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Documentation and 3D Modeling of Mountain Castles Using Drone Photogrammetry at the Historic Forg Castle

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Abstract

Forg Castle is a mountain fortress dating back to the Late Islamic period (from the Afsharid to the Qajar era). Due to its strategic location and unique architecture, the castle has always attracted attention and necessitates precise documentation using modern methods. Drone photogrammetry is one of the modern technologies that, with the advancement of technology in recent decades, has become increasingly used in this type of study. Whether used alone or in combination with other techniques, it has been widely employed in the 3D modeling of immovable cultural heritage and archaeological sites. This technology creates accurate and photorealistic 3D models of historical structures and sites using 2D images. Such documentation is valuable for conservation efforts and sustainable development. The present applied research was conducted with the aim of assessing the capabilities of drone photogrammetry in a mountainous castle with significant elevation differences. The study focused on modeling Forg Castle for documentation and the creation of a 3D map. It was carried out in three stages: fieldwork, software processing, and archival research, using an analytical approach. As a result, a 3D model of the mountainous Forg Castle was produced with true texture and a Ground Sample Distance (GSD) of 0.97 centimeters per pixel. The accuracy of the results was evaluated using four ground control points (GCPs) and three check points, indicating the high performance of drone photogrammetry as a fast and effective method for the documentation and 3D modeling of mountainous castles and their architectural features despite elevation differences with a ground accuracy of 6.2 centimeters.

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1. Introduction

Forg Castle is one of the most important and beautiful historical castles in South Khorasan Province and is registered as a national heritage site of Iran. It is located in the village of Forg, a part of Darmian County, approximately 90 kilometers east of Birjand. Due to its strategic location and unique architecture, the castle holds special significance. The construction of Forg Castle began in the early year 1160 AH (during the reign of Nader Shah Afshar) by Mirza Baghakhan, the then governor of the region, and was completed by his son, Mirza Rafi‘ Khan, after whom the castle is also named (Darmiani, 1986). Forg Castle, due to its strategic location overseeing the entire village, surrounding farms, and communication routes in the eastern region, held great military and defensive importance and served as a strong fortress resisting enemy attacks. The castle was registered as a national heritage site of Iran under number 3450 in the year 2000 CE and also holds the potential to be listed as a UNESCO World Heritage site. This castle is classified among mountainous castles, which are recognized as significant cultural heritage monuments, but due to their rugged terrain and complex structures, accessing and documenting them is challenging.

Traditional surveying methods are often time-consuming, costly, and sometimes unsafe. In recent years, UAV photogrammetry (using drones) has emerged as a powerful tool for documenting, preserving, and monitoring such sites. Recent advancements in data acquisition techniques leveraging Unmanned Aerial Vehicles (UAVs), or drones, coupled with cost-effective aerial imaging sensors, have greatly accelerated 3D mapping across diverse applications, including civil engineering, agriculture, military operations, and archaeology. 3D photogrammetry is a scientific discipline that utilizes 2D images to generate precise and realistic 3D models of objects and environments. This technology employs specialized software and complex algorithms to create point clouds from digital camera images, offering an accurate representation of the object’s or environment’s shape, size, and structure. These point clouds are then converted into editable 3D models. This technique holds significant potential for cultural heritage, contributing to the creation of 3D models of archaeological sites (Kanun *et al.,* 2021) and the extraction of building geometries (Eisenbeiss *et al.,* 2005). New 3D digital tools offer unique advantages for informing, educating, and preserving artifacts and sites. These tools not only enhance public access for museums and historical locations but also extend reach to researchers who might otherwise be unable to access these materials and sites (Zarnowski *et al.,* 2015). However, the use of UAVs for documenting mountainous sites, including castles, comes with certain limitations and challenges. For instance, steep slopes, dense vegetation, and complex structures can create shadowed areas that reduce the quality of the captured images (Chiabrando *et al.,* 2017). Additionally, wind, rainfall, and sudden changes in weather conditions in mountainous regions significantly affect UAV flight safety and the quality of the collected data (Nex & Remondino, 2014). Local regulations regarding UAV flights in protected areas may restrict full operational permissions (Colomina & Molina, 2014). Finally, the captured images generate large volumes of data that require powerful hardware and software for processing (Eltner *et al.,* 2016). This study focuses on the precise documentation and 3D modeling of the mountainous Forg Castle, characterized by significant elevation differences, using drone technology. It also aims to measure the margin of error and ground sample distance (GSD), taking into account the elevation variation and the number of ground control points. However, the castle is currently in a partially abandoned state and, despite severe damage, still retains significant architectural and structural value. This study aims to provide a precise and quantitative approach to lay the groundwork for its future interpretation, as well as for potential conservation and restoration efforts.

