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Review / Pregledni znanstveni članak

Quality Evaluation of 3D Heritage Monument Models Derived from Images Obtained with Different Low-Cost Unmanned Aerial Vehicles

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ABSTRACT. This paper describes the preparation of documentation of a part of the cultural and historical heritage of Bosnia and Herzegovina, the famous chapel on the Orthodox cemetery 'Holy Archangels George and Gabriel' located in Sarajevo, by the method of UAV photogrammetry. Two aircrafts (semi-professional and amateur) DJI Phantom 4 Pro and DJI Mavic Pro were used, and 3D models were made based on the photos taken. The quality of chapel 3D models was evaluated by estimating the geometrical accuracy, with different aspects and combinations. The obtained absolute 3D accuracy of the high-resolution model is 14 mm, while the relative accuracy is 9 mm.

Keywords: UAV, photogrammetry, cultural heritage, Phantom, Mavic, 3D model, accuracy.

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1. Introduction

Many cultural-historical and natural heritage sites are threatened due to factors like war destruction, natural disasters, neglect and lack of maintenance, insufficient financial resources, unresolved property and legal relations, non-compliance with legal regulations and non-application of sanctions, insufficient awareness of the value of heritage. One example of the systematic and intentional destruction of cultural monuments is the war in Bosnia and Herzegovina that lasted from 1992 to 1995 (Walasek 2015). During the Bosnian war, the conquest of territories and the ethnic cleansing of settlements wasn't sufficient. Nothing less than the destruction of past historical identities was needed (Chapman 1994). UNESCO estimated that approximately 75% of the entire cultural heritage in Bosnia and Herzegovina was destroyed (Hadžić and Molnár 2019). Unfortunately, destruction and the irremediable loss of valuable cultural heritage continues today (Ocón 2021). The world is losing architectural and archaeological cultural heritage faster than experts in various fields can document. Therefore, the primary goal is to document existing cultural and historical monuments.

Nowadays, a laser scanning and photogrammetry, as surveying and three-dimensional (3D) modelling techniques, are extremely important for documentation of cultural heritage (Guarnieri et al. 2013). In all the branches of cultural heritage field the 3D survey is an essential support for a number of activities: the object documentation, different kinds of analysis (statistical analysis, historical reconstructions, etc.), the communication and promotion of the sites, deformation estimation, adoption of BIM (Building Information Modelling) etc. (Aicardi et al. 2018, Georgopoulos et al. 2016, Rodríguez-Moreno et al. 2016).

Aside from providing a record for future generations, photogrammetry can aid in the more practical quantitative planning of conservation and restoration. Another important feature of the photogrammetric product is its ability to visualize proposed interventions using a precise and realistic 3D model of the site. Thus, both the aesthetic and practical implications of restoration and conservation work can be assessed easily before work commences. Furthermore, site planning and management can employ this feature to envisage and model potential changes to a site in the future (Ruther et al. 2009). According to Aguilera and Lahoz (2010), photogrammetry has the duty of heading towards two goals: the popularization of its results and the popularization of its own technique readily available in a user-friendly environment. The creation, publication, and interaction of high-resolution 3D textured models remain rather challenging and difficult tasks (Mulahusić et al. 2016). With the application of modern methods of digital photogrammetry, new possibilities of application appear by introducing faster, cheaper and more complex procedures, based on digital technique (Mulahusić et al. 2013).

A somewhat more innovative and newer method of photogrammetry is a type of aerial photogrammetric method, but not the classic one, with large planes and cameras that took images, but the use of unmanned aerial vehicles (UAV) that carry cameras of various characteristics (Žilić 2015, Kosmatin Fras et al. 2020). The implementation of UAVs in cultural heritage projects is highly recommended, due to its overall agility (Stek 2016). Many recent studies (Murtiyoso and Grussenmeyer 2017, Sun and Zhang 2018, Marić et al. 2019, Wojciechowska 2019, Dasari et al. 2021, etc.) revealed that UAV-based approach is very efficient for the photogrammetric survey of cultural heritage sites.

