Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 38, 2026, Sofia

DOI: https://doi.org/10.3897/arb.v38.e18

AN EFFICIENT METHODOLOGY FOR GENERATING A DETAILED THREE-DIMENSIONAL MODEL OF AN ARCH MONUMENT BY EMPLOYING AN OPTIMIZED UAV FLIGHT PLAN

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Key words: *unmanned aerial system (UAS), Smart 3D Capture, three-dimensional modelling, monument-arch, efficiency*

Abstract

Remote sensing methods enable the collection of information about objects from a distance, particularly where ground-based imaging is difficult or impossible. The rapid development of unmanned aerial systems has greatly expanded the potential to generate high-precision, three-dimensional photogrammetric models of cultural heritage monuments. These models not only facilitate spatial documentation and visualisation but also support efforts in reconstruction, restoration, conservation, adaptation, and the integration of such sites into the socio-cultural environment. The emergence of new close-range photogrammetric acquisition techniques and the ability to capture images from varying camera orientations, including capturing images with camera axes oriented perpendicularly to vertical surfaces, has led to an increase in model accuracy and the level of detail. This article presents a methodology for photogrammetric modelling of an arch monument using the new "Smart 3D Capture" flight-planning feature, implemented in modern flight-planning applications in 2025, and for automating the photogrammetric processing workflow. An accuracy assessment of the results was carried out by measuring a set of control distances. This study aims to present a methodology for capturing and generating detailed photogrammetric models of such objects, featuring similar characteristics and bas-reliefs, and to establish optimal workflow parameters. The results confirm the effectiveness of the proposed methodology, which allows not only for the generation of detailed models but also for monitoring the condition of monuments and similar objects, providing specialists from various fields with the means to perform such tasks at an affordable cost.

Introduction

In recent years, the development of unmanned aerial systems (UAS) has been very dynamic, with increasingly small aircraft offering ever more advanced capabilities. At the same time, new image capture methods are being integrated into applications used to create flight plans, also known as missions. This development necessitates research into these innovations – both to address various practical tasks and to assess the accuracy and effectiveness of the resulting data. Creating three-dimensional models of cultural monuments, buildings, or other objects that may be complex in shape and considerable in height is a challenging task. To address it effectively, a practical, readily applicable methodology is required, one that ensures sufficient accuracy and detail in the final product while relying on relatively affordable equipment.

The established methods for capturing architectural monuments, such as the use of oblique or combined nadir and oblique images and/or free-flight missions [1–3], do not always guarantee high-quality three-dimensional models without errors or imperfections. These shortcomings often arise from factors such as distance to the object, the inability to capture vertical surfaces with a perpendicular camera axis, operator errors, and other limitations.

Other methods used for creating high-accuracy models rely on a combination of terrestrial laser scanning (TLS) and unmanned aerial systems (UAS) [4–6]; however, the current high cost of laser scanners limits the accessibility and efficiency of this methodology.

Developing optimised solutions that utilise a rough model of the object during the flight plan preparation offers an alternative approach capable of achieving higher model accuracy and detail compared to conventional oblique image acquisition [7].

The unmanned aerial systems introduced in 2025, such as the Matrice 4E and Matrice 4T, together with their associated flight-planning applications based on optimised solutions, enable image capture at closer distances and at varying camera-axis orientations relative to the surveyed object. The ability to design precise mapping routes adjusted for capturing buildings and irregularly shaped objects allows for higher spatial resolution of captured images and, consequently, greater detail in the resulting models. Such models can also be used for remarkably efficient structural inspection [8].

In addition to automatic image capturing, another factor influencing workflow efficiency is automating the process of establishing the photogrammetric processing parameters for UAS-generated three-dimensional models of cultural heritage monuments of specific shapes and sizes, for which ground-based image capturing cannot be achieved.

The present study aims to propose an efficient methodology based on automated image acquisition and established photogrammetric data processing parameters, accessible to a wide range of users across various fields at an affordable cost.

