Estimation of deformations of steel constructions of cranes based on photogrammetry

A Yu Ganshevik*, N S Shikhov¹, and N M Stoyantsov²

¹Academy of Water Transport, Russian University of Transport, 22 building 3 Novosushevskaia street, Moscow 127055, Russian Federation
²JSC “Northern Port”, 57 Leningradskoe shosse, Moscow 124195, Russian Federation

E-mail: gansalex@mail.ru

Abstract. The paper considers the results of the application of photogrammetry to assess the deformations of rod and plate elements of the steel constructions of hoisting machines, the analysis of the main problems arising in their processing and the proposed solutions to ensure the necessary accuracy. The authors, based on their own research and practical experiences application in the use of photogrammetry, carried out accuracy rating the magnitude of deformations. Based on a brief review of normative documents, proposals for rationing the permissible values of measurement errors are given. The paper also considers the problems that may arise in the assessment of the deformed state of design status and proposes approaches to solving these problems. One of the problems solved in the study was to assess the magnitude of the deformation of the rear belt of support of blocks of equalizing polyspast, resulting from an emergency situation during the operation of the crane KPL-16-30. In addition to assessing the overall deformed state of the entire element, the deformation in some sections of the structure was assessed. The application of some approaches to estimating the deformation of rod structure elements based on modeling the shape of the curved axis of a beam or rod. Also considered the experience of deflection measurement the deflection of the 0.5 t electric hoists guide in the laboratory of hoisting machines. The authors shared their inspecting of the wagon tippler No. 2 examination. In addition to the assessment of transverse deformations, the task was to check the possible torsion of the metal structure of the moving part. In the process of work some problems were also revealed, the solution of which will make it possible to provide the necessary accuracy of measurements. When evaluating the approximation accuracy, the authors propose to use several approaches.

1. Introduction

At the present time actively develops checks the methods the technical condition control of various industrial and civil construction sites using remotely piloted aircraft (RPA) [1-2]. The published results of using photogrammetry [1-5] already allow us to talk about the possibility of not only visual, but also measuring control of individual elements of buildings [1], structures [2] and other objects [3-5]. In [3] the successful experience of estimating the planned-altitude position of bridge crane tracks was described, and the measurement accuracy was achieved that is commensurate with the accuracy of laser surveying. As experience shows [4], using special lighting of the survey object and certain methods of data processing it is possible to achieve modeling accuracy of small objects, at which the relative error does not exceed 0.03 mm.

For several years, the authors have conducted theoretical studies and tests on the introduction of photogrammetry in the practice of inspection of hoisting cranes as part of the examination of industrial
safety [6-7] in the JSC “Severn Port”, Moscow. The use of RPA allowed to significantly reduce the time of crane inspection and search for defects, but the problems of measuring the values of detected defects were not fully solved.

In [7] approaches to measuring the deflection value of elements of the steel construction of portal cranes are shown, but the solutions proposed in this paper are applicable mainly for rod elements of the structure, or for the estimation of edge deformations of sheets. It is worth noting that to estimate the deflection magnitude from photographs, a number of conditions [7] is required, in particular on the reciprocal positioning location of the camera and the measured object, the magnitude of radial and tangential distortions of the camera, the presence of the whole object in the frame. Fragmentary shooting of objects with the subsequent construction of volumetric digital model often does not provide the necessary accuracy of measurements [1-2].

At present, the application of photogrammetry for diagnosing hoisting machines, in the author’s opinion, is limited by low accuracy of measurements. The present paper contains a description of the results of the application of photogrammetry to assess deformations of elements of hoisting machines, analysis of the main problems arising in their processing and proposed solutions to ensure the necessary accuracy.

2. Materials and methods

2.1. Objects and applicable equipment

The investigations presented in this paper were conducted at the following objects:
- Portal cranes “Albatros” and “Albrecht” in JSC “Northern Port”, Moscow
- Floating crane KPI-16-30 owned by LLC Ekos-G, Moscow
- Portal crane “Sokol” and wagon tippler №2 in Vanino seaport
- Hoist with a carrying capacity of 0,5 ton in the laboratory of lifting machines of the PPTM and R department of the RUT Academy of Water Transport

Quadcopters Xiaomi Mi Drone 4K and Hubsan Zino Pro 2.0 were used to shoot objects.

The digitization of the measurement results, the construction of spatial networks and their export for further processing was carried out using the 3DF Zephyr Lite program.

The processing of the measurement results was carried out using Matlab, AutoCAD and author’s calculation modules.