2. Research Background

The 3D modeling of the Stenico Castle in Trentino, Italy marked one of the first significant applications of UAV photogrammetry in the field, utilizing both aerial and terrestrial images (Gonzo *et al.,* 2004). This foundational study paved the way for subsequent research and the broader adoption of the technology. In the years that followed, the scope of this research expanded. For example, Lerma & Colleagues (2010) investigated the use of UAVs for documenting historical castles in Spain and proposed methods to improve the 3D modeling process. Over time, more comprehensive approaches for using UAVs in cultural heritage documentation emerged (Remondino and Barazzetti, 2011). extensively explored the application of UAVs for documenting sites with limited access, such as mountain castles. These studies highlighted the importance of using UAVs in challenging environments. A significant advancement in this area was the integration of UAV imagery with Geographic Information Systems (GIS), (Verhoeven, 2011). This demonstrated how such integration could lead to a better understanding of the spatial context of hill-top castles and their historical defensive advantages, providing new insights into spatial analysis. In recent years, numerous studies have presented the practical application of UAV photogrammetry in conservation and restoration programs. For instance, Koutsoudis & Colleagues (2017) highlighted the potential of this method for cultural heritage preservation and digital archiving using UAV photogrammetry for the Kastania Castle in Greece created accurate 3D models for structural assessment and restoration planning by mapping the Byzantine Platamon Castle in Greece (Hatziyazaro *et al.,* 2018). Additionally, in a comprehensive study on the medieval Mundojar Castle, Orihuela and Molina utilized UAV photogrammetry to support conservation efforts and sustainable development (2021). The most recent research on Noe-Wildon Castle in England has also emphasized the benefits of UAV-based documentation and 3D data acquisition (Bauer *et al.,* 2025).

3. Geographic Setting

Forg village is located 107 kilometers southeast of Birjand in South Khorasan Province. It has a population of 690 people in 204 households and is situated in Darmian Rural District, within the Central District of Darmian County. The village lies entirely on the slopes of Momenabad Mountain and has a cold, mountainous climate. It is considered one of the summer highland areas (yeylaq) of South Khorasan (Choubdari *et al.,* 2021). This region is entirely mountainous and lies along the southern highlands of Khorasan, which significantly influences its climate and vegetation. The dominant climate of the rural district is arid and desert-like; however, due to its higher elevation, the northern and more elevated areas enjoy a milder climate compared to the surrounding plains (Fig. 1).

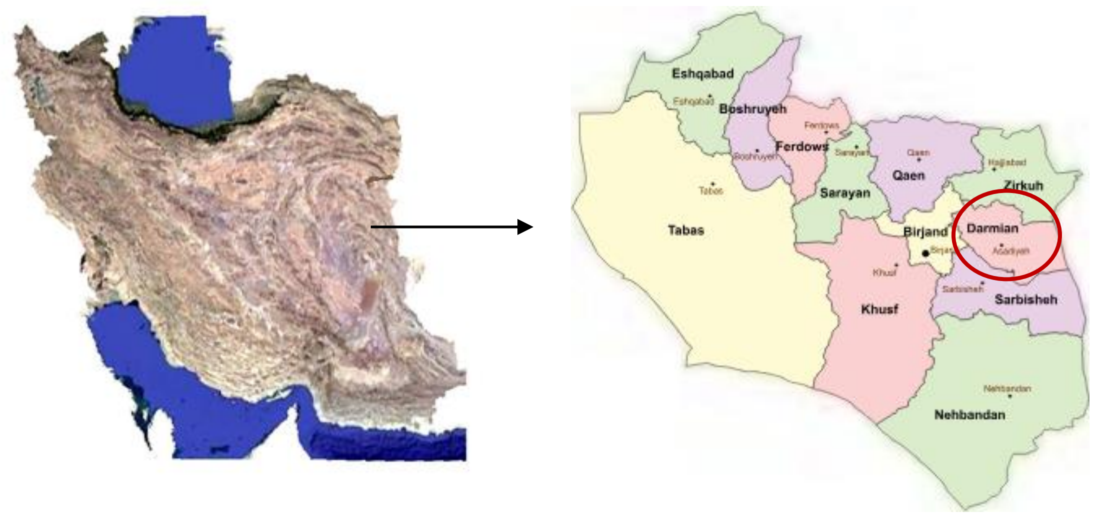

Fig. 1: The location of Darmian county (Authors, 2024).

