

Article

Graphic Applications of Unmanned Aerial Vehicles (UAVs) in the Study of Industrial Heritage Assets

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Abstract: As a typology of cultural heritage, a wide range of singularities must to be taken into account when analysing industrial heritage assets. Graphical resources have been usually employed in heritage assets research. Nowadays, Unmanned Aerial Vehicles (UAVs) offer the possibility to obtain images of complex and difficult access areas that cannot be observed on the ground. Furthermore, aerial images allow to analyse heritage assets as a whole. Therefore, in this work, different photographs and videos has been carried out in the San Joaquin sugar cane factory and in the Aguila aqueduct, located in Nerja (Spain). These images have been used to analyse both assets as a set. Different indirect measurements on the factory chimney and irrigation water pond were taken. A Strengths, Weaknesses, Opportunities, and Threats (SWOT) about the use of UAV graphic applications in heritage assets was developed. Finally, the possibilities of conventional photograph technologies and UAV application were compared. Using UAVs allows more image acquisition possibilities than conventional systems. However, both technologies can be complemented and applied together when analysing heritage assets.

Keywords: industrial heritage; unmanned aerial vehicles; UAV; graphic applications; sugar cane factory; aerial photograph; SWOT

1. Introduction

Interest in historical and cultural heritage has evolved over time. Initially, it was related to the economic value associated to some movable and immovable assets. This value was the result of the materials employed, the materialization quality and the social meaning that owning these goods had, since these possessions were a sign of wealth and high social status [1]. Then early centuries of Middle Ages were a warlike period and a great number of assets were destroyed. In the Renaissance period, the heritage concept evolved considering that they are transmitters of knowledge, so they must be analysed and conserved [2]. In nineteenth century, the development of museums represented the initiation of cultural heritage democratization. This fact suggests that society, regardless of economic status, will be interested in historical and cultural heritage and it could be a knowledge transmission way for society [3].

Nowadays, the historical and cultural heritage idea encompasses all these facts taking into account that the historical and cultural heritage represent the identity of a society, being witnesses of a past that must be evoked and remembered. Therefore, heritage conservation, as well as the transmission of the knowledge generated from the study of heritage elements, must be of interest to current societies.

In this sense, actually, numerous studies on cultural and historical assets are being carried out [4–6]. The following figure (Figure 1) graphically summarizes the described evolution of the heritage concept:

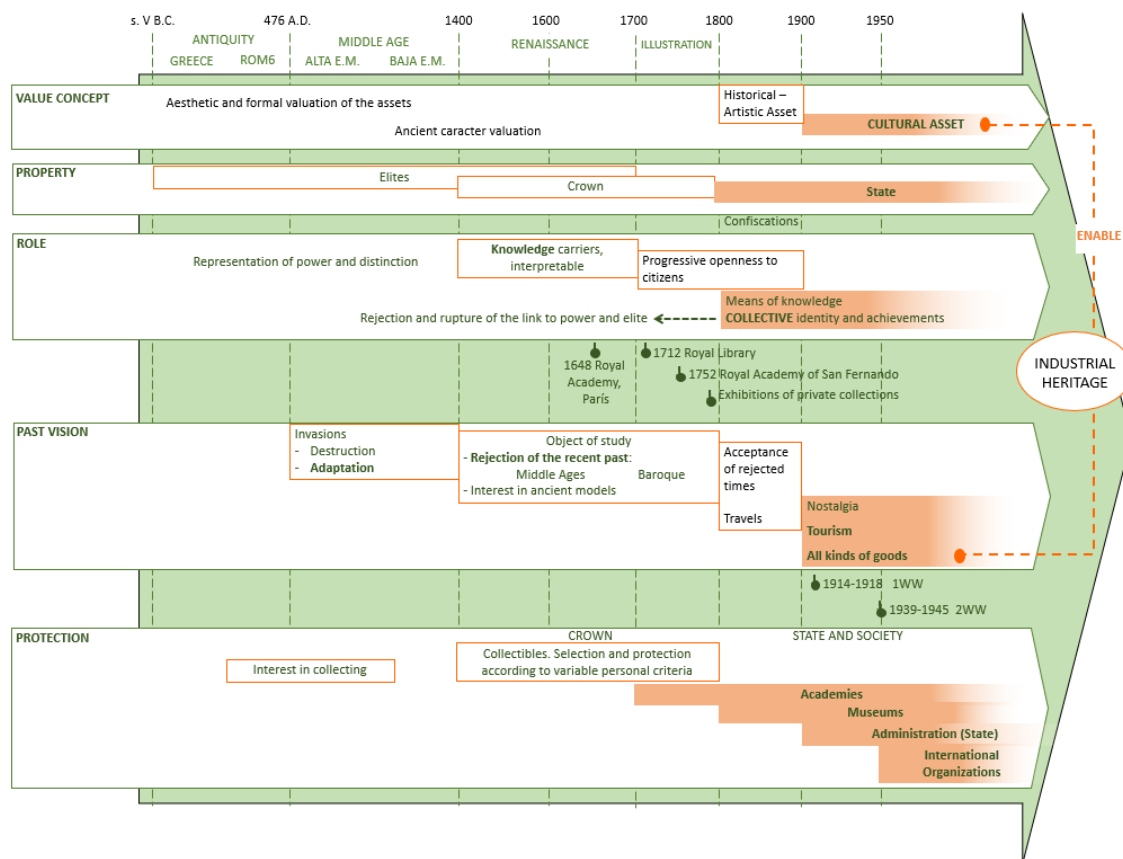


Figure 1. Heritage concept evolution [7].

During the last decades, industrial heritage has been internationally accepted as a heritage typology. The Water Management System of Augsburg (Germany) and the industrial city of the 20th century in Ivrea (Italy) are examples of this typology included in the UNESCO World Heritage List [8]. Furthermore, different organizations and associations have been created recently to protect industrial heritage. In this sense, Association for Industrial Archaeology (AIA) or The International Committee for the Conservation of the Industrial Heritage (TICCIH) were created with this purpose [9,10].

In comparison to other heritage typologies, industrial heritage has some special characteristics. Most of its assets date from the First Industrial Revolution, so it is a relatively young typology. Its relation to labour exploitation has provoked a certain initial social rejection. In spite of this, currently, this sense has been changing and the importance of this heritage typology is being recognized [11]. The loss of their original function and the pressure of urban development on many of their locations are other aspects that make the management and protection of these assets more difficult.

Industrial heritage research should not be faced through approaches focused on particular industrial buildings or industrial equipment. The study of this typology should be considered as a whole [12]. Therefore, it is important to evaluate the industrial landscape which provides information about the moment of the activity develop [13].

Traditionally, graphic resources (photographs and videos) has been employed to document heritage assets. Furthermore, these graphic resources allow to generate high quality information to carry out interventions on heritage assets (conservation, restoration, etc.) or as a catalogue tool [14–16]. Nevertheless, this method does not always allow to obtain images of a complete asset. Elevated building areas (roofs) or difficult access areas are inappropriate environments to obtain good images in this

way [17,18]. Thanks to recent technology evolution Unmanned Aerial Vehicles (UAVs) are able to solve these difficulties [19–21].

One of the advantages of the UAVs is that they can incorporate high-quality image capture systems generating high resolution photographs and high definition videos [22]. Thus, UAVs allow obtaining aerial images of large land areas and also accessing areas and spaces with difficult access at a lower cost. Furthermore, depending on the built-in image capture system, thermal and multispectral images can be generated. These functions are useful, among others, in efficiency energy studies or in the analysis of water resources, which can be applied in heritage research [23,24].

