ISSN: 0975-833X

Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 14, Issue, 07, pp.21954-21960, July, 2022
DOI: https://doi.org/10.24941/ijcr.43791.07.2022

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

RESEARCH ARTICLE

USE OF RPAS (DRONES) FOR MASONRY ARCH BRIDGES INSPECTION: APPLICATION ON GRAJAL BRIDGE

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ARTICLE INFO

Article History:
Received 19th April, 2022
Received in revised form
15th May, 2022
Accepted 24th June, 2022
Published online 30th July, 2022

Key words:

Drones, Heritage Buildings, Inspection, Structure, Mediaeval Bridge.

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ABSTRACT

The use of remotely piloted aircraft systems (RPAS), better known as drones, has spread with multiple and very diverse applications in recent years. It includes architectural heritage elements inspections, singular constructions inspections and old structures inspections. This article is based on a detailed inspection over a medieval bridge, which is located next to another 19th century bridge that currently supports road traffic. This inspection had a purely experimental purpose. With its completion and with the information obtained, we will be able to have enough information to assess whether the aircraft can serve as a quality tool for carrying out these works, considering that these works are currently carried out by qualified personnel, requiring transportation and installation of cumbersome auxiliary means and a high economic and time investment, especially in the careful planning of the works. Similarly, there is an emphasis on safety and risk reduction: safety and risk reduction towards the monument to be inspected, and risk reduction for the safety and health of the workers who inspect the monument.

Citation: ***Rodríguez Elizalde, Rubén.* 2022**. "Use of rpas (drones) for masonry arch bridges inspection: application on Grajal Bridge.". *International Journal of Current Research*, 14, (07), 21954-21960.

INTRODUCTION

On July 7th, 2022, the author of this article participated in a medieval bridge detailed main inspection. Its purpose was purely experimental: to verify the drones applicability to carry out this type of inspection. In fact, this intervention was based on the conviction that the inspection of structures is essential, because it allows obtaining the necessary data to know the functional, resistant and aesthetic state of a structure at any given time. At the same time, using a drone, the work is much cheaper and faster and safer for the workers as well. Structural inspection is an essential operation to preserve any construction. This has been applied particularly, and from the outset to the structural field. In essence, it is based on checking, characterizing and monitoring the construction as a whole, as well as each of the different elements that make it up. Depending on the type and scope of the inspection carried out, this inspection may be accompanied by tests that complement the diagnosis made through visual inspection. The Bridge is in Spain and, therefore, the inspection was in Spain. For this reason, we are going to consider the Spanish Ministry criteria (Ministerio de Fomento) to classify the different inspections. Thus, we have (1) (2):

- Routine inspection. It is a basic inspection performed by unqualified personnel (usually maintenance staff). This inspection objective is to monitor the structures state properly and detecting apparent damages as soon as possible. We must be clear that if this damage is not detected on time, they will involve significant maintenance costs or, if they are not corrected in time, repair costs.
- Main inspection. It is deeper than routine inspection, but essentially visual as well. It includes all visible building elements examination. Therefore, in many cases, we need auxiliary means that allow us to reach certain elements for observation. The need to employ these means of access subdivides main inspections into two categories (2):
- General main inspection: detailed visual observation of all the visible elements of the construction, without the need for extraordinary means of access (only simple auxiliary elements).
- Detailed main inspection: the use of extraordinary means of access to inspect all visible elements is essential.
- Special inspection. Unlike the previous two, this inspection is not systematic. This inspection usually

arises as a result of the damage detected in a main inspection or, exceptionally, as a result of an exceptional situation. In addition to the visual examination, these inspections carry out complementary tests and measurements, using special techniques and equipment. It is therefore the most complex and complete of the three.

