"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0
Article ID: enviro.2017.237
DOI: https://doi.org/10.3846/enviro.2017.237

Low-cost Photogrammetry for Culture Heritage

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Abstract. Culture heritage will always remain one of the priorities of any state. Taking a cultural or historical object under protection is impossible without inventory. The best technology, which allows getting high-quality inventory, is close-range photogrammetry. Unfortunately, the full capabilities of this technology is fully owned by professionals only. The situation changed significantly with the advent of mobile devices that are equipped with digital cameras and low-cost software that does not require any special knowledge in the theory and practice of photogrammetry. These developments have been called low-cost photogrammetry technologies. In the present study, we examined the use of smartphones and nano UAV and PhotoScan software for solve the problem fortifications II World War inventory near the city of Kiev. For qualitative data, the calibration of digital cameras in smartphones and ultra-light UAV was performed on calibration bench. One of the features of this project was the integration of the terrestrial photos and photos captured by nano UAVs. As a result of work performed were obtained 3D models of fortifications. Results showed high efficiency of the low-cost photogrammetry technologies. At the end of work some practical guidelines were provided, how to get high-quality data using low-cost photogrammetry technologies.

Keywords: low-cost photogrammetry, culture heritage, camera calibration, UAV, inventory.

Conference topic: Technologies of geodesy and cadastre.

Introduction

Preservation the historical and cultural heritage is one of the main tasks of any state. In this case to such objects may include various types of structures, are widely known to the public, as well as less known and sometimes abandoned. In the case of the latter, to date it is primarily a task of restoring such objects of cultural heritage. The separate category of cultural heritage objects are the fortification constructions. In the world today, where historic sites are under the influence of various anthropogenic and natural factors, documentation of cultural heritage can help in monitoring tasks, restoration and recovery of such structures (Almagro Vidal *et al*. 2015). Conventionally, for such a task the most popular and studied is the technology of close-range or terrestrial photogrammetry (Hassani 2015). With the advent of digital photography, and multi-function software, almost every user has the possibility to use the technology of terrestrial photogrammetry to solve various practical problems. The most popular among non-professional users of photogrammetric technologies are inexpensive digital cameras, which are equipped with mobile phones, smartphones, tablets etc. Today, almost anyone can in a few minutes, take the pictures of the object, and not knowing the features of images photogrammetric processing in automatic or semi-automatic mode to execute the construction of high-quality three-dimensional models. This technology is called low-cost photogrammetry (D'Annibale *et al.* 2013; Hassani, Rafiee 2013; Ancona *et al*. 2015; Bolognesi *et al*. 2015; Robleda Prieto, Pérez Ramos 2015). One of the first applications of low-cost photogrammetry technology was described and studied in the work (Gruen, Akca 2008). In the case of solving the problem of cultural heritage objects documentation, this technology is effective in terms of cost and speed of work. However, the qualitative and quantitative assessment of the results still remains one of the most important tasks of professional photogrammetry. In the present paper attempt to study the theoretical and practical low-cost photogrammetry technology as an example of documentation the fortifications II World War near the city Kiev was done.

Object description

One of the most dramatic stages of the II World War is considered to be the defense of Kiev, known as The First Battle of Kiev. Defense Kiev lasted for 72 days from July 7 up to September 26, 1941. The most important role in this operation played The Kiev Fortified Region (Russian abbreviation KiUR). Unique defense complex of defensive structures, consisting of permanent and field fortifications and engineering obstacles and long anti-tank ditches. The main parts of Kiev Fortified Region were the battalion defense areas with pillboxes. The building of this object was started in 1929 and was not finished in 1941. The total length of the fortified region is about 85 km from the river Dnieper coast on the North from Kiev to the river Dnieper coast on the South from Kiev. Generally, The Kiev Fortified Region had the three fortifications lines with depth from 1 to 6 km (Fig. 1).