This paper describes the photogrammetric method and its application in documenting cultural and historical heritage with a focus on the method of UAV photogrammetry, on the example of the Orthodox chapel 'Heroes of St. Vitus Day' in Sarajevo, Bosnia and Herzegovina. The image processing procedure, the software used and the algorithm for obtaining 3D models of the chapel are illustrated in detail. The main purpose of this study was to assess and compare the geometric accuracy of 3D models obtained with the use of two popular UAVs (DJI Mavic Pro and DJI Phantom 4 Pro+). In many recent studies (Barba et al. 2019, Rogers et al. 2020, Gabara and Sawicki 2019, etc.), different UAVs were employed to test the accuracy of final photogrammetric products. Contrary to previous studies, this research was conducted to explore and evaluate both absolute (1D, 2D and 3D) and relative accuracy, based on statistically significant number of high-precision control observations. The basic idea was to quantify how 3D models of chapel generated from two UAVs differ, and to identify and characterize remaining geometric distortions.

2. Materials and Methods

2.1. Object of interest – orthodox chapel at the cemetery 'Holy archangels George and Gabriel' in Sarajevo

The presence of old Muslim, Orthodox, Jewish and Catholic buildings within walking distance in the historic center of Sarajevo, capital of Bosnia and Herzegovina, is often mentioned as an example of cultural pluralism and interrelatedness dating back to the city's foundation period (Musi 2012). A stone chapel dedicated to Gavrilo Princip and his collaborators is situated inside the Orthodox cemetery 'Holy Archangels George and Gabriel' which is part of the Koševo cemetery complex. Serbian nationalist Gavrilo Princip shot and killed Archduke Franz Ferdinand, the heir to the Austro-Hungarian imperial throne and his wife Sophie in Sarajevo, on June 28, 1914 (Subotić 2017). This assassination led directly to World War I (Jezernik 2013). The assassins became known among Serbs as the Heroes of St. Vitus Day. In 1939, their remains were moved to a specially constructed Orthodox chapel in the Koševo cemetery, prior to its formal dedication in October 1939.

Fig. 1. *Chapel 'Heroes of St. Vitus Day' (photo taken by Jasmin Ćatić).*

The chapel 'Heroes of St. Vitus Day' (Fig. 1), designed by a Belgrade architect Aleksandar Deroko, largely followed Serbian Orthodox church architectural conventions but featured a large red brick cross incorporated into its eastern side (Donia 2014). There is a simple inscription with names of Princip and his 10 collaborators, and the text in Cyrillic, arched around the Ortodox cross: 'Blessed is the one with the eternal life-he had a reason to be born' (Harrington 2014).

2.2. UAVs used for imagery collection

The UAV (Unmanned Aerial Vehicles) can be operated in the field via a pilot operating the aircraft, while having visual contact with it. Today, it is easier and more efficient to use autopilot software, where a flight route is planned using an appropriate computer or mobile device software. For the purposes of this work and the creation of a 3D model of the chapel, two aircraft with different characteristics were used, namely DJI Mavic Pro and DJI Phantom 4 Pro+. These consumer-grade UAVs are equipped with stabilized visible light cameras. In order for the image to be photogrammetrically correct, it is necessary to adequately stabilize the camera (Gašparović and Gajski 2016). The technical data of both cameras are presented comparatively in Table 1.

Both used drones are rotating wings type. The biggest advantage of rotating-wing drones is the possibility of vertical landing and take-off. The possibility of hovering in place (hover) is also a great advantage of these aircraft. This mode is often used for monitoring and targeting objects from a short distance. Although they are often used in photogrammetric surveying with vertical axes, their great advantage over fixed-wing drones is the ability to capture terrain and objects with horizontal and oblique measuring axes.

Table 1. *Technical data of drone-mounted cameras.*

Technical Data	DJI Mavic Pro	DJI Phantom 4 Pro+
Sensor	12 MP 1/2.3” CMOS	20 MP 1” CMOS
FOV (Field of View)	78.8°	84°
Focal length	4.7 mm	8.8 mm
Flight time	27 min.	30 min.
Maximum speed	65 km/h	72 km/h
Internal memory	No	No
Weight	734 g	1388 g
Lens aperture	*f*/2.2	*f*/2.8 – *f*/11
Image size	4:3 and 16:9	3:2, 4:3 and 16:9
Application for flight	DJI GO 4 (+ Pix4D)	DJI GO 4 (+ Pix4D)

2.3. Photogrammetric data acquisition, data processing and generation of 3D models

The chapel ‘Heroes of St. Vitus Day’ was photographed using two aircraft with different characteristics but according to the same algorithm and operating procedure, and was georeferenced and modelled in the same way. Similarities and differences in results will be described later. The complete procedure consists of the following steps:

(1) Field reconnaissance,
(2) Flight permit,
(3) Establishment of geodetic network in the field and measurements,
(4) Defining control and check points on the object for the purposes of georeferencing and absolute accuracy assessment,
(5) Designing the concept of photographing the object (autopilot, manual flight or combination),
(6) Capturing images of the subject,
(7) Measurement of control distances on the object for the needs of relative accuracy assessment,
(8) Storing of captured measurement data in in a specific format required for processing,

(9) Procedure of data processing and creation of 3D models in software,
(10) Accuracy assessment (absolute, relative, resolution, accuracy rating from report software),
(11) Visualization of the model in various ways and
(12) Documenting the model in a suitable format for the needs of preservation and documentation of cultural and historical heritage.

The well-defined ground control points (GCP) at the object were used in this photogrammetric project. These points were measured using a tacheometry since this method is very suitable for the establishment of a coordinate reference (Petrovič et al. 2021). Later, in the processing phase, the GCPs were used to rotate, rescale, and fit images into the same coordinate system as ground control points (Aber et al. 2010).

Before UAV flights, it was necessary to establish a geodetic control network that is consisted of 4 points. This network served as basis of determination of 10 GCPs for georeferencing the UAV images and 25 check points used to estimate the accuracy of the model. Before the start of UAV data acquisition, it was planned in detail. Planning means that, based on reconnaissance of the terrain and insight into the surroundings of the recorded object, the flight procedure was revised and the optimal flight altitude, image overlaps, distance from the recorded object was considered. The weather conditions on the day of flying were very important. The best weather for photogrammetric UAV flight is when it is cloudy.

The object was photographed using the Pix4D flight application installed in the Android operating system of the controller. As for the autopilot shooting mode, 3 circular missions were made at different heights (10, 20 and 30 m above the object) in order to better represent the shape of the chapel. In the Pix4D recording application, it is possible to set the mode of manual control with automatic triggers (Free Flight) at certain horizontal and vertical shifts. Namely, the automatic shooting and saving of the photo is set when the aircraft moves 1 m in the horizontal and vertical direction.

After the photogrammetric mission was completed, the control distances on the chapel were determined by total station. These distances represent various combinations of lengths on the object from the smallest to the largest. It is desirable to measure as wide a range of different length values as possible. Based on the measured distances, a relative assessment of the accuracy of the model was made later. In total, 33 distances in the range from 0.03 m to over 7 m were determined on the building by Coordinate Geometry (Cogo) function which calculate the azimuth, horizontal, vertical, and slope distances between two measured points.

After completed field works, i.e. establishing the geodetic network, determining the coordinates of network points and coordinates of detailed points and points for georeferencing, then photographing the object with a UAV and finally measuring the control distances, the image processing and creation of chapel 3D models has been started. It should be noted that before the flight with the UAV, the calibration of the aircraft was done in terms of checking all the necessary parameters.

Fig. 2. *Textured models – MP.*

Fig. 3. *Textured models – P4P.*

After all the necessary data was collected, the processing of data recorded with DJI Mavic Pro and DJI Phantom 4 Pro was started. Data were processed separately, in two different projects but by the same methodology. The number of photos taken with the DJI Mavic Pro (MP) aircraft is 522, while with the DJI Phantom 4 Pro+ (P4P) 271 photos were taken. This refers to filtered photos, from good angles and without blurry images. The reason why almost twice as many photos were taken with the Phantom aircraft is the size of the sensor, the resolution of the camera and thus the size of the photo. Using the Mavic UAV, it had to be done in much more details and with more photos in order to get the best possible high-resolution model. Agisoft Metashape Pro software was used to process the images. Agisoft Metashape Pro is software that processes digital photos and generates 3D models. The processing steps in the software are as follows:

(1) Import of measured data (images),
(2) Overlapping images by Structure from Motion (SfM) method,
(3) Camera calibration in software (determination of internal orientation parameters),
(4) Georeferencing of the model,
(5) Generate a dense point cloud,
(6) Creating a high-poly mesh,
(7) Creating texture over a poly mesh and
(8) Creating a tiled 3D model.

High-quality textured models for DJI P4P and MP are presented in Fig. 2 and Fig. 3.