The previous classification criterion has been extended to more areas than road structures (3) (4) (5). This is the reason to present it here as a starting point. Obviously, there are many other classification criteria followed by other institutions and organizations that could be applied for this same purpose (6) (7) (8). On the other hand, the concept of aircraft without an onboard pilot, Unmanned Aerial vehicle (UAV) or Remotely Piloted Aircraft System (RPAS), emerged a few years ago. All of them are synonyms; all of them are referred to drones. The incorporation of some accessories to these aircraft (recording cameras or high-resolution image capture) and the development of increasingly precise and affordable micro technologies (9) allowed drones to be incorporated into the inspections framed in the previous classification a few years ago. The results have been very satisfactory: in many cases, a cheaper, faster and safer job has been achieved (10). For this reason, this article propose this tool application to heritage buildings inspection. In this case, as the inspection was exclusively visual and a drone was used as auxiliary mean (if we had not used the drone, we would have had to use extraordinary means of access to be able to analyze some elements of the Bridge), according to the previous classification, the inspection what we are going to present next was a detailed main inspection

MATERIALS AND METHODS

The bridge inspected was the "Puente del Grajal" (Fig. 1). It is a Bridge located at the following coordinates:

- **Latitude:** 40º 31' 9.12" N
- **Longitude:** 3º 47' 20.8" S

The Bridge is more than a thousand years old: it was built in the Middle Ages, during the Muslim domination of the Iberian Peninsula. Between the 9th and 11th centuries, the bridge was part of a military road in the Muslim Andalusian kingdom, which linked two border posts of great defensive importance (11) (12). It is possible that its original origin was Roman and it was associated with a secondary Roman road with transversal development that crossed where the bridge was built (13).

Fig. 1: Photograph taken with the drone used in the inspection, where we can seethe Grajal Medieval Bridge, north elevation, with the nineteenth-century bridge behind it (photograph by the author)

It is a bridge built with granite masonry. Only the vault voussoirs and the arch ring are regular ashlars (Fig. 3), in contrast to the external spandred wall masonry and the parapet masonry. It is configured with a round arch, with 10 m span. The deck is 3.34 m wide. This width is equivalent to 6 rassassíes cubits, one of the most used measures in Islamic bridges. It still preserves the original pavement of large stone slabs located in a typical profile of "donkey's back" (with a raised ridge) characteristic of the Middle Ages (14). The Bridge is founded directly over the rock, and it is excellently preserved. The Bridge was remodeled during the 18th century, through an operation that slightly altered its appearance. It has been recently restored after, in 2013 (15). Due to the Bridge limitations, another single-arch bridge much more modern was built in 1895 (11) (12), next to the first one, downstream (Fig. 1). This new bridge supports the vehicles circulation on the overlying road (Fig. 2).

Fig. 2: Roadway over the medieval bridge (right) and traffic road over the nineteenth-century bridge (left). It gives an idea about the separation between the two bridges (photograph taken by the author)

There are many and very diverse types of drones today (16). For this reason, it is very important to know in each case the most suitable type of aircraft for each situation. Among all the classification criteria, the most interesting for us is the one that attends to the form of support of the equipment in the air. Thus, we distinguish between fixed-wing drones and rotary-wing drones. There is no doubt that a fixed-wing drone has great advantages that make it suitable for many applications (17). However, its inability to perform a vertical takeoff and maintain a stable position in the air makes it unsuitable for inspecting old construction (unless we need to image large areas, which is very rare). For this reason, the drone used for the works analyzed here is usually a rotary-wing drone, and more specifically multirotor (18): they are drones with multiple propellers (always pairs) that take off vertically and can rotate on themselves. This makes them ideal for performing vertical work and maintaining a certain fixed position in suspension in the air, in order to allow an accurate analysis to be carried out. The existence of a fluvial current, Manzanares River, the Bridge geometric dimensions and the inaccessibility to certain areas of the Bridge, made the Grajal Bridge a perfect structure to verify the validity of the multirotor drone use for anheritage building inspection.

Fig. 3. Drone approaching to the medieval Bridge for its inspection (photograph taken by the autor)

Besides, there would be the consideration of the beauty, the relevance, the historical value and the patrimonial value of the Bridge: they increase the value of the inspection carried out. For this reason, a quadcopter drone was used for the inspection. It was able to approach visible areas of the Bridge, but not accessible, making a photographic capture of the most outstanding observations made during the flight. Next, we can observe the four-propeller drone used approaching the bridge (Fig. 3), to analyze the points of greatest interest from suspension.

