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PRIOR CALCULATION OF THE ACCURACY OF MONITORING OF CULTURAL HERITAGE OBJECTS USING UAVS AND LASER SCANNING

Olga CHUMAK[1*], Julia GORKOVCHUK[2]

[1]Department of Engineering Geodesy, Kyiv National University of Construction and Architecture, Kyiv, Ukraine
[2]Department of Geoinformatics and Photogrammetry, Kyiv National University of Construction and Architecture, Kyiv, Ukraine

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Abstract. In the last few years, intensive measures have been taken to monitor and inventory the cultural heritage of Ukraine. An important aspect is the preservation of such objects and their transmission to future generations. It is important to use such a methodology and technology when performing monitoring works, which in the future will make it possible to perform a number of other tasks, in relation to a certain specific object, based on previously obtained data. Therefore, this paper proposes a method of cultural heritage monitoring using UAV-filming.

The work examines the methods of monitoring cultural heritage objects and presents an a priori assessment of the accuracy of monitoring of cultural heritage by means of UAV photography and laser scanning. The work focuses on the fact that the monitoring of cultural heritage sites should be carried out precisely with the help of modern filming methods, which have a number of advantages compared to traditional methods. The reliability of the proposed methods is presented and substantiated by calculating an a priori estimate of the accuracy of potential results.

Keywords: a priori assessment of accuracy, root mean square error (RMS), point cloud, terrestrial laser scanning, UAV surveying, objects of cultural heritage (OCH).

Introduction

In the conditions of Russia's war against Ukraine, special attention should be paid to the objects of cultural heritage (OCH) in the interests of current and future generations. Military operations have already caused significant destruction to the OCH, and in the future the urgency of reconstruction and restoration will only increase. In order to ensure the performance of such works at a high-quality level, the task of preserving geospatial data on the OCS by methods that are optimal in terms of time, cost and quality arises. Today, photogrammetric, in particular laser scanning and UAV-surveying, are among the most common methods of executive surveys of the OCS, the result of which is a cloud of points as an initial stage for further processing and modeling (Chumak et al., 2022).

The use of UAV-removal and laser scanning technologies for the measurement of OCH will allow solving the following tasks:

– creation of the OCH geo-information system;
– creation of 1:20 scale drawings;
– creation of 3D models of OKS objects for design, reconstruction and restoration with model construction accuracy from 3 to 5 mm;
– monitoring and determination of the deformation of the OCH;
– removal of hard-to-reach and difficult objects;
– full automation of the process;
– visualization of the process of measuring OCH in real time;
– minimizing the influence of the human factor on the measurement results (Zolotova, 2009).

The reliability of these methods can be substantiated using an a priori assessment of the accuracy of potential results.

1. Main text

Solving the problems of inventorying historical and cultural objects by photogrammetric methods was considered in works (Shults et al., 2017; Bolognesi et al., 2015; Roy, 2007; Hassani & Rafiee, 2013; Bohm, 2004). The use of available means of the so-called "lowcost photogrammetry" is

*Corresponding author. E-mail: *olgachumak94@gmail.com*

complicated by the need to carry out additional research on camera calibration and integration of different types of data, but the result shows high efficiency. The work (Shults et al., 2017) describes an approach using smartphones, UAVs and PhotoScan software to solve the problem of inventorying a fortification structure of the Second World War near the city of Kyiv. The results of experimental tests conducted using the Dji Phantom 2 UAV equipped with a GoPro hero3 + Black Edition camera and the PhotoScan software in comparison with high-precision simulations indicate the possibility of practical use of non-metric widely available cameras (Bolognesi et al., 2015).

Supplementing ground laser scanning with additional classical photogrammetric surveying is described in the following studies (Roy, 2007; Hassani & Rafiee, 2013; Bohm, 2004). Digital surveying is also performed for further easier deciphering of contours and decorative elements of buildings.

Another vivid example of the application of the close-range photogrammetry method is the three-dimensional modeling of the tower of the Harrakan tomb in the work (Hassani & Rafiee, 2013), where the exact geometric dimensions of the building for actual drawings and documentation were established based on the results of shooting by amateur cameras and modeling in the PhotoModeler environment.

The purpose of the work is the analysis of errors that affect the result of executive surveys by photogrammetric methods, in particular laser scanning and UAV, and an a priori assessment of the accuracy of measurement results – point clouds as the basis for further modeling.

In order to calculate the accuracy of OCH monitoring, it is necessary to classify certain types of work. As you know, from traditional geodesy, the set of factors affecting the result of measurements is called a set of conditions. The set of conditions for the monitoring of the OCH includes: the object (the facade of the OCH, architectural structures, etc.) and the device (camera, total station, laser scanner). For each type of work, there are systematic errors that affect the measurement result (Table 1). The general equation for determining the a priori calculation of OCH monitoring will look like this:

$$m_\Sigma = \sqrt{\sum m_i^2}, \qquad (1)$$

where: m_Σ – RMS of the type of work; m_i – RMS of the measuring device.

The sum of the root mean square errors included in the RMS of the camera measurement can be different and depends on the choice of the camera and its characteristics. The removal of OCH structures can also be performed by various methods, in particular, traditional removal methods, so in the work we do not stop at a detailed description of errors in such measurements.

For practical testing, an a priori assessment of the accuracy of the results of the removal of the cultural heritage object, the monument to Bohdan Khmelnytskyi in Kyiv, was calculated. The cloud of points is obtained by merging the results of a ground laser scanner and a UAV. The ultimate goal of the work is high-precision three-dimensional modeling of the object for the purpose of monitoring and preserving the cultural heritage. Photogrammetric work was performed using a DJI Mavic 2 Pro UAV with a 1"CMOS Hasselblad L1D-20c sensor and laser scanner of the Swiss firm Leica ScanStation C10.

The equation for a priori calculation of measurement accuracy for 3D model assembly will have the following form:

$$m_{pc} = \sqrt{m_c^2 + m_{ls}^2}, \qquad (2)$$

where: m_{pc} – RMS point cloud; m_c – RMS measurement by camera; m_{ls} – RMS of laser scanning.

The measurement error of laser scanning m_{ls} is calculated taking into account the technical characteristics of the device used.

$$m_{ls} = \sqrt{m_r^2 + m_{a.m}^2 + m_{comp}^2}, \qquad (3)$$

where: m_r – RMS rangefinder; $m_{a.m}$ – RMS of angular measurements; m_{comp} – RMS compensator. According to the technical characteristics of the Leica ScanStation C10 device: m_r = 4 mm $m_{a.m}$ = 12" i.e. in linear form 1.2 μm, m_{comp} = 2 mm, then by substituting the value in Equation (3) we get: m_{ls} = 4.6 mm.

Table 1. Classification of works during monitoring of OCH

Type of works	Creating an orthophoto	Geodetic surveys	3D modeling
Object	Facade	Constructions	Facade + constructions
Devices for execution	Camera	Camera + tacheometer	Laser scanner + camera (+tacheometer)
m_i	m_c	$m_c + m_t$	$m_c + m_{ls} + (m_t)$
RMS equation m_Σ	$m_c = \sqrt{m_d^2 + m_{pzz}^2 + m_Y^2}$ where: $m_{\Sigma c}$ – RMS measurement by camera; m_d – RMS for camera lens distortion; m_{pzz} – RMS position of the PZZ-matrix relative to the focal plane; m_Y – RMS definition of the ordinate	$m_{\Sigma m} = \sqrt{m_{\Sigma c}^2 + m_{\Sigma t}^2}$ where: $m_{\Sigma m}$ – RMS of geodetic surveys; $m_{\Sigma c}$ – RMS measurement by camera; $m_{\Sigma t}$ – RMS measurement with a tacheometer	$m_{\Sigma 3D-m} = \sqrt{m_{\Sigma c}^2 + m_{\Sigma ls}^2 + m_{\Sigma t}^2}$ where: $m_{\Sigma 3D-m}$ – RMS measurements for 3D modeling; $m_{\Sigma c}$ – RMS measurement by camera; $m_{\Sigma ls}$ – RMS of laser scanning; $m_{\Sigma t}$ – RMS measurement with a tacheometer

To calculate the camera error, we will use the classic approach, using the Hasselblad L1D-20c camera as an example of the calculation. Technical characteristics of the camera are given in Table 2.

Table 2. Technical characteristics of the Hasselblad L1D-20c camera

Technical data	L1D-20c (Hasselblad)
Sensor size	1″, 20 MP
Pixel size (μm)	2.41
Lenses (field of view – FOV)	FOV 77 (28 mm (35 mm Format Equivalent)) f/2.2
Focus	1m to ∞, auto/manual focus
ISO sensitivity range	100–6400 (video), 100–12,800 (image)
Electronic shutter speed	8 s–1/8000 c
Image size (pixels)	5472 × 3648
Photo modes	Single shot, continuous shooting: 3/5 frames, auto exposure. Bracketing (AEB): Brackets 3/5 frames by 0.7 EV, interval
Video modes	4K: 3840 × 2160 24/25/30 p 2.7K: 2688 × 1512 24/25/30/48/50/60 p FHD: 1920 × 1080 24/25/30/48/50/60/120 p
Image file format	JPEG, DNG
Video file format	MP4/MOV (MPEG-4 AVC/H.264, HEVC/H.265)

The equation for calculating the RMS measurement by the camera is as follows:

$$m_c = \sqrt{m_d^2 + m_{pzz}^2 + m_Y^2}\,, \tag{4}$$

where: m_d – is RMS for camera lens distortion; m_{pzz} – RMS position of the PZZ matrix relative to the focal plane; m_Y – RMS determination of the ordinate.

Errors due to distortion of shooting non-metric cameras have already been sufficiently studied and corrections are introduced pixel by pixel, which determines its minimum value (Glotov & Smoliy, 2008). The error due to m_d distortion should not exceed 2 mm (Glotov & Chyzhevsky, 2005). The study of the slopes of the PZZ matrices with respect to the focal plane also confirmed the minimal error of these values, which can be neglected (Glotov & Smoliy, 2008). Deviation of the CCD matrix relative to the focal plane m_{pzz} = 20″, i.e. in linear form m_{pzz} = 2 mm (Glotov & Pashchetnyk, 2008). According to (Lobanov, 1972) RMS coordinates m_Y can be calculated using the equation:

$$m_Y = \left\{ m_{Ys}^2 + \left(\frac{x}{f}\right)^2 \times m_{Xs}^2 + X^2 \times \left[\left(1+\frac{x^2}{f^2}\right)^2 \times m_\alpha^2 + \left(\frac{x \times z}{f^2}\right)^2 \times m_\omega^2 + \left(\frac{z}{f}\right)^2 \times m_\chi^2 - \left(\frac{1}{f}\right)^2 \times m_{x0}^2 + \left(\frac{x}{f^2}\right)^2 \times m_f^2 + \left(\frac{1}{f^2}\right)^2 \times m_\chi^2 \right] \right\}^{1/2}. \tag{5}$$

According to the technical characteristics of the Hasselblad L1D-20c camera: x = 11 mm, z = 7 mm. Average horizontal size of the object under investigation: X = 15 m. Measurement accuracy of the shooting base: $m_{Xs} = m_{Ys}$ = 1 mm. The accuracy of measuring the coordinates of the points on the image in the software: m_x = 5 μm. Accordingly, the internal orientation elements must be determined with the same accuracy, i.e.: $m_{x0} = m_f$ = 1 mm. The RMS of the angular elements of external orientation are equal to m_α = 3.5″, m_ω = 3.6″, m_χ = 2.2″ (Glotov & Smoliy, 2008).

Let's calculate m_Y for the focal length f = 18 mm, as a result of the calculations we will get: m_Y = 2.7 mm. According to expression (4), the RMS measurement by the camera is equal to: m_c = 3.9 mm.

Thus, the aggregated result of calculating the RMS of the cloud of points according to expression (2) is equal to m_{pc} = 6 mm.

The basis for calculating the maximum accuracy is the construction tolerances and installation errors of volumetric planning and structural elements of the OCH. Marginal errors when measuring metal and reinforced concrete structures are accepted three times smaller than the corresponding construction tolerances of stone structures, therefore, based on this, when measuring stone buildings and structures up to 100 m in size, errors in the longitudinal and transverse directions of 2–5 cm are allowed, and in the vertical direction – 1–2 cm.

Thus, during measurements performed for the purposes of reconstruction and restoration, it is necessary to ensure a root mean square measurement error of the order of 1–2 cm (Table 3), which is twice the a priori accuracy of the measurement results obtained by experimental calculations.

Table 3. Characteristics of accuracy of measuring works

Types of measurement	Marginal errors, sm		Scale	Types of work
	The main ones	Auxiliary		
Highly accurate	0.3–0.5	1–1.5	1:20	drawing
Accurate, II	1–2	3–5	1:50	drawing
Accurate, III	3–5	10–15	1:100	drawing
Technical, IV	10–15	20–30	1:200	drawing
Technical, V	20–30	30–50	1:500	drawing

Conclusions

The general method of a priori assessment of the accuracy of the results of executive works in the monitoring of OCS is a reliable justification for one or another shooting method. It is the choice of optimal equipment and methodical approach that will ensure effective preservation of high-quality data on unique objects in extreme conditions of war. The calculated total root mean square errors of the object and the device cannot exceed the limit values specified by regulatory documents or practical requirements.

According to the results of the practical implementation of the method, namely the calculation of total errors when performing UAV photography with a Hasselblad L1D-20c camera and a Leica ScanStation C10 laser scanner, it can be stated that the a priori estimate of the accuracy of the resulting cloud is 6 mm, which is significantly less than the normative indicator of the ultimate accuracy of this type works (1–2 cm).

Measurements of architectural ensembles and individual historical buildings can be carried out by various methods, but the use of UAVs and ground-based laser scanning has a number of advantages, including high accuracy and speed of work.

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