4. Introducing Forg Castle

Many travelers have explored the Forg region. For instance, Colonel C.M. MacGregor, in his travelogue "A Journey Through the Province of Khorasan", wrote: Forg is built on a hill 2,000-2,500 feet high, making it vulnerable to artillery fire from the northern and western heights. To its south, and on its other two sides, lies a mountain, with its peak 1,200 yards from the castle walls. MacGregor further noted that "within the castle, three large cisterns are built, said to hold enough water to supply a large garrison for a year and a half." (MacGregor, 1987: 98). In 1933 (1312 in the Persian calendar), the author of "Ein al-Vaqayeh" visited the Darmian region and Forg Castle, describing it as: Forg Castle is situated on a mountain, its walls and towers strongly constructed from baked bricks, with a stone foundation. It was surrounded by two 'Haji Lions' (likely referring to stone lion sculptures) and two earthworks, each five zars thick [approximately 5 meters]" (Riazi Heravi, 1993: 110).

Given the castle's location on uneven terrain with significant elevation changes, its designer opted to follow the existing natural topography rather than using predefined plans and altering the mountain's structure. Consequently, the castle's layout lacks the typical regularity often seen in desert castles. The castle covers an area of approximately 9,200 square meters, with its extent stretching from east to west. The main entrance is located on its eastern wall, which is also the lowest point of the castle. The castle is divided into three sections: eastern, central, and western. In the eastern section, the entrance corridors, watchtowers, and a water reservoir are visible. The central section is situated at a higher elevation, but due to significant destruction, its original purpose cannot be determined. The western section, which is the most important and highest part of the castle, is separated and guarded by two towers, indicating its strategic significance. This section includes spaces such as vestibules, connecting corridors, stables, a food storage area, watchtowers, and an underground passage. It consists of two floors, with the upper floor having been destroyed (Fig. 8).

5. Materials and method

This research is an applied study conducted using both field and documentary methods. In the field phase of this research, specialized drone-based photogrammetry software, such as Agisoft Metashape version 2.2.1, was evaluated on various data from the Forg castle. The main stages of this study included: flight plan design in PIX4D PRO software, identification of control points on the site using multi-frequency GPS, data acquisition using a Mavic 2 Pro drone, transferring the acquired images to Metashape software, generating a point cloud, and designing a model using the point cloud. Subsequently, in addition to three-dimensional cartography, the spatial structure and physical distribution of the city were studied using documentary information, including historical texts. In this research, a Mavic 2 Pro multi-rotor drone with a 20-megapixel Hasselblad camera and high-definition (HD) images, along with 8 kilometers of obstacle detection sensors in four main flight directions, was used to acquire aerial images. A Raymand multi-frequency GPS model was also utilized to identify control points. A preliminary design sketch was prepared in advance for data acquisition from the historical Forg castle for its three-dimensional modeling. Field operations were conducted at the Forg castle, in the castle area, for 2 hours (Table 1) The workflow stages of the photogrammetry project using a drone consisted of: photogrammetry process parameters, flight process, flight quality, image processing by photogrammetry software or other specialized software, Ortho photo generation, and the application of the obtained data (Suziedelyte Visockiene *et al.,* 2016).

Table 1: Drone and camera specifications in the research (Authors, 2024).

Gauge Specifications		**UAV specifications**	
Type of Gauge	Hasselblad camera with a 1-inch CMOS sensor attached to the drone.	Type of drone	Multi-Rotor (DJI Company)
ISO and shutter speed.	Automatic	GPS	Yes
		Weight	907 g
		Flight Speed	Km per hour68
The number of pixels	MP 20	Continuity of flight	30min
		Wake up mode	Automatic
		Sitting mode	Automatic - Semi Automatic

5.1. Aerial survey network design

PIX4D software was used for designing, guiding, and controlling the flight in this research. To design the flight in the aforementioned software, after selecting the drone type, the flight area was determined as the first step. Considering the drone type, which was a multi-rotor with a flight speed of 10.5 meters per second and equipped with a Global Positioning System (GPS), the flight settings and camera angle with respect to the horizon were entered into the software. Thus, based on the actions taken, the longitudinal and lateral overlap values of the acquired images were determined to be 80% and 85% respectively (Fig. 2). According to the Ground Sample Distance GSD 0/97, the flight altitude was set at 40 meters and the flight starting point was defined at the center of the castle.