Photogrammetry techniques are widely employed in different disciplines: architecture, topography, archaeology and cartography are some examples [25–27]. These techniques aim to calculate the dimensions and positions of objects in space, from measurements made with photographs. Photographs taken from the field can be employed, but the use of aerial photographs has allowed to carry out analysis of larger extensions of land, reducing the time required. In this sense, UAVs are considered a great interesting tool in the use of this techniques [28–30]. Besides, the aerial images facilitate the generation of 3D models, from photogrammetry techniques, which have a great interest in heritage research and assets' monitoring.

Enriquez et al., in [31], used an UAV on the Mozarabic church ruins in Bobastro (Málaga, Spain). The use of an UAV allowed them to take the necessary photographs of the ruins to generate a 3D model using photogrammetry techniques. Additionally, a digital elevation model was produced in order to determine where the structure of the church was built. The final results were a virtual recreation of these archaeological ruins.

A similar methodology was employed in [32], where the authors generated a 3D model of Hatfaludy Mansion, in Hida (Romania), using a UAV. The final research purpose was to generate enough information using the UAV to promote the asset as a local tourist attraction. Previously, this information can be integrable to heritage conservation and reconstruction process.

Papakonstantiou et al. in [33] used a UAV to generate orthophoto maps for mapping and detecting cultural heritage sites in the coast of Lesbos Island (Greece). The UAV flight height was carried out at 100 m around Mytilene ancient harbour and the Eresos ancient harbour, with an orthophoto resolution of 2.5 cm/pixel, what shows the high capacity to capture images that an UAV has. Additionally, authors developed a metadata cataloguing system in order to facilitate online search operations.

UAVs allow one to mount different camera typologies, depending on the type of images to be obtained. In [34], Tucci et al. employed a conventional photographic camera and a thermal Infrared camera to perform a thermal characterization of a dry-stone wall terraced vineyard in the Chianti area (Tuscany, Italy). Fuldain installed an infrared camera in a UAV to produce a Normalized Difference Vegetation Index (NDVI) orthomosaics plan from different areas along a Roman road [35] in Avila (Spain). The purpose of these orthomosaic photos was to identify where the road crossed.

In this sense, Leon et al., in [36] used an UAV to take aerial photographs of the Añana Salt Valley and the Nueva Cerámica de Orio Factory, both of them in the Basque Country. Regarding the Salt Valley, UAV-assisted close-range photogrammetry enabled generation of a digital terrain model. On the other hand, for the Factory of Nueva Cerámica, the authors created a building information model (BIM). With this objective, outdoor and indoor photographs were captured using a UAV. The authors also analysed the difference between laser scanning and photogrammetry technique using a UAV. They observed that the UAV reduces capture time and economic cost. They also established that UAVs can be employed not only in larger land extensions, but also in more reduced areas in which laser scanners cannot be placed and used.

Thus, the review of the scientific literature on the application of UAVs to cultural heritage assets allows one to identify interesting examples. Nevertheless, despite its potential, this technology has not yet been widely used in the study and management of industrial heritage, what opens a promising field of research.

SWOT analysis is an efficient management tool to evaluate the strategic positioning of an organization, and it has been widely used in different context and industries [37–39]. This method is usually applied to well defined processes, but it can also be applied to the analysis of emerging technologies, such as electric vehicles [40], BIM technology [41], methanol-fueled vehicles [42] or information technology [43], among others [44,45], allowing one to evaluate their current state and future possibilities. In this sense, an application of SWOT analysis to UAV technology has not been found in the literature review, and in that sense this research can provide valuable information about its application to the heritage field.

The sugar cane industry was widely developed in the South of Spain from the early 19th century to the mid-20th century. Particularly, the east coast of Málaga and the so-called Tropical Coast of Granada represent examples of this productive activity. The weather conditions and the combination of a mountainous orography and a location near the coast, provided water both for sugar cane cultivation and to the manufacturing process, promoting the development of this activity. Furthermore, the proximity to the sea facilitated both national and international product distribution [46,47].

Currently there are many remains of this industrial typology in the province of Málaga, and the San Joaquín sugar cane factory, located in Nerja, is one of them. Its proximity to the Águila aqueduct, which was used to supply the factory with water, makes it unique. The relationship between both elements requires a joint evaluation.

For all this, the present work aims to establish a methodology able to explore the usefulness and potential of UAVs for obtaining images of this type of heritage assets, providing new analysis possibilities. As a previous to define this methodology, a SWOT analysis was carried out focused on the utility of UAVs in the study of heritage assets. This methodology will be applied to the analysis of the San Joaquin sugar factory and the Aguila aqueduct in Nerja (Málaga), evaluating both assets together. Finally, a comparison will be made between conventional image capture systems versus the application of UAVs.

2. SWOT Analysis Applied to UAV

A SWOT matrix was developed to analyse the UAV application. This analysis is focused on the use of UAV in historical and cultural heritage assets, including industrial heritage typology. Table 1 shows strengths, weaknesses, opportunities and threats items. The main strengths considered regarding the use of UAVs for the analysis of heritage assets, and included in Table 1, are described below.

Table 1. SWOT Matrix for UAVs applications in heritage assets.

Strengths	Weaknesses
S1. Different UAVs typologies	W1. Short battery life
S2. Low equipment cost	W2. Device fragility
S3. High image and video quality	W3. High computational cost of information processing
S4. Low human risks	W4. Complexity of flight in dark spaces
S5. Low contamination technology	W5. Limitation in adverse weather conditions
S6. High dimensional accuracy	W6. Maintenance costs
Opportunities	Threats
O1. Aerial images performance	T1. Damage risk to third parties
O2. Image capture devices combination	T2. Privacy invasion
O3. Low inspection cost in hard-to-reach areas	T3. Mobile laser scanning systems
O4. Extensive areas analysis	T4. Restricted airspaces
O5. Assets digitalization models	T5. Complex information processing
O6. Indirect measurements	T6. Non-uniform aeronautical legislation
O7. Enhancement assets application	T7. Pilot qualification and accreditation
O8. Aligned with Sustainable Development Goals from United Nations	

2.1. Strengths

S1. Different UAVs typologies: Different UAVs typologies are available in the market. One classification considers the wing arrangement: rotatory or fixed. Rotatory wing models are widely employed for economic reasons and because they allow the UAVs to remain hover immobile in the air. This fact makes it possible to obtain higher accuracy images. On the other hand, fixed wing UAVs are employed to analyse higher land extensions requiring less capture image time and less battery autonomy. Hence, fixed or rotatory wing UAVs can be selected based on the research needs of each case study.

S2. Low equipment cost: The stability of the aircraft and the possibility of incorporating different devices are the main characteristics that affect the UAV price. For professional uses, the cheapest models (rotatory wings) are around €1000 (i.e., Mavic and Phantom series). A high-quality visual camera (S3) is integrated and good flight stability can be assumed in these models. Fixed wing models are more expensive than rotatory wing ones. In spite of this, a professional fixed wing UAV with an integrated high-quality visual camera can be acquired for €2000. Notwithstanding, the price of UAVs that incorporate different devices increases to approximately €5000, and, depending on the characteristics of the device, can reach €10,000. In spite of the fact UAV prices are higher than those of a conventional photographic camera, the opportunities offered by UAV technology in heritage asset research are higher (O1, O3, O4 and O5).