3. Results

When assessing the scientific and practical value of the results, geometric (positional) accuracy is the most important criterion for evaluation. For the quantitative expression of the geometric quality of data collected by UAV, two criteria of accuracy are defined: (1) Absolute accuracy, (2) Relative accuracy (Mulahusić et al. 2020).

3.1. Absolute accuracy evaluation of high-resolution 3D models

The absolute accuracy of the model is the accuracy of fitting the model into the State Coordinate System. The Bosnian-Herzegovinian State Coordinate System is defined by the Bessel 1841 reference ellipsoid and Gauss-Krüger map projection of 3 degrees meridian zones with linear scale 0.9999 along the central meridian (Tuno et al. 2017). Absolute accuracy assessment was done by comparing the reference coordinates of points measured by using a total station (coordinates of check points on the chapel) with the corresponding points on the created and georeferenced 3D model (a total of 25 points).

Absolute accuracy of high-resolution 3D models is illustrated by the statistical measures in Table 2. Table 2 shows the quality of the 3D models obtained by photographs captured by Mavic Pro and Phantom 4 Pro+ UAV, evaluated on the basis of the differences between reference coordinates and coordinates obtained from a 3D model:

$$dy_i = \tilde{y}_i - y_i, \quad dx_i = \tilde{x}_i - x_i, \quad dH_i = \tilde{H}_i - H_i \quad (i = 1, \ldots, 25) \tag{1}$$

and 2D and 3D errors:

$$d_{yx} = \sqrt{d_y^2 + d_x^2}, \quad d_{yxH} = \sqrt{d_y^2 + d_x^2 + d_H^2}. \tag{2}$$

Table 2. *Absolute accuracy assessment of high-resolution 3D models.*

Statistical indicator		Mavic Pro					Phantom 4 Pro+				
		d_y	d_x	d_{yx}	d_H	d_{yxH}	d_y	d_x	d_{yx}	d_H	d_{yxH}
Minimum [mm]		–12	–22	3	–12	3	–14	–18	2	–11	3
Average [mm]		–1	1	10	2	13	0	1	11	3	13
Maximum [mm]		20	20	30	10	30	19	19	25	14	25
Range [mm]		32	42	27	22	27	33	37	23	25	22
RMSE [mm]		7	10	12	7	14	7	10	12	7	14
residuals distribution [%]	|0–5 mm|	56	44	20	44	12	52	32	16	44	4
	|5–10 mm|	36	28	44	48	20	40	44	44	36	32
	|10–15 mm|	4	12	12	8	40	4	4	16	20	32
	|15–20 mm|	4	8	16	0	20	4	20	16	0	20
	|20–25 mm|	0	8	4	0	4	0	0	8	0	8
	>|25 mm|	0	0	4	0	4	0	0	0	0	4

The analysis of the statistical indicators given in Table 2 has shown that the overall accuracy of both 3D models is practically the same, since there are no differences in the corresponding RMSE values. However, there are some minor differences in residual distribution. For example, 92% of check points showed a d_H below 10 mm in the case of Mavic Pro, compared to 80% in the case of Phantom 4 Pro+.

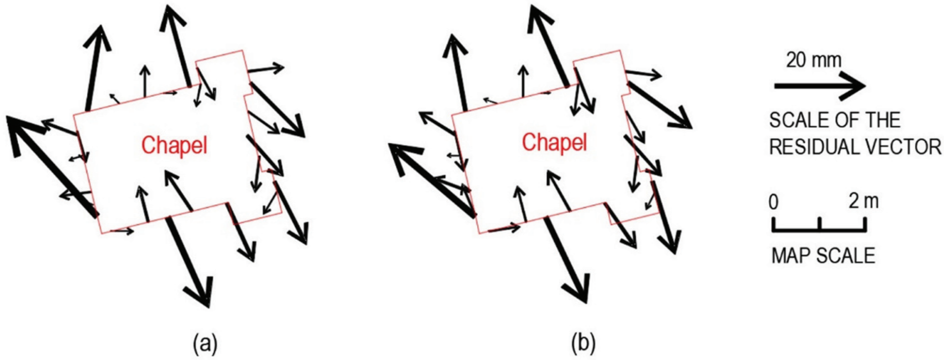

Fig. 4. *Vectors of positional displacement at chapel's check points: (a) Mavic Pro, (b) Phantom 4 Pro+.*

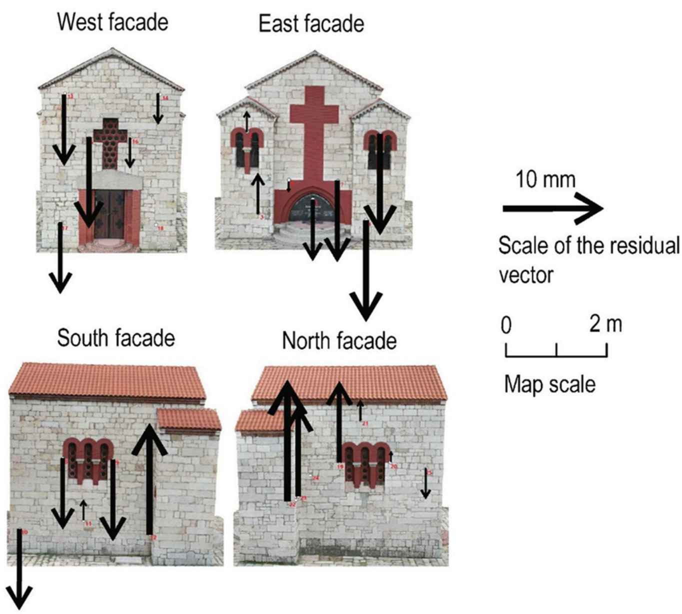

Fig. 5. *Vectors of vertical displacement at chapel's check points (Mavic Pro).*

The visualization of the planimetric accuracy through residual (error) vectors (Fig. 4) shows that most of the remaining positional distortions have the same propagation, depending on the orientation of the chapel sides (global tendency). For example, all vectors on the east side of the chapel are directed from east to south, however, their values vary. Error vectors are almost identical for both 3D models obtained from data collected by Mavic Pro and Phantom 4 Pro+ UAV i.e. each check point has more or less the same direction and magnitude of error in both reconstructions. It may mean that it is mostly due to the reconstruction process, and is independent from which drone was used. Possibly, the check points with higher error were in areas not fully visible from the shooting position, or were in areas with not enough surface detail to ensure a good reconstruction. Similar considerations can be applied to the height displacement vectors (Fig. 5). These vectors generally have the same direction in all check points located on the same facade of the chapel, but vary in their amounts.

3.2. Relative accuracy assessment of high-resolution 3D models

Relative accuracy represents how close the measured value (measured length on the model) is to the true value (length measured by total station), in relative terms, i.e. independent of the translation and rotation. Relative accuracy was calculated based on a comparison of 33 lengths determined by total station and the corresponding lengths measured on the model in the software.

Relative accuracy assessment of high-resolution 3D models – Mavic Pro or Phantom 4 Pro+ is given in Table 3. The accuracy analysis was performed based on the comparison of the data obtained by direct measurement of the lengths on the monument D_i (reference values) with the lengths D_{P4Pi} between corresponding points of the 3D model created with Agisoft and Phantom 4 Pro+, and lengths D_{MPi} between corresponding points of the 3D model created with Agisoft and Mavic Pro:

$$d_{MPi} = D_i - D_{MPi}, \quad d_{P4Pi} = D_i - D_{P4Pi} \quad (i = 1, \ldots, 33) \tag{3}$$

Table 3. *Relative accuracy rating of high-resolution 3D models – Mavic Pro or Phantom 4 Pro+.*

Statistical indicator		Mavic Pro d_{MP}	Phantom 4 Pro+ d_{P4P}
Minimum [mm]		–9	–19
Average [mm]		3	3
Maximum [mm]		28	16
Range [mm]		37	35
RMSE [mm]		10	9
residuals distribution [%]	|0–5 mm|	48.5	48.5
	|5–10 mm|	33.3	18.2
	|10–15 mm|	3.0	18.2
	|15–20 mm|	6.1	15.2
	|20–25 mm|	6.1	0.0
	>|25 mm|	3.0	0.0

The directly measured distances on the monument have higher accuracy compared to distances obtained from 3D models, and they can be considered as true values (Mulahusić et al. 2020), so it is possible to calculate the corresponding RMSE values based on the remaining residuals d_{MPi} and d_{P4Pi} Table 3 shows that the overall relative accuracy obtained with two UAVs is very similar. The results have been slightly improved in the case of 3D model created with Phantom 4 Pro+, since the residuals are more evenly distributed above and below 0, and all of them are less than 20 mm. The second model contains almost 10% distance residuals greater than 20 mm.

