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Creation of surface model using unmanned aerial vehicle (UAV) photogrammetry in cultural heritage areas: The example of Kilistra Ancient City

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Abstract

Historic buildings have been damaged by natural events and human hands for centuries. For this reason, the importance of studies on the preservation, documentation and restoration of historical buildings is increasing worldwide. In addition, technological opportunities are also becoming necessary for carrying out more comprehensive studies on the sustainability of historical buildings. Studies on modelling many cultural heritage (CH) works worldwide continue. Precise data about the structure must be obtained to evaluate these models in reconstruction studies. In parallel with technological developments, the measurement sensitivity of devices in this field has also increased. In addition, different technological tools that will assist in measurement activities are entering our lives daily. Unmanned Aerial Vehicle (UAV) systems are one of them. 3D data from UAVs and photogrammetric systems are sensitive data obtained quickly and cheaply. This data provides the opportunity to be used in interdisciplinary studies. This study investigates the use of UAVs in the digital documentation study of the Ancient City of Kilistra in Konya/Gökyurt. The study showed that UAVs are more practical and effective than traditional measurement techniques. It has been revealed that, if appropriate conditions are provided, UAVs can be a suitable alternative in terms of time and cost in documenting CH sites. Finally, it has been determined that the high-resolution digital maps obtained not only speed up the process of documenting large areas but also provide advantages in accuracy and precision.

1. Introduction

CH is commonly defined as the collective bond shared by communities [1]. Another definition described CH as the tangible and intangible cultural artefacts created by previous generations and passed down through generations [2]. In this sense, CH can connect the "past, present, and future" [3]. The 1972 Convention for the Protection of the World Cultural and Natural Heritage, organized by UNESCO in Paris, addressed CH in terms of both tangible and intangible cultural values [4]. This convention specifies that tangible CH includes monuments, groups of buildings, and sites [5]. Similarly, the Convention for the Protection of the Archaeological Heritage of Europe [6] recognizes all ruins, assets, and other traces of human existence found in various locations as elements of the archaeological heritage [7]. Therefore, CH encompasses structures, constructions, architectural groups, designated protected areas, movable assets, and other types of monuments and their surroundings, whether on land or underwater.

CH are all kinds of tangible and intangible assets with local and universal values that have survived to the present day and identify a nation's past life and social environment [8]. With the establishment of national states in the last century, preserving, displaying and passing on the traces of the knowledge of the past to future generations has become widespread worldwide [9]. International agreements have made the permanent identification, discovery, protection and sustainability of cultural assets and historical artefacts. The decisions of these agreements are sometimes advisory or sometimes mandatory for countries. The 1954 Hague Convention preamble stated that "any violation against cultural monuments, regardless of which nation they belong to, will be considered a violation against the cultural property of all humanity." Similarly, in the preamble of the 1972 UNESCO World Heritage Convention, it is stated that "the deterioration or destruction of any part of the cultural and natural heritage constitutes a harmful impoverishment of the heritage of all the nations of the world and that participation in the protection of the cultural and natural heritage is the duty of the entire international community" [10].

CH is constantly damaged by both human hands (urbanization, industrialization, agricultural activities, etc.) and natural conditions [11]. With the sustainability of CH, it aims to bring a scientific approach at international standards to the restoration, reuse, protection, arrangement, operation and management of historical settlements, protected areas, archaeological sites and museums that have tourism value [12]. The most critical challenge to overcome in CH's sustainability is that tourism and CH have different priorities and structures [13]. While tourism deals with the marketing-oriented economic benefits of cultural heritage [2], CH deals with long-term preservation [14]. Therefore, the most important thing to do is to achieve a balance between these two concepts. While developing the tourism function in CH areas, as in all areas that need to be protected, management planning, adequate protection of the areas and a precise determination of how this planning can be carried out are essential [2]. Otherwise, it should be considered that the historical environment may be irreversibly damaged [73].

Türkiye is one of the leading countries in the world in terms of CH [15]. Türkiye's CH includes the wealthiest and most diverse sites and works among European countries. Artefacts belonging to many civilizations, from the Hittites to the Byzantines, have been meticulously preserved during the thousand-year Turkish history of Anatolia. Today, many excavations, conservation, restoration and exhibition works continue. However, the failure to effectively prepare the CH inventory and surveys in Türkiye and incorrect practices in the current restoration, documentation and restitution works cause further destruction of the tangible heritage intended to be improved [16]. In short, the rich CH in Türkiye is in danger of not being transferred to future generations due to inadequacies in field studies, incorrect practices in existing studies, and lack of documentation.

Among the causes of deterioration of CH, apart from internal reasons arising from the structure itself, environmental factors are also included [17]. Historical walls, towers and monuments, which constitute a large part of the tangible CH in the world, undergo various deformations over time because they are made of stone material. It is seen that stone structures are subject to further deterioration due to the effect of increasing air pollution and changing climate conditions [18]. Today, the opportunities offered by the advanced photogrammetry technique have added different dimensions to documentation studies within the scope of sustainability.

Photogrammetry, offering a simple and cost-effective method to create three-dimensional (3D) data from two-dimensional images, is highly advantageous in CH documentation studies [19]. The ability to generate 3D data and models from images and analyze them in digital environments makes this technique particularly noteworthy [20-21]. Although photogrammetry has been around for many years, its importance in documentation studies has surged with the civilian availability of UAVs, thanks to the benefits they bring in aerial data collection [22-23]. UAVs provide significant advantages over traditional photogrammetric tools due to their advanced technological capabilities [24]. They have become a staple in CH and archaeological research, offering higher-resolution images than satellite imagery [12]. Their low-altitude imaging abilities [25] make them ideal for remote sensing of geospatial information [26, 75].

Moreover, UAVs are favored for surveying CH sites due to their affordability, reliability, and user-friendliness [27-28]. The integrated positioning systems in UAVs greatly facilitate photogrammetric processes, especially during internal orientation. Lo Brutto et al. [29] conducted studies at the Temple of Isis and Cretto of Gibellina archaeological sites in Italy to investigate the potential of UAVs in CH areas. The study results revealed that UAV technology provides higher-resolution images, offers more detail, and analyses faster than traditional methods in archaeological structures. Barba et al. [30] performed an accuracy assessment of 3D photogrammetric modelling of the Avella Roman Amphitheatre in Italy using a UAV. Şasi and Yakar [21] utilized UAVs for the 3D photogrammetric documentation of Sakahane Masjid, a site from the Anatolian Seljuk Empire period, obtaining precise and reliable data for restoring damage from potential natural disasters and physical wear. Tzvetkov [31] created 3D Models of many historical sites in Bulgaria using UAVs within the scope of the "Archaeological Map of Bulgaria" project. Bakirman et al. [32] explored ultralight UAVs in CH documentation, using the Ottoman period Otag-ı Humayun Palace as their study area. Their findings indicated that, under the right conditions, ultralight UAVs offer a fast, reliable, and cost-effective method for CH documentation. Orihuela and Molina-Fajardo [33] created a 3D model of Mondújar Castle, a medieval castle in Granada, Spain, using UAV photogrammetry. This study identified areas of CH that needed urgent intervention. Kanun [40] demonstrated in his study on UAVs in CH documentation that they provide significant advantages in terms of time [71], cost, and accuracy. Using UAV photogrammetry, Gasparini et al. [35] created 3D models of five archaeological sites from different ages in the Guadiato Valley in Córdoba, Spain. Thus, they identified anomalies in the archaeological sites and created the infrastructure for future planned archaeological interventions.

CH sites are important attractions for the tourism sector. However, these attractions also carry a great responsibility in terms of sustainability [74]. While CH sites are an essential part of tourism, the artefacts in these sites must be preserved and managed sustainably. Increasing visitor numbers is a natural and human factor that is putting pressure on the sustainability of CH areas. At this point, UAVs can be considered essential in managing and protecting CH areas. UAV photogrammetry is an effective method that can document and monitor resources in CH areas without damaging the ecosystem [36]. Although various documentation techniques are found in the literature, the photogrammetric method stands out from other techniques. With the integration of the recently popular UAVs in this field, significant improvements have been achieved in documenting large areas. In this study, the UAV photogrammetry technique has been applied to the documentation of CH of historical importance, covering a large area. At the end of the study, the advantages and disadvantages of the method are discussed, as well as the importance of CH documentation in terms of sustainability and tourism.

2. UAV Use in CH Areas, Legislation and Ethical Approach

The use of UAV is generally divided into two: civil and military. Those for civilian use are used in map production, archaeology, media, forestry, agriculture, nature observations, disasters [69], maritime, logistics, health, animal husbandry, meteorology, construction, public safety, etc. [24,37]. Archaeological applications mainly include mapping of CH sites and 3D modelling of artefacts, survey studies, and virtual reality and augmented reality studies [38]. CH sites' physical and cultural environment affects the location and distribution of settlements. At this point, UAV systems are a powerful analytical tool that reveals the relationship between the environment and settlements. One of the most essential advantages of using UAVs in protected areas, especially in CH areas, is that historical objects, places or spaces can be modelled without contact [39].

The Constitution of the Republic of Türkiye constitutes the basic principles of legal legislation in Türkiye. There is no direct or indirect provision in the Constitution of the Republic of Türkiye regarding using UAVs [40]. However, ethical violations that may occur with the use of UAVs are protected by the articles of the constitution that protect the privacy of private life, inviolability of the home, freedom of communication, and personal rights and freedoms. The fundamental law regarding aviation regulations in Türkiye is the Turkish Civil Aviation Act No. 2920, which came into force on 14 October 1983 [40-41]. The definition and characteristics of an “aircraft” are clearly stated in this law. According to Article 27 of the Law, all local and foreign actual and legal persons and public institutions and organizations that carry out civil aviation activities in Türkiye or abroad and that are resident abroad and provide services within the scope of civil aviation activities in Türkiye are subject to inspection and examination by the General Directorate of Civil Aviation [42]. In addition, according to Article 144 of the same law, the procedures and principles regarding the import, sale, licensing, registration and recording of civil UAV systems to be operated or used in Turkish airspace, airworthiness certification, qualifications to be sought in persons who will use the systems, granting of flight permits and air traffic services are determined by the General Directorate of Civil Aviation [42]. According to Article 18 of the General Directorate of Civil Aviation UAV Systems Instruction, it is prohibited to fly any class of UAV in the areas defined as areas subject to special permission (red) and listed below without conducting a risk analysis and obtaining permission from the General Directorate [43]:

a) Regardless of altitude, at airports less than 5 NM (9 km) from the edge of the nearest runway,

b) Regardless of altitude, navigation aids, heliports, helipads, air parks, sea/landing and take-off areas published on the General Directorate's official website, etc., within a 5 NM (9 km) radius area as the centre,

c) For flights above 400 ft,

d)Türkiye AIP ENR 5.1 section "Prohibited, Restricted and Dangerous Areas",

e) Around critical structures, facilities and assets such as military buildings and facilities, prisons, fuel depots and stations, weapon/cartridge factories and depots,

f) In areas declared with “notice to airman” (NOTAM),

According to Article 13(3) of the General Directorate of Civil Aviation UAV Systems Instruction, regardless of the class and registration status of the UAV, in exceptional cases, in areas subject to special permission (red) and areas subject to permission, it is mandatory to conduct a risk analysis that takes into account maintenance, pilot, insurance and collision risks with people/structures/other aircraft, and to determine the measures that will eliminate or reduce the identified risks. Examples of issues to be considered in risk analysis are as follows [43]:

a) UAV technical information

b) Area to be flown (crowded, very crowded, uncrowded area)

c) Purpose of usage

d) Pilot training and experience

e) Day, night and meteorological conditions

f) Maintenance status

g) Insurance

h) The situation of people and structures

g) Risk of collision with other aircraft

ı) Actions to be taken to eliminate/reduce identified risks

On the other hand, some issues that occupy the agenda regarding the use of UAVs are privacy and ethical concerns. Legal issues that may arise due to the surveillance and monitoring capabilities of UAVs bring up the issues of privacy and protection of personal data. Unauthorized collection and use of images or data obtained, especially by UAVs, may violate individuals' privacy rights. Many countries have conducted numerous legal and legislative studies regarding using UAVs in their airspace. However, the issues of privacy and ethical violations have not been addressed sufficiently in these studies [41]. According to Article 20(1) of the Constitution of the Republic of Türkiye, everyone has the right to demand respect for their private and family life [44]. Türkiye has also acceded to the Convention for the Protection of Individuals about Automatic Processing of Personal Data (ETS No. 108) of the European Convention on Human Rights, which stipulates that everyone must respect the right to private and family life, home and correspondence in 1981 [45]. It is seen that Article 134 of the Turkish Penal Code states that "anyone who violates the privacy of individuals shall be punished with imprisonment from six months to two years or a judicial fine." [41]. According to the same article, if privacy is violated by recording images or sounds, the lower limit of the penalty cannot be less than one year. Therefore, violations of ethics and privacy issues related to the use of UAVs are subject to penal sanctions by the mentioned legislation. In order to obtain the data required for this study, national and international civil aviation rules, flight regulations, privacy and ethical rules were observed during the UAV flights.

3. Method

In this study, the photogrammetry technique was chosen as the documentation method. UAV was used to collect photogrammetric data, and the study focused on the UAV photogrammetry technique. This part of the paper introduces the study area and describes the materials and data collection. Finally, the photogrammetry technique is discussed.

3.1. Study area

The ancient city of Kilistra, selected as the study area, is located southwest of Konya, Türkiye (Figure 1). Kilistra is about 34 km from Konya and is within the boundaries of Gökyurt village. As a result of the studies carried out in Kilistra, the settlement dates back to the 3rd century BC. In the ancient city, rock settlements were formed by carving Cappadocian-style rocks in the 7th century AD. The ancient city was believed to have been built by carving into the hills of natural volcanic rocks. The structures partially resemble the Cappadocian Fairy Chimneys and are similar to the ancient cities of Adıyaman Perre and Mardin Dara. The fact that the ruins in the ancient city of Kilistra are mostly churches and sanctuaries shows that it has a feature regarding religious settlement. It shows that most of the structures, such as churches, large water cisterns, monasteries, cross-pillar chapels (tombs), watchtowers, shelters and ancient roads in the settlement bear traces of the early Christian period and that there was intensive construction activity in this period. Because of these characteristics of the ancient city, it has been the subject of this research.

3.2. Material and data acquisition

Photogrammetry techniques are divided into terrestrial and aerial. Recently, UAV photogrammetry has emerged using UAVs for spatial data acquisition and mapping. This study used the Phantom 4 v2.0 for aerial data collection (Figure 2).

Figure 2. Phantom 4 UAV

This UAV has four rotating wings, enabling stable low-altitude flights that capture high spatial-resolution images. Its lightweight, versatility, and user-friendliness make it a popular choice among professional aerial photogrammetry users today [76]. Additionally, its 20-megapixel gimbal-mounted camera allows for image acquisition in challenging locations, which is crucial for mapping building facades beyond standard map production and hovering capabilities. The UAV is equipped with a multi-frequency, multi-constellation GNSS receiver capable of receiving GPS and GLONASS signals. The technical specifications of the UAV are provided in Table 1. A fully automated flight mission was designed to capture aerial photographs for the study.

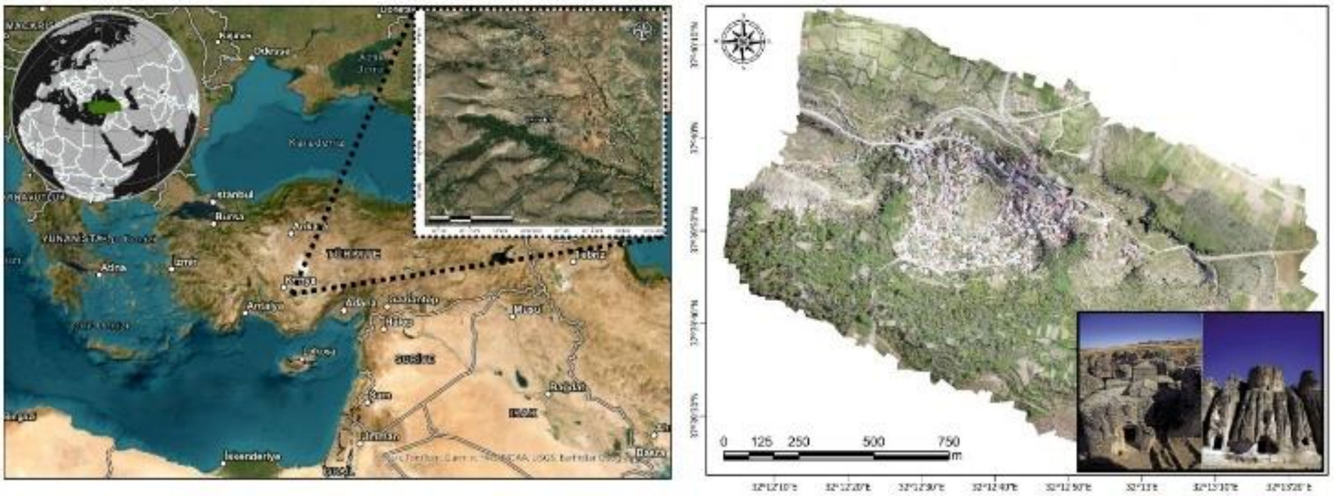

Figure 1. Study area general view of the ancient city of Kilistra.

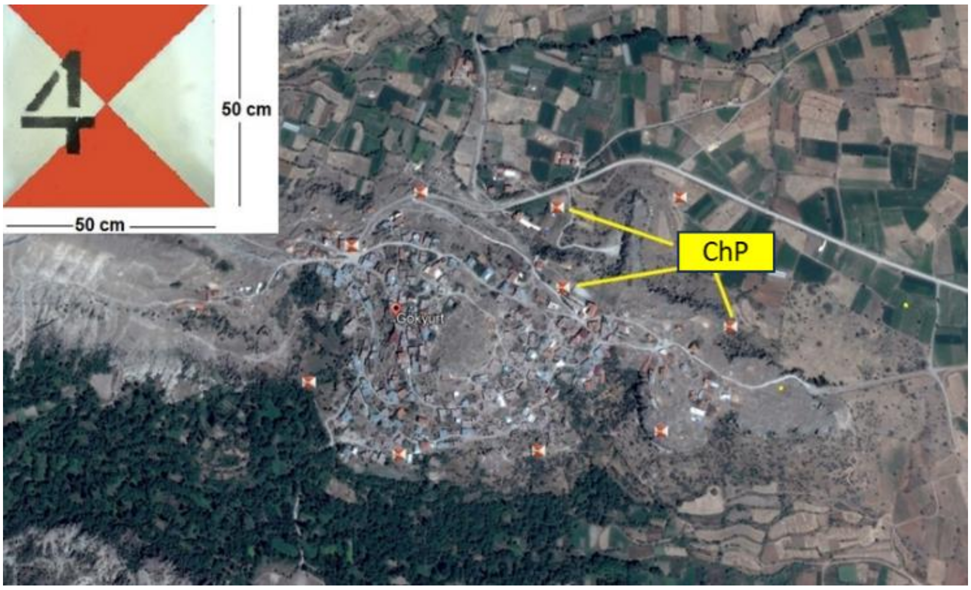

Figure 3. Distribution of ChP.

The DJI Phantom 4 pro v2.0 flight planning was done with Pix4D software, and six flights of about 15 minutes were made. One thousand two hundred eighty-six images were taken during the flight. The flight altitude was 150 meters (above ground level), and the ground sampling distance (GSD) was 4.11 cm/px. The longitudinal and transversal overlap ratios were 80 and 70 per cent. During the photogrammetric processing of the aerial photographs taken by the UAV, ground control points (GCPs) were installed on the terrain to aid in internal orientation to ensure accurate and precise scale and t Eighteen GCPs were placed in the terrain, paying particular attention to points that are homogeneously distributed in the terrain and where the roughness changes frequently. Out of these points, eight were used as GCPs for photogrammetric adjustment, and ten were used as checkpoints (ChP) for accuracy analysis. The distribution of ChPs used for accuracy analysis is shown in Figure 3.

Table 1. Technical specifications of the UAV used.

Specification	Value
Size	Diagonal 35 cm
Weight	1,375 kg (including camera)
Payload	-
Max flight time	30 minutes
Max speed	20 km s $^{-1}$, positioning mode 13 89 m s $^{-1}$
Max ascent speed	6 m s $^{-1}$, positioning mode, 5m s $^{-1}$
Rotors	4
Camera	Integrated 1” CMOS 20 Mp
Effective pixels	5,472 x 3.648 (20 MP)
Sensor size	Diagonal 1 inch
Image format	JPEG, DNG (RAW)

The target placed on the land was measured using GNSS, and the data were obtained using global coordinates. The measurement process was carried out using the CHC 180 GNSS/CORS device. A general view of the instrument and a sample measurement are shown in Figure 4.

Figure 4. GCP and ChP measurement.

3.3. Photogrammetry and SfM

Photogrammetry is a low-cost remote sensing technique that uses 2D image sequences and a triangulation algorithm to create 3D point clouds of objects [46, 67]. Because a single image cannot determine the 3D coordinates of a point, a point in a 2D image corresponds to all locations along the line of sight (ray) from the camera center to that point in the 3D scene [47]. Photogrammetry relies on the camera positions and external orientation parameters of overlapping images to determine the 3D coordinates of points on an object's surface. These external orientation parameters can be determined if at least three control points exist between overlapping images [48]. Although internal orientation parameters must be known in advance, self-calibration techniques, such as structure from motion (SfM), have eliminated this requirement with state-of-the-art algorithms [49]. Photogrammetric software based on the SfM algorithm has simplified 3D modelling and surface reconstruction from images taken by conventional cameras [50]. SfM, a photogrammetric method or algorithm, can resolve scene geometry, camera positions, and orientation without a predefined target mesh with known 3D locations [51]. The introduction of digital cameras, camcorders, and camera phones has increased the use of SfM, a measurement technique based on computer vision [11]. Due to its low cost, fast results, and simple 3D measurement capabilities, SfM has become widely used in scientific research and has had a transformative impact on geoscience research [52]. SfM generates 3D structures from overlapping image frames by identifying and matching standard features between overlapping images.

SfM operates on the same principles as stereoscopic photogrammetry. The main difference is that SfM automatically performs the calculations needed to obtain the correct position of a point in three-dimensional space, and perfect camera positioning is not required. Furthermore, video recordings can be used in SfM since changes in camera orientation do not affect the reconstruction of positions in space. Fonstad et al. [53] argue that SfM is advantageous in cost savings and ease of use. According to Carrivick et al. [54], the SfM workflow is significantly more automated, making it easier and more accessible than traditional photogrammetry. Gienko and Terry [55] stated that 3D models created with SfM can reliably and accurately represent natural objects, making the technology useful for fast and accurate evaluations [56]. Packet Block Adjustment is an engineering software that uses SfM to reduce projection errors between the snapshot and the expected point position. Built-in methods for automatically extracting common points between photographs to create a sparse point cloud form the basis of SfM software. The most widely used algorithm for this process is the scale-invariant feature transform (SIFT) technique, which operates on radiometric pixel values. The sparse point cloud produced by SfM is relative and must be corrected to actual dimensions using several known ground control points (GCPs or target marker data). Another step in SfM is generating a dense point cloud using the Dense Multi-View Stereo algorithm. In this step, the matched pixels and their estimated 3D positions become a point cloud that creates mesh models. Finally, the images are used to give the model a photorealistic mesh. In order to apply the SfM algorithm to the images captured by the UAV, the location characteristics and geo-tagging of the digital images are required. This is because the camera position derived from the SfM algorithm does not have the scale and orientation provided by the coordinates. Therefore, to accurately measure the GCPs as the fundamental ground truth, 8 GCP reference points and 10 ChP measurements were made to verify the position accuracy using a precision measuring device (e.g., Figure 4). These points were selected as control points and used in the accuracy analysis.

In the image acquisition phase, high-resolution images were obtained using the Phantom 4 Pro v2.0 UAV. The UAV, equipped with a 20-megapixel camera, captured images in JPEG format to ensure the highest possible quality and flexibility in post-processing. A flight plan was devised to attain the desired GSD. The flight altitude was 150 meters above ground level, resulting in a GSD of 4.11 cm/px. The longitudinal and transverse overlap ratios were set at 80% and 70%, respectively. The flights were conducted around noon to minimize the impact of shadows and ensure optimal lighting conditions.

All captured images were imported into the Pix4D project in the initial processing phase. Camera calibration was conducted using the internal library of Pix4D, employing the standard calibration method, which is suitable for use with the non-fisheye lens of the Phantom 4 Pro v2.0. To ensure comprehensive matching, the maximum number of keypoints per image was set to 40,000 for keypoint extraction and matching. The entire image scale was employed for keypoint extraction to ensure maximum detail and accuracy. The "Aerial Grid or Corridor" matching strategy, optimized for UAV-captured images, was selected in the initial alignment stage. The keypoint image scale was set to "Full" to capture the highest level of detail. The scene's complexity adjusted the requisite number of key points, ensuring robust alignment.

GCPs were strategically positioned throughout the study area, ensuring a uniform distribution and identifying locations where terrain roughness exhibits frequent fluctuations. A total of 18 GCPs were utilized, comprising 8 for photogrammetric adjustment and ten as ChPs for accuracy analysis. High-precision GNSS devices were employed to measure GCP coordinates to ensure accurate scaling and georeferencing.

The dense point cloud generation phase employed the Dense Multi-View Stereo (DMVS) algorithm. This phase entailed identifying and matching standard features between overlapping images, generating a point cloud that accurately represented the 3D structure of the study area. The dense point cloud was generated using optimal parameters, resulting in 239,064,363 points. The process required 15 hours and 17 minutes to complete. Subsequently, the dense point cloud was converted into a photorealistic three-dimensional model by applying texture mapping techniques. The original images were employed to provide a realistic and natural surface appearance. The final 3D model was generated using advanced algorithms to ensure high precision and detail.

Several parameters were considered in the phase of generating the DSM (Digital Surface Model) and orthomosaic. To ensure the generation of high-resolution surface models, the resolution of the DSM was set to match that of the GSD. In the case of the orthomosaic, the blending method was set to "Mosaic" to achieve seamless transitions. However, "Average" blending was also employed to balance exposure. The export resolution of the orthomosaic was set to match the original image GSD to maintain the highest quality output. To ensure accurate geospatial representation, the orthomosaic was exported in GeoTIFF format. In the final phase, 3D models were exported in widely used formats, including OBJ, FBX, and PLY, to ensure compatibility with various analysis and visualization tools.

Additionally, the orthomosaics were exported in GeoTIFF format with the resolution set to align with the project requirements, typically matching the original image GSD. By meticulously adjusting these parameters at each stage, high-quality and accurate photogrammetric outputs were ensured using Pix4D software. This approach enabled the comprehensive and dependable documentation of the ancient city of Kilistra, furnishing invaluable data for preserving and analysing cultural heritage.

3.4. Accuracy analysis

Accuracy analysis is the final step in measuring the accuracy and reliability of the study [46], and it could be performed using the root mean squared error (RMSE) method. In this method, the difference between two data of the same unit is identified (Equation 1), and the squared mean error is calculated by dividing the square of the difference by one minus the number of data and taking the square root (Equation 2) [66]. A small squared mean error value means the data are close and the measurement is sensitive. In this study, GNSS CORS data are accepted as the reference data.

$$\mathrm{V}_{\mathrm{x,y,}z\mathrm{,_i}} = X, Y, \mathrm{Z}_{\mathrm{GNSScors_i}} - X, Y, \mathrm{Z}_{\mathrm{UAV_i}} \tag{1}$$

$$RMSE_{\mathrm{x,y,z}} = \sqrt{\frac{[\mathrm{vv}]}{\mathrm{n}-1}} \tag{2}$$

4. Result and Discussion

The low-altitude flight capability of UAVs, combined with their advanced technical imaging systems, provides significantly higher resolution and more detailed information than satellite imagery and manned aircraft data. In today's UAV platforms, an integrated system has been created with the camera, automatic imaging module, and GNSS/IMU/RTK. Especially with the GNSS/IMU/RTK modules, the geographic coordinates (latitude, longitude, ellipsoidal height) can be collected instantly with the photographs taken, providing advantages in the photogrammetric processing. The orthophoto maps, orthomosaic maps and digital elevation models produced as a result of this technique have allowed the use of different tools to analyze and study the surface relief characteristics of the topography.

The main advantage of the photogrammetry technique used in documenting large CH sites such as the one in this study is that it can produce photorealistic models because it uses real photographs. The camera's resolution is essential when taking aerial photographs with a UAV. In addition, the most critical parameter in digital photogrammetry and SfM algorithm is the GSD. The GSD is the mean distance between two adjacent pixels in the image, corrected due to internal orientation in the photogrammetric process. Since this parameter depends on the resolution of the photosensor taking, it affects the flight altitude, i.e., the distance between the centroid projection and the target object, and is one of the most critical parameters. In UAV photogrammetry, as in aerial photogrammetry, flights should be made at noon (around 11:00 am) when the sun angle is steep to collect images with optimal quality and sensitivity and avoid shadow areas. The other most important point when creating a flight plan in UAV photogrammetry is flight planning. Two different types of flight plans that are most preferable in taking aerial photographs are known as grid and double grid. The grid flight type is generally used to save time for non-precision studies, while the double grid flight type is recommended for many photogrammetric studies. Finally, the angle from which the images are taken is essential for data collection [46-48]. In UAV photogrammetry, nadir images are generally taken, but oblique images can be taken for various purposes. With recent developments, highly equipped UAVs can take oblique and nadir images [52, 62, 65]. In this study, since the orthomosaic of the historic site will be created, nadir images were taken, as shown in Figure 5.

Figure 5. Aerial photograph taken with the sample UAV.

With the development of technology, the digital photogrammetric method is usually performed automatically using algorithms [57]. In digital photogrammetry, the SfM algorithm calculates the internal and external orientations and generates the final products. SfM is a photogrammetric algorithm that automatically solves the scene geometry, camera positions and orientation without requiring the prior definition of a target mesh with known 3D locations. The SfM algorithm uses a series of overlapping image frames to create a 3D structure. It works by finding and matching common points in overlapping photographs. SfM, a computer visualization-based measurement method, is an inexpensive method that has recently become popular through digital cameras, video cameras, or smartphones with cameras.

Before generating the sparse point cloud, the camera parameters were automatically incorporated from the software's internal library. The most optimal parameters were selected for the sparse point cloud. Additionally, the software recommended selecting the default settings for Tie and Key Point, which were 4000 and 40000, respectively. Software using SfM algorithms and methods first sorts and pre-balances the images and then creates sparse point clouds. This is done using algorithms that automatically find matching points between images. Another stage of SfM is the creation of dense point clouds. The algorithm used in this stage is the DMVS algorithm. In the dense point cloud generation process, point clouds are generated by estimating the pixels to be mapped and their virtual 3D locations (Figure 6). 239,064,363 points were generated from the study area, and it took 15 hours and 17 minutes to generate the dense point cloud.

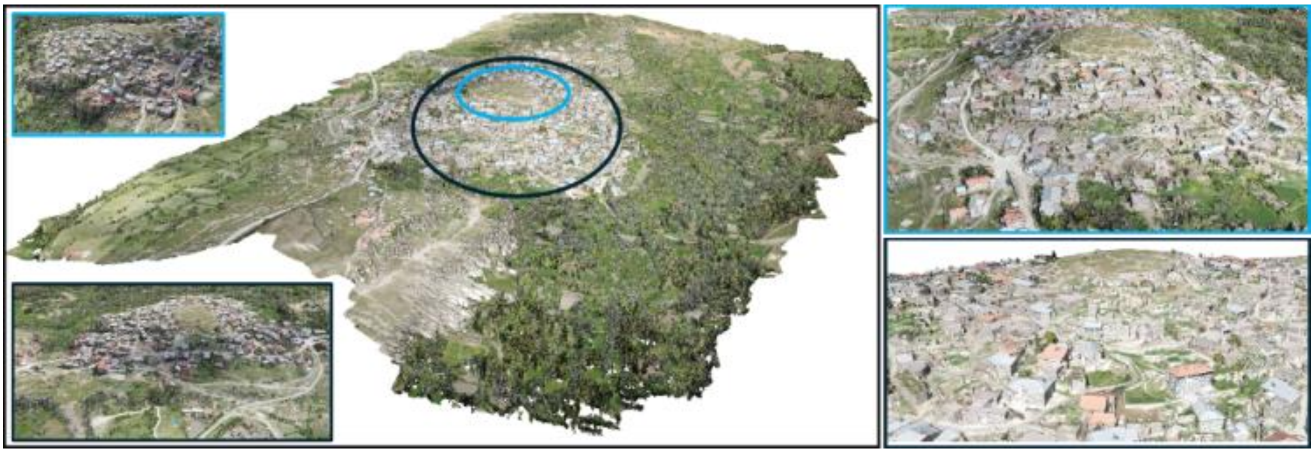

Figure 6. Point cloud of the study area.

Figure 7. 3D model of the study area.

The final step is to obtain a photorealistic 3D model by using the image to give the model created in virtual space a realistic and natural surface (Figure 7). The ability to simultaneously solve camera parameters and surface point locations for multiple overlapping images, especially with bundle adjustment algorithms, has significantly contributed to the process. The MVS algorithm has been widely used to improve model resolution with extensive point extraction. In addition, SfM/MVS technology has become increasingly popular, especially in the 3D modelling of objects such as cartography, archaeology and architecture, landscapes, rooms in monuments, and pottery, with its success in producing 3D models with Red-Green-Blue (RGB) textures.

Some studies have reported that the accuracy of 3D models produced by SfM/MVS technology is comparable to laser scanning, with some exceptions for relatively large objects. The image acquisition process is a critical technical issue in applications using SfM/MVS technology. The success of SfM/MVS depends on the quality of the photographs taken; poor coverage of the focal object or low-quality photographs can significantly reduce the accuracy of a 3D model. This method is typically performed automatically using algorithms. The SfM algorithm is a photogrammetric technique determining the calibration parameters needed for internal orientation elements through self-calibration. To create 3D geometry, two or more overlapping images are required. Height information can be determined by knowing the orientation of the images based on the cross-correlation between two or more overlapping images of the same object. Repeating this process for every image pixel creates a 3D point cloud. One advantage of using dense image matching over LiDAR for generating point cloud data is that colour attributes are automatically stored within the points, providing a photorealistic representation of reality in geometry and RGB values. The SfM algorithm also reduces costs in the product manufacturing process and speeds up the photogrammetric process, making it a popular choice, especially in research, for producing 3D models. In the SfM algorithm, sequential and overlapping images (with common areas between consecutive images) are required for the 3D reconstruction of a scene. Overlapping images enable the identification and matching of common points, allowing for digital reproduction of the scene.

The process begins by estimating the 3D structure from two images and determining their camera poses. Additional camera poses are then sequentially added, and the new 3D structure is updated as more of the scene is observed. Block balancing is performed repeatedly as more cameras are added to ensure high-quality reconstructions and prevent drift. SfM follows a general procedure to filter out outliers and estimate camera poses or structures from successive images. Although camera self-calibration significantly improves the performance of the SfM algorithm, pre-calibration is sometimes necessary for optimal results. Most modern digital photogrammetric software includes algorithms that automatically estimate the internal orientation parameters of cameras using a self-calibration technique [58]. At this stage, the relative poses are determined by estimating the camera positions and the absolute orientation of the cameras in the given images. Triangulation then computes the 3D position of an image coordinate tracked through two or more images. All cameras with estimated poses are used to estimate the 3D point of a track, and block balancing adjusts the track of the tie points after the initial estimate while keeping all camera parameters constant. To triangulate features accurately, there must be a sufficient baseline between the cameras relative to the point's depth. Points with excessive depth and a small baseline are highly inaccurate. For successful estimation, at least one pair of cameras must have a sufficient field of view for the estimated path. The poses are the (potentially calibrated) positions of the two cameras, and the points are the 2D image points of the matching features used to triangulate the 3D point. Triangulation is achieved by finding the closest point between two rays, with the ray origins being the camera positions and the directions being the ray directions of the features in 3D space. Although this method is less efficient in minimizing the re-projection error, it is about ten times faster than other triangulation methods. All cameras and 3D points are optimized through nonlinear optimization to minimize the re-projection error. View pairs containing the relative poses between matching geometrically validated views are computed, along with the cameras' previously estimated global (absolute) orientations. Camera positions are then estimated using specific strategies and implementations determined by the derived classes. The main goal is to sort the images and build a preliminary model.

After the orientation process, new workflows are defined for creating digital products such as dense point clouds and 3D models. In the pre-equalization stage, the highest setting was selected to obtain more accurate camera position estimates for all objects. Lower accuracy settings can be used to obtain coarse camera positions more quickly. At the highest accuracy setting, the software uses full-size images; the medium setting downscales the image by a factor of 4 (2 times on each side); the low accuracy setting downscales the source files by a factor of 16; and the lowest value means four times more downscaling. Since anchor point locations are estimated based on feature points in the source images, enlarging a source image may help accurately locate an anchor point. However, the Highest Accuracy setting is recommended only for very sharp image data and is mainly used for research purposes due to the time-consuming processing involved. Additionally, the Highest setting will match images with the most negligible overlap, while the other settings will not match images with less overlap and will not generate points from unmatched images. In photogrammetric evaluation, the software settings are as crucial as the quality of the photographs [59].

In all SfM algorithm-based software used in the photogrammetric process, the key point and anchor point limits are essential during the pre-compensation and internal orientation stage. The number of key points indicates the upper limit of feature points in each image to be considered during the current processing stage. Setting this value to zero ensures that as many key points as possible are found but may result in many less reliable points. The anchor point count indicates the upper limit of matching points for each image, while setting it to zero disables any anchor point filtering. After this stage, the model should be scaled using ground control points (GCP) to scale and georeference the model once the sparse point cloud has been created. Next, the parameters should be adjusted to produce a dense point cloud. The most critical parameter for dense point cloud generation is the depth map, which determines the desired quality of the data. Higher-quality settings yield more detailed and accurate geometry but require longer processing times. The interpretation of quality parameters here is similar to the accuracy settings in the Image Alignment section. The difference is that in this case, the Ultra High-Quality setting means processing the original images, while each subsequent step involves reducing the pre-image size by a factor of 4 (2 times on each side). Once the dense point cloud is created, a Triangulated Irregular Network (TIN) is generated, a digital tool for representing surface morphology. The TIN creates non-overlapping triangular surfaces with contiguous edges and can be used to capture the location of linear features that play an essential role on a surface, such as ridge lines or flow paths. From the solid model (Figure 8) and dense point clouds (Figure 6), elevation maps and orthomosaic maps (Figure 9) can be created.

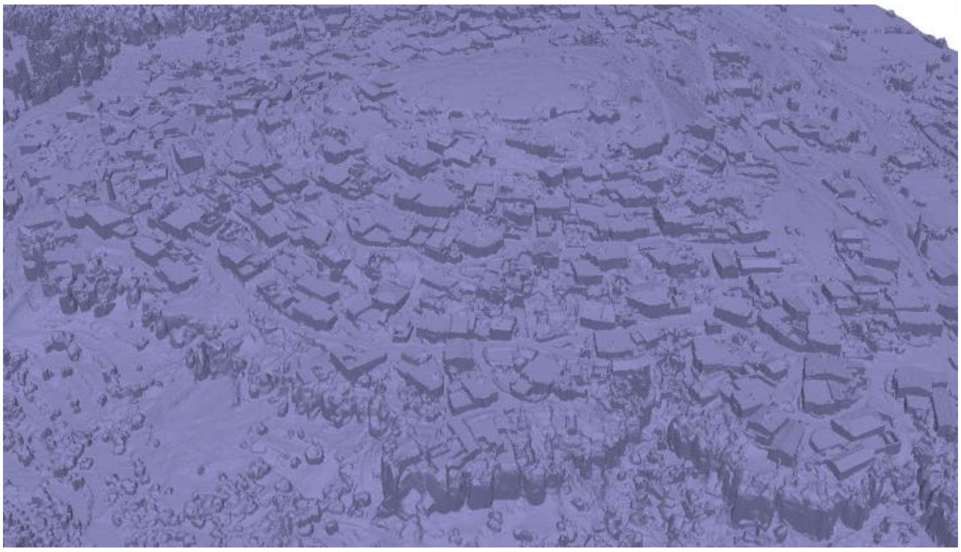

Figure 8. TIN and Solid model of the study area.

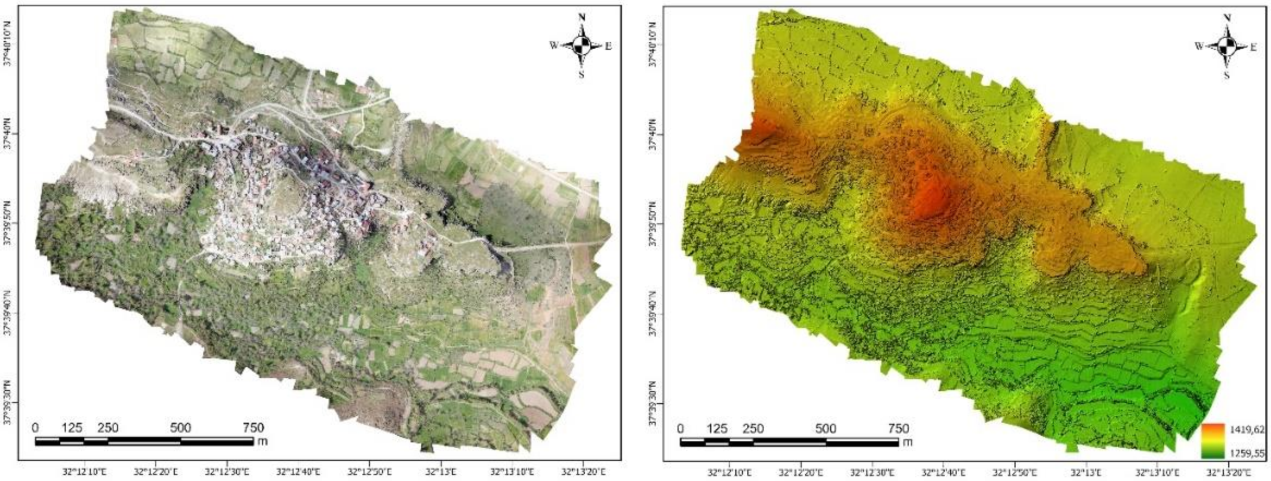

Figure 9. Orthomosic (left) and DEM (right) of the study area.

In order to georeference the final products produced by the photogrammetric method, it is necessary to make detailed measurements of the terrain. Another reason for this process is that the products produced by different methods should be used in the same coordinate system. For this reason, target marks, i.e. GCPs, should be installed at the appropriate points of the study area in a homogeneous distribution. In addition, ChP should be installed to analyze the accuracy of the products generated from the UAV data. In the distribution of GCP and ChP, care should be taken to select locations where the slope and elevation change so that the distance between each point does not exceed 250 meters. To determine the geographic position, ellipsoidal heights and global coordinates of these points, measurements should be made with the CORS GNSS instrument. To increase accuracy, an RTK network should be established. All target marks should be measured at least 30 epochs (each epoch is 1 second), two times at least 1 hour apart. Depending on the study area's hilly terrain and vegetation cover, the time required to establish GCP and ChP will vary. The accuracy analysis using GNSS data as reference and ChP coordinates obtained from UAV data is shown in Table 2.

The analysis of UAV data reveals that UAV photogrammetry yields highly accurate spatial data, which is vital for documenting and preserving cultural heritage sites. The low RMSE values indicate the precision with which UAVs can capture detailed measurements, thereby establishing their viability as an alternative to traditional methods. The deployment of UAVs in the Kilistra Ancient City has demonstrated notable enhancements in the efficiency and cost-effectiveness of documentation procedures. UAVs can rapidly capture high-resolution images [68], enabling the coverage of expansive areas that would otherwise be time-consuming and costly using traditional methods. Furthermore, incorporating GNSS with UAVs enables precise georeferencing, thereby augmenting the dependability of the spatial data obtained. This capability is of particular significance in the context of cultural heritage documentation, where accuracy is paramount for preserving historical sites. The comprehensive statistical analysis presented above reinforces the validity of our conclusions regarding the effectiveness of UAVs in cultural heritage documentation. UAV photogrammetry offers a practical and cost-effective solution while ensuring high accuracy and reliability, thus making it an essential tool in modern documentation practices.

In conclusion, the statistical analysis of UAV data corroborates UAV photogrammetry's high accuracy and effectiveness in cultural heritage documentation [70]. The low RMSE values and the capacity to rapidly obtain high-resolution images render UAVs a more effective alternative to conventional techniques. These findings highlight the necessity of incorporating advanced UAV technologies into the preservation and documentation of cultural heritage sites.

Table 2. Accuracy analysis using GNSS and UAV coordinate data from my ChP point data.

Point Number	**Vx (cm)**	**Vy (cm)**	**Vz (cm)**	**VxVx (cm^2)**	**VyVy (cm^2)**	**VzVz (cm^2)**
1	-2,32	1,40	2,69	5,39	1,95	7,24
2	1,42	2,70	3,95	2,02	7,29	15,62
3	2,40	-1,89	1,65	5,77	3,59	2,71
4	-1,62	1,06	4,26	2,64	1,13	18,13
5	2,73	-0,13	1,94	7,44	0,02	3,76
6	1,32	0,44	-2,12	1,75	0,20	4,48
7	-2,85	2,19	-2,21	8,10	4,81	4,88
8	2,32	1,69	-4,13	5,39	2,85	17,02
9	1,33	-2,95	-3,49	1,78	8,71	12,19
10	1,67	3,22	-0,72	2,78	10,39	0,52
$m_{x,y,z}$				43,06	40,94	86,54
$RMSE_{x,y,z\ (cm)}$				2,19	2,13	3,10

5. Conclusion

Initially developed for military applications, UAVs have become widely used in many civilian applications. One of the civil applications where UAV photogrammetry is widely used is the studies carried out in CH areas. The most important reasons for this are the low cost of UAVs, research speed, ability to map inaccessible areas, providing higher resolution images, etc. [29].

This paper applies various 3D models and orthophotos to the CH structure, enabling different applications and operations to be performed on these models. For instance, elements and structures of the CH area can be modelled to create 3D models from point clouds. Following this line of research, UAV photogrammetric surveys applied to CH play a fundamental role in managing, evaluating, and conserving historical-architectural heritage. Applying SfM-MVS algorithms to images acquired by UAVs is an excellent combination for creating accurate and detailed 3D models. Indeed, UAV photogrammetry for representing CH is a rapidly growing field, as evidenced by the increasing number of articles in various databases[72]. UAV photogrammetry has become more prevalent in CH applications in recent years, and this study demonstrates that 3D models created with UAV imagery and its orthomosaic quality can be used with superior specifications, especially in the CH field. The study shows that 3D technology should be accepted as foundational data for various purposes in a process-oriented manner in large CH areas.

The main advantage of using UAVs in the 3D modelling of CH sites is that accuracy is relatively high with the development of technology. The point cloud, orthomosaic, elevation map, and 3D model produced by this study were realized much shorter and at a lower cost than conventional field studies. This result supports many literature studies [32, 34, 60]. In addition, studies are showing that UAVs can be advantageous in small areas [61, 62, 63] while creating disadvantages in large areas and border regions when producing photogrammetric maps in cultural heritage areas [64]. The most critical parameter affecting positional accuracy in UAV photogrammetry is the sufficient number of GCPs installed homogeneously in the study area.

Similarly, other critical parameters affecting accuracy include flight altitude, camera resolution, and sensor size. Achieving high-quality photogrammetric output requires thorough pre-flight planning. This planning should optimally determine the flight route and altitude, the overlap ratios of the photographs, and the placement of ground control points according to the project's purpose. Additionally, an accuracy analysis must be performed at the end of the photogrammetric evaluation to ensure that mean squared error rates are acceptable. In our study, analyzing Table 2 showed that the errors were relatively low and acceptable for large heritage sites. Consequently, this study highlights the significant role of UAVs and the software used to document historical artefacts. The digital data obtained from the 3D study can also be used in other engineering fields, such as excavation studies, architectural restoration, and landscape planning.

Conflicts of interest

The author declare no conflicts of interest.

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