RESULTS

Once the inspection began, the first thing was to analyze the foundation. The drone allowed us to approach it, because here it was partially visible (Fig. 4). Thus, we have been able to verify that the abutments of the bridge rest on a base of granite, a material identical to that which makes up the masonry of the bridge. The foundation and the base of the vault were in good condition (Fig. 4). The drone was useful for a detailed visual inspection of the foundation (at least, the visible part). Thanks to this, we were able to verify that the bridge is effectively founded directly on solid rock. It was the usual procedure in the Middle Ages (19). In addition, with the incorporated technology, the aircraft can estimate the type and dimensions of the foundation element and help us with other important operations in this type of structure, such as approximate estimation of the type of terrain, estimation of the longitudinal profile of the riverbed, estimation of the cross section upstream and downstream of the bridge, determination of the degree of cleanliness of the channel and setting out of the drag elements in it. After analyzing the foundation, we continue with the structural inspection of the rest of the elements. The most interesting point was the vault intrados. The intrados is interesting because of the damage found on it and it is also interesting because of its inaccessibility. In order to carry out a complete visual inspection of the intrados, we would need to enter the river, swimming or sailing on a boat. But in none of these cases could the level of approach to the top that the drone allows be achieved. The monument constitutive granite presents deteriorations in the intrados, due to the actions synergy of diverse nature: chemical nature phenomena and biological nature phenomena. Thus, we observe various black crusts formation, especially in the outer ashlars (Fig. 5 y Fig. 6), presumably linked to the contaminating agents action and especially to the river humidity. We know that this Bridge has been restored a few times: the last one was in 2013(15).

Fig. 4. Photograph taken with the drone, where the found ations of the easternabutment of the Medieval Bridge can be seen (photograph taken by the author)

The use of lime mortar in the last restoration could have increased this damage. In addition to the dark crusts, we can see blackening spots. This damage is characteristic of structural elements exposed to high humidity as well. These stains result from the joint action of water (humidity), the crystallization of salts provided by contaminating agents and granite masonry (20). The inspection allowed to locate efflorescences in the intrados vault central area. They were those whitish spots that we can observe (Fig. 5 y Fig. 6). Efflorescences usually appear around areas where there is a high concentration of humidity as well. In this case, the cause of efflorescence seems to be related to the use of lime mortar as well (20). Thus, every microcrack that appears on the lime mortar joints can become an open door for water access to the interior of the masonry. As the Bridge is in a humid environment, there is much more water and, therefore, the amount of water that enters the masonry through the joint is greater (21).

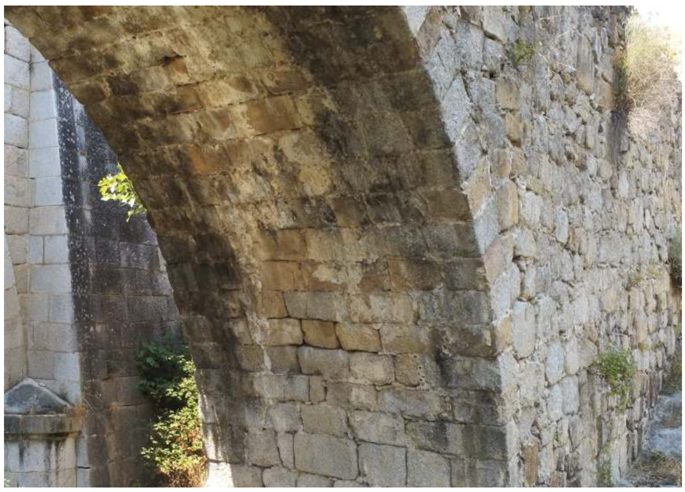

Fig. 5: Image captured with the quadcopterdr one at the western start of the vault, where various lesions can be observed, such as efflorescencesordarkcrusts (photograph by the author).

This water access may be prior to a subsequent attack by salts and ice (20). We have detected rooted vegetation in a lot of joint points of the Bridge (Fig. 7). This is the best proof that these micro cracks exist in the mortar joints. The most curious thing of all, is that this mortar was used to restore surely to prevent plants from taking root between the masonry (21).

Fig. 6. Image captured with the quadcopterdr one at the eastern start of the vault, where various lesions can be observed, such as efflorescence or dark crusts (photograph by the author

We must remember that crusts and especially efflorescences are result from salts crystallization. These salts tend to agglutinate around points where high concentrations of moisture occur. This anomaly is produced by soluble salts crystallizing, dissolved in the granite porous system (20). The drone was effective in detecting efflorescence and in detecting possible salt (22) sources as well (coming from the masonry itself or from external agents-pollution, materials from previous interventions, etc.). In the upper part of Bridge intrados, in addition to the aforementioned damage, we discovered, thanks to the drone, the blistering and sanding of several voussoirs (Fig. 7). This alveolization process is directly related to the previous processes: humidity and salts can cause this deterioration as well. Generally, this appears at the confluence of internal waterways (from the extrados to the intrados, through the fill, due to poor drainage) with the erosive action of the wind (21). Therefore, they are located in exposed areas where moisture accumulates, as is the key to the vault. There, the exit routes of the internal water and the desiccation surface join. Once the process is started, the eddies of wind in the cavity accelerate it (20).