S3. High image and video quality: A common professional UAV incorporates a visual camera that can capture high resolution images and film high definition (HD) videos. This fact allows obtaining images with the aircraft at a sufficient distance to reduce the accident risks that could affect the aircraft performance and cause material or personal damages.

S4. Low human risks: Heritage assets are usually in a dilapidated state or are situated in difficult to access areas. Heritage building structures are often unstable, so access poses a high risk to persons. Furthermore, other heritage assets have very reduced access zones that persons cannot physically access or present a risky environment for people. The remote-control system allows the UAV to access these hard-to-reach places, eliminating any risk to persons during the experimental research process.

S5. Low contamination technology: UAV flights do not generate polluting emissions to the environment due to their use of rechargeable batteries. Besides, it is important to highlight that this technology allows the replacement of elements (i.e., wings, cover structure, external battery, devices) without the need to replace the aircraft completely, reducing the waste generation.

S6. High dimensional accuracy: Professional UAVs incorporate Global Positioning System (GPS) () technology. This technology allows generating georeferenced orthophotographs that, using photogrammetry techniques, can create three-dimensional models related to Geographical Information Systems (GIS) with errors of less than centimetre magnitude. This strength provides an opportunity to digitalize heritage assets with high dimensional accuracy (O5).

2.2. Weaknesses

Regarding weaknesses, the use of UAVs has the following negative aspects:

W1. Short battery life: The usual battery lifetime during flight is around 15 or 20 min, depending on the flight conditions. This reduces the possibility to record long duration videos or sufficient inspection time, requiring frequent landings to perform battery exchanges. At least four batteries and a previous flight plan are required to complete a heritage asset analysis. In spite of this, or 3D generation models using photogrammetry techniques, a battery can be considered enough to capture the required images. In addition, the batteries can be recharged approximately 3000 times, without reducing their efficiency.

W2. Device fragility: Short battery life or flying in reduced areas or with objects around can cause the aircraft to crash. Occasionally, depending on the speed and height of the flight, the UAV can become unusable. To reduce the possibility of crashes, UAVs have proximity sensors and battery life monitoring systems.

W3. High computational cost of information processing: Due to the high definition image capture and high definition video recording capacity, the treatment and manipulation of this information requires high capacity software and hardware. The application of photogrammetry techniques to the captured images require high performance hardware systems and usually involves a lengthy computational time cost.

W4. Complexity of flight in dark spaces: In addition to the possibility of an aircraft crash during flight, high performance camera systems are often required to generate images in dark spaces, increasing the UAV cost. Furthermore, open space night flights are submitted to restrictive legal conditions for safety reasons.

W5. Limitations under adverse weather conditions: High wind speeds and rain preclude flights for safety reasons. Even if the wind speed is not high enough to prevent the UAV from flying, the stability of the aircraft may be affected and the results obtained may not be satisfactory. In addition, it is necessary to consider the possibility of drafts in reduced space flights, which can cause the aircraft to fall unexpectedly.

W6. Maintenance costs: In spite of the fact preventive aircraft maintenance is not necessary for basic UAV, a civil liability insurance is required to cover any possible damage to third parties in the case of a crash. Additionally, replacement insurance is recommended at least during the two first years of the aircraft's life. This represents a maintenance cost of around €500 per year.

2.3. Opportunities

Regarding the opportunities, different aspects that represent the potential applications of UAVs in heritage research have been considered:

O1. Aerial Image Performance: Currently, aerial image generation with UAVs is the most widely used application. Conventional photo or video capture systems require a physical support to capture zones that cannot be observed on land. This is usually expensive and can cause user risks. Notwithstanding, UAVs image capture systems allow obtaining images in any area without the need for any external support and without user risk (S4). Furthermore, the image capture quality is on the order with that achieved with conventional capture systems. Another aerial image performance advantage with UAVs is the possibility to make orthophotographs, that can be applied to obtain indirect measurements between captured elements.

In heritage asset analysis, the aerial images can be employed to analyse the environment in which the assets are located, generating a greater context for the study. In addition, aerial images in heritage assets promotional videos can increase interest in visiting it.

O2. Image capture device combinations: Most UAV models allow the incorporation of different image capture devices that can generate photographs in the visible or infrared spectrum, thermographic or multispectral. Some of them allow one to do so from different positions and take different images on a single flight. However, others require the plane to land to change out the imaging device.

The application of infrared and thermographic images can be considered in the conservation and restoration of heritage assets, being widely used in the energy efficiency analysis [48,49]. On the other hand, multispectral images can be employed to analyse the environment in which the heritage assets are located.

O3. Low inspection cost in hard-to-reach areas: Sometimes, access to certain areas is prevented, due to the state of conservation of heritage assets. For the O1 opportunity, the use of UAVs reduces the cost of external supports (scaffolding or lifting equipment) needed to enable inspection.

O4. Extensive areas analysis. The UAVs flight allows observing the assets from a different perspective. Aerial images can show the environment where the asset is situated. Furthermore, the distribution of the different buildings that were part of the assets can be observed. This fact enriches the information about how the industrial activity was carried out. Opposite, conventional photography on the ground only allows generating individual images for the asset elements, losing the context where they are placed.

O5. Asset digitalization models. The actual technology development allows one to generate 3D models, applying photogrammetric techniques. The UAV can capture different orthophotographs from a land area for inspection operation and then a terrain topographic survey can be generated. Furthermore, a photograph set, representing different positions of an asset, can be used to generate a 3D model of it. Actually, building information models (BIMs) have become a tool of great interest in building situations. In this sense, the UAV use allows one to generate a 3D model that can be used as a starting point for a BIM generation. In addition, in the heritage field, this information model can be applied in conservation projects, where graphic information is required prior to the conservation activities, considering a heritage building information model (HBIM) [50,51].

O6. Indirect measurements. A photograph can be considered as an object scale representation. From a real measurement reference that appear in the image, the remaining dimensions of the represented object can be obtained using indirect measurements. This method can be applied to measure elements that present a difficult access, complex geometry or large dimensions to measure using direct measurement methods. Aligned with O1 and O3, UAVs can take photographs in these complex or extended areas and, using design software, measurements with good accuracy can be obtained [52].

O7. Asset enhancement applications. Photography and video heritage asset generation is a common resource used for heritage enhancement. The use of UAVs allows generating images from alternative points of view that enrich the appreciation of the patrimonial analysis. Furthermore, aerial images are more attractive and can increase societal interest in heritage knowledge, being a promotion tool.

O8. Alignment with the Sustainable Development Goals (SDG) of the United Nations (UN). UAV technology, focused in heritage research, favours sustainability development according to Goal 4, education quality, and Goal 9, related to industry, innovation and infrastructure [53].

2.4. Threats

Finally, different external conditions can affect negatively on the application of UAVs to heritage research. The threats that can be considered in its use are indicated below:

T1. Risk of damage to third parties. Occasionally, the realization of flights in a confined or reduced space, can produce a collision with an obstacle, like a possible pilot error. The fall of the aircraft can cause damage to people, items and the aircraft itself. Therefore, a prior analysis of the flight environment is required as well as awareness to avoid people's movement under the flight path. Many heritage assets are situated in urban areas, so it is necessary to consider this threat in the UAV use.

T2. Privacy invasion. The UAV flight allows aerial images to be obtained by overcoming obstacles that are used to protect the privacy of people and property, which is protected by law, despite the fact that the flight takes place over a public space. For the correct use of the UAV in the study of the patrimonial assets it is necessary to obtain the authorization of the owner, as well as an adequate treatment of the information generated from the flight.

T3. Mobile laser scanning systems. In addition to photogrammetry techniques for 3D model generation, laser scanning technologies have developed new mobile systems that allow scanning reduced spaces with a high accuracy. Nevertheless, a person is still required to move with the capture system. From another point of view, this technology could be equipped on a UAV and both technologies combined.

T4. Airspace restrictions. UAV flights near airports or military areas are restricted for security reasons. In addition, the flight of the UAV is also restricted in protected natural areas because it may pose a risk to birds. Thus, the area where the patrimonial property is located can limit or prevent its use, and so, the flight could only be done with special permits.

T5. Complex information processing. The photogrammetry techniques used for the UAV image require a complex analysis process, using specialized software. The laser scanning process directly

generates 3D models, using a customized equipment software supplied by the manufacturer, which cost must be considered.

T6. Non-uniform aeronautical legislation. Different legislations are applied in each country related to UAV flights. This means that the user must know the regulations depending on where the flight takes places. Some countries establish very restricted conditions for the flight of UAVs, especially for foreign users (i.e., Morocco, Brazil, Thailand). On the other hand, the European Union has developed a common regulation for all member countries.

T7. Pilot qualification and accreditation. To carry out the flight operation, pilots require previous governmental accreditation. Obtaining accreditation depends on the conditions required by each country, however it is common to have to take a course related to UAV management and pass its corresponding evaluation. The FAA in USA or the AESA in Spain are public organisms that establish the requirements to obtain the UAV pilot accreditation.

In spite of the different threats evaluated, the SWOT analysis has shown that the UAV can be considered an interesting tool for heritage conservation and promotion. Furthermore, the low cost of UAV technology makes it accessible to any user.

3. Methodology for the UAV Use in Graphic Application

In this section, a general methodology for the UAV use in graphic application for a set of heritage assets is proposed. A general methodology can be considered with the follow steps (Figure 2):

- (1) Selection and identification of the heritage assets. The initial step is the asset selection, considering the objective of the case study of interest. In the field of industrial heritage, the traditional or singular manufacturing activities of a region and the relationship between its heritage elements often generate special interest.
- (2) Heritage assets location. A Geographical Information System (GIS) or some other map analysis system (i.e., Google Maps) is required to know where the assets are located. These systems establish geographical coordinates (latitude, longitude) or Universal Transverse Mercator (UTM) that allows the positioning of heritage assets. In addition, the extent of the terrain and environmental around the assets can be considered on the selection of the UAV model.
- (3) Flight restrictions. Most countries have UAV flight regulations. In general terms, UAV flight is restricted near airports, in urban areas and in protected environments, for security reasons. In addition, the weight of a UAV is another variable to consider within the regulation. Thus, the level of restriction and the need for local government authorization depend on the area to be overflown and the characteristics of the UAV.
- (4) Heritage asset visits. An initial visit to the assets is required to identify the key details. This allows to decide the elements that will be captured, due to the special interest that they represent. On the other hand, the existence of possible obstacles in the flight of the UAV can be controlled, allowing to define the most appropriate position of the pilot. Finally, it makes it possible to analyse the conservation status of the assets. These characteristics should be considered when selecting the UAV model.
- (5) UAV model selection. The stability of the flight, the quality of the camera and the size and weight of the UAV must be taken into account to select the most appropriate model for the analysis of a particular heritage asset. Low weight reduces the need for flight authorizations and small size facilitates flight between possible obstacles and in small areas. However, the stability can be affected by the wind, making it difficult to take pictures during the flight. Multi-rotor UAVs are often considered an appropriate typology due to the wide variety of existing models. However, the fixed-wing UAV typology is more appropriate for analysing a large terrestrial extension, due to the low battery life of multirotor UAVs.
- (6) Flight plan. A flight plan is required to ensure proper execution. The plan will include a selection of items to photograph and the video recording area. Due to the low battery life, several flight

operations are often required. The plan will structure the actions to be carried out in each flight operation, so the number of batteries required must be estimated beforehand. In addition, the position of the pilot will be decided on the basis of the actions to be carried out. Finally, the necessary safety measures shall be considered in order to reduce the risk of accidents.

- (7) Flight execution. Prior to the flight operation, climatic conditions must be analysed. High wind speed, rain or poor visibility will prevent its execution. Good weather conditions allow the flight operation and so, the planned actions could be carried out.
- (8) Information processing and data analysis. Finally, the image obtained can be analysed relating the asset with the environment where is situated, or with other assets located in the immediate vicinity. Additionally, video editing actions to promote the asset or conservation actions can be considered.

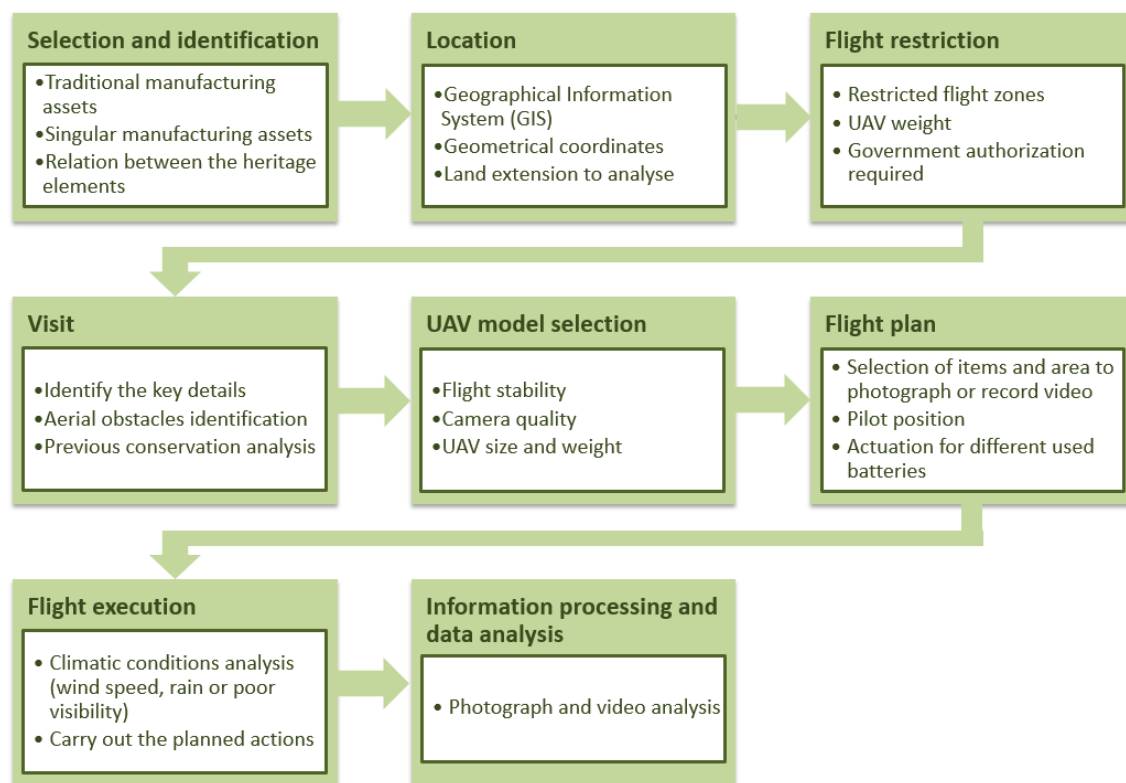


Figure 2. Methodology for the UAV use in graphic applications.

It is important to highlight that this proposed methodology can be applied to the use of UAVs in heritage research, the generation of 3D asset models using photogrammetry techniques, the study of energy efficiency as well as to other actions on the assets. This only requires adapting the methodology of information processing and data analysis.

For 3D assets models using photogrammetry, during flight execution different apps can be employed to take photographs (i.e., Pix4D Capture, Mission Planner, etc.) where the image captures are distributed around the asset area. In addition, different photogrammetry software packages can be employed to process the different images and generate the assets 3D model (Pix4D, Drone2map, Agisoft Metashape, etc.). On the other hand, referring to asset energy efficiency analysis, thermographic images can be taken using a special camera mounted on the UAV, and the captured images can be processed using different software (testo IRSoft, FLIR Tools, etc.).

This general methodology has been applied to generate aerial images in the case of the San Joaquin sugar cane factory and the Aguila aqueduct, located in Nerja (Spain). The main reasons to select these

assets are that, in this area, different sugar cane factories were installed in the second half of the 20th century, and both assets are related due to the aqueduct that supplied water to the factory.

Google Maps was employed for the asset location analysis. The geographical coordinates of the aqueduct ($36^{\circ}45'29.24''$ N $3^{\circ}50'59.70''$ W) and the factory ($36^{\circ}45'36.26''$ N $3^{\circ}51'13.54''$ W) have been obtained and the distance between both assets has been measured (398 m). Moreover, the environment around the assets has been analysed. The third party damage risk is reduced due to the location of the assets on agricultural land and the lack of pedestrian access around the area. In spite of this, a road with normal vehicle traffic separates the aqueduct and the factory and so, special attention is needed when the UAV flies over the road.

Restricted flight area maps of the national authority have been consulted, not finding any restrictions. In this case, no governmental authorization is required.

The assets were visited prior to the flight operation. Different interesting elements to photograph (chimney, irrigation pond, etc.) were selected and possible obstacles to flight operation (electrical wiring, bridge, etc.) were identified.

A multirotor UAV has been selected for the flight operation. A MAVIC pro platinum model has been employed (Figure 3). The main UAV technical characteristics are listed in Table 2.



Figure 3. MAVIC pro platinum model UAV.

Table 2. MAVIC pro platinum technical characteristics.

Weight (Including Battery and Propellers)	734 g
Satellite positioning system	GPS/GLONASS
Camera sensor	1/2.3' (CMOS). 12.71 Mpx
Focal distance	35 mm
Image size	4000 × 3000
Video mode	C4K, 4K, FHD, HD
Battery capacity	3830 mAh
Battery weight	240 g

Once the environmental and the information of the assets of interest were collected, a flight plan was developed. This plan list different actions to be carried out and the materials required. Furthermore, these actions were divided into three flight operations considering the UAV's 15 min of attery life.

The flight operations were carried out with the UAV according to the flight plan. In addition, different references were measured in the assets to obtain indirect measurements that would be very complex or too expensive to carry out directly (chimney diameter, chimney height, irrigation water

pond area, etc.). The photographs and video generated were processed and analysed. In addition, different indirect measurements were obtained.

Finally, a comparison between the use of conventional imaging systems (video or photograph camera) and UAVs have been made. Different items have been considered and a score from 1 to 5 has been assigned.

4. Case Study and Results

4.1. Sugar Cane Factory San Joaquín and the Aguila Aqueduct

Sugar cane cultivation was introduced along the coasts of Málaga by the Muslims. In the 16th century there was already a pre-industrial production of sugar in the region. The introduction of the steam engine allowed a strong sector industrialization in the mid-nineteenth century. At that time, the province had 37 sugar factories that employed thousands of people [46].

The San Joaquín sugarcane factory is an example of this manufacturing activity in the region. This factory was built in 1879 and was dedicated to sugar production and alcohol distillate made from sugarcane. Around the factory, 200 ha were dedicated to sugarcane cultivation being considered as an agricultural colony [54].

The property had several owners throughout its history, due to the economic situations of each moment and the entry of new investors. However, the productive activity continued to develop until the middle of the 20th century, when it ceased definitively. Actually, numerous remains of the factory are preserved, despite the threat of ruin to some parts [55].

In an aerial photograph of the factory obtained with an UAV flight, different structural elements and its distribution can be observed (Figure 4):



Figure 4. Factory elements distribution. Aerial image obtained in the UAV flight operation.

- (1) Factory enclosure. The factory has an extension of some around 5000 m² surrounded by a masonry wall. The enclosure had two entrances. The pedestrian entrance, situated on the south side of the factory (1a), which gave access to the main entrance to the sugar factory. The other one (1b), located in the southeastern side of the enclosure, was the collected sugarcane entrance and the manufactured sugar exit. Actually, remains of the masonry wall can still be observed, although much of it is destroyed.
- (2) Worker houses. In the north part of the factory enclosure, eight houses were built for factory workers (2a). Actually, only part of the remain buildings can be observed. In addition, outside the factory enclosure, at the southeaster entrance, another building can be observed (2b), being dedicated to factory worker living quarters. The second structure remains in a better conservation state.
- (3) Warehouse. One element of the industrial set was a warehouse near the southeastern entrance. This building was dedicated to store the harvested sugarcane.
- (4) Office. Administrative and management tasks were carried out in an office building, located next to the warehouse.
- (5) Factory. The main building was made up of four H-shaped structural elements. Two central elements, with a rectangular floor attached on the longest side and two lateral rectangular floors, perpendicular to the central ones. The factory was equipped with English-made steam machinery, which was purchased by catalogue. This fact allowed it to be custom-built according the machinery dimensions.
- (6) Additionally, a chimney can be observed on the north factory facade. This element was built with smudging bricks (Figure 5a). It is characterized by a double band of a darker hue brick that runs longitudinally and forms rhomboid shapes, having a wider quadrangular pedestal. This chimney is the only example of such a decorated chimney in the province.
- (7) Irrigation water pond. For the irrigation of the sugar canecrops and for the steam engine operations, a water pond was built on the south factory facade. This oval-shaped pond stored water supplied by the Aguila aqueduct (Figure 5b).
- (8) Owners' residence. The last element initially corresponded to the owners' house, located in the west side of the enclosure, next to the main entrance to the sugar factory (7). Later on, this building would be used as the factory director's residence.

All the buildings had a gable roof. They were closed with wooden trusses. Currently, only the office roof remains. In general terms, the industrial set show a poor state of conservation and reconstruction actions are required. Particularly, the chimney shows different cracks that could end up with its destruction.

The Aguila aqueduct (Figure 6), located in the Maro ravine, was built to provide water to the crops from the Las Alberquillas aquifer. Furthermore, the aqueduct is related with the San Joaquin sugarcane factory due to the necessity of plenty of water for the production process. In spite of this, the aqueduct design was conceived a few years before the construction of the factory, and initially they shared the same owner. The aqueduct provided water at an average flow rate of 0.125 m³/s.

The aqueduct is 98 m long and 51 m high. The design has four levels or arches distributed with openings resolved in banded semi-circular arches, increasing the number of arches in each level. The arches are built with tile bricks held together with hydraulic lime mortar, inspired on the Mudejar style. In addition, the initial aqueduct design (Figure 6a) shows a series of pedestals on which seventeen balls originally rested but which have had disappeared nowadays.



Figure 5. (a) Factory chimney; (b) Irrigation water pond.

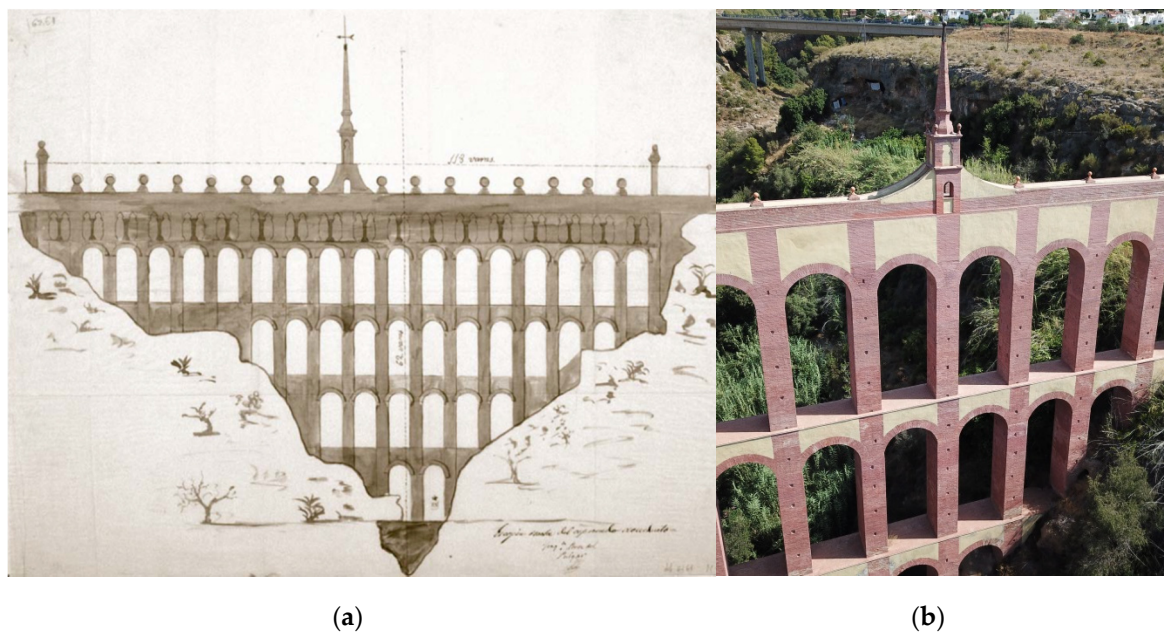


Figure 6. Aqueduct of the Aguila (a) Aqueduct design [56]; (b) Aerial photograph.

The entire aqueduct arches (Figure 7c) have 1.70 m radius, with a 3 m dome depth at the lower level, decreasing 0.35 m in each one. The aqueduct structure is finished off with a pinnacle on which a weather vane is placed (Figure 7a) in the shape of a double-headed eagle that gives name to the Aguila aqueduct. At the aqueduct central temple, the religious legend “Pura y Limpia Concepción” (Pure and Immaculate Conception) can be read [56]. Nowadays, the aqueduct belongs to the city council of Nerja, which restored it in 2012.

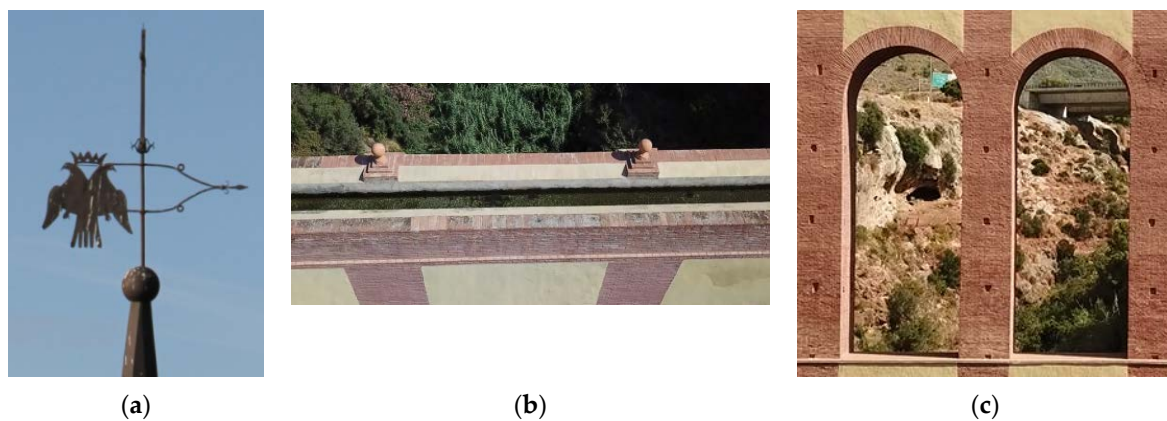


Figure 7. (a) Weather vane on the pinnacle; (b) aqueduct waterway; (c) arches.

4.2. UAV Flight Operation Analysis

The UAV flight operation was carried out in three sessions, due to the availability of three UAV batteries. The first flight operation was focused on the factory. Different orthophotographs (irrigation water pond, chimney, plot, etc.) and aerial photographs of the factory were taken. An additional video was recorded with factory landscape images.

The first part of the second flight operation was focused on the factory and different photographs from the chimney conservation state were taken. The second part was focused in the aqueduct, taking several photographs in different positions focusing in the general structure of the aqueduct (Figure 6b), the weather vane (Figure 7a), the waterway (Figure 7b) and the arches' characteristics (Figure 7c).

Finally, a video was recorded in a single shot around the aqueduct and the factory. The UAV was positioned in the mid-point between the aqueduct and the factory. The aqueduct was recorded initially, flying the UAV around it, in a south-north direction. Then, the land between the assets was recorded, paying special attention to the waterway. Finally, the factory was recorded, flying the UAV around it, in a north-south direction. This fact allows analysing the environment around the assets and following the waterway completely, from the aqueduct to the factory.

Regarding the factory, a poor state of conservation is observed. The building roof has completely disappeared, except from the office building, allowing one to appreciate the construction of the factory. In addition, the floor and many internal partitions of the buildings have been destroyed. In spite of this, the building envelopes still remain standing, which would allow their reconstruction, maintaining the main construction characteristics of the factory, except for the workers houses, located in the north of the enclosure, of which there are hardly any remains.

Furthermore, the main historical and cultural interest element, due to its singular decoration, is the chimney. It remains complete despite the observation of different cracks along its structure and the deterioration of its upper part (Figure 8). Two important cracks can be observed in the chimney structure. One of them is located in the central part of the structure (Figure 8a), oriented to the east. This crack runs vertical and horizontally, bordering each of the bricks and its unions. The other one (Figure 8b) is located at the upper chimney zone, oriented to the northeast, running vertically and bordering along the brick unions. Chimney zenith photographs (Figure 8c) show that some of the upper bricks have disappeared and others are loose, presenting a major fall risk.

This inspection allows considering the chimney conservation need. Despite that an imminent detachment of the chimney structure cannot be ensured, the lack of maintenance may cause this to occur over time.

The aerial photographs have allowed indirect measurements of different asset elements. Particularly, the chimney and the irrigation water pond measurements. The results are listed in Table 3.

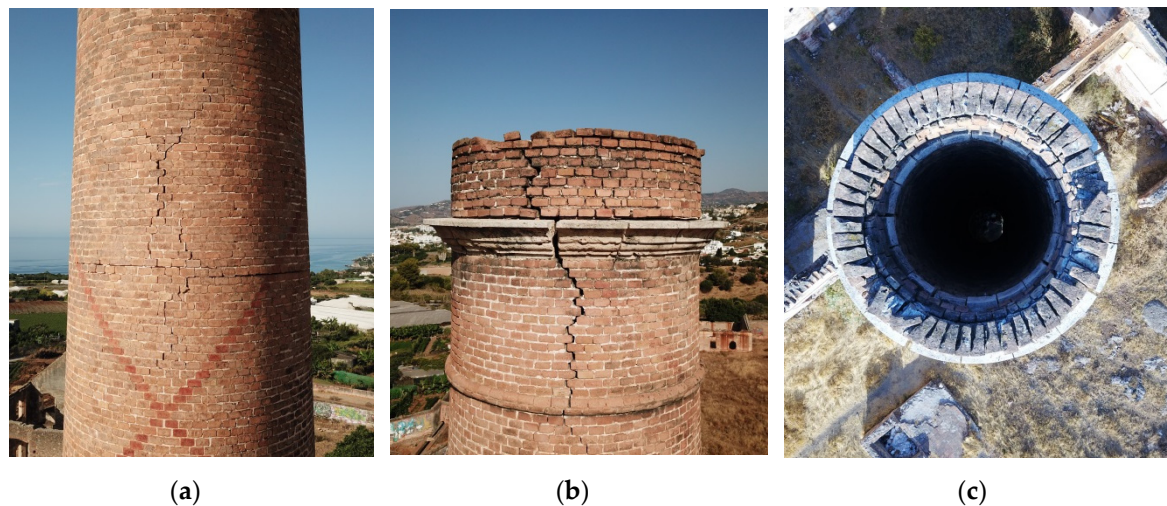


Figure 8. Chimney factory cracks (a) crack 1; (b) crack 2; (c) zenith photograph of the top of the chimney.

Table 3. Indirect measurements of chimney and irrigation water pond.

Element	Dimension	Value
Chimney	Length	22.47 m
	External bottom diameter	2.66 m
	External upper diameter	1.46 m
	Internal upper diameter	0.84 m
	Crack 1 length	2.06 m
	Crack 2 length	2.28 m
Irrigation water pond	Length	38.20 m
	Width	20.23 m
	Area	627.35 m ²

Possible errors in the dimensions measured from UAV photography depend on different variables: the distance between the UAV and the element to be measured, the visualization angle (cosine error) and the camera resolution. A higher error can be expected in the length of the irrigation water pond due to the longer camera distance from the photographed element. Taking into account the image size of the camera (4000×3000 , Table 2), the division between the length of the water irrigation pond in the photograph (38.20 m) and the image size (4000) one can estimate the maximum error obtained in the indirect measurement, which is 0.01 m.

To compare this with conventional camera errors, one should analyze how a certain dimension W_h is measured (i.e., width of a crack at a height h). In this case, the following variables could be used (Figure 9).

The values of θ_{cc} and l_{cc} affect the length obtained for the element in the photograph, reducing the value when θ_{cc} and l_{cc} increase. On the other hand, for the same resolution in the UAV camera and in the conventional camera (identical pixel size), the measurement is still a comparison between the number of pixels covered by the element, being lower in the conventional camera. In addition, the error obtained, is related with the measurement that represents a pixel, thus the error in conventional camera is higher than the one obtained with the UAV.

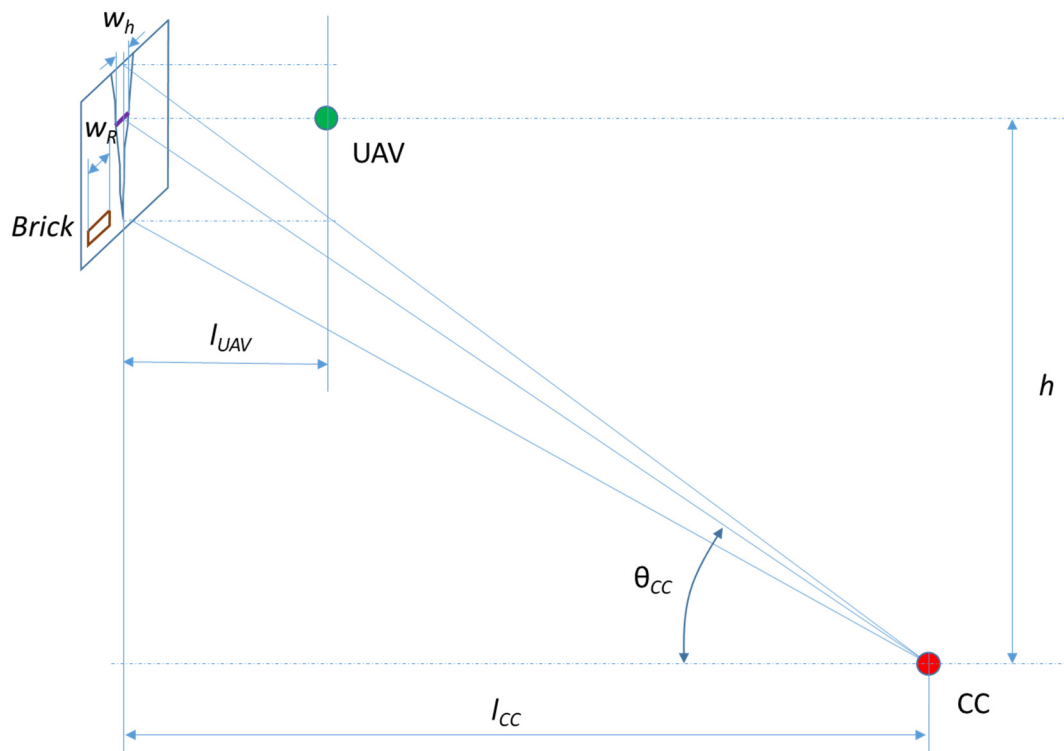


Figure 9. Comparison between conventional and UAV application photograph. The different variables are: CC: Conventional camera position; UAV: UAV position; h : UAV flight height; l_{UAV} : Distance from the UAV to the element to be measured; l_{CC} : Distance from the conventional camera to the element to be measured; θ_{CC} : Conventional camera angle observation with the element to be measured; W_R : Reference dimension.

It's important to highlight that the UAV has allow obtaining these measurements without the need of external elements, only using the flight operation. Nevertheless, a direct measurement of the chimney dimensions established in Table 3 or the inspection of the upper section requires an external structure or elevation equipment for a person to do that. This fact represents an important cost and a person's risk during the operation that is not generated during a UAV flight operation. Additionally, despite the fact the length and the width of the irrigation water pond can be measurement directly, the geometrical form makes the area measurement difficult. Therefore, the use of UAVs shows a clear opportunity to evaluate the conservation or to obtain measurements of singular elements in heritage assets.

Finally, the video recorded in a single shot shows the relationship between the factory and the aqueduct. This video has made it possible to monitor the canal that supplies water from the aqueduct to the factory. In addition, two aspects of interest have been observed, allowing understanding the location of both properties: the mountainous complex to the northeast of the aqueduct and the sugar factory, where the water was collected for irrigation, as well as the extension of the land facing south of the factory, where the sugarcane cultivation was carried out, presenting a downward slope that facilitates the irrigation of the crop without any need for pumping equipment and the distribution of water from the aqueduct to the factory, which is also located at a lower height.

4.3. Conventional and UAV Photography Comparison

The use of UAVs has shown different opportunities for application to industrial heritage studies. In spite of this, conventional photography is still widely employed in heritage analysis. In this section, a comparison between UAV application and conventional photography has been carried out. Different characteristics have been considered to compare them:

C1. Low equipment cost. Conventional camera technology is widely developed and nowadays, the acquisition costs of a conventional camera producing good quality images is low, around €90. On the other hand, a UAV with similar image acquisition potential costs €400. It is important to stand highlight out that the UAV system increases the cost due to the flight technology required.

C2. Image perspective possibilities. Conventional cameras only allow taking pictures on the ground. This fact prevents from one from obtaining images of elevated areas in heritage assets such as the status of the building roof, requiring external elements to achieve it. Nevertheless, the UAV can generate images from different perspectives, being the aerial perspective a resource to photograph areas that cannot be observed on the ground, and it requires shorter times in comparison with conventional photography.

C3. Accessibility. Occasionally, heritage asset structures are in a dilapidated state, so the access to its interior can be complex or can pose a risk to the user. In this sense, the use of UAVs enables one to access these complex areas without personal risk. On the other hand, UAV flight operation requires high pilot skill if the space is reduced.

C4. Indirect measurement. One usual action in heritage assets evaluation is to measure singular elements or the surface extension where the assets are located. Furthermore, the measurement of deteriorated elements allows to one to decide if conservation actions need to be carried out. Direct measurement of elements located in complex access zones or elements with high dimensionality require non-conventional measurement equipment, which is expensive. Indirect measurements using photographs and reference measurements can be considered a solution. However, simple photographs generate cosine errors in the indirect measurement. In spite of this, a set of images in different positions allows one to generate orthophotographs that represent a scale of the element in its true magnitude. In this case, the use of UAVs can generate images from different positions and allows one to obtain indirect measurements with high accuracy. In addition, zenith photographs of elements located at a ground level are more easily obtained from aerial images.

C5. Large area images. Heritage assets cannot be considered as an isolated element. The environment where the asset is located or the relationship between the different elements that the asset constitutes, provides information for the heritage analysis. Aerial images offer the possibility of to evaluating the assets completely. Furthermore, elevated points to take pictures allow one to represent the environment around the assets and observe or interpret the relationship it may have had with this environment. Conventional images taken on the ground, reduce the image extension or the presence of different obstacles can prevent it.

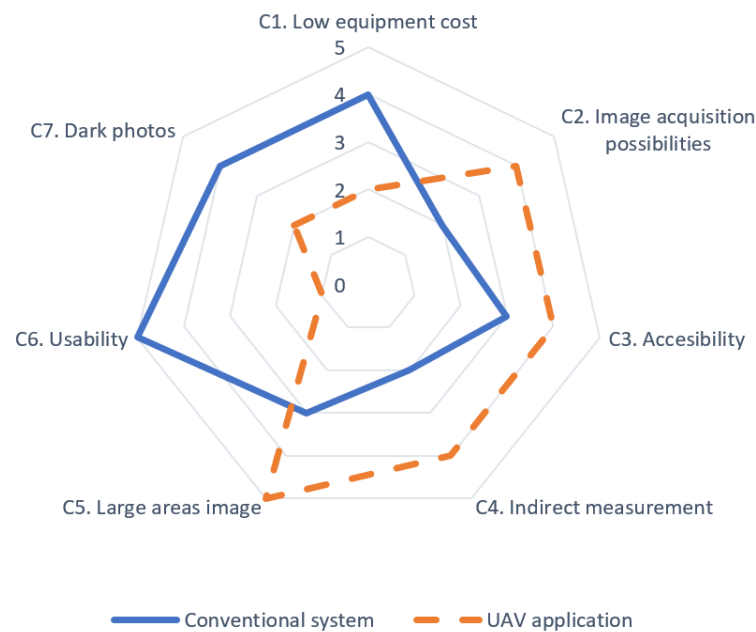
C6. Usability. Technology application require specific knowledge by the user. The use of conventional photographic equipment is a fairly widespread technology which does not require a deep learning to generate the images. On the contrary, although the UAV image capture system is similar to conventional camera technology, the UAV flight require special abilities and aeronautical knowledge that difficult its use. A great number of countries demand flight licenses to operate UAVs.

C7. Dark photos. In dark environments, the UAV flight and the image capture procedure become more complex due to the illumination system incorporated on the front of the UAV, generating dark spaces above and below the UAV. Conventional photograph cameras include flash systems that illuminate in the photograph direction, generating clear images in the darkness.

Using a metric scale between 1 to 5, with 1 corresponding with low agreement and 5 with high agreement, the different characteristic values listed in Table 4 can be observed. In addition, a comparison between the conventional and UAV photography has been presented in Figure 10.

Table 4. Characteristic values for conventional and UAV photography.

Characteristics	Conventional Photography	UAV Photography
C1. Low equipment cost	4	2
C2. Image acquisition possibilities	2	4
C3. Accessibility	3	4
C4. Indirect measurement	2	4
C5. Large areas image	3	5
C6. Usability	5	1
C7. Dark photos	4	2

**Figure 10.** Conventional system and UAV application comparison.

In general terms, the use of UAVs to photograph heritage assets allow more possibilities in heritage research than conventional photography. In spite of this, the need for a pilot license and the need for aeronautical knowledge, occasionally difficult the use of this technology. On the other hand, conventional photography is a simple to use and low-cost technology. Therefore, focused in heritage research, both technologies can be complementary and can capture images from different points of view that enrich the information obtained.

5. Conclusions

In this work, an analysis of the UAV graphic application in industrial heritage has been carried out. A general methodology to generate images for the heritage field, using UAV technology, has been performed. In addition, a SWOT analysis focused on the use of the UAV in heritage research has been developed.

Regarding the SWOT analysis, the UAV technology shows many possibilities for its application on the study of heritage assets in general and, specifically, for industrial patrimony assets, despite the different threats and weaknesses evaluated.

The general methodology proposed has been applied to generate images and videos in the San Joaquin sugarcane factory and in the Aguila aqueduct, which have been analysed. Both assets were related due to the aqueduct supplied water to the sugarcane factory. In this case, the use of the UAV has allowed to analyse them as a set of heritage assets.

The aerial images obtained represent all the elements that constitute the sugarcane factory, making it possible to identify its elements. Furthermore, aerial images have allowed the identification of different

cracks in the factory chimney and have been used to analyse its conservation state, conducting a first assessment of the most urgent restoration actions. Crack lengths have been measured from the images obtained and indirect measurements of the irrigation water pond surface has been performed.

Finally, conventional photography systems and the use of the UAV to generate images in heritage assets have been compared. The use of the UAV for graphic applications offers more possibilities than conventional systems, despite the complexity of the UAV usability. Nevertheless, both technologies can be considered complementary and applied together in heritage studies.

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