Materials and Methods

Object of Study

The "Arch of Freedom" monument is located in the Central Balkan Mountains, on Mount Goraltepe (1.595 m) in the area of the Troyan Pass, also known as Beklemeto. It lies 25 km from the town of Troyan and 100 km from Plovdiv (Fig. 1). The monument was designed by sculptor Prof. Velichko Minekov and architect Georgi Stoilov. It stands on a concrete platform and represents a massive concrete structure, with a height of 35 m, shaped as an arch. The monument features bas-reliefs depicting Bulgarian haiduks, partisans, as well as Russian and Soviet soldiers. On the northern side of the arch can be seen bas-reliefs of women in traditional Bulgarian costumes welcoming them with bread and salt in 1878 and 1944 [9].

Fig. 1. Object of study: (a) geographic location; (b) photograph of the monument – author's archive

Equipment and Data Acquisition

The photogrammetric survey was carried out using a DJI Matrice 4E unmanned aerial system (UAS), designed for geodetic surveying, mapping, construction, and inspection tasks. The aircraft has a takeoff weight of 1,219 g and supports high-speed image acquisition, with a maximum flight speed of 21 m/s and a capture interval of 0.5 s, significantly improving operational efficiency. Its camera is equipped with a 24 mm wide-angle lens (f/2.8–f/11) featuring a mechanical shutter and a 4/3 CMOS sensor with a resolution of 20 MP. The UAS withstands wind speeds of up to 12 m/s, and its maximum flight time under calm conditions is 49 minutes. The UAS integrates a DJI RTK module supporting multi-frequency GNSS (GPS, Galileo, BeiDou, GLONASS) and the extended L5 frequency band. The module works in combination with a GNSS+Vision Fusion positioning and navigation system, guaranteeing high stability and reliability even under limited or weak satellite signal conditions. The RTK module provides positioning accuracy of ±1 cm + 1 ppm horizontally and ±1.5 cm + 1 ppm vertically [8, 10].

The flight plan (mission trajectory) was created using the DJI Pilot 2 application. The latest image acquisition feature introduced in 2025, called "Smart 3D Capture" mode, enables the generation of precise and detailed 3D models. The method is designed to apply intelligent image-capturing strategies that allow dynamic adaptation of the flight trajectory based on the morphology of the object.

This functionality simplifies the 3D modelling process by automating the mapping process based on a preliminary rough model of the object, thus increasing efficiency by approximately 40% when compared to traditional oblique image acquisition [11]. In “Smart 3D Capture” mode, the Distance to Slope parameter defines the perpendicular distance the UAS maintains from the surface being captured and the object. The parameter value was chosen to ensure an optimal Ground Sample Distance (GSD) of precisely 0.22 cm. Similarly, a distance of precisely 8 m was selected in another study describing the generation of a three-dimensional photogrammetric model of the Ryhope Engines Museum building, which was achieved using the same “Smart 3D Capture” mode [12].

Another parameter influencing the vertical and horizontal accuracy is the image overlap ratio. Higher frontal and side overlap ratios increase the accuracy of the generated 3D point clouds by eliminating false matches and extending the reliability of the points in the vertical direction [13]. For the object of this study, the frontal overlap was set to 80%, and the side overlap to 70%. The flight parameters are shown in Table 1, and the flight plan is illustrated in Fig. 2.

Table 1. Flight plan parameters

Indicator	**Value**
Distance to Slope (m)	8
Ground sample distance (cm)	0.22
Along the track overlap (%)	80
Across the track overlap (%)	70

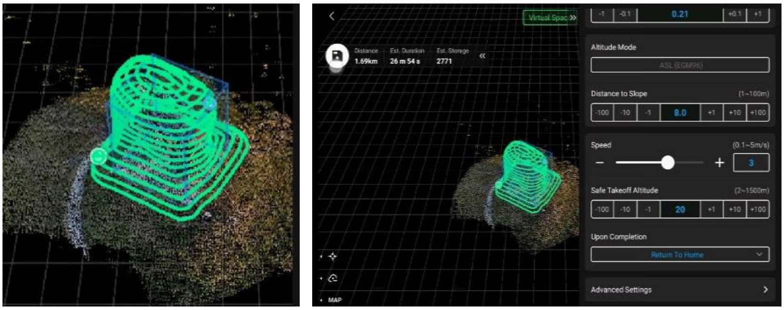

Fig. 2. UAS flight plan executed in the DJI Pilot 2 application, version 2.2.5

Due to the monument's location at the top of Mount Goraltepe, relatively strong wind gusts were observed for most of the day, even under calm, sunny conditions. Despite these conditions, the UAS successfully completed its flight mission within 26 minutes, capturing 2,276 images.

