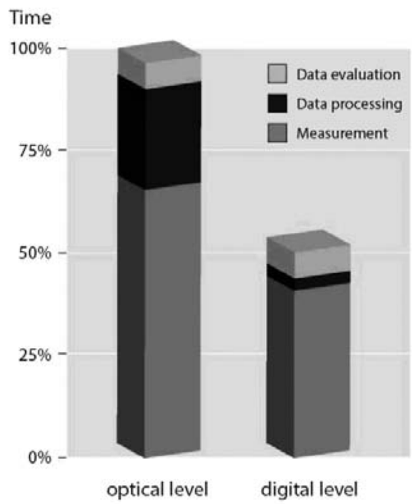

Fig. 1. Work time saving with optical and digital levels

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received in the processor of the instrument an exact distance from the axes of the instrument to the surface of the level staff is calculated. According to the information received by decoding the data from the photoelectric matrix the height of the placed level is calculated by the processor. During this operation the coded view of the staff is compared with that saved in the memory of the instrument. The true staff height position is determined according to the shift of the image in the photoelectric sensor (pixels) matrix.

Precision investigations of a particular model of levels and coded staffs and digital leveling are necessary. The investigations of technical, geometrical and methodological parameters of instruments are also needed. The scope of this work includes application of digital automatic levels and impact of their accuracy on construction measurements (Aksamitauskas *et al.* 2007; 2010).

2. Accuracy investigation of bar code staffs

A set of digital levels includes bar code staffs that have a significant impact on the digital leveling results. The choice of the type of staff depends on its length, material and meteorological factors. One side of a staff has bar code graduations for the digital leveling, while the other side has the traditional scale (in cm).

The reference bar code of the staff is stored in the device memory and during the measurement is correlated (compared) with the code view of the staff in the linear converter (detector). A two-step correlation is used: exact and approximate. The approximate correlation reduces the search area and the calculation volume, as well as shortens the measurement time. The precision correlation determines the exact position of the code line image with regard to the reference bar code, i.e. the staff bar code image is equated with the reference bar code. For this purpose, a linear detector consisting of 256 photodiodes (pixels) is used. The accuracy depends on the pixel dimensions, their number and the sensitivity function of the detector. This, in turn, affects the accuracy of readings obtained in the level indicator (Krikštaponis 2000; 2001; Becker *et al.* 1994; Becker 1999).

Usually, during the accuracy control, the effort is made to place the control staff into a position where it is used during the operation, i.e. in a vertical position. However, there are cases when the staff is tested in a horizontal position and such a composition easies considerably the measurement and reduces the required height of a room.

Possible structural variations of the staff comparators are listed in Table 1.

Staff calibration is carried out according to the following principle: the staff in the comparator is moved using a special lifting system and a step gear. The staff position is read by a laser interferometer and edges of the staff scale are recorded with a special charge coupled device (CCD) camera. Automatic climate control system records the ambient temperature, pressure, humidity, seeing as the staff length and the laser wave propagation should be reduced taking into account environmental factors. This whole system is controlled by a computer program (Giniotis *et al.* 2007).

The position accuracy of the leveling staff lines is performed by comparing photogrammetric images of the support and control staffs or replacing the base measure with photogrammetric support staff image recorded with a digital camera and transferred to the computer memory. In this case, the scale line position of the bar code support staff is compared with the position of the calibrated staff lines using the analysis window comprising in the recording unit, which includes the compared lines of both staffs. The scale line positions of both staffs is evaluated by performing a local (in the area of the compared lines) correlation analysis of the digital information, and the calibration result is determined by the difference in readings between the line positions of the reference and calibrated staffs at the information extremes of the digital line positions (line edges).

The principle of this device is that for the staff calibration by a reference measure, a reference (support) staff and a CCD camera are used relocating them into a number of positions parallel to the staff axes and recording the line images of both staffs and their positions in regard to each other. The calibration results are then evaluated according to the measurements made with an additional scale situated on the computer screen, determining the digital difference between the positions of the measured and reference scale lines.