Based on photogrammetry, the following were monitored: changing the shape of the element, as a whole, changing the shape of the section, changing the shape of individual surfaces of the structure.

2.2. Methods of measurement and results processing

In general, the following work was done: photo or video shooting, building a point cloud and primary filtering, building a mesh with additional filtering, model calibration, smoothing the mesh and building the envelope, accuracy evaluation, surface mapping, drawing conclusions.

The measurement accuracy was evaluated by calculating the relative error using the formula (1) in accordance with the recommendation GOST 29266 (ISO 9373) “Cranes and related equipment. Accuracy requirements for measuring parameters during testing.”

\[
\delta = 100\% \cdot \mu^{-1} \cdot \left( N \cdot \sum_{i=1}^{N} z_i^2 - \left( \sum_{i=1}^{N} z_i \right)^2 \right) / \left( N \cdot (N - 1) \right)^{1/2}
\]

where \( \mu \) – the scatter between the global maximum and minimum of a curve or surface, constructed as a result of approximation of measurement results, \( N \) – number of measurements; \( z_i \) – meaning i-th measurements.

Calculation of \( \mu \) value was performed according to the results of approximation of the point cloud by a curve or surface. For this purpose, a fragment corresponding to the surface, the deformation of which was to be determined, was extracted from the point cloud. For the chosen fragment, the position
of the average plane was determined by the least-squares method, which for further calculations was taken as the $xy$ plane of Cartesian coordinate system. In this case, the direction of the $x$-axis coincided with the maximum dimension of the studied area. Further in the text, this plane will be referred to as the reference plane. The coordinates of the points were redefined in the $xyz$ system associated with the reference plane.

For extended structural elements (beams and truss rods), the approximation problem was reduced to a two-dimensional formulation – the construction of deflection curve of beam, which was approximated by a polynomial of degree $m$. The degree of the polynomial was determined by the method of iterations under the condition of achieving the smallest value of the relative error $\delta$. For flat structural elements (girders and walls of box elements), the approximation was performed by $m$-th order surfaces.

An additional check of the approximation quality was to evaluate the shape and parameters of the distribution law of the deviations of the experimental points from the approximating curve or surface. The standard deviation $\sigma$ and asymmetry coefficient $\gamma$ were used as control parameters. The standard deviation is an indicator of the dispersal of the point cloud relative to the approximating curve or surface and can, in first approximation, give an estimate of the accuracy of the measurement in units of length. The asymmetry coefficient allows to estimate the presence of points in the sample that do not obey the normal distribution law. High value of the coefficient $\gamma > 0.5$ is an indicator of a large number of points in the sample, which do not belong to this surface. Such points appear when the camera is inaccurately focused, small objects located at a certain distance from the studied surface (wires, brackets, etc.) or in the presence of light flare from the surface being photographed are caught in the frame. At high values of $\gamma$, new sampling group were formed from which erroneous points were excluded.

The deflections obtained by photogrammetry were checked by direct measurement with a metal ruler and a caliper, the error of measurement was calculated by the formula (2):

$$\Delta = 100\% \cdot \left(\frac{|\mu - f|}{\mu}\right)$$

where $f$ – value of the controlled parameter, obtained by direct measurement.

Standard GOST 29266 sets as a permissible the value of the relative error equal to 1%, which is a rather stringent condition. In GOST 27584 “Electric overhead travelling cranes and gantry cranes. General specifications” and GOST 25251 “Electric gantry cranes. Testing methods” it is recommended to use an acceptable error value of 10% in determining the deflection of the structure. In this study, the authors considered satisfactory the results when the error does not exceed 10%.

3. Results and discussion

3.1. Estimating the deformation of the shells

One of the tasks, solved during the research, was to estimate the magnitude of deformation of the back wall of the counterbalance chain blocks resulting from an emergency situation during the operation of the crane KPI-16-30. Shooting was performed from the Xiaomi Mi Drone 4K quadcopter outside in natural light. The point cloud was created in 3DF Zephyr Lite program based on the video.

The deformed surface was approximated by a second-order spline-surface using the "loess" function of the MathCAD software. As a result of iterations, the maximum accuracy at measurement error $\delta=31\%$. was achieved. The deformed surface is shown on Figure 1, and its approximation by spline-surface on Figure 2.
The obtained accuracy cannot be considered satisfactory, however, in a detailed analysis it was found that it is a consequence of low plasticity of the second-order surface when approximating surfaces with large changes in curvature. RMS deviation of points from approximated surface was $\sigma = 32$ mm, that, apparently, is a consequence of low quality of approximation. At the same time, the asymmetry coefficient was $\gamma = 0.04$, which is an indicator of the absence of erroneous points.

At similar approximation of the results of photogrammetry of the support table of the wagon tipper №2, having low constant curvature, the relative error was $\delta = 51.1\%$, although the RMS deviation was low $\sigma = 1.2$ mm. High relative error is explained by small absolute value of deflection, therefore when estimating accuracy of photogrammetry results it is necessary to consider not only relative error but also absolute values of deviation. In this case, it is suggested to determine the relative error of measurement by the formula (3):

$$\delta = 100\% \cdot \left(6 \cdot \frac{\sigma}{[f]}\right)$$

where $[f]$ – the permissible deflection curve of beam value according to the hoisting machine data sheet or related regulatory documents.

In addition to estimating the general deformed state of the whole element, the deformation was estimates for some sections of the structure. For this purpose, points located at a distance of $\pm 25$ mm from the line of the section under study were extracted from the cloud.

The results of the deformation estimation for the middle section (section A-A) of the strut of the pulley blocks are shown in Figure 3. Figure 3(a) shows the location of section A-A on the model built in the program 3DF Zephyr Lite, Figure 3(b) shows the view of section A-A with the point cloud and the approximating polynomial of order 19. The relative error of the deflection estimate was $\delta = 1.4\%$, $\sigma = 1.75$ mm, and the asymmetry $\gamma = 0.01$. The plot of density distribution of deviation of points from the approximating curve, combined with the histogram of the experimental data is shown in Figure 3(c).

The considered example shows that a low error of deformation measurement even of complex elements can be achieved by a correct choice of processing method of photogrammetry results.
Figure 3. Results of the deformation estimation in the middle section of the column.

The accuracy was evaluated by comparing the results of photogrammetry with the results of direct measurements of general and local deformations performed on the slipway during repair work. Calculation was carried out according to formula (2). According to the test results, the measurement error $\Delta$ does not exceed 10% in all cases.

3.2. Estimating of deformation of rods and beams

To estimating the deflection of rod elements of the structure, approaches based on modeling the shape of the curved axis of a beam or rod were used. At the nowadays the methodology has been tested on rod elements with flat surfaces curved in one of the planes and having no torsional deformation.

The magnitude of the deformation of the rack of the Albrecht crane's derricking mechanism was estimated based on the approximation of the surface of its upper belt by a flat curve located in the median longitudinal plane of the rack. The rack shown in Figure 4 has a visible bend in the vertical plane, the task of the study was to determine its magnitude.

Figure 4. Rack of derricking mechanism of portal crane “Albrecht”.
To solve the task, a video shot of the rack was made using the Xiaomi Mi Drone 4K quadcopter on the street in natural lighting. The creation of the dense point cloud was performed in the program 3DF Zephyr Lite based on the video.

The estimation of the deformed state of the rack axis was performed based on approximation of the points of the upper belt of the rack by a fourth-order polynomial using the "regress" function of the MathCAD software package. As a result of iterations, the maximum accuracy at measurement error $\delta = 6.0\%$ was achieved. The result of approximation is shown on Figure 5.

![Figure 5. Result of approximation of the curved rack axis of portal crane “Albrecht”.

The standard deviation was $\sigma = 4.5 \text{mm}$ and the skewness coefficient $\gamma = 0.37$. The increased value of the skewness coefficient is explained by the presence of erroneous points corresponding to the minimum outreach limiter plate (the dropping out points can be seen in Figure 5 in the upper right part, and the plate itself in Figure 4). Checking the accuracy of the measurement by direct measurement with a string and ruler showed an error of $\Delta = 5.5\%$.

The experience of measuring the deflection of the 0.5t electric hoist guide in the laboratory of lifting machines was less successful. Despite the availability of calibration patterns specially developed by the authors, it was not possible to ensure the accuracy of measurements at the specified level $\delta = 90\%$. In addition, the value of the asymmetry coefficient was also extremely high $\gamma = 0.87$. Such low results, according to the authors, are due to a variety of reasons: insufficient illumination of the shooting place, the presence of two electric hoists on the beam, the power wire to them and the string on which it is attached. It is also worth noting that the accuracy of determining the linear dimensions - the assessment was carried out using calibration patterns - was extremely high: the error does not exceed $\Delta \leq 1.2\%$.

3.3. Evaluating the relative positioning of surfaces
When inspecting the wagon tippler №2, in parallel with the assessment of shear deformations, the task was to check the possible torsion of the metal structure of the moving part. The results of this job were not quite satisfactory: the measurement of the angles between the surfaces next to each other was performed with an accuracy of 0.5°, but for the surfaces located on opposite sides of the wagon tippler, the difference between several measurements was 1.5...3°. According to the authors, the reasons for such discrepancies are unsatisfactory filming conditions: low light in the warehouse, interference in the form of the wagon being processed and filming with a low resolution of the camera.

4. Summary
The investigation showed that under certain conditions it is possible to measure the deformations of crane steel constructions using photogrammetry with an error not exceeding 10%. However, in the process of work some problems were identified, the solution of which will ensure the necessary accuracy of measurements.
High relative error in the creation of the point cloud can be reduced by using additional lighting, high-resolution cameras, accurate focusing, choosing a path of camera movement that eliminates the appearance of flares.

To reduce the distortion of the model shape is possible by calibrating the camera to account for radial and tangential distortions \cite{8-9}, continuous consecutive shooting along the entire length of the structural element and installation of calibration templates and control points \cite{10}. Another method to improve the accuracy of surveys of long objects, the authors believe the use of gravity referents – plumb bins of special shape, which will verify the mutual positioning of distant parts of the structure.

The authors propose to estimate the approximation error differentially: for large deformations – by formula (1), for small – by formula (3).

In general, according to the authors, the experience of using photogrammetry can be considered successful, despite the presence of certain difficulties.

5. References

\cite{Korenev2018} Korenev V V, Orlova N S, Ulybin A V and Fedotov S D 2018 Building inspection of buildings and structures by means of multicopters and photogrammetry Construction of Unique Buildings and Structures 2(65) 40–58

\cite{Barbasov2016} Barbasov V K, Orlov P Yu and Fedorova E A 2016 Primenenie bespylotnykh letatelnych apparatov dlya obseledovaniya linii elektroperedachi Electrichesciye stancii 10 31–35

\cite{Costantino2019} Costantino D, Pepe M, Alfio V, Carrieri M 2019 Geomatic Techniques for Monitoring and Verifying of the Wear Condition of the Runways of the Bridge Cranes. ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W18 23-30 DOI: 10.5194/isprs-archives-XLII-2-W18-23-2019

\cite{Faresin2019} Faresin E and Salemi G 2019 Buddhist stele of swat valley: point cloud analysis and interpretation Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2/W18, 31–37 DOI: 10.5194/isprs-archives-XLII-2-W18-31-2019

\cite{Wu2018} Wu Y, Qin Y, Wang Z 2018 A UAV-based visual inspection method for rail surface defects Applied sciences, 8, 1028 https://doi.org/10.3390/app8071028

\cite{Ganshkevich2018} Ganshkevich A Yu and Turkin A G 2018 Perspektivy ispol`zovaniya portativnyx letatelnykh apparatov pri tekhnichescom diagnostirovanii gruzopod`emnikh cranov Proc. 21st Int. Sci. and Technical Conf. "Intercrterymech–2018" (Moscow: MGSU Publ.) 298–301

\cite{Ganshkevich2019} Ganshkevich A Yu, Turkin A G, Stoyantsov N M, Shikhov N S and Rozov V V 2019 Some aspects of application of unmanned aerial vehicles for technical diagnosing of lifting crane Mater. Int. Sci. and Technical Conf. "Energy-saving and resource-saving technologies and equipment in the road and construction industries" (Belgorod: BSTU Publ.) 22–28

\cite{Altyntsev2019} Altyntsev M A, Shcherbakov I V and Tretyakov S A 2019 Application of unmanned aerial vehicles for the as-built survey of railways Mater. Int. Sci. and Technical Conf. "Interexpo Geo-Siberia" 1(1), 111-118 DOI: 10.33764/2618-981X-2019-1-1-111-118

\cite{Kostyuk2010} Kostyuk A S 2010 Calculation of the parameters and evaluation of quality with uav aerial photography, Mater. Int. Sci. and Technical Conf. Geo-Sibir’-2010: 4. [Proceedings of GEO-Siberia 2010: 1] 83–87 Novosibirsk: SSGA Publ. [in Russian].

\cite{Villanueva2018} Villanueva J K S, Blanco A C 2018 Optimization of ground control point (GCP) configuration for unmanned aerial vehicle (uav) survey using structure from motion (SFM). The Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sci., XLII-4/W12, 2019 5th Int. Conf. on Geoinformation Sci. – GeoAdvances 2018, 10–11 October 2018, Casablanca, Morocco, 167–174 https://doi.org/10.5194/isprs-archives-XLII-4-W12-167-2019