Apart from the flight parameters, the model’s accuracy – especially vertical accuracy – is influenced by the available ground control points (GCPs). Previous studies have shown that using only RTK data for georeferencing may result in systematic errors in elevations [14, 15]. Therefore, in the present study, 7 reference points were used – 4 as control points and 3 as checkpoints (the marking on the fourth checkpoint was destroyed). The points were evenly distributed around the monument on its concrete platform (foundation) and marked with black-and-white square targets (30 × 30 cm). The positions of the control points and checkpoints on the foundation are shown in Fig. 3. Additional checkpoints were placed on the monument's arches approximately 2 m above the ground, marked in the same manner but in a different colour and slightly smaller in size. These points were also used in the accuracy assessment of the model.

A local geodetic network consisting of seven polygonal points was established around the monument for model georeferencing. These points were measured using a CHCNAV CHS-A100 total station, with a direct angular measurement accuracy of 2″ and a distance measurement accuracy of ±2 mm + 2 ppm with a prism or ±3 mm + 2 ppm without a prism (up to 300 m). This total station was also used to determine the positions of all ground control points and checkpoints, both on the foundation and on the monument itself, as well as to measure identical reference points on the object, which were later used for analysing the results.

The global positioning of the polygon was determined through GNSS observations in compliance with the existing Bulgarian national regulatory framework for determining geodetic points using GNSS [16]. The measurements were carried out in the WGS84 / UTM Zone 35N (EPSG: 32635) spatial reference system. To achieve high positioning accuracy in the present study, a CHCNAV i76 GNSS-RTK receiver with an inertial measurement unit (IMU) was used, operating with the LandStar 7 field software. The receiver provides a standard RMS accuracy of approximately 0.8 cm horizontally and 1.5 cm vertically under optimal conditions.

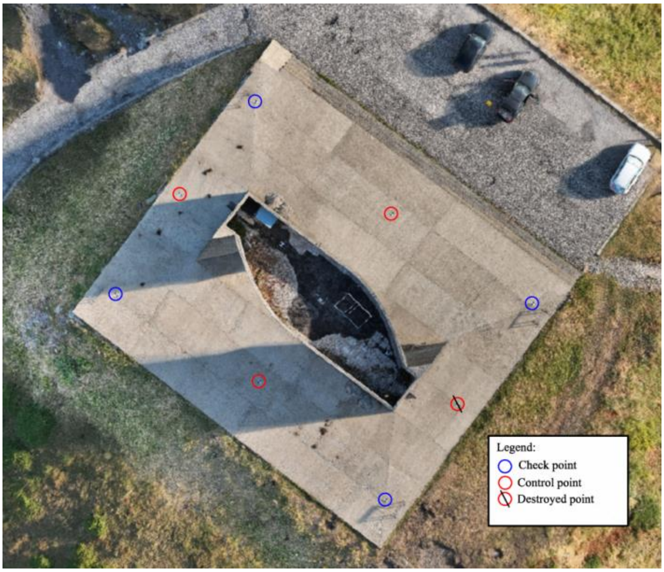

Fig. 3. Location of control and check points on the foundation

Photogrammetric Processing and Analysis of Results

Photogrammetric Processing

The processing of captured imagery data was carried out using Agisoft Metashape Professional, version 2.2.2. It is known that both the processing method and the selected parameters influence the model's accuracy. In this study, the Structure-from-Motion (SfM) algorithm was applied – a photogrammetric method that simultaneously reconstructs three-dimensional geometry and estimates the camera's internal and external orientation parameters based on multiple overlapping images captured from different spatial positions. The accuracy and reliability of the reconstructed model directly depend on the imaging geometry, image resolution, and the selected reconstruction parameters.

During the first stage (Align Photos), the processes of Aerial Triangulation (AT) and Bundle Block Adjustment (BBA) are carried out [17]. SfM employs the correlation of common feature points in the input images to determine the camera positions and the spatial configuration of the objects. Therefore, two key processing parameters in this study are the key point limit and the tie point limit. In studies aiming to extract the maximum number of image matches and achieve a stable geometric configuration, both parameters are commonly set to zero (i.e., key point limit = 0, tie point limit = 0) [18, 19]. The same parameter values were adopted and applied in the present study.

An important stage is the incorporation of ground control points and checkpoints and subsequent optimisation. A primary method for assessing the accuracy of the georeferenced three-dimensional model is the root-mean-square error. In the present study, the root mean square error for the ground control points was 0.002 cm, while for the checkpoints it was 0.012 cm

The next stage of processing involves cleaning the model from noise, also referred to as removing spurious or parasitic points. In this study, an automated filtering procedure was implemented using the Gradual Selection function. This filtering automatically removes unnecessary points from the model without operator intervention, thereby increasing the methodology's overall efficiency. The filtering parameters were analysed, and based on the obtained results, certain parameter values were specified, which are presented in Table 2. Fig. 4 illustrates the point cloud before and after the applied filtering. The same table also consecutively lists the parameters applied in the subsequent workflow stages of photogrammetric processing, including automatic generation of the textured three-dimensional model.

(a) (b)

Fig. 4. Comparison of the generated point cloud before and after applying filtering

The next stage of processing involves generating a dense point cloud. This process is based on depth maps computed for overlapping image pairs, taking into account their relative external and internal orientation parameters as estimated through bundle adjustment. The resulting set of depth maps is then merged into a combined depth map, during which erroneous depth measurements are filtered out. These maps are subsequently converted into partial point clouds, which are later merged into a final unified point cloud. The Agisoft Metashape software typically produces point clouds with densities comparable to, or even exceeding, those of LIDAR clouds [17]. Evidence of this is the dense point cloud of the arch monument generated in this study, which contains 301,289,009 points.

Table 2. Parameters of the workflow applied in Agisoft Metashape Professional

Alignment Cameras	Accuracy: High Generic Preselection: Yes Reference Preselection: Yes Key Point Limit: 0 Tie Point Limit: 0
Gradual Selection	Reconstruction Uncertainty: 10 Projection Accuracy: 3 Reprojection Error: 0.3
Optimize Cameras	k3, k4, p3, p4: No
Build Point Cloud	Quality: High Depth Filtering: Mild
Build Model	Source data: Depth maps Quality: High Face count: High Interpolation: Enabled Depth filtering: Mild
Build Texture	Texture type: Diffuse map Source data: Images Mapping mode: Generic Blending mode: Mosaic Enable hole filling – yes Enable ghosting filter – yes

The final stages of processing involve the creation of the polygonal and textured model. The process of generating the polygonal model can be described as the reconstruction of the surface geometry by converting the dense point cloud into a continuous mesh of interconnected triangles. For this purpose, algorithms for spatial interpolation and topological optimisation are applied. A total of 37,795,937 triangles were generated for the object under study. The photogrammetric processing concludes with the creation of a photorealistic visualisation of the three-dimensional model - namely, the construction of the model's texture. A portion of the resulting three-dimensional textured model is shown in Fig. 5. On the right side of the figure, the fine detail of the bas-relief on this part of the arch can be seen, while on the left, part of the facade reinforcement is visible. This demonstrates that such models can also be effectively used for the inspection of cultural heritage monuments.

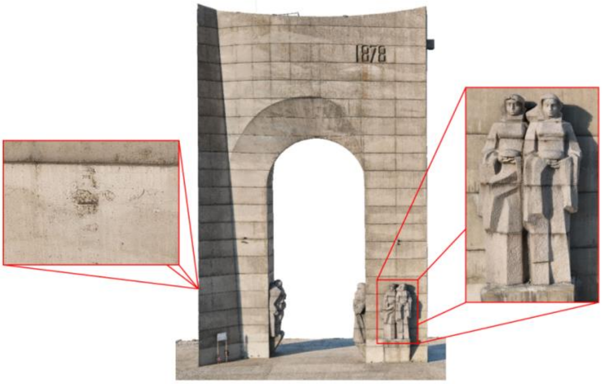

Fig.5. Portion of the three-dimensional textured model of the "Arch of Freedom" monument

Analysis of the Results

To assess the accuracy of the generated three-dimensional photogrammetric model, 46 distances were measured across the monument's surface at various heights. A statistical series of the errors between the control-measured distances and their corresponding model-derived distances was compiled. A gross error check was performed using the $\pm 3\sigma$ criterion. The calculated skewness and kurtosis values were smaller than their corresponding 3σ limits, indicating that the hypothesis of a normal distribution is consistent with the experimental data. The median and mode values were close to the mean, further supporting this hypothesis.