Photoshooting both the reference staff and the staff under calibration, an additional millimeter scale (or analog staff) is installed next to the staffs for control. The additional scale is used to process results of the digital images in the computer. It also allows for performing readings along the scales between the line positions of the reference millimeter scale, the reference staff and the staff under calibration. The scale graduations are read by an indicator connected to the analyzing window – diaphragm. Instead of the scale, a coordination grid of the AutoCad software was used in this study. Calibration system is shown in Fig. 2.

Table 1. Principal structure of comparators

Placement	Used reference	Mobile part
Vertical	Laser interferometer	Calibrated staff
Horizontal	Laser interferometer	Carriage with CCD camera and reflecting prism
Vertical, horizontal	Digital view of the reference staff	Without a move or with a partial move (when a digital camera is reset with a certain step)

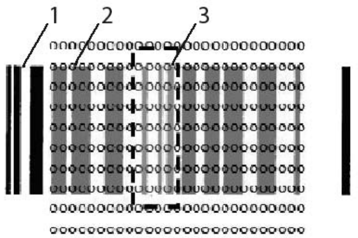

Fig. 2. Principal system of calibration: 1 – coded bars of the staff; 2 – array of CCD sensors; 3 – analyzing window

In the initial position, moving the analyzing window 3 with an index, the initial position of the staff lines is read. This is done by setting the window 3 on the initial lines and recording a certain correlation coefficient value in the computer correlation unit. Then, using a selected step, the window 3 is moved along the staff image and the diaphragm position is corrected by moving it along the measuring staff 1 to the position where the correlation coefficient becomes equal to the initially selected correlation coefficient. The diaphragm position is recorded using the scale 2 and index or the computer graphical coordinate system. Then the same procedure is performed with the reference view 2, adjusting the diaphragm position in the coordinate system to the selected correlation coefficient value, only this time capturing it from the view 2. The difference between the obtained values shows the linear error of the line positions of the two staffs. The procedure is repeated to the entire length of the staffs being calibrated (Aksamitauskas, Rekus 2009).

3. Scale accuracy studies of bar code leveling staffs

A digital camera used to obtain digital images of bar code staffs should be calibrated and internal orientation elements, the symmetrical and unsymmetrical distortions, should be determined. The calibration is carried out by a computer program using a special stand-point with known point coordinates. The accuracy of the obtained results is then estimated. The camera calibration results are used for the further image processing (Sužiedelytė-Visockienė 2007).

All photos used in the study were transformed into a plane in order to eliminate distortion of the camera lens and to make objects in the photographs more detailed. To assess the calibration accuracy of the bar code staffs and to obtain the code scale accuracy of the bar code leveling staffs, experiments were performed transforming parts of the photos of the digital bar code leveling staffs into digital information using a specially designed computer program.

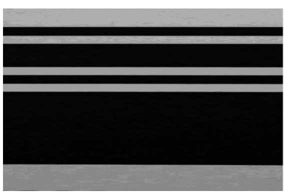

Fig. 3. Scale fragment of a coded leveling staff

Fig. 3 shows one of the code scales used in the study. The highlighted area in the central part of the code scale indicates the data that was converted into digital information (the digital matrix). The central part was selected in order to minimise as much as possible the inaccuracies in the data matrix (Giniotis *et al.* 2008b).

It was experimented by measuring the digital photo fragments of scales of the bar code leveling staffs in formats: JPEG, BMP 16-bit, BMP 256-bit, BMP 24-bit, BMP MONOCHROME, TIFF and GIFF. The most suitable format for the determination and investigation of the code scale edges was 24-bit BMP, as the clearest view of the code scale edge limits between black and white lines and the lowest distortion in the digital photos could be obtained (Aksamitauskas, Rekus 2009).

Fig. 4 demonstrates a fragment of the digital matrix, which was obtained using the specially designed computer program. Darker color pixels are expressed with smaller numbers, while brighter pixels are represented by larger numbers. As a result, a boundary between the black and white line edges or mechanical damages of the code scale can be identified.