Fig. 7: Image captured with the quadcopterdr one in the intrados of the upper part of the vault, where in addition to the previous injuries Fig. 5 y Fig. 6) we observed vesiculation of ashlars (author's photograph)

Along with these damages, we observe abundant presence of biocolonies (plants). They have grown taking root in the joints that are arranged between the masonry, especially in the joints of angular points (Fig. 8).

Fig. 8: Image captured with the quadcopterdrone, where you can see vegetation (a fig tree) rooted in the joints of the masonry (photograph by the author)

Fig. 9. Image captured with the quadcopterdr one in the intrados of the vault of the new bridge, with lesions identical to those of the medieval bridge being observed: efflorescences or dar kcrusts (photograph by the author)

Fig. 10: Image captured with the quadcopterdrone, where a detail of the west abutment can be seen, with root edvegetation, black crusts and run off watermarks (photograph by the author).

This vegetation enters into feedback with the phenomena of humidity, efflorescence and runoff water, according to what the observed stains reflect (for example, the black spots we observed in the spandred wall, Fig. 3). Special care must be taken with vegetation, especially the larger ones, due to the action of tree roots and other plantations on the factory (21). Drone can help us to control the vegetation appearance and the plants growth. The damages previously collected are not structural damages. They are damage related to the durability of the materials that make up the construction. In other words, they are not injuries that affect the integrity of the monument, at least in the short term. However, they are injuries that can end up in more serious damage if they continue to develop. Proof of this are the sandstone voussoirs. When we talk about damage related to the durability of the material that makes up an element, we refer to damage that arise from the interaction of deteriorated material with the environmental conditions imposed by it. In other words, the material durability must be understood as the material ability to resist the environmental action. It includes all chemical, physical and biological attacks, or every other environmental process that tends to deteriorate the material. The presence of efflorescence indicates two important aspects (20) (21): the first one, in some masonry, a process of chemical degradation is taking place, in principle not very dangerous. The second of them, important internal mechanical stresses due to the crystallization of the salt may be generating, depending on the masonry porous system. Drone can help us, through subsequent inspections, to study such pathologies. When two (or more) old and heritage buildings are close together, they are made of the same materials. This is due to the transport limitations that existed in the past. This fact made this construction especially interesting: the 19th century bridge erected next to the medieval one, with identical materials, should have suffered the same damaging processes, although to a lesser extent. Indeed, the drone allowed to corroborate the above. The vault of the nineteenth-century bridge showed the same injuries, although with different intensity (Fig. 9): black crusts, runoff water marks and efflorescence. On the walls, there were also black crusts and runoff water traces, in synergy with vegetation rooted in the joints between ashlars (Fig. 10). The only injury of this bridge, which was not included in the old Bridge, was an anthropic vandalism injury: a graffiti on the east abutment wall (bottom left of Fig. 9). It is a damage to take into account, given the deterioration caused by the graffiti products (41).

DISCUSSION

The previous sections have exposed the carrying out of a reconnaissance technical inspection on a Medieval Bridge. Routine inspections or main inspections, especially detailed main inspections, require a visual check, by a specialized operator, of all visible elements of the structure, whether they are accessible or not. This condition of inaccessibility can lead to the need to use extraordinary means of access, which guarantee the inspection of every visible part (Fig. 11). These means of access are cumbersome, difficult to transport, economically expensive and, what is even more important, their use always poses a risk to the safety of the worker who must use them or climb on them in order to access those parts of the monument that, although visible, are more difficult to access. Indeed, visual inspections of structures, when carried out directly by personnel, usually require the use of mobile work teams that move people to a certain position, which allows the inspection to be carried out. The use of these auxiliary means implies the coexistence of workers with risks such as falling to the same or, above all, to a different level, the equipment overturning, the fall of materials on people or goods, blows, shocks or entrapment of the operator or of the machine itself against fixed or mobile objects; entrapment between any of the moving parts of the machine's structure and between it and the chassis, to name just a few examples. Practically all of these risks disappear when the inspections are carried out with drones, the case of falling from a height being especially significant for this purpose, as it is unnecessary for any operator to have access to this type of auxiliary means or have to go down to access to complex points. Apart would be the damage that can be caused to the monument.