A check for the presence of systematic errors was conducted using Student's t-test at a significance level of $q = 0.05$. The results showed that the mean error did not differ statistically significantly from zero, indicating the absence of systematic deviations in the measurements.

In summary, one can say that the measurement errors are small (root mean square error = 0.011 m). Their distribution is symmetric and close to normal, without statistically significant shifts or extremes, confirming the accuracy and reliability of the measurements used in constructing the three-dimensional model.

Conclusion

The advantages of remote sensing methods are indisputable when creating models of objects that cannot be captured from the ground. The dynamic development of unmanned aerial systems and the emergence of new modes for automated flight execution have made it possible to model three-dimensional spatial representations of cultural and historical sites and to monitor them with remarkable accuracy and detail.

Both terrestrial laser scanning and aerial unmanned image acquisition [20], as well as their combination [4–6], have found broad application when solving problems while documenting immovable cultural heritage. However, in terms of efficiency and cost, the methodology based on optimised UAS image acquisition is preferable. It enables the capture of otherwise inaccessible objects and allows for process automation, thereby minimising the influence of human factors.

The results of the present study demonstrate that, given the specific type and shape of the studied object, the image acquisition method, image quality, and established data processing workflow, the proposed methodology ensures high accuracy in generating point clouds and three-dimensional models of architectural monuments. The model's high level of detail is a result of the fine spatial resolution of 0.22 cm, achieved through the optimised image acquisition of the object. This accessible methodology allows for efficient surveying of similar monuments even in urban environments, allowing not only their modelling but also regular monitoring.

A limitation of the methodology is its dependence on weather conditions and, to some extent, on processing time, which in this case amounted to 36 hours. It should be noted, however, that the processing was performed on a desktop computer with the following specifications: Windows 64-bit, AMD Ryzen 9 5950X 16-Core Processor, 64 GB RAM, NVIDIA GeForce RTX 3090. From a cost perspective, this can even be viewed as an advantage, since professional photogrammetric workstations are typically at least four times more expensive.

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ЕФЕКТИВНА МЕТОДОЛОГИЯ ЗА ГЕНЕРИРАНЕ НА ДЕТАЙЛЕН ТРИИЗМЕРЕН МОДЕЛ НА ПАМЕТНИК АРКА ПРИЛАГАЙКИ ОПТИМИЗИРАН ПЛАН НА ЛЕТЕНЕ

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Резюме

Дистанционните методи осигуряват набирането на информация от дистанция за обекти при които е невъзможно или затруднено заснемането от земната повърхност. Динамичното развитие на безпилотните летателни системи разкриват все по-големи възможности за създаване на триизмерни фотограметрични модели на паметници на културата не само за визуализация, но и за реконструкция, реставрация, консервация, адаптация и социализация на подобен тип обекти в социално – културната среда. Появата на нови начини за заснемане от все по-близка дистанция и възможността за заснемане с различно положение на снимачните оси включително и перпендикулярни на вертикалните повърхнини на обектите, водят до повишаване точността и детайлността на моделите. Статията представя методология за фотограметрично моделиране на паметник - арка, целящо използването на нов начин на заснемане „Smart 3D Capture“ внедрен в съвременните софтуери за планиране на полети през 2025 г. и автоматизиране на работния процес за фотограметрична обработка. Извършен е анализ на точността на получените резултати, като са измерени набор от разстояния. Целта на изследването е да представи методология за заснемане и генериране на детайлни фотограметрични модели на такъв тип обекти със сходни характеристики и барелефи върху тях, както и да се установят оптимални параметри на работния процес. Получените резултати доказват ефективността на предложената методология. Тя ще позволи не само създаването на модели, но и извършване на мониторинг на състоянието на паметници и други подобни обекти и ще даде възможност на различни специалисти да реализират такъв тип задачи на достъпна цена.