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USE OF UNMANNED AERIAL VEHICLES (DRONES) FOR THE AUSCULTATION OF HISTORIC ARCHITECTURAL FEATURES AND ANCIENT STRUCTURES

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Abstract: The use of unmanned aerial vehicles (RPAS), better known as drones, has been expanding in recent years with multiple and very diverse applications, among which are the inspections of architectural heritage elements, singular constructions and old or delicate structures. The present article arises precisely from several routine inspections, carried out in an experimental way on diverse heritage elements, and from a detailed main inspection, carried out on a medieval bridge: the Brandomil Bridge. With the completion of all of them and the information obtained, it will be possible to assess whether the aircraft can serve as a quality tool for carrying out the work that is currently carried out with qualified personnel, the transport and installation of expensive auxiliary means and a high economic and time investment, especially in the careful planning of the work. Similarly, special emphasis is placed on safety and risk reduction: safety and risk reduction for the monument to be inspected, and risk reduction for the safety and health of the workers currently performing the work.
Keywords: Drones, Heritage, Roman Bridge, Inspection, Heritage Conservation.

INTRODUCTION

Structural inspection is, from the beginning, an essential operation in the field of the conservation of any construction, having been applied particularly, and from the beginning, to the structural field. In essence, it is based on the checking, characterization and monitoring of the construction as a whole, as well as of each of the different elements that make it up, and may be accompanied, depending on the type and scope of inspection to be undertaken, by tests to complement the diagnosis made by visual inspection.

The different types of inspection were collected in the different guides developed by the Spanish Ministry of Public Works for the performance of inspections of road network crossing works (VVAA, 2009; VVAA, 2012). Thus, a distinction is made between:

- Routine inspection. This is a basic inspection carried out by non-specialized personnel, generally maintenance personnel. The Guide (VVAA, 2009) states that these inspections are carried out in all structures with a span of 1.00 m or more. Its purpose is to monitor the condition of the structures in order to detect apparent faults as soon as possible, which could lead to significant maintenance costs or, if not corrected in time, repair costs.

- Primary inspection. This is a more thorough inspection than the routine one, but it is still essentially visual. It must include an examination of all the elements of the passageway that are visible. Therefore, in many cases it will require the use of auxiliary means that make such observation possible. The need to use these extraordinary means of access (Figure 1) subdivides the main inspections into two categories (VVAA, 2012):

  - General main inspection, which consists of a detailed visual observation of all the visible elements that make up the bridge without the need for extraordinary means of access: the use of simple auxiliary elements is sufficient.

  - Detailed main inspection, in which it is essential to use extraordinary means of access that guarantee the possibility of inspection of all visible parts.

- Special inspection. This type of inspection, unlike the rest, does not have to be carried out systematically; it arises, as a general rule, as a consequence of damage detected in a main inspection or, exceptionally, as a consequence of a singular situation. In these inspections, in addition to a visual examination, additional tests and measurements are required, using special techniques and equipment. This level of reconnaissance always requires a plan prior to the inspection, detailing and assessing the aspects to be studied, as well as the techniques and means to be used.

Figure 1 - Inspection of the deck of a viaduct that crosses the Rías Bajas Highway (A-52), at the height of the municipality of A Gudiña, in the province of Ourense (photo by the author).

The above classification criterion has been extended to more areas than just road structures (Official State Gazette, 2005; ADIF 2020 a; ADIF 2020 b), hence the decision to present it here as a starting point.

On the other hand, a few years ago, the concept of pilotless aircraft or unmanned aerial vehicles emerged; these are aircraft that can be remotely controlled by the pilot or programmed and completely autonomous. The incorporation of certain accessories to this equipment, such as cameras for recording or capturing high-resolution images, and the development of increasingly precise and affordable microtechnology (Cuerno Rejado, 2015), opened the door some time ago to the possibility of incorporating drones for carrying out this type of inspections.

In recent years, in the field of civil engineering, many advances have been made and a large number of inspections have been carried out using drones (Rodríguez Elizalde, 2022 a; Rodríguez Elizalde, 2022 b); the results have been very satisfactory, as in many cases the work has been cheaper, faster and safer (Rodríguez Elizalde, 2022 a; Rodríguez Elizalde, 2022 c), hence the possible application of this tool to the field of heritage inspection is being considered (Rodríguez Elizalde, 2022 a; Rodríguez Elizalde, 2022 c).Figure 2).