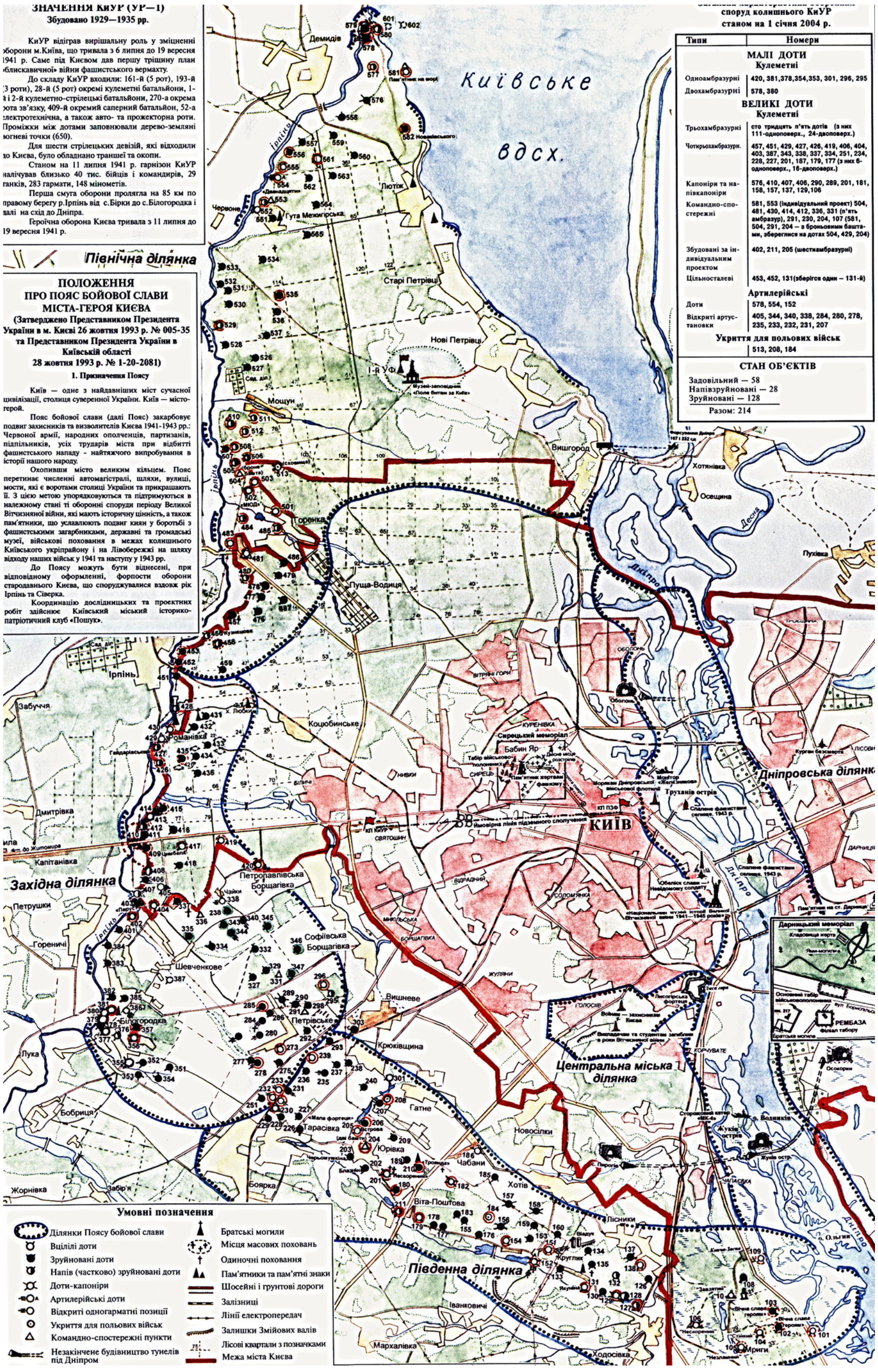

Fig. 1. The old map of The Kiev Fortified Region (http://kiur.io.ua/)

By the Decision of the Cabinet of Ministers of Ukraine in 1993 The Kiev Fortified Region was granted the status of a museum. For more than 20 years, unfortunately, an inventory of the state of The Kiev Fortified Region was not held. Today, thanks to low-cost photogrammetry technology, the opportunity to explore this unique object and create three-dimensional model of the defense area has appeared. The use of low-cost photogrammetry technology for documentation of fortification objects considered in (Takahashi, Chikatsu 2009; Salvador, Vitti 2011; Kapica *et al.* 2013; Kersten *et al*. 2015; Rodríguez-Gonzálvez *et al*. 2015). As a test object, we chose Pillbox № 456. It is a two-storey, machine-gun bunker with three loopholes. During the liberation of Kiev in 1943the object was partially destroyed (Fig. 2).

Fig. 2. Pillbox No. 456

On this example of the test object, we tried to evaluate the effectiveness of low-cost photogrammetry technology. The main criteria that were considered were: the hardware cost, the software cost, time of work and the quality of the resulting three-dimensional model.

The basic equipment that were used were: laser Leica Disto (to perform control measurements); laptop (for calibrating the cameras and three-dimensional modeling); two smartphones HTC Desire SV and MEIZU M3 Max (for pictures capturing); ultra-light UAV FocusDrone (for shooting roofs and inaccessible areas); the software Matlab camera calibration toolbox (for calibrating digital cameras) and Photoscan (for the three-dimensional modeling).

Since the main source of data is a digital photo, the quality of the obtained three-dimensional model will depend on the quality of the original photographs. Thus, the first important step is the calibration of digital cameras.

Camera calibration

For digital cameras calibration we used Matlab camera calibration toolbox. This is a free program code (Sužiedelytė-Visockienė 2012). This toolbox uses the well-known Brown's distortion model, the disclosure of which can be found in (Scaramuzza *et al*. 2006; Douskos *et al*. 2009). In our case, we used a simplified model, which contained the following parameters: focal length in pixels; principal point coordinates; image distortion coefficients (just radial). In accordance with the work (Scaramuzza *et al*. 2006) let's take P is a point in the camera coordinate system with the origin at the point $S_0 = \left(X_0, Y_0, Z_0\right)$. Now we get the projection of this point on the image plane based on the elements of interior orientation $\left(f_x, f_y, x_0, y_0, k_i\right)$. For this purpose, the normalized coordinates $\mathbf{x}_n$ is used:

$$x_n = \begin{pmatrix} X_0 / Z_0 \\ Y_0 / Z_0 \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix}. \tag{1}$$

Taking into account the elements of interior orientation, the normalized coordinates $\mathbf{x}_d$ of the point will be:

$$\mathbf{x}_d = \begin{pmatrix} x_{dx} \\ x_{dy} \end{pmatrix} = \left(1 + k_1 r^2 + k_2 r^4 + k_5 r^6\right)\mathbf{x}_n + d\mathbf{x}; \quad d\mathbf{x} = \begin{pmatrix} 2k_3 xy + k_4\left(r^2 + 2x^2\right) \\ k_3\left(r^2 + 2y^2\right) + 2k_4 xy \end{pmatrix}, \tag{2}$$

where $r^2 = x^2 + y^2$ and $d\mathbf{x}$ is the tangential distortion, which we do not consider due to bad solution.

To perform calibration you must have the test pattern in the form of a chessboard (Rufli *et al*. 2008; Prokos *et al*. 2012). In our case, we just displays an image of the chessboard at the laptop screen and perform calibration in the field. The calibration values were obtained with the assessment of the accuracy of the calibration. Calibration results are shown in Table 1.

Table 1. Camera calibration results

Device	Calibration error m_x/m_y, pix	Focal length f_x/f_y, pix	Focal length error m_{fx}/m_{fy}, pix	Principal point δ_x/δ_y, pix	Principal point error $m_{\delta x}/m_{\delta y}$, pix	Radial distortion coefficients, k_1/k_3	Radial distortion coefficients errors, m_{k1}/m_{k3}	Matrix size, pix
FocusDrone	0.4/0.5	863.6/867.3	13.9/14.1	311.7/223.2	11.4/9.3	0.0011/–0.8268	0.0478/0.3585	720×480
HTC Desire SV	1.0/1.0	2660.1/2662.4	5.2/5.0	1634.4/957.5	5.0/3.9	0.0998/–0.2022	0.0047/0.0116	3264×1952
MEIZU M3 Max	0.7/0.8	3133.1/3132.8	4.5/4.4	2102.7/1526.	3.0/2.2	0.0396/–0.053	0.002/0.0038	4208×3120

For a better perception and a clear understanding quantities and nature of the distortion caused by digital cameras imperfections, done graphical construction distortion models in the form of vector fields in Figures 3–5.

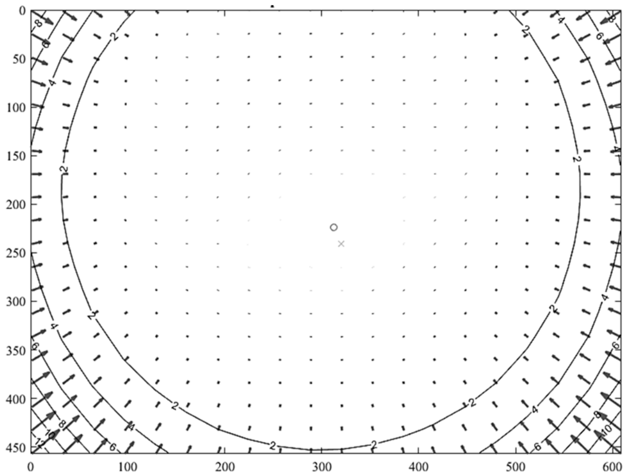

Fig. 3. Complete distortion model for FocusDrone camera

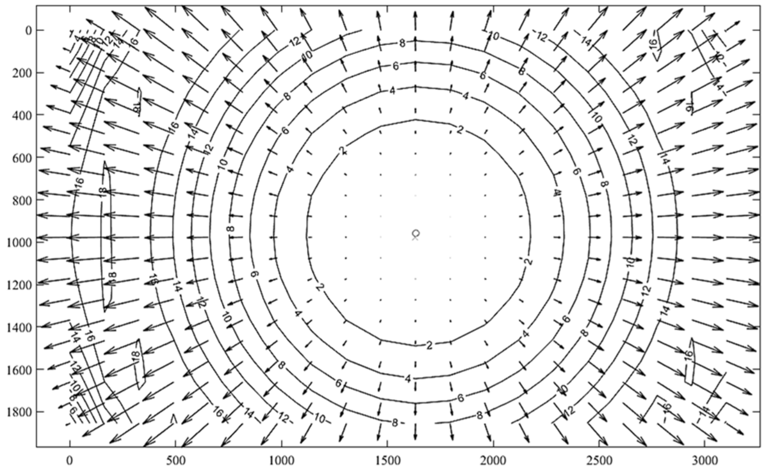

Fig. 4. Complete distortion model for HTC Desire SV camera

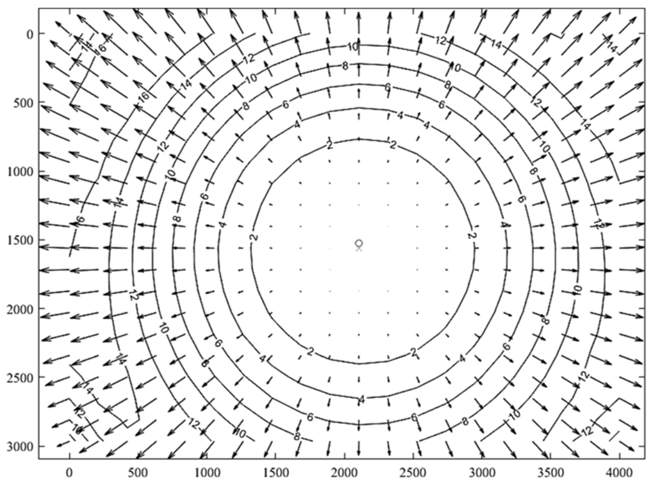

Fig. 5. Complete distortion model for MEIZU M3 Max camera

We would like to note that the quality of the modern cameras in smartphones is high enough. This is evidenced by the relatively small value of lens distortion (20 pix). The obtained results allow, knowing the size of the object to perform accuracy estimation of the points coordinates by the photographic images.

Preliminary accuracy calculation

To perform a preliminary calculation, we assume that the acceptable distance photographing depends on the accuracy of determining the distance to object m_Y . From research of professor. V. Serdyukov (Serdyukov 1977), the maximum speed of photographic works achieved at value of the longitudinal parallax $p_{opt} = l_{pix}\frac{N}{2}$ equal to half of the frame, then the allowable distance photographing will:

$$Y_{\max} = \frac{m_Y}{m_p} l_{pix} \frac{N}{2}, \tag{3}$$

where, l_{pix} – CCD pixel size; N – pixels horizontally; m_p – RMS of longitudinal parallax measurements.

The accuracy and efficiency of non-metric digital camera depends on the expected number of reflections point to the picture and precision coordinate measurement point on a digital image. For precision measurements of the longitudinal parallax can be written:

$$m_p = \sqrt{m_{x_1}^2 + m_{x_2}^2}, \tag{4}$$

where, m_{x_i} – RMS coordinate measurement points on a single digital image. This is calculated as:

$$m_{x_i} = \sqrt{m_{dist}^2 + m_{meas}^2}, \tag{5}$$

where, m_{dist} – RMS of remaining image distortion after non-metric camera calibration; $m_{meas} = 0.5 l_{pix}$ – RMS of point fixing on the digital image. Then we will have:

$$m_{x_1} = \sqrt{m_{dist}^2 + 0.25 l_{pix}^2}. \tag{6}$$

Now consider that under the use of non-metric digital camera with previous calibration the one area multiple display object in different parts of the image. We use the following initial condition:

$$m_Y = \frac{Y_{\max}^2}{Bf}\sqrt{2m_{dist}^2 + 0.5 l_{pix}^2}. \tag{7}$$

Calculate the number of single point's measurements on a pairs of images. For this, use the allocation formula. Then the number of point's measurements will:

$$r = \frac{n!}{k!(n-k)!}, \tag{8}$$

where, $k = 2$ – number of images in a pair, n – total number of images on which point was reflected.

Taking into account this value, the accuracy of the distance to the object m_Y will:

$$m_Y = \frac{Y_{\max}}{f}\sqrt{m_f^2 + \frac{Y_{\max}^2\left(2m_{dist}^2 + 0.5 l_{pix}^2\right)}{B^2 r}}. \tag{9}$$

Using the formula (9) and the results of camera calibration, preliminary accuracy calculation is made. The calculation results are shown in Table 2.

Table 2. The results of the preliminary accuracy calculation

Device	B, m	Y_{max}, m	n	m_Y, mm
FocusDrone	1	2	3	30
HTC Desire SV	1	3	4	6
MEIZU M3 Max	1	4	4	6

As we can see from Table 2, even in the case of using cheap FocusDrone camera under adopted proper shooting conditions the model accuracy is completely acceptable. Recall that for objects of this type maximum precision is set at 50 mm level.

We now turn to the object modeling based on obtained photographic materials.

3D modelling of pillbox

To perform our modeling has been used relatively inexpensive software AgiSoft Photoscan, which is using high-quality images allowing to build three-dimensional model in the automatic mode (Jiroušek *et al.* 2014). In order to simulate, 42 photos from MEIZU M3 Max camera and 26 photos from HTC Desire SV camera for interior were used. To fill the gaps in the model in the field of roof were used 12 photos from FocusDrone camera. In order to scale models were made six control measurements of distances between the natural contours on the object. The result was a three-dimensional model of the object, a fragment of which is shown in Figure 6.

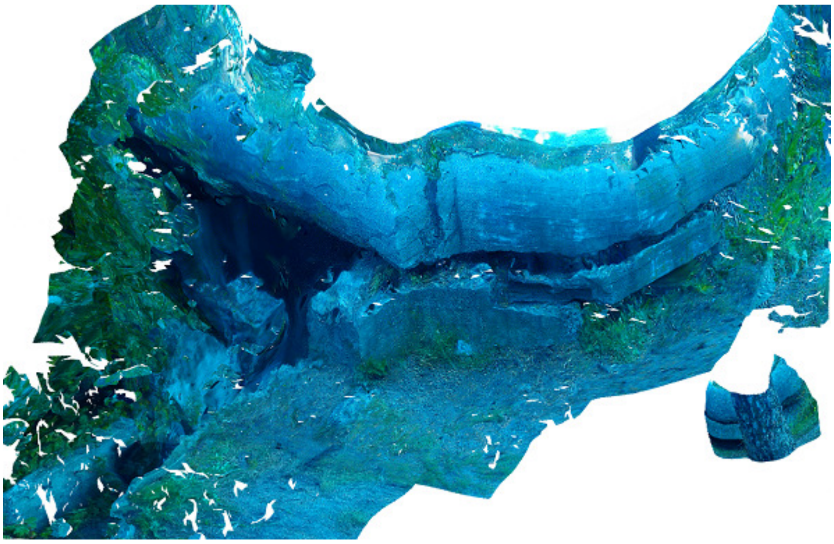

Fig. 6. A fragment of a pillbox three-dimensional model

Additionally, based on the interior photos were obtained cross sections of pillbox, which were adjusted by the archival materials in injured places (Fig. 7).

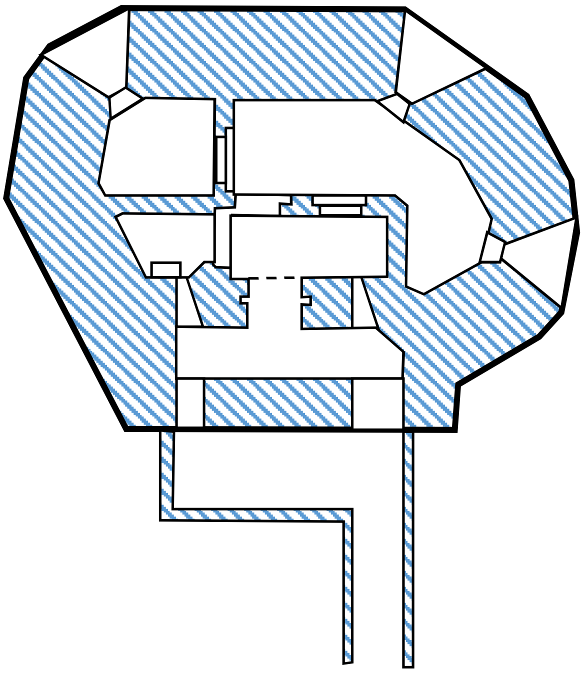

Fig. 7a. Pillbox cross section upper floor

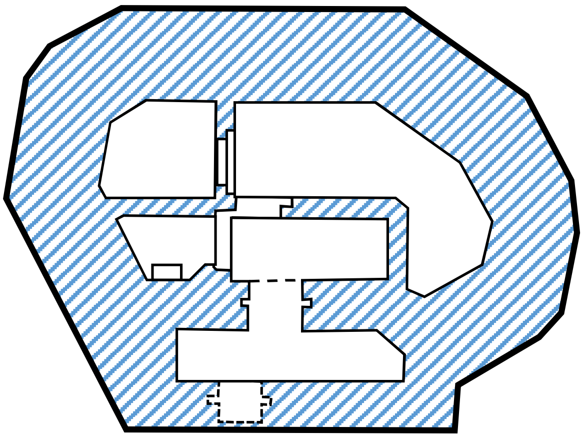

Fig. 7b. Pillbox cross section underground floor

Scaling of model is made in two mutually perpendicular distances. The remaining four distances were used for control. The average absolute value of differences in lengths, which were obtained from the model, was 9 mm.

Conclusions

Summarizing the work carried out would like to make the following conclusions. The considered technology of low-cost photogrammetry proved effective enough to meet the challenges for documenting cultural heritage. The resulting accuracy and detail of the model correspond to the requirements for the inventory of the historic structures. During work with inexpensive equipment necessary to provide the mandatory implementation of the photographic equipment calibration twice: directly ahead image capturing and after image capturing. Modern camera calibration programs allow doing this very quickly. An important element of the technology is to implement control measurements. Because the technology does not provide for the use of surveying equipment (total stations, GNSS precision equipment etc.) and marked points, the only option is to carry out control measurements of distances. Such measurements should be at least 5–6 and as much as possible on all sides of object.

Considered technology is very promising. On the one hand improves the quality of images obtained with the ultra-light UAV, on the other hand, modern smartphones already allow you to measure distances and tilt of object and thus nearly eliminate the use of any other measuring equipment. The study of these issues will be the subject of further publications.

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