In Fig. 6, the individual differences d_{MPi} and d_{P4Pi} of all control distances are shown. It is obvious that there is some correlation of the residuals resulting from the distance measurements in the 3D models, which is also confirmed by looking at the polynomial trend lines.

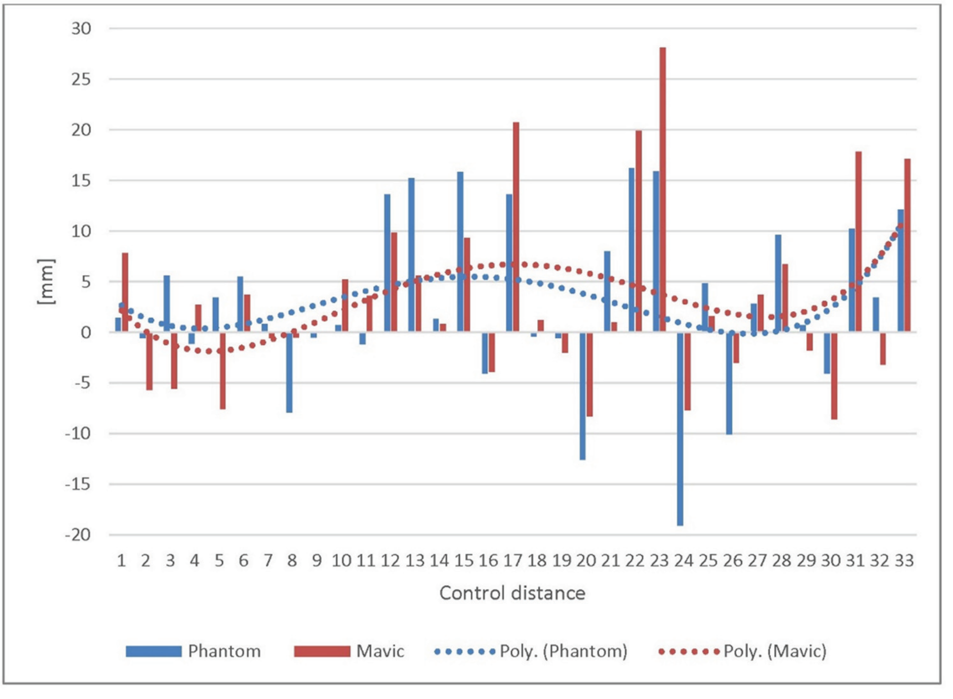

Fig. 6. *Residuals* d_{MPi} *and* d_{P4Pi} *of all control distances.*

4. Discussion

The high-quality models from both UAVs have millimeter resolution and millimeter details can be discerned. The absolute accuracy for the high-resolution models obtained from both aircraft is quite similar, which is confirmed by the obtained *RMSE* indicators. Based on this, it can be concluded that the same accuracy of the high-resolution models was obtained from both UAVs, when it comes to the comparison. Since the coordinates of the points of the geodetic network, from which the coordinates of the points used to assess accuracy, were determined by the RTK method, which has centimeter accuracy, the obtained absolute accuracy is more than satisfactory. Therefore, on the model it is possible to determine the 3D coordinate of any point in the State Coordinate System of Bosnia and Herzegovina with an accuracy of 25 mm (on the high-resolution model) at the 95% confidence level. On the basis of the obtained *RMSE* indicators for relative accuracy, it is possible to draw similar conclusions as with absolute accuracy. The trend of differences of control distances and the obtained accuracy is very similar for both aircraft. The difference between *RMSE* values is only 0.6 mm, which can be ignored. Relative accuracy represents the accuracy of measurements without considering the coordinate system, and represents the accuracy with which any measurements can be made on the model (independent of the coordinate system), and in this case this accuracy is 18 mm at the 95% confidence level.

What is also interesting is the visualization of the model obtained with the Mavic Pro and the Phantom 4 Pro UAVs in terms of model fidelity and colour on the model. Namely, when images were captured with the Mavic Pro aircraft, it was a sunny day, and a lot of light entered the lens during shooting, given the aperture of *f* / 2.2. Based on that, a very luminous model was obtained, shadows are visible and the most realistic image of the same is not shown. On the other hand, when the Phantom 4 Pro was used to acquire of the images it was also a sunny day but a lot less light was reaching the sensors as the aperture was *f* / 5.5. A model was obtained that faithfully represents the image of the chapel and on which there are not as many visible shadows as was the case with the model obtained with the Mavic Pro aircraft.

The resolution of the model is very similar considering the proximity of the subject. With the DJI Phantom 4 Pro, a high-resolution model was obtained based on 271 images, while the model of the same resolution with the Mavic Pro aircraft was obtained based on 522 images. So, it took a lot more (almost double) images and twice as much processing time to achieve quite similar results. But, again, the Phantom 4 Pro showed the subject more faithfully with regard to better camera parameters (aperture, shutter speed, etc.), while the Mavic Pro showed a rather bright object on one side, and shaded on the other.

5. Conclusion

A comparison of 3D models of the ‘Heroes of St. Vitus Day’ chapel revealed that the model obtained with the Phantom 4 Pro UAV is very realistic and faithful, which means that it represents the actual appearance of the chapel in question quite well. The model obtained with the Mavic Pro UAV is too bright on one side, while too shaded on the other. The reason for this is the possibility of reducing the aperture and less light transmission reaching the sensor in the Phantom 4 Pro, while in the Mavic Pro the aperture was larger and more light reached the sensor and over-sunlit photographs were obtained, and shadows were present on the other side. In addition, the camera on the Phantom 4 Pro obviously has better characteristics in terms of taking uniform photos regardless of the position of the aircraft in relation to the light source, because mostly photos of uniform brightness were obtained and there are no shadows on the model.

Absolute (14 mm) and relative 3D accuracy (9 mm) are in accordance with the specifications of both types of UAVs. However, it is evident that 271 images were taken with the Phantom 4 Pro, and processed at high resolution in order to obtain a millimeter resolution model with the stated accuracy. On the other hand, 522 images were taken with the Mavic Pro, and based on that, a very similar model was obtained in terms of accuracy and resolution. So, almost twice as many photos were needed to achieve almost the same results. The reason for this is primarily the capabilities of the camera, where the Phantom 4 Pro has far better specifications, as this research has shown.

Amateur and semi-professional UAVs can achieve the same results in terms of accuracy and resolution of the final model, while for more accurate visualization the weather conditions should be considered. It is preferred to perform the UAV photogrammetric missions on cloudy days, especially with amateur aircraft due to camera deficiencies. To get the most accurate model with an amateur aircraft, more photos are needed, closer shooting distance, greater photo overlap, but also high-quality processing. Due to superior the camera specifications, semi-professional aircraft does not need to fly close to the object, which means fewer photographs and shorter flight times, and in the end high-precision and high-resolution 3D model was achieved.

What is important about both UAVs is to have a professional workstation for data processing, with demanding hardware components and supported software. It is possible to get high-resolution models with an amateur UAV (only with more photos and more demanding processing), as well as with a semi-professional UAV (moderate number of photos and moderately demanding processing), and based on this it can be concluded that UAV photogrammetric method provides very good results in the field of accurate, high-resolution and cost-effective way of documenting cultural and historical heritage.

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Ocjena kvalitete 3D modela spomenika kulturno-povijesnog nasljeđa izrađenih temeljem snimanja različitim jeftinim bespilotnim letjelicama

SAŽETAK. U ovom radu opisana je priprema dokumentacije dijela kulturno-povijesne baštine Bosne i Hercegovine, tj. poznate kapele na pravoslavnom groblju „Sveti arhanđeli Georgije i Gavrilo“ u Sarajevu, metodom UAV fotogrametrije. Korištene su dvije letjelice (poluprofesionalni i amaterski dronovi) DJI Phantom 4 Pro i DJI Mavic Pro, a korištenjem prikupljenih fotografija izrađeni su 3D modeli snimljenog objekta. Pokazatelji kvalitete 3D modela kapele dobiveni su kroz ocjenu geometrijske točnosti, s različitim aspektima i kombinacijama. Dobivena apsolutna 3D točnost modela visoke rezolucije iznosi 14 mm, dok je relativna točnost 9 mm.

Ključne riječi: *UAV, fotogrametrija, kulturno nasljeđe, Phantom, Mavic, 3D model, točnost.*

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