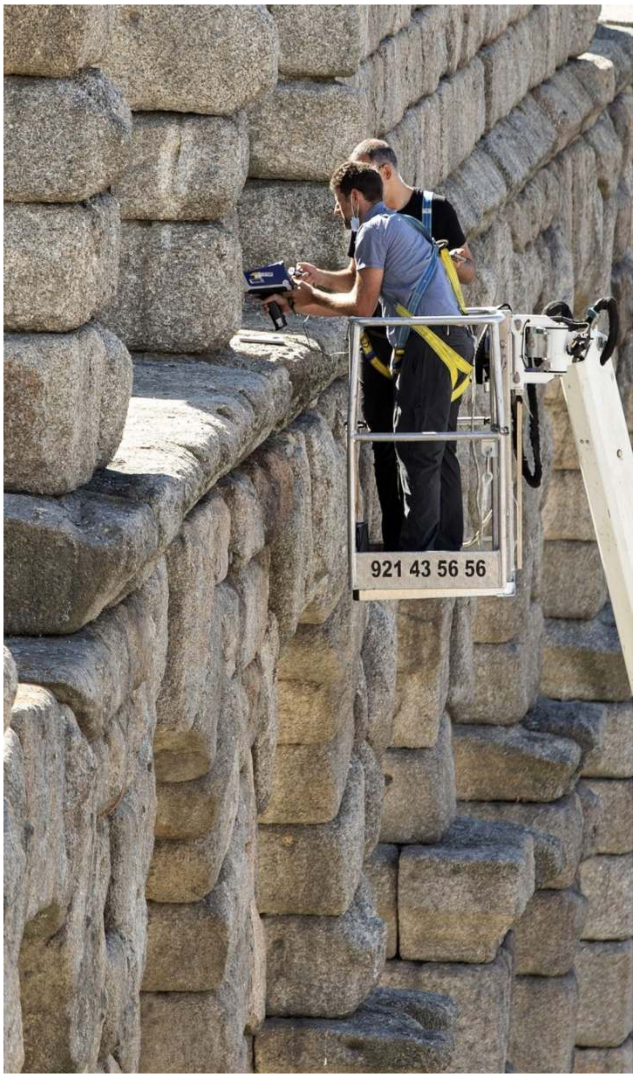

Fig. 10. Image of a check-up inspection (special inspection) of the Segovia Aqueduct: two workers from the Spanish Geological and Mining Institute (IGME) take data from granite that makes up the stone a shlarsforit sgeo chemical characterization (photograph by Rosa Blanco [24]).

CONCLUSION

Thanks to the visual inspection carried out with the drone, we were able to have a complete photographic report of all the visible elements of the Bridge. This photographic report has allowed us to diagnose all the injuries suffered by the viaduct. Fortunately, none of these deficiencies are serious and there is no safety hazard to the monument. The photographs can now be stored and used as a reference for future inspection. With the photographs of future inspections, we could analyze the evolution of the damage detected or diagnose the appearance of new damage. The inspection results shown that the use of a suitable drone allows perfectly detailed visual observation of every visible elements, accessible and non-accessible, that form a heritage construction, such as Puente del Grajal. With this tool, it has not been necessary to resort to extraordinary means of access, as if they would have been necessary if the drone was not available. Therefore, based on the experience gathered here, the following conclusions can be drawn:

- The drone simplifies planning work, because it reduces the planning and acquisition of auxiliary means of access.
- The drone simplifies field work, for the identification and assessment of deterioration of each of the constituent elements of the monument.
- We can work faster thanks to the two previous simplifications.
- The drone reduces a lot of risks for the safety workers who should collaborate in the inspections. We must think in the danger inherent to the use of certain auxiliary means to access to certain structure elements: with a drone, no worker has to, for example, exposing them self to the risk of falling from height.
- The four previous points justify a considerable economic saving, which does not imply a decrease in the work quality.

With the data collected with the drone, as this article exemