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Utilization of unmanned aerial vehicles for the detection and localization of deteriorations in historical structures: a case study of Ishak Pasha Palace

Emirhan Özdemir [*1], Rüştü Çallı [1], Selim Kartal [1]

[1] *Iğdır University, Vocational School of Higher Education for Technical Sciences, Iğdır, Turkey, emirhan.ozdemir@igdir.edu.tr, rustu.calli@igdir.edu.tr, selim.kartal@igdir.edu.tr*

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Abstract

The historical structures are one of the cornerstones of cultural heritage, shedding light on humanity's past. With their artistic and architectural values, they serve as significant monuments reflecting the lifestyles, beliefs, and technological advancements of past civilizations. Therefore, the aim of this study is to identify and document the deteriorations occurred after the restoration of Ishak Pasha Palace located in the Doğubayazıt district of Ağrı province, using a UAV (Unmanned Aerial Vehicle) obtained 3D model and orthophotos. Within the scope of the study, three main types of deterioration arising from physical, chemical, and biological effects on Ishak Pasha Palace were investigated using the 3D model. As a result of the research, deformations such as crystallization, formation of plant and formation of moss were generally observed on the side walls of the historical building, while deformations such as missing part, surface contamination, metal corrosion formation and lichen formation were observed in the interior walls and roof parts of the building. Subsequently, all obtained results were visualized in detail. Identification of these types of deterioration is crucial for the preservation and restoration of historical structures, enabling appropriate interventions to be made. Regular maintenance and conservation of architectural structures are of critical importance in the transmission of cultural heritage to future generations. Ultimately, it is believed that this study will contribute to the widespread adoption of UAV usage in the detection of deteriorations observed in historical structures.

1. Introduction

Historical structures constitute significant monuments that shed light on humanity's past, forming an essential part of cultural heritage. Typically valued for their artistic and architectural merits, these structures reflect the lifestyles, beliefs, and technological achievements of various civilizations throughout history. Historical structures not only serve as physical remnants of the past but also have the potential to illuminate the social, political, and economic conditions of their respective eras. Spanning from ancient times to the present day, these structures offer a rich legacy in cultural and historical contexts. Therefore, the detailed examination and preservation of historical structures are paramount for their transmission to future generations [1].

Historical structures are vital elements for the culture, history, and landscape of a place, requiring measures to ensure their preservation over time. However, environmental and human-induced factors lead to constant changes and pose significant risks [2]. Stone, the most commonly used material in historical structures, is threatened by deterioration processes due to various reasons [3]. Deteriorations observed in structure physics are primarily categorized into three main types: physical, chemical, and biological deteriorations. A review of the literature reveals similar perspectives [4-11]. Building upon this observation, the types of deterioration in structures are classified as shown in Table 1.

Table 1. Types of deterioration seen in structures

Physical Deterioration	Chemical Deterioration	Biological Deterioration
Crack-Fracture formation	Surface contamination	Formation of moss
Wear (Erosion) effect	Crystallization formation	Lichen formation
Missing part	Pitting	Formation of plant
Joint drain effect	Metal corrosion formation	Bioaccumulation

Failure to control and take preventive measures against deterioration in stones due to such factors can lead to small-scale deterioration evolving into large-scale deterioration over time, resulting in the loss of cultural traces in historical areas [12]. Since each type of deterioration requires a different repair method, classifying deteriorations according to their types will assist in a clearer understanding of the problem and in completely eliminating or reducing the effects of damage.

Currently, the most commonly used technique for the inspection of historical structures, damage detection, or evaluation of changes over time is visual inspection [13]. At this stage, trained personnel conduct inspections on the structure and determine the areas/sections of deterioration and the level of deterioration on the structure [14]. Subsequently, an action plan is developed. However, visual inspection techniques can be time-consuming and costly. In addition, limitations in access to critical points may also affect factors such as business continuity, efficiency or service quality.

With the advancement of technology today, the 3D modeling of cultural structures and documentation through these models, as well as inventorying, are generally accomplished through two different methods [15]. The first method involves active remote sensing techniques such as laser scanning or radar-based systems, while the second method involves passive/optical image-based modeling (photogrammetric, Structure from Motion (SfM) or computer vision methods) [16, 17].

Terrain-based scanning systems (TLS) can be considered a traditional and reliable scanning method, thanks to advancements in technology and computer graphics as well as their widespread use by practitioners and researchers [18-21]. TLS enables the generation of sufficient geometric data to obtain dense point clouds and facilitate facade modeling processes. The 3D point cloud data produced by this system are characterized by high precision and accuracy. However, the use of laser scanning techniques can become time-consuming due to factors such as station setup, device transfer, scanning duration, and excessive station setup to prevent shadowing [15]. Additionally, the high cost of this equipment hinders its use in small-budget projects [23]. When reviewing the literature, it is evident that there are numerous studies on point cloud and 3D model obtained with UAVs [24-31]. Particularly, studies on real-time deformation monitoring using UAV-based photogrammetric methods are prevalent [32, 33]. When UAVs are integrated into restoration works of historical buildings, they reveal many potential results and some challenges in terms of sustainable management and preservation of cultural heritage. UAVs equipped with high-resolution cameras can capture detailed imagery of structures, enabling a better understanding of their current condition and identification of restoration needs. This becomes a crucial step in preserving the delicate intricacies of historical buildings and ensuring their long-term sustainability. Additionally, UAVs can provide time and cost savings, expediting the restoration process. However, addressing technical challenges, data management and analysis, as well as issues of precision and accuracy, are imperative. Furthermore, considerations of legal and cultural constraints regarding the preservation of historical structures must be taken into account. Overcoming these challenges necessitates adequate training, technical skills, and collaboration. Compared to TLS, the use of UAVs offers advantages such as lower cost, faster data collection, and, most importantly, better representation of reality with the use of textures in the 3D model [34-36].

In parallel with the technological advancements over the past decade, remote sensing technologies have been effectively utilized in various fields. In this context, the objective of this study is to identify and document the deteriorations occurring after the restoration of Ishak Pasha Palace located in the Doğubayazıt district of Ağrı province, using UAV-obtained 3D models and orthophotos. This endeavor is anticipated to contribute to the detection and repair of material deterioration issues in historical structures, both pre- and post-restoration, for the sustainable management of regional structures. The study begins by providing information on the historical significance and spatial condition of Ishak Pasha Palace, followed by an explanation of how the building's 3D model and orthophotos were obtained using UAV photogrammetry. The findings section encompasses the detection of deteriorations in the historical structure via the 3D model, while the conclusion provides intervention suggestions for repairing the identified deteriorations and preventing the recurrence of similar issues in the future.

2. Material and Methods

2.1. Study area and historic information

Ishak Pasha Palace, located in the district of Doğubayazıt in Ağrı province, is one of Turkey's most significant historical and cultural structures. The palace was constructed during the 17th century under the rule of the Ottoman Empire. The construction of Ishak Pasha Palace was initiated by Ishak Pasha, who served as the governor of the region at that time [37]. However, completing the palace took a considerable amount of time, and it was finished by his son, Mehmed II, after

Ishak Pasha's death. The construction of the palace incorporates influences from Ottoman, Iranian, Seljuk, and Armenian architecture. With these characteristics, Ishak Pasha Palace is considered an example of cultural interaction.

Geographically, Ishak Pasha Palace is situated approximately 5 kilometers southeast of the urban center of Doğubayazıt, on a dominant hill overlooking the city. The palace is located near the foothills of Mount Ararat and close to the border with Iran (Figure 1). This strategic location contributes to the significance of the palace both architecturally and historically. Ishak Pasha Palace is preserved today as an important historical and cultural heritage site, attracting tourists and researchers alike.

Ishak Pasha Palace has been able to survive to the present day through various repairs since the 1950s. The repairs carried out on the structure can be categorized into periods before 1993, between 1993 and 1996, and after 2006 (Figure 2). The post-restoration condition of this historical structure has been selected as the focus area for the preservation of the structure and for the detection of potential damage that may occur in future periods due to renovations or deteriorations, along with the measures to be taken.

Figure 1. Ishak Pasha Palace location map

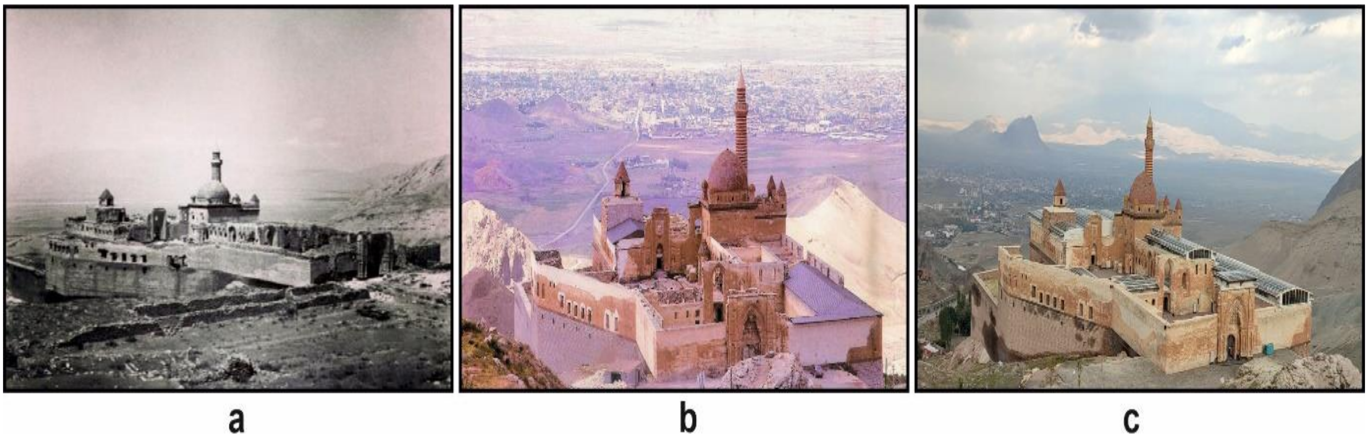

Figure 2. Ishak Pasha Palace from past to present; a) before 1993, b) between 1993-1996 and c) after 2006

2.2. Software and hardware

In this study, the DJI Phantom 4 RTK unmanned aerial vehicle (UAV) was utilized for the generation of the 3D model of Ishak Pasha Palace, employing precise mapping and topographic surveys (Figure 3). This device is notable for its capability to provide centimeter-level accurate positioning by adopting real-time kinematic (RTK) systems. Equipped with an integrated camera featuring a 1-inch CMOS sensor and a resolution of 20 megapixels, it allows for the acquisition of high-quality images. With these features of the UAV used within the scope of the study, positional information of the deformed parts with cm precision can be obtained through the 3D model. Thus, changes in deformation over time can be detected positionally in addition to visual inspection. The technical specifications of the UAV are detailed in Table 2.

The Agisoft Metashape Demo Version was chosen for its user-friendly interface, facilitating the adjustment process of UAV-captured photographs and the generation of point clouds, 3D models, and orthophoto products for the study area.

Figure 3. DJI Phantom 4 RTK Unmanned Aerial Vehicle

Table 2. UAV technical specifications

Positioning System	
Operating frequency	2.400 GHz- 2.483 GHz (Europe, Japan, Korea) 5.725 GHz- 5.850 GHz (United States, China)
Accuracy Range	RTK is active and working properly: Vertical: ±0.1 horizontal: ±0.1 m RTK off Vertical: ±0.1 m (vision positioning); ±0.5m (GNSS positioning) Horizontal: ±0.3m (Vision positioning); ±1.5 m (GNSS positioning)
Camera	
Sensor	FOV 84°; 8.8mm / 24mm (35mm format equivalent: 24mm);
Lens	FOV 84°; 8.8mm / 24mm (35mm format equivalent: 24mm); f/2.8- f/11, autofocus, 1 m
Image Size Maximum	4864×3648(4:3);
Photo format	JPEG

2.3. Data acquisition

The data collection process within the scope of the study encompasses field inspection, flight planning, and capturing of photographs. When determining the flight plan, criteria such as environmental obstacles, lighting conditions, flight altitude, and camera resolution should be accurately identified and planned accordingly. In line with this, three different flight plans were designed for the study. In the first stage aiming to achieve better visibility of the side walls of the historical structure and inner courtyard sections in a three-dimensional model, photographs were taken with an oblique flight plan at a ground sample distance (GSD) of 1,17 cm/px from a height of 40 meters with gimbal camera angle of 60°, with a along the flight direction overlap of 80% and a side lap overlap of 70% (Figure 4a). In the second flight plan, Nadir photographs were taken from a height of 100 meters with a GSD of 2.74 cm/px, with 80% overlap in the direction of flight and 70% side lap overlap, to detect the historical building and surrounding objects (Figure 4b). The final flight involved the manual capture of photographs by the UAV operator in RTK mode, aiming to enhance the detailing of processing motifs and individual points (Figure 4c). The first two flights will be enough for the 3D model. However, during the last flight performed manually by the UAV operator, the photos were additionally taken. The reason why these photos were taken from a certain region is that there are more details on the historical structure in those regions than in other regions.

2.4. Data processing

During the data collection stage, a total of 1538 photographs were captured during the oblique photogrammetry flight, 405 photographs during the Nadir photogrammetry flight, and finally, 51 photographs during the manual flight. Following the fieldwork, these images captured by the UAV were inputted into the Agisoft Metashape Demo Version program, and the adjustment process commenced. In the first step, the calibration parameters of the photographs taken (focal length, shooting angle, etc.) and the position of each photograph in the world coordinate system were automatically determined from the metadata of the photographs by the software used. Then, photogrammetry calculations were made and a 3D point cloud was created from photographs taken from various perspectives (Figure 5a). This point cloud is created by matching similar features identified in each photograph, and the point density is calculated as approximately 112 per square meter (points/m^2). In the third step, the point cloud was densified, and relationships between the surfaces of points were established to create a 3D model (Figure 5b). In the last stage, the adjustment process was completed by obtaining an orthophoto of the study area with a spatial resolution of 1.94 cm/px (Figure 5c). As a result, an image-matching-based point cloud, 3D model, and orthophoto of Ishak Pasha Palace were obtained.

3. Results

Historical structures are subjected to various influences over many years. These influences often result in significant deteriorations, particularly on the materials used in the roofs, exterior walls, and facades of the structures. Deteriorations observed in building physics are broadly categorized into three main types: physical, chemical, and biological deteriorations. Among these deteriorations, those identified on four different facades of Ishak Pasha Palace have been visualized on the 3D model (Figures 6-9).

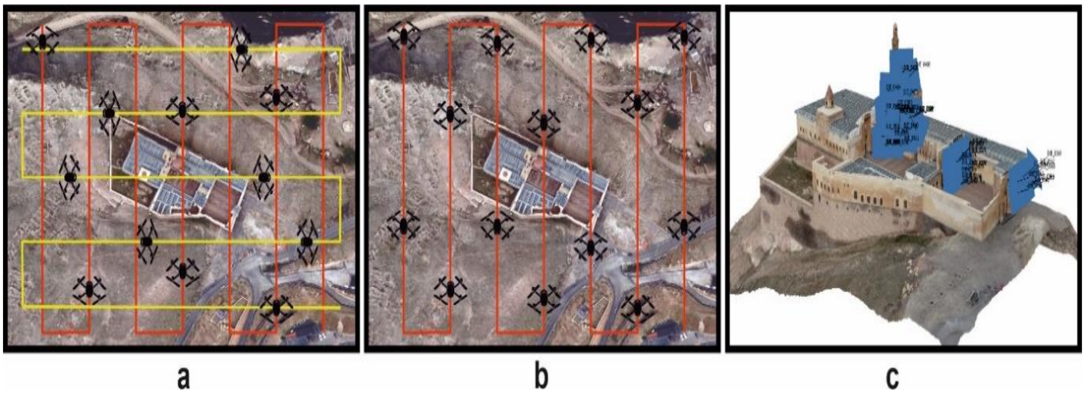

Figure 4. Flight plans; a) multi-orientation, b) 2D photogrammetry and c) manual photography

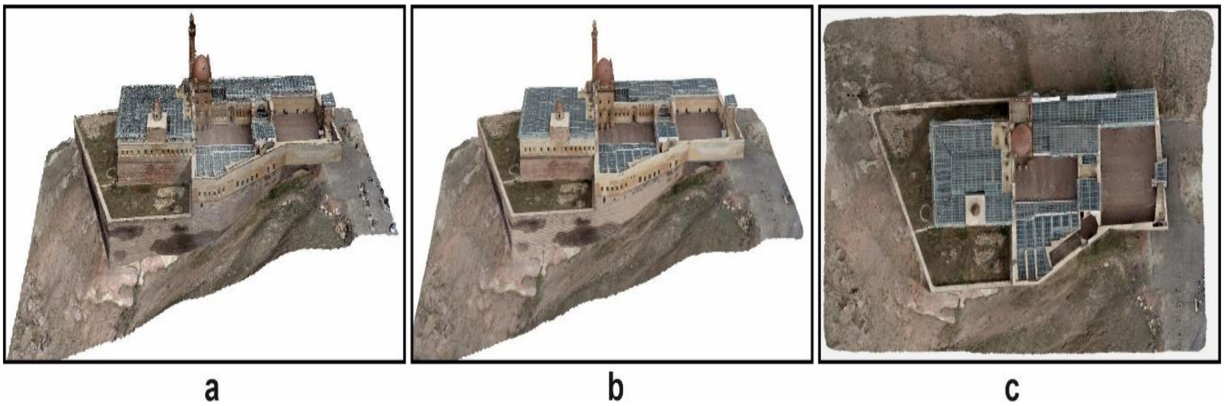

Figure 5. Ishak Pasha Palace photogrammetric adjustment process results; a) point cloud, b) 3D model and c) orthophoto

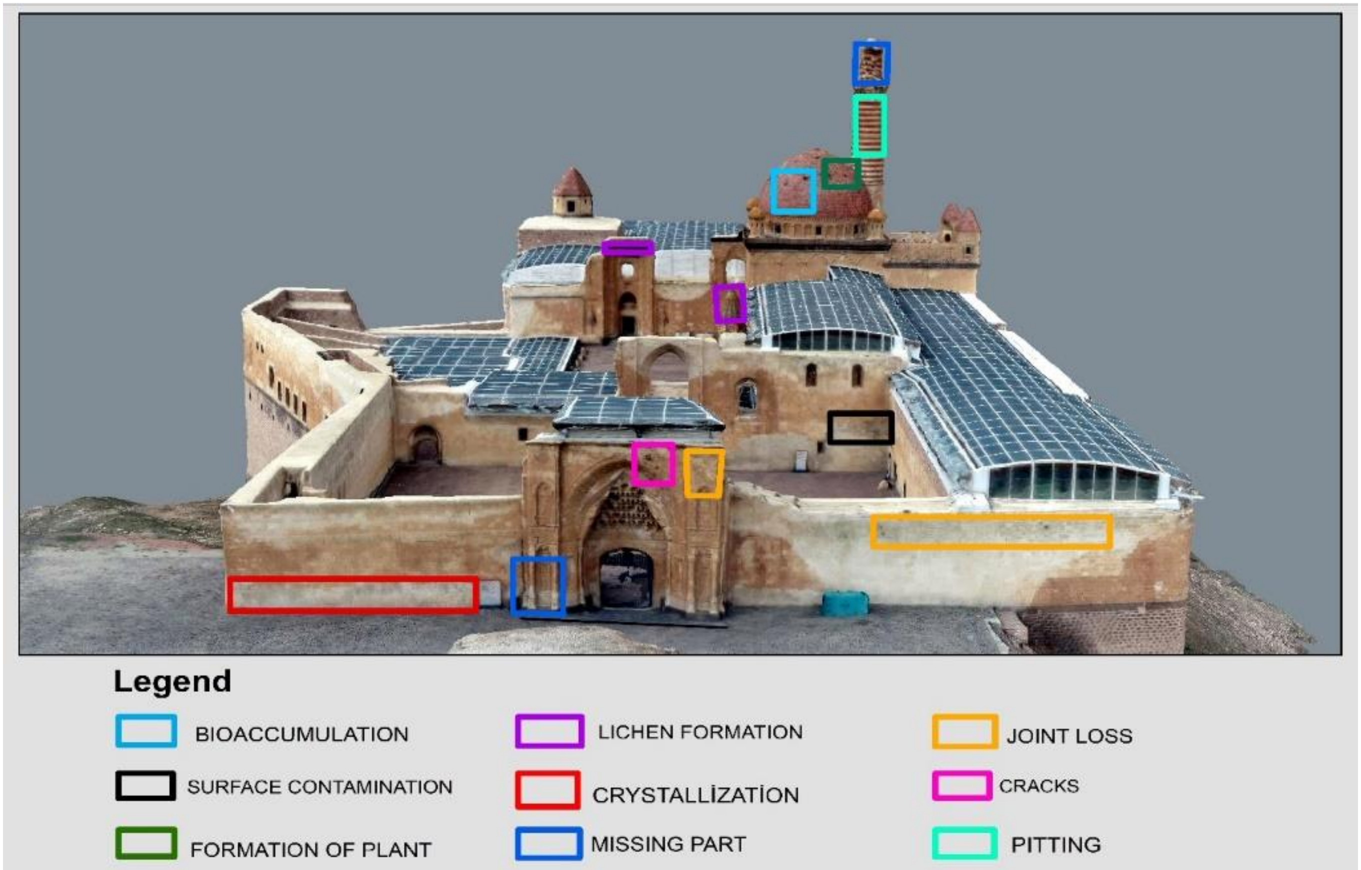

Figure 6. Detected distortions; East facade view

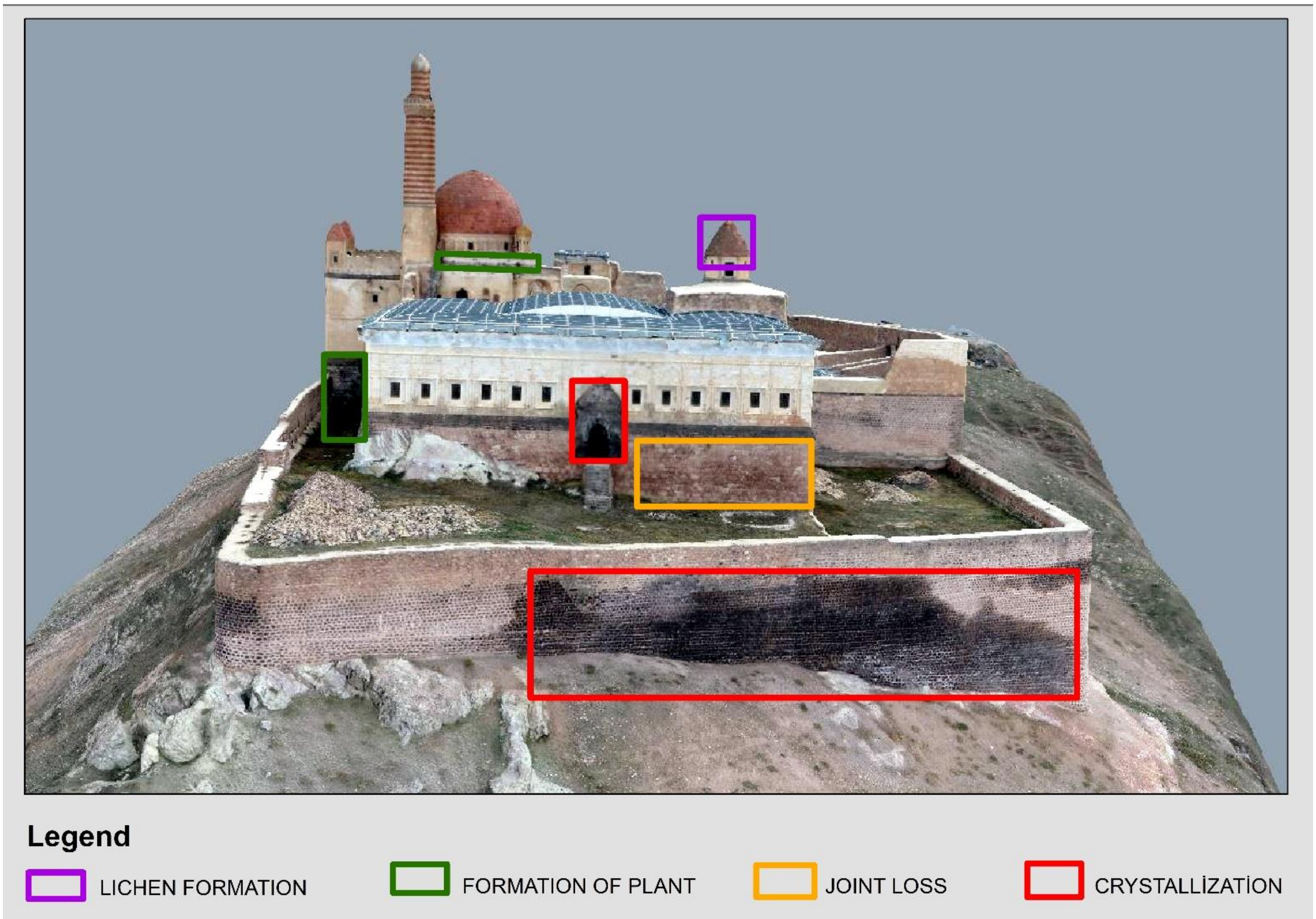

Figure 7. Detected distortions; West facade view

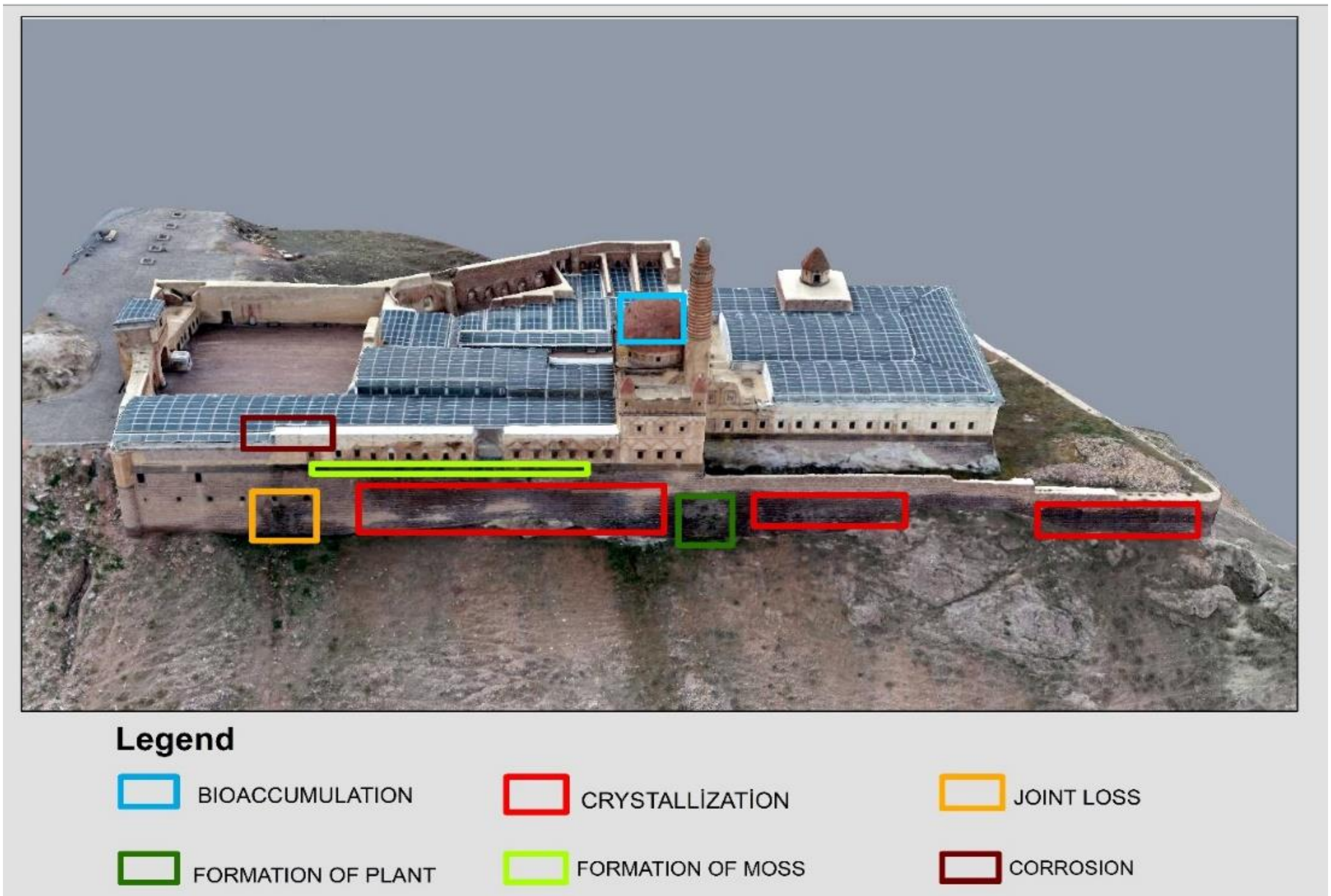

Figure 8. Detected distortions; North facade view

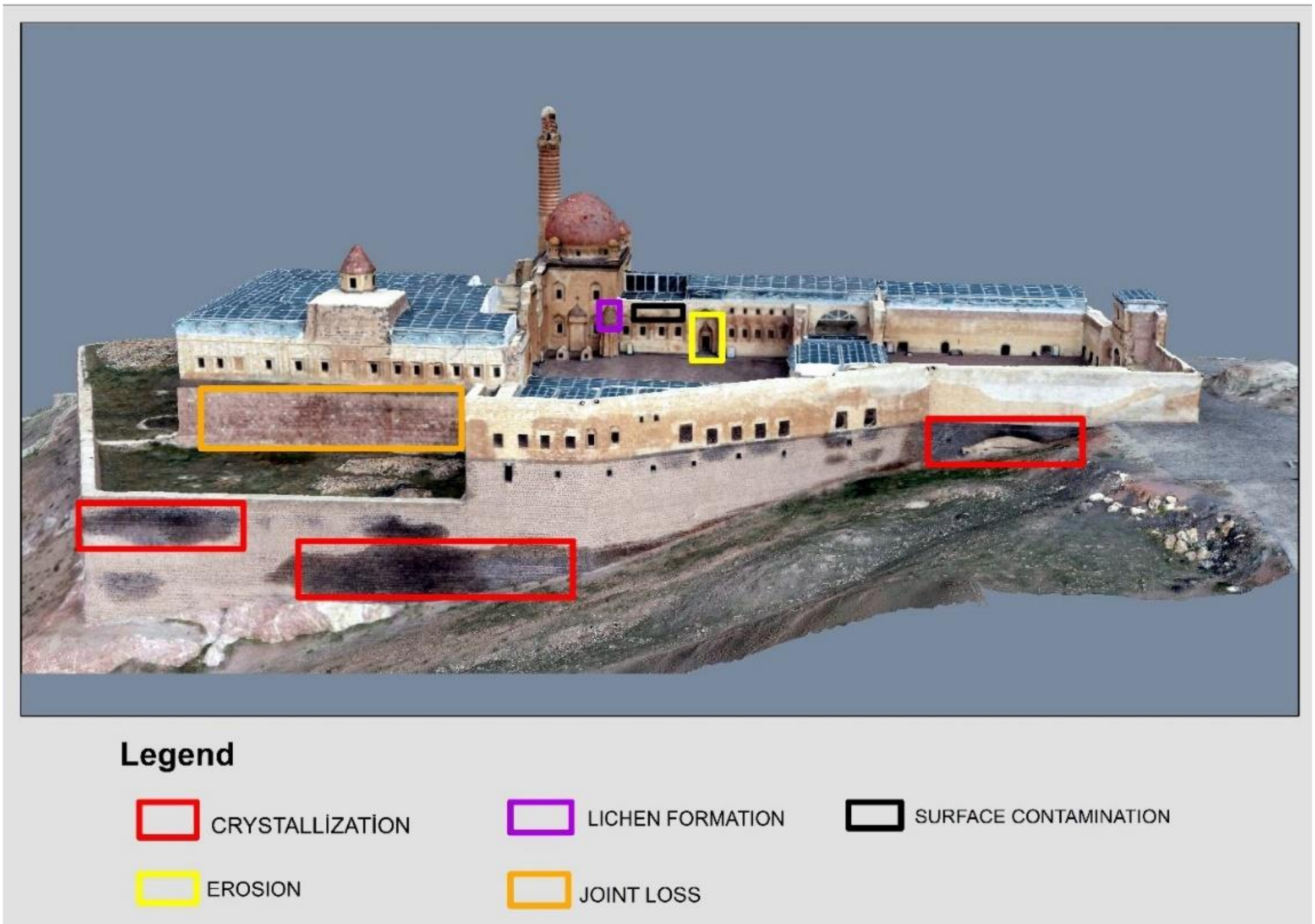

Figure 9. Detected distortions; South facade view

3.1. Physical deterioration

Physical deteriorations refer to the weakening of bonds within the minerals constituting the stones, leading to their fragmentation and disintegration without any change in their structures. Various types of physical deterioration are observed, including Crack-Fracture formation, Honeycomb weathering, Abrasion, Loss of parts, and Joint displacement, as illustrated in Table 1.

3.1.1. Crack-Fracture formation

Mechanical deformations resulting in the cracking or fracturing of stone can occur due to factors beyond pressure exertion on the stone, such as ground movements or voids within the stone structure [11]. These deteriorations arise from climatic and physical events, including repetitive temperature fluctuations, freezing and thawing cycles, which affect the material's inherent structure. If left unaddressed, the sizes of cracks may enlarge over time, accelerating the deterioration process and leading to loss of parts [7]. Cracks have been identified in the walls of Ishak Pasha Palace, at the entrance crown gate, the second crown gate leading to the second courtyard, and in the minaret. Some of these cracks, particularly those in the crown gate and minaret, have resulted in the loss of parts (Figure 10).

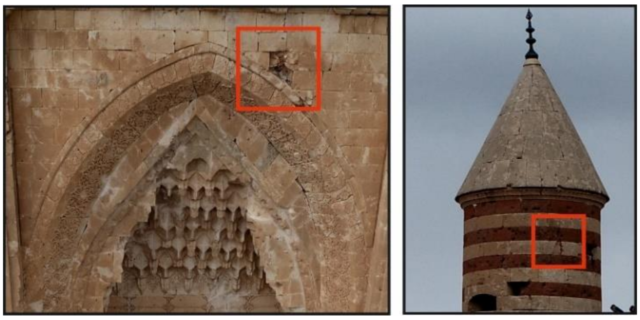

Figure 10. Crack-fracture formations detected in Ishak Pasha Palace

3.1.2. Wear (Erosion) effect

The surface abrasions predominantly observed on stone materials are primarily attributed to climatic factors such as rainfall, snow, and wind. Depending on the material's structure and the environmental influences it encounters, both superficial and deep abrasions may occur [7]. Furthermore, abrasions are commonly observed in thresholds or courtyard pavements of many historical stone structures due to the intense and continuous human movement they endure [4]. Such abrasions result from the stone's exposure to friction, causing gradual diminishment of its sections over time [38]. Abrasion has occurred on the stones constituting the steps of the salutation and harem entrance stairs of the palace, attributed to intense human circulation (Figure 11).

Figure 11. Erosion formation detected in Ishak Pasha Palace

3.1.3. Missing part

Material loss occurring throughout the entirety of the material due to factors such as physical impact and fracture. Losses in material integrity typically manifest as deteriorations such as fragmentation, abrasion, cracking, and fracturing [8]. Particularly, fragmentations are observed in decorative elements and details located in crown gates, mosque body walls, audience chamber walls, and harem exterior walls (Figure 12).

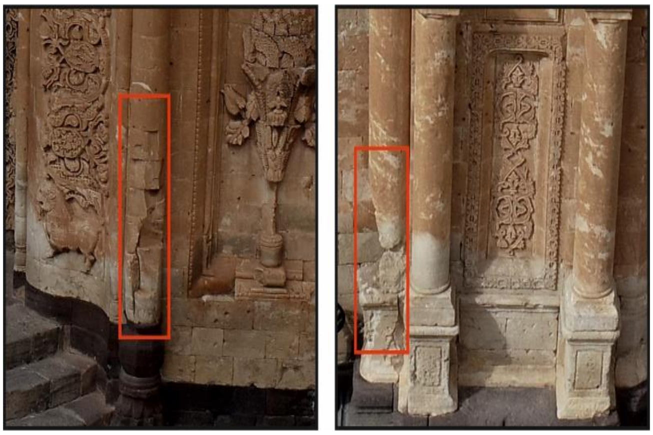

Figure 12. Fragment missing detected in Ishak Pasha Palace

3.1.4. Joint drain effect

The partial or extensive loss of mortar in the stone masonry, starting from the outer surface and progressing inward, denotes the phenomenon of joint displacement. Mortars, being among the most vulnerable materials to outdoor conditions, undergo fragmentation and disintegration due to factors such as wetting-drying/freezing-thawing, leading to advanced joint displacements over time [8]. As a result of joint displacement, the surface between stones is left exposed, triggering the deterioration process in the stones [10]. Localized joint displacement is observed in the retaining walls, exterior and interior walls, crown gates, mosque body walls of the palace, where mortar fillings are depleted (Figure 13).

Figure 13. Joint drain detected in Ishak Pasha Palace

3.2. Chemical deterioration

Chemical deteriorations arise from changes in the structure of minerals constituting the stones. Chemical deteriorations will be examined under the subheadings of Black layer formation, Salinization-Efflorescence, Pitting-Cavitation, Weathering, and Metal corrosion formation, as shown in Table 1.

3.2.1. Surface contamination

The accumulation of foreign materials on the stone surface, unrelated to the stone itself, typically observed as a thin layer of gray color and usually associated with air pollution, is referred to as soiling. The color, structure, and relationship with the surface of the dirt vary depending on the type of stone and the source of contamination. Especially in porous natural stones, the accumulation of dirt in pores constitutes a significant and challenging form of deterioration. The method of cleaning also varies depending on the condition of contamination and the type of stone [10]. Localized formation of a black layer is observed on the window and door tops of the reception wall facing the first courtyard of the palace. Additionally, partial formation of a black layer is detected on the upper and lower sections of windows on the north facade of the reception area and the harem (Figure 14).

Figure 14. Black layer formation detected in Ishak Pasha Palace

3.2.2. Crystallization formation

The absorption of water into the building elements, followed by its spreading on the surfaces and evaporation due to climatic effects, leads to the evaporation of water, while salts crystallize, causing the formation of hard surfaces [39]. Over time, salt crystals formed on the surface contribute to the deterioration of stone surfaces and mortar joints. Particularly, salt efflorescence due to water and moisture is observed, especially on the retaining walls of the palace, with a higher occurrence rate on the northern facade. Additionally, the salt efflorescence rate is high on the northwest wall of the mosque and the northern and western body walls of the harem (Figure 15).

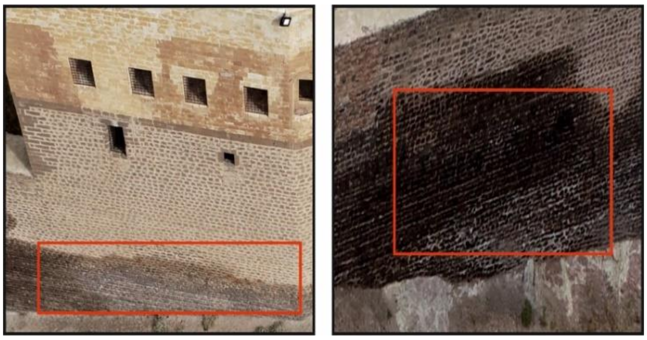

Figure 15. The salinization formation detected in the Ishak Pasha Palace

3.2.3. Pitting

The formation of hollows and recesses observed in natural stones is the result of the weakening and detachment of coarse grains due to atmospheric effects. Consequently, random voids of various sizes occur on the stone surface. These voids accelerate other deterioration processes as they provide areas where water can easily accumulate or plants can grow [10]. Significant instances of hollowing deterioration have been encountered particularly at the main entrance portal of the palace, in the dome and body walls of the mosque, and in the body and honeycomb of the minaret (Figure 16).

Figure 16. Pitting formation detected in Ishak Pasha Palace

3.2.4. Metal corrosion formation

Corrosion is the phenomenon of metal materials undergoing chemical and electrochemical reactions from the surface towards the depths, resulting in alteration or erosion of the material. Metals undergoing corrosion contribute to visual pollution on building stones [40]. Generally, metal corrosion formation is observed on the roofs of the palace, which have laminate wood-beamed, aluminum, and tempered glass upper protections (Figure 17).

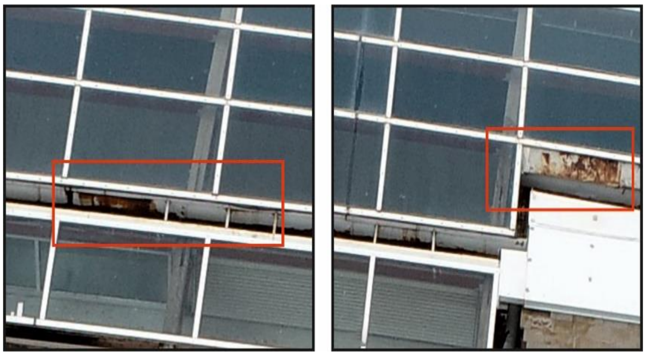

Figure 17. Metal corrosion formation detected in Ishak Pasha Palace

3.3. Biological deterioration

Biological deterioration is a type of degradation that occurs due to various types of living organisms. The primary factor in this type of deterioration is living organisms. Biological deterioration will be examined under the headings of Algal growth, Lichen formation, Plant growth, and Biological accumulation, as shown in Table 1.

3.3.1. Formation of moss

Algal growth is a form of biological deterioration that develops in continuously humid environments. It is typically observed in the lower regions of walls due to rising dampness or environmental conditions. Algae cover the surface, hindering the breathability of the wall structure [9]. Intensive algal growth is observed on the north facade of the palace and in the northwest corner of the mosque (Figure 18).

Figure 18. Moss formation detected in Ishak Pasha Palace

3.3.2. Lichen formation

Lichens inhabiting the surfaces of calcareous and siliceous stones, being water-absorbent in nature, retain moisture on stone surfaces for extended periods, leading to deterioration. Lichens firmly adhere to the stone by releasing certain acids through fungal filaments in their structure, causing abrasion over time [41]. Lichen formation is observed in the upper section of the harem entrance portal, on the dome of the mausoleum, and on the north facade walls of the palace (Figure 19).

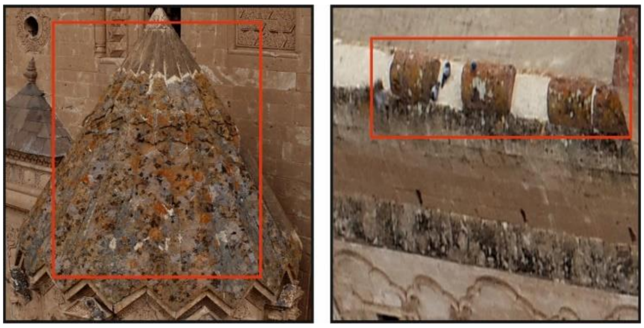

Figure 19. Lichen formation detected in Ishak Pasha Palace

3.3.3. Formation of plant

The growth of plants from seeds settling in small gaps on the wall surface, in joint crevices, or within voids in stones over time is referred to as plant formation [10]. Especially in the voids formed due to losses and disintegration in the masonry (such as in body walls and bottoms, cracks, and domes) and in the soil-filled gaps resulting from losses in the mortar joints, the vegetative formations accumulated exhibit mechanical pressures during their development, causing significant damage to the structure and contributing to the escalation of the deterioration process [8]. Plant formations have been intensively detected in the wall surface gaps and on the wall tops north of the main entrance portal of the palace, on the wall tops of the second courtyard entrance portal northward, on the stairs of the harem entrance portal, on the north and south walls of the harem entrance portal, on the mosque roof and dome, on the west wall of the mosque, on the north walls of the harem and the audience hall, and on the north retaining walls of the palace (Figure 20).

Figure 20. Plant formation detected in Ishak Pasha Palace

3.3.4. Bioaccumulation

The deterioration type typically associated with bird droppings on stone surfaces, where accumulated excreta with its acidic nature affects stone surfaces and leads to deterioration over time, is known as avian fouling [11]. Intensive biological units have been identified on the window sills of the north facade of the palace, on the domes of the mausoleum, towers, and harem exit tower, on the roof parapets and corbels of the mosque, on the dome of the mosque, and on the minaret's balcony and pedestal (Figure 21).

Figure 21. The formation of biological accumulation detected in the Ishak Pasha Palace

4. Conclusion

In this study, deformations occurring on the facades of the Ishak Pasha Palace, one of the historical structures dating back to the Ottoman period located in the Doğubayazıt district of Ağrı province, were examined using photographs taken with Unmanned Aerial Vehicle (UAV) and the generated 3D model. There are many different studies in the literature regarding the deterioration problems of historical structures. In the scope of the examined studies, the deterioration causes were identified and categorized under three headings. Accordingly, Physical deterioration (Crack formation, Wear, Part loss, and Grout loss), Chemical deterioration (Formation of black layer, Salting-flowering, Pitting, and Metal corrosion formation), and Biological deterioration (Algal growth, Lichen formation, Plant growth, and Biological accumulation) were classified. In this research conducted based on these deterioration types, problems such as Crack formation, Part loss, Grout loss, Salting, Pitting, Metal corrosion formation, Algal growth, Plant growth, and Biological accumulation were prominently observed in the Ishak Pasha Palace.

Mechanical deformations resulting from the cracking or fracturing of stone cause loss of parts in the stone structure. Rainwater entering through cracks, holes, and joint gaps on the surfaces of the walls leads to moisture on the wall surfaces. Salting and grout loss occur on the stone surfaces, especially moss growth and plant formation in the sections exposed to north facade, due to this moisture. Stones with cracks and part loss should be replaced with new ones, and the voids observed in the grouts should be filled with mortar suitable for the original structure according to the analysis results. Moreover, rising waters from the ground cause salting on the basement walls and retaining walls. Additionally, rainwater accumulating in the soil area in the courtyard causes deterioration on both the walls of the harem and the retaining wall. Firstly, rainwater accumulated in the courtyard should be drained, and contact with water inside the structure should be cut off. Water flowing from a drain located in the northwest corner of the mosque comes into contact with the body wall and the base of the walls, causing moisture in these areas. Therefore, details that will divert rainwater from the structure body walls should be resolved. Especially, pitting in areas directly exposed to atmospheric effects and rainfall should be filled with suitable mortar as it accelerates the deterioration process of the stone. Plants growing in joints and cracks throughout the structure should be cleaned, and necessary parts should be filled with grout to prevent further formation. Corrosion formation is observed on metal parts in the roof cover of the building. The rust problem encountered in metal materials can be eliminated with various rust remover chemicals, and after that, protective materials against rusting can be applied to the surface for protection.

Preserving and transferring architectural products, which are important elements of cultural heritage, to future generations is of great importance. Architectural structures convey information about the construction technique of the period they were built, building material, and the social and economic situation of the society [42]. Therefore, necessary measures should be taken to transfer the architectural works we possess to future generations in their original and preserved form, and maintenance should be periodically performed in accordance with these measures.

As a result, within the scope of the study, it was concluded that examining and detecting the deformations that occurred in historical buildings over time is possible with UAV systems that are used effectively in many areas in today's technology. In this study, it is aimed to detect the types of deformations visually detected from the images obtained by UAV systems autonomously with the help of current artificial intelligence / machine learning algorithms in future studies.

Author contributions

Emirhan Özdemir: Conceptualization, Methodology, Software, Writing-Reviewing and Editing, **Rüştü Çallı:** Data curation, Writing-Original draft preparation, Software, **Selim Kartal:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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