Considering the area of the designated zone within the Forg castle, the flight was designed in double grid, and then the flight plan was saved onto the drone's memory by the software (Fig. 3). The drone's flight was completely automatic and without manual intervention because a multi-rotor drone was used. After traversing the designed paths and acquiring images at the designated

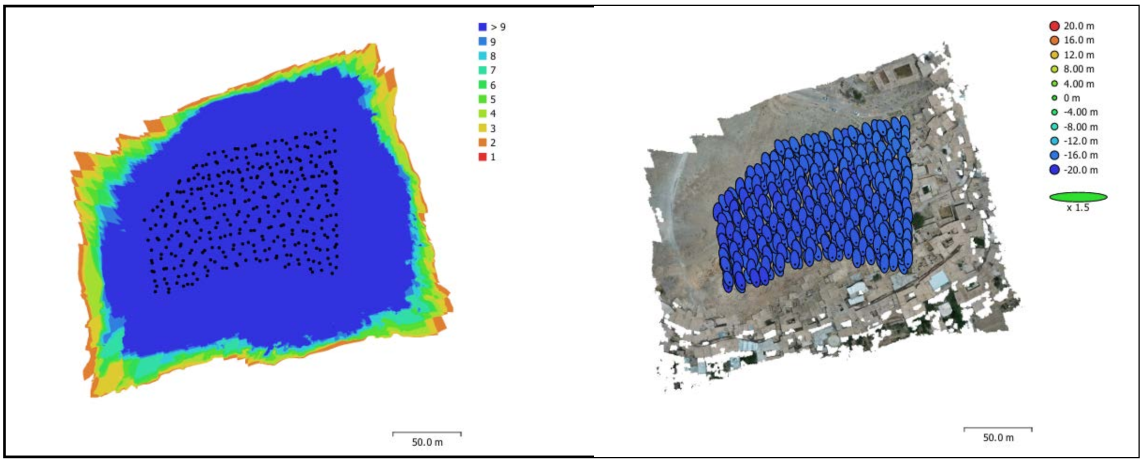

Fig. 2: Left, Camera locations and error estimates; Right, Camera locations and image overlap (Authors, 2024).

Fig. 3: Flight design of Forg castle in PIX4D software (Authors, 2024).

points, the drone was landed by the operator (pilot). Ultimately, during this aerial photography, 358 aerial photos with good quality and specific geographical locations were recorded.

5.2. Photogrammetric Image Processing

Prior to processing, the aerial images were georeferenced using the flight information. These images were reviewed before being loaded into the processing software. Fortunately, all 358 photos of the Forg Castle were successfully loaded in high quality into Metashape software. Subsequently, the software detected the camera position and orientation for each image, and tie points were automatically identified and extracted. The photogrammetric processing of the acquired images was performed using Agisoft Metashape, version 2.2.1. This software is an advanced image-based 3D modeling package. The workflow for generating a 3D model from the images in the software is summarized in the following stages: image alignment, dense point cloud generation, and mesh creation.

After loading the images, the software begins the alignment stage by detecting and matching corresponding points in overlapping images. It then calculates and determines the camera's position for each exposure and refines the camera's calibration parameters. This process results in a sparse point cloud that illustrates the camera positions (Fig. 4). In the next stage, based on the estimated camera positions, the software generates a dense point cloud. Finally, based on the dense point cloud derived from the measurements taken from the surface of the imaged subject, it reconstructs a 3D polygonal mesh. By applying the texture extracted from the images onto this 3D mesh, a final 3D model with a realistic texture is achieved.

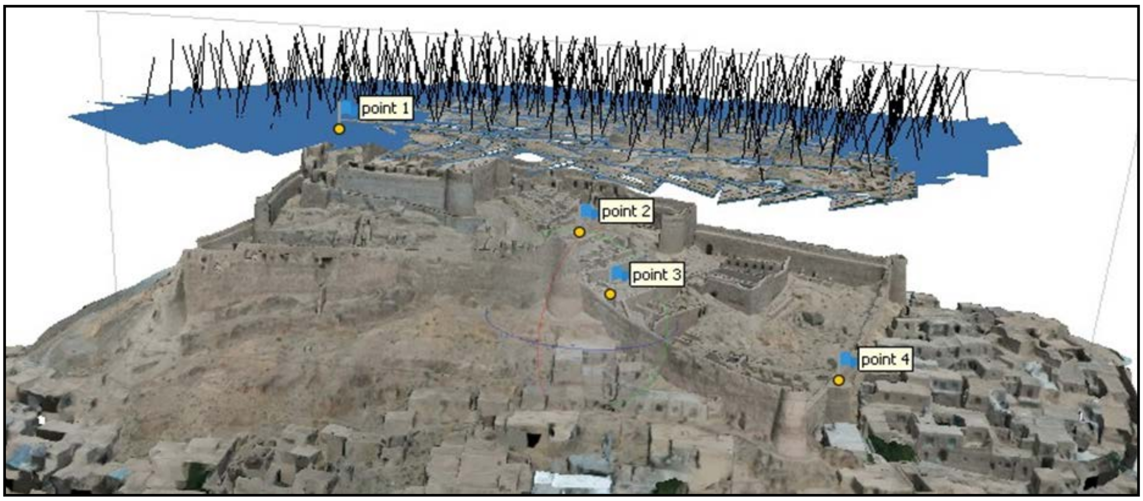

Fig. 4: Determining the location of aerial images and generating scattered sparse point clouds in the Forg castle (Authors, 2024).

6. Result

The accuracy of the resulting model for Forg castle is as follows, according to the tables below. For the Forg castle, four ground control points (GCPs) were utilized with a multi-frequency GPS (Fig. 5). These points were strategically placed to be readable both directly and from the 3D model (Fig. 6). The table displays the values that were read directly and those obtained from the

Table 2: Determining planar and elevation errors of Forg castle control points (Authors, 2024).

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
Point 1	-3.08213	0.714379	1.43184	3.47275	4.099 (14)
Point 2	4.16879	-5.19675	-1.13059	6.75746	0.913 (59)
Point 3	-0.612847	3.91492	-0.977236	4.08132	0.943 (56)
Point 4	-0.473791	0.567434	0.675988	1.00171	1.097 (74)
Total	**2.62099**	**3.28501**	**1.08862**	**4.34119**	**1.444**

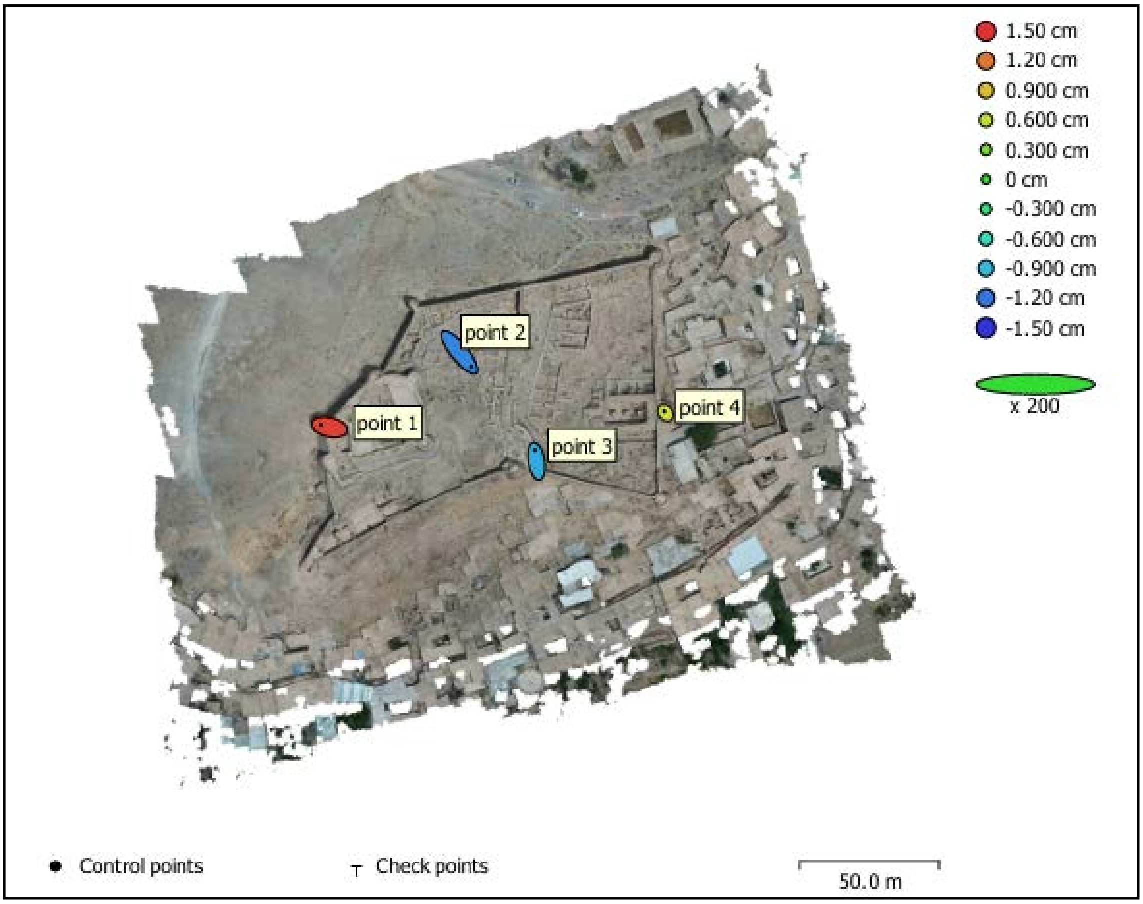

Fig. 5: Ground Control Points (GCP) locations and error estimates (Authors, 2024).

3D model (Table 2). As it can be observed, the error rates along the longitudinal (Y), transverse (X), and vertical (Z) axes are 3.28501, 2.62099, and 1.08862, respectively. In addition to the 3D model, a digital elevation model (DEM) was also obtained (Fig. 7). In figure 8, the details of the most important and highest part of the castle, namely the western section, are clearly visible (Fig. 8).

7. Disscusion

Documenting mountainous castles in 3D has always been more challenging than documenting

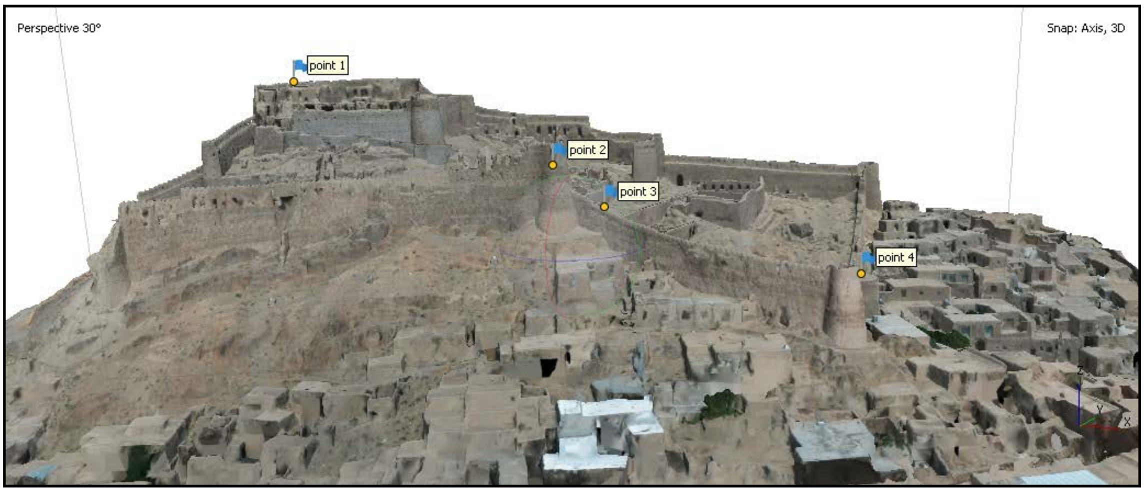

Fig. 6: Output of the 3D model of the Forg castle with real texture (Authors, 2024).

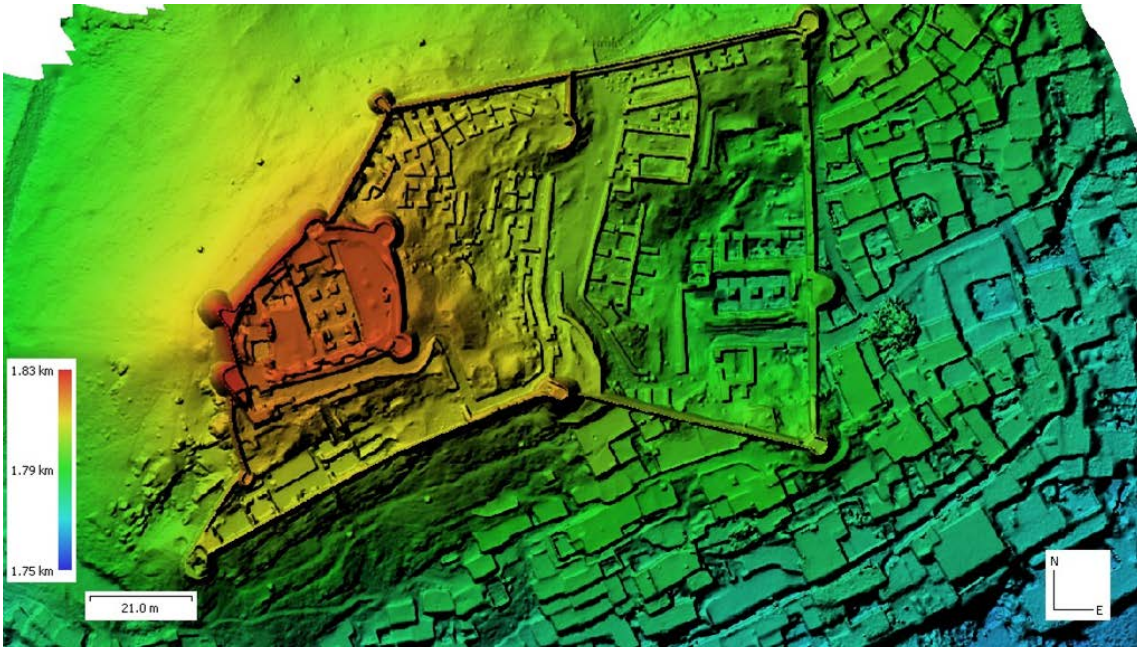

Fig. 7: Output of the Reconstructed digital elevation model (DEM), (Authors, 2024).

sites located on flat terrain due to their positioning on rugged mountainous landscapes and significant elevation differences. Additionally, because fortresses typically cover smaller areas compared to large-scale open archaeological sites, drone-based documentation activities can be somewhat restricted. For instance, in a site with considerable elevation variation, it is possible to set the drone's flight mode based on the area's DEM (Digital Elevation Model), allowing the drone to automatically adjust its altitude according to the site's topography without pilot intervention. However, this approach becomes difficult in smaller sites like the Forg mountainous castle which, despite having elevation differences and spanning about 9200 square meters, is located on a hilltop and includes towers and ramparts. Although flying based on the DEM would have been beneficial in such a terrain, the limited area of the site made this flight mode impractical. Therefore, the

Fig. 8: The highest part of the castle, located in the western section, is guarded by two watchtowers (Authors, 2024).

drone's flight was initiated from the center of the fortress, and a flight altitude of approximately 40 meters was chosen. In this documentation project, in addition to the four Ground Control Points (GCPs) discussed in the results section, three test points were also defined.

In addition to providing high accuracy in identifying the location of architectural structures, this 3D model can also be used to calculate the volume of archaeological excavations at the site of Forg castle. For example, the exact area of soil removal can be marked on the DSM models before and after excavation, allowing the software to calculate the volume of material removed (excavation) and, if applicable, the volume of material added (backfilling). Another important application of this 3D model of the castle is in analyzing damage caused by erosion and natural hazards over time.

To calculate the root mean square error (RMSE) in the X and Y directions, the following formula was used. The second formula is a simplified version of the first formula.Here, X_1 and Y_1 represent the model points, and X_2 and Y_2 correspond to the sample test points.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}} \qquad \text{a)}$$

$X_1 - X_2 = X$

$Y_1 - Y_2 = Y$

$\sqrt{X^2 + Y^2} = RMSE$

Table 3: Determining root mean square error (RMSE) of Forg castle (Authors, 2024).

Test Points	X error(cm)	Y error(cm)
Point1	2	3
Point2	6	3
Point3	6	6
Total	6/2 cm	

8. Conclusion

In this study, conducted to evaluate the capability of drones in the 3D modeling of the mountainous Forg Castle, a multi-rotor UAV was used to collect aerial data. The results demonstrate that, depending on the specifications of the equipment used and the flight altitude, drones can provide accurate metric documentation of mountainous castles with varying elevations. The generated 3D model successfully captured all geometric, spectral, and textural details of the site. The key advantages of this method include rapid, low-cost, and non-destructive data acquisition from complex, expansive sites with limited accessibility. In the case of Forg Castle, a 3D model was created using four control points and three test points, achieving a Ground Sampling Distance (GSD) of 0.97 cm. The model reached an accuracy of 4.34 cm at the control points, with a final overall accuracy of 6.2 cm. The castle, located in a natural mountainous setting with a 50-meter elevation difference between its highest and lowest points, was thoroughly documented and modeled in 3D. The model preserved the photorealistic texture of the castle, and precise dimensions of the construction materials, as well as all architectural angles, were accurately recorded. This study, which tested the use of UAV-based 3D photogrammetry in elevated mountainous environments such as this, concludes that the most effective way to minimize error in large areas with significant elevation differences is to fly the drone following a Digital Elevation Model (DEM) of the region. However, due to the relatively small size of the castle and the presence of high walls and towers, DEM-based flight was not feasible in this case. Instead, by setting a fixed flight altitude of 40 meters and starting from the center of the site, and by defining control points, the error could be reduced to an acceptable level. A limitation of the current study was in data acquisition across the site, which highlights the need to integrate this method with complementary technologies. The authors offer suggestions for improving future research, including the use of drones equipped with RTK/PPK technology to enhance the accuracy of 3D modeling and mapping. This approach is particularly well-suited for mountainous sites such as Forg. A data fusion approach can also be utilized. In this approach, data from various sources such as 3D laser scanning, aerial data, and ground-based surveys are combined to create a more accurate and comprehensive final model. In the data fusion approach, in addition to laser scanning, LiDAR data can also be used. LiDAR can provide more accurate elevations of rocky surfaces and castle walls, which is crucial for 3D modeling and structural change analysis. Furthermore, LiDAR can identify subsurface features, which complements the 3D photogrammetry process of the castle.However, in many areas of Iran, the use of LiDAR-equipped aircraft is prohibited, and researchers may face certain limitations. Therefore, the authors in this paper have adopted a cost-effective and relatively accurate method suitable for Iran.

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Conflict of Interest

Authors declared no conflict of interest.

Authors' Contribution

Conceptualization, Fereshte Azarkhordad and Hasan Hashemi Zarajabad.; methodology, Hasan Hashemi Zarajabad; software and modeling , Fereshte Azarkhordad . formal analysis, Fereshte Azarkhordad .investigation, Fereshte Azarkhordad , Hasan Hashemi Zarajabad.; resources, Fereshte Azarkhordad. data curation, Fereshte Azarkhordad.; writing original draft preparation, Fereshte Azarkhordad.; writing review and editing, Hasan Hashemi Zarajabad. All authors have read and agreed to the published version of the manuscript.

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مـطالعات باسـتان‌شـناسی
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مستندسازی و مدل‌سازی سه بُعدی قلاع کوهستانی با استفاده از فتوگرامتری با پهپاد مطالعۀ موردی: قلعۀ تاریخی فورگ

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چکیده

قلعه فورگ، ازجمله قلاع کوهستانی است که مربوط به دورۀ متأخر اسلامی (افشاریه تا قاجار) می‌باشد این قلعه به‌دلیل موقعیت استراتژیک و معماری منحصربه‌فرد همواره موردتوجه بوده و نیاز به مستندنگاری دقیق با استفاده از روش‌های نوین می‌باشد. فتوگرامتری پهپاد، یکی از روش‌های نوینی است که با پیشرفت تکنولوژی در دهه‌های اخیر در این زمره از مطالعات قرار گرفته است که به‌صورت منفرد یا در ترکیب با روش‌های دیگر، به‌طور گسترده‌ای در مدل‌سازی سه‌بُعدی میراث‌فرهنگی غیرمنقول و محوطه‌های باستان‌شناختی استفاده می‌شود. این فناوری، با استفاده از تصاویر دو بعدی، مدل‌های سه‌بُعدی دقیق و فتورئالیستی از آثار و محوطه‌های تاریخی تولید می‌کند. این نوع مستندنگاری جهت اقدامات حفاظتی و توسعۀ پایدار آن‌ها سودمند است. پژوهش کاربردی حاضر با هدف ارزیابی توانایی فتوگرامتری پهپاد در یک قلعۀ کوهستانی با اختلاف ارتفاع قابل‌توجه صورت گرفته است که به مدل‌سازی قلعه فورگ جهت مستندنگاری و تهیۀ نقشۀ سه‌بعدی پرداخته شد. این پژوهش در سه مرحلۀ میدانی، نرم‌افزاری و اسنادی و به روش تحلیلی انجام شده است که نتیجۀ آن ایجاد مدل سه‌بُعدی قلعه کوهستانی فورگ با بافت واقعی و اندازۀ نمونۀ زمینی (GSD) ۰/۹۷ سانتی‌متر بر پیکسل به‌دست آمد. در این پژوهش، ارزیابی نتایج تدقیق‌شده توسط چهار نقطۀ کنترل زمینی و سه نقطۀ آزمایشی، بیانگر عملکرد بالای فتوگرامتری پهپاد به‌عنوان روشی سریع در مستندنگاری و مدل‌سازی سه بُعدی قلاع کوهستانی با اختلاف ارتفاع در بستر کوه و آثار معماری آن‌ها با دقت زمینی ۲/۶ سانتی‌متر است.

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