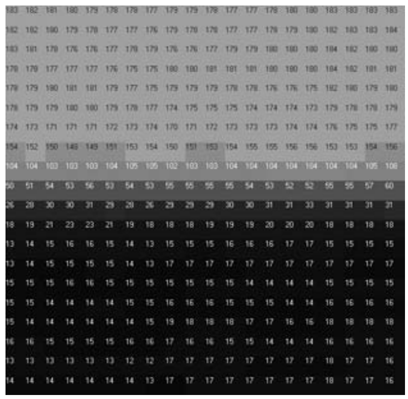

Fig. 4. Coded scale piece of digital information

Using the obtained digital matrix results, it is possible to identify the line thickness of each scale that is needed for the further calibration. The line thickness of the code scale was obtained using AutoCAD software by loading code scale digital matrix results into the working window. To assess the accuracy of the performed tests, the line thickness of the code scales were measured with a microscope UIM-21, No. 640072 (Fig. 5).

Fig. 5. Microscope UIM-21, No. 640072

The obtained measurement results and their differences are given in Table 2 and Fig. 6.

The obtained differences No. 1 and No. 2 of the scale No. 1, as well as difference No. 3 of the scale No. 3 were very large (the microscope analyses had large errors), therefore they were excluded from the further analysis. Analysing the other final results, it can be seen that the min difference is about 2 μm and the max difference does not exceed 10 μm.

The measurement accuracy in both cases is nearly equal and the measurement results differ insignificantly. The line thickness of the code scales determined using a microscope and with AutoCAD software had an accuracy of few micrometers.

4. Statistical hypothesis testing

The superposition of the measuring line image can be made using the principle of the highest correlation coefficient by statistically comparing the digital information received from calibrated and standard staffs. The statistical assessment of the line position in such case is performed by stepwise moving the digital information sequence of the measuring staff in respect to the reference staff and searching for the best match of the correlation coefficients (Čekanavičius, Murauskas 2004; 2006; Sakalauskas 2003).

The calculation of the correlation coefficients of the digital information is carried out according to the Eq (1):

Table 2. The line thickness of the bar code scale measured with a microscope and the AutoCAD environment

Sequence No.	Bar code scale line thickness, measured with UIM, mm	Bar code scale line thickness, measured with AutoCad, mm	Difference Δ, mm
Scale No. 1			
1	2.0849	1.8497	0.2352
2	1.9216	1.5999	0.3217
3	4.7599	4.7500	0.0099
4	0.9333	1.6000	−0.6667
5	1.8056	1.7997	0.0059
6	1.6090	1.6003	0.0087
7	14.8039	14.8001	0.0038
Scale No. 2			
1	1.0481	1.0498	−0.0017
2	0.9557	0.9498	0.0059
3	2.7551	2.7503	0.0048
4	0.9467	0.9502	−0.0034
5	1.0512	1.0495	0.0017
6	0.9905	1.0002	−0.0097
7	8.5549	8.5499	0.0050
Scale No. 3			
1	0.6032	0.6003	−0.0029
2	0.4064	0.4009	0.0055
3	1.3362	1.3990	−0.0628
4	0.4578	0.4490	0.0088
5	0.5528	0.5502	0.0026
6	0.4560	0.4505	0.0055
7	4.3949	4.3988	−0.0039

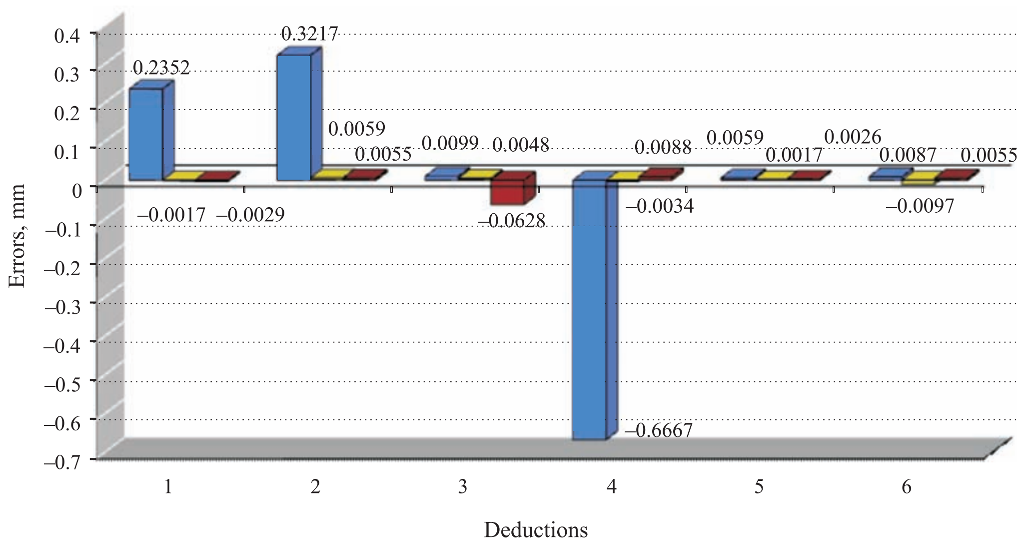

Fig. 6. The errors measured with UIM and AutoCad software in scales 1 (blue column), 2 (yellow column) and 3 (red column)

$$r = \frac{S_{xy}}{\sqrt{S_x^2 S_y^2}}, \tag{1}$$

where r – correlation coefficient; S_x^2 – the empirical variance of the corresponding line; S_y^2 – the empirical variance of another line.

A more reliable estimate of the line edges can be determined using the linear regression approach. The digital information of the line edge is analysed statistically determining the consistency of these figures with the rectilinear dependence. During the regression estimations, the following hypothesis is tested:

$$H_0 : a_x = a_y, \tag{2}$$

while the corresponding averages are not equal with the alternative hypothesis:

$$H_a : a_x \neq a_y. \tag{3}$$

Since the corresponding variances are unknown, the significance criterion is applied:

$$T = \frac{\overline{x} - \overline{y}}{\sqrt{\frac{s_x^2 - s_y^2}{n}}}, \tag{4}$$

which is distributed according to the Student's distribution with $v = 2n–2$ degrees of freedom, where H_0 is true; n – the number of measurements.

Choosing the significance level α, the critical value of $t_{\alpha,\, 2n-2}$ is found in the Student's distribution tables. Then, the hypothesis that the averages are equal is true (statistical data (measurement results) do not contradict the fact that the averages are equal).

If $|T| \geq t_{\alpha,2n-2}$ the hypothesis that the averages are equal is rejected and the alternative hypothesis is accepted, i.e., the averages are not equal. When the significance level $\alpha = 0.05$ (the probability that the conclusions are wrong) $T_{0.05,\, 2\times20-2} = 2.024$. In the Eq (4), $\overline{x}$ is the empirical average of the corresponding line, $\overline{y}$ is the empirical average of another line, s_x^2 is the empirical variance of the corresponding line, and s_y^2 is the empirical variance of another line (Giniotis *et al.* 2008a; Skeivalas, Giniotis 2000).

After the mathematical statistical calculations are done, using a series of data of the coded scale number matrix and obtained variance and correlation coefficient values, we can accurately identify the line boundaries of the coded scales between the black and white line edges and identify mechanical damages of the coded scale.

Using the analysing window and changing its position in the entire digital information matrix, we can choose and calculate the max correlation coefficient between the line position coordinate of the analysed staffs and define the step by which this coordinate differs from the line coordinate of the reference scale. This step will be equal to the absolute error of the line position of the calibrated staff. Calculating these absolute errors for the entire staff length, a systematic error of the calibrated staff can be determined.

5. Conclusions

The designed computer program allows expressing the digital image pixel values of the leveling staff code scales with numeric values. Darker-colored pixels are expressed in terms of smaller numbers, while brighter pixels are represented by larger numbers.

Using the developed software it is possible to perform accuracy tests of the line edges of the code scales.

To assess the accuracy of the performed tests, the line thickness of the code scales were measured with a microscope UIM-21. The min difference between the two types of measurements was about 2 μm and the highest difference did not exceed 10 μm.

When all the mathematical statistical calculations are done, using a series of data of the coded scale number matrix and obtained variance and correlation coefficient values, an accurate identification the line boundaries of the coded scales between the black and white line edges and mechanical damages of the coded scale can be identified.

Initial studies have shown that the digital image analysis is highly dependent on the light during the photography, the light reflectance coefficient on the staff surface as well as the surface cleanliness, the distance between the camera and the staff surface, and the contrast of the code lines.

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