Figure 2 - Quadcopter drone approaching for an inspection over the Ponte da Chanca, a railway viaduct located in the city of Lugo, which celebrated its 150th anniversary on December 20, 2021 (photo by the author).

OBJECTIVES

Based on the premise that the inspection of any construction is essential, as it allows to obtain the necessary data to know, at any time, its functional, resistant and aesthetic state, the main objective of this article is to check the applicability of drones for the performance of these inspections in the heritage field.

The author's experience and the analysis of a detailed main inspection, carried out by him on an engineering monument of great relevance and significance, the Brandomil Bridge, will serve as a basis for verifying the fulfillment of the objective established here.

MATERIAL AND METHODS

There have already been incursions and studies in various areas of application of the use of drones in the field of heritage conservation, especially highlighting the use of this equipment for photogrammetric flights that allow subsequent modeling and reconstructions (Domínguez Torrado, 2015; Rodríguez Elizalde, 2022 c).

There are many and very diverse types of drones currently available (Hernández Correas et al., 2019), so it is important to know in each case the most appropriate type of aircraft for each situation, and particularly for the performance analyzed here. Among all the classification criteria, the most interesting for this purpose is the one that takes into account the way the equipment is sustained in the air. In this way, a distinction is made between fixed-wing drones and rotary-wing drones (Oñate de Mora, 2015). Undoubtedly, the fixed-wing drone has great advantages that make it suitable for a multitude of applications, but its inability to perform a vertical takeoff and maintain a stable position in the air does not make it suitable for the inspection of an old construction, unless it is intended to take images of large surfaces, which is very rare.

Therefore, the type of drone used for the work contemplated here is usually a rotary wing drone, and more specifically a multirotor (Figure 2): these are drones with multiple propellers (always in pairs) that take off vertically and also have the ability to rotate on themselves, which makes them ideal for vertical work and to maintain a fixed position in suspension in the air, thus allowing a precise analysis to be carried out.

To test the validity of the drone for performing this type of inspections, the Brandomil Bridge, located at the following coordinates, was chosen as a sample:

- 43º 00’ 29.0” N.
- 8º 55’ 17.9” W.

The bridge is located in Galicia, in the municipality of Zas, in the province of A Coruña. It spans the course of the Xallas River. This bridge is especially representative because, although it does not currently support road traffic, it was part of the final section of the old road to Santiago, the one that communicates Santiago and Fisterra (Casado, 1969). It did fulfill the mission of fully supporting the passage of carriages along the overlying road until eighty years ago: in the forties of the twentieth century, a concrete bridge was built to relieve it a few meters upstream (Roseman, 1996). Through Brandomil, and specifically over this bridge, the pilgrims who had disembarked at the ports of Muxía and Fisterra, on their way to Santiago de Compostela, used to travel (Suárez, 2022). The width of the roadway over the bridge is 2.75 meters.

The bridge has four ashlar arches (Figure 3): three of them with the same span (8.20 meters), and the last one, at the south end of the bridge, with a considerably smaller span (4.30 meters). The piers, with sills rising to the crown (Figure 5), are very thick, about 3.00 meters. The two vaults on the right bank (Figure 3 and Figure 4) have double threads. Both the vaults and the tympanums and parapets are made of ashlar (Alcaide & López, 2013). Due to its characteristics, both constructive and aesthetic, the date of its construction is dated to the 17th century, although there is evidence of the existence of an earlier bridge in this same place (Casado, 1969).

Figure 3 - General view of the downstream elevation of the Brandomil Bridge, in an image captured with the multi-rotor drone used in the inspection of this article (photo by the author).

Figure 5 - General view of the upper part of one of the cutwaters of the Brandomil Bridge, in an image captured with the multi-rotor drone used in the inspection (photo by the author).

The existence of a fluvial current under the bridge, such as the Zas River, its geometric dimensions and the inaccessibility of certain areas (the two central piers penetrate the water of the river), made the Brandomil Bridge a perfect structure to verify the validity of the use of a drone for the inspection of this heritage construction. Apart from this, the beauty, relevance and historical and patrimonial value of the bridge were taken into consideration, which undoubtedly gave an added value to the inspection carried out: its great historical and archeological interest, as well as its engineering and pathological interest reaffirmed this idea.

Figure 6 - Multi-rotor drone used in the inspection of the Brandomil Bridge, entering the interior of the minor arch vault for inspection from the upstream side of the bridge (photo by the author).

Figure 4 - General view of one of the major arches of the Brandomil Bridge, in image captured with the multi-rotor drone used in the inspection from the downstream side of the bridge (photo by the author).

Figure 7 - Multi-rotor drone used in the inspection of the Brandomil Bridge, approaching the upstream elevation of the bridge for inspection of various constituent elements (photo by the author).

As mentioned in previous sections, a quadcopter drone was used for the inspection of the Brandomil Bridge (Figure 6 and Figure 7), which was able to approach all visible areas of the bridge, whether they were accessible or not, the images above show the four-propeller drone used, analyzing in suspension the interior of the smaller vault of the bridge (Figure 6) and approaching one of the larger vaults over the course of the river for reconnaissance (Figure 7). The equipment incorporated a high-resolution camera with zoom and allowed the capture of the images shown below, which could constitute a complete photographic report with the most outstanding observations during the flight.

In addition, it should be taken into account that one of the hallmarks of this bridge is the use of the minor round arch as a guideline for its vaults, as opposed to the common Roman use of the arch. Given the low deflection of the smaller vault, access to its interior for the analysis of the state of the soffit was somewhat complicated (Figure 6), hence the interest of introducing a drone. It is true that there are points in galleries where access can be much more complicated than in this one, since here the width of the vault is 4.20 m and in case of need an operator could access to perform the relevant inspection; but this experience serves to demonstrate that the drone can perform this function perfectly well, without having to put the safety of any professional at risk and obtaining perfectly valid results and even better than those that could be obtained by an operator.

RESULTS AND DISCUSSION

In general terms, the bridge was in an adequate state of preservation. The inspection verified the existence of efflorescence, although in a very slight proportion: such lesions were observed in the soffit of some of the vaults and in the elevation of some piers or abutments. Efflorescence is usually concentrated around areas where there is a high concentration of humidity. Since it is a river bridge located in the Galician region, it is evident that it is in a location where humidity is high.

The soffit of the vaults is undoubtedly the most critical point from the pathological point of view and also the most difficult to access for inspection by manual means. As can be seen (Figure 8), all the elements that make up the vaults are made of granite, with ashlars and voussoirs dry-laid, being the rounding of the vertices, characteristic of the alteration of the granite (García de Miguel, 2009), one of the most remarkable aspects.

Figure 8 - General view of the downstream elevation of the Brandomil Bridge, in an image captured with the multi-rotor drone used in the inspection of this article (photo by the author).

The granite constitutive of the monument presents, in the interior of the vaults, certain deteriorations as a consequence of the synergy of actions of diverse nature, fundamentally chemical and biological. Thus, the formation of several black crusts can be observed

(Figure 8), presumably linked to the action of contaminating agents (particularly sulfur compounds). Together with these crusts, there is an abundant presence of biocolonies (plants), which have grown rooting in the joints between the ashlars, especially in the joints of angular points (Figure 9 and Figure 10), which enter in feedback with the phenomena of humidity, efflorescence and runoff water, as reflected by certain observed stains.

Also linked to the humidity is the proliferation of small carbonation crusts, detected in the interior of the vaults: in this case, they are crusts due, fundamentally, to the dissolution of calcium carbonate coming from the mortar placed between the ashlar joints. The dark marks of runoff water, observed in some points of the bridge, are linked to this process of development of black crusts.

In this regard, it should not be forgotten that crusts and, to a much greater extent, efflorescence are manifestations resulting from the crystallization of salts, which usually agglutinate around points where there is a high concentration of humidity; this anomaly is triggered by the crystallization of soluble salts present in solution in the porous system of the masonry (García de Miguel, 2009).

In principle, the damage described above is not structural damage, but damage related to the durability of the materials used in construction. When we speak of damage related to the durability of the material that makes up an element, we are referring to the injuries that arise from the interaction of the deteriorated material with the environmental conditions imposed by the environment in which the element is installed. In other words, the durability of a material can be understood as its capacity to resist the action of the environment, which includes all chemical, physical, biological attacks, or any other environmental process that tends to deteriorate it.

In other words, these are not lesions that affect the integrity of the monument in the short term, but they can lead to more serious damage, such as alveolization or even sandblasting of the stone material, if they continue to develop. The particular detection of efflorescence, on the one hand, shows that a process of chemical degradation is taking place, although of little danger; and, on the other hand, it is a warning that internal mechanical stresses of some consideration may be being generated, due to the crystallization processes of the salts.

Figure 9 - General view of the smaller arch of the Brandomil Bridge, seen from the upstream side, in an image captured with the multi-rotor drone used in the inspection, where the abundant presence of vegetation rooted in the multiple elements can be observed (photo by the author).

Figure 10 - view of one of the major arches of the Brandomil Bridge, seen from the upstream side, in an image captured with the multi-rotor drone used in the inspection, where the abundant presence of vegetation rooted in the multiple elements can be observed (photo by the author).

This section closes by reiterating the presence of vegetation rooted in the joints between the ashlars (Figure 9 and Figure 10). Because of the humidity, and given the susceptibility of the granite to biological attack, the drone was also able to record films or mottling, resulting from the accumulation of plant microorganisms, such as moss or similar (Figure 9 and Figure 10).

However, although none of the damage compromised the safety of the monument, the drone allowed the location and diagnosis of such injuries, given that many of them were not visible from the position of a passerby. In addition, the inspection with the unmanned aircraft provided graphic documents that, in subsequent inspections, will make it possible to assess the evolution of the damage and thus estimate the relevance of a possible restorative intervention.

CONCLUSIONS

The results of the inspection carried out show that the use of a suitable drone allows a detailed and complete visual observation of all the visible, accessible and non-accessible elements that make up a monument of a certain size. With this tool, it is not necessary to resort to extraordinary means of access, as would have been necessary if the multirotor aircraft were not available.

Therefore, in light of the experience gathered here, the following can be concluded:

1. The drone simplifies planning work by reducing the planning and acquisition of access aids.

2. The drone simplifies the field work, in order to identify and assess the deterioration of each of the constituent elements of the monument.

3. The above simplifications allow the work to be carried out more quickly.

4. The drone reduces a considerable part of the risk of damage to the monument. The Brandomil Bridge preserves its primitive form which, like any other construction, needs care for its proper conservation. The drone has proved to be a very effective tool in this regard, not coming into contact with the monument at any time.

5. The drone reduces all kinds of risks to the safety of workers who would have to collaborate in inspections, given the danger inherent in the use of certain auxiliary means to access certain elements of the structure: with a drone, no worker has to, for example, expose himself to the risk of falling from a height.

6. The above five points justify a considerable economic saving, which does not imply a decrease in the quality of the work.

With the data collected with the drone, as exemplified here, a complete technical report of the inspection can be generated in the office, in addition to providing the relevant information for its incorporation into a management system and to obtain the condition indexes of each of the elements and of the construction as a whole, to assess whether any urgent action is required or to verify, through regular verification of the injuries detected by means of periodic flights, the evolution of such injuries.

It goes without saying that the experience of the experimental inspection carried out for the preparation of this article can be extrapolated to many other works of identical nature, which opens up an infinite range of opportunities for these small devices that have undoubtedly come to stay and to change the way of inspecting singular elements.

FUTURE LINES OF RESEARCH

This article has focused exclusively on the use of drones in the field of inspection of heritage elements. The images, and even the videos, that are captured with the cameras incorporated in a drone can be used as visual documents for multiple other purposes that go beyond the inspection analyzed here.

The incorporation of other sensors, of a visual or thermal nature, can be used to locate invisible lesions or to better understand the origin of visible lesions for which initially no explanation can be found. In this case, we would enter the realm of special inspection, as discussed in the Introduction, using indirect tests that would not cause any deterioration to the monument under analysis (Figure 36).

The drone can also be of great help in the geometric reconstruction of an element from the photographs obtained during photogrammetric flights. This requires extensive knowledge of data capture, which is beyond the scope and objective of this article, since it is necessary to obtain measurable data (whether two-dimensional or three-dimensional) and the subsequent processing of the data collected for modeling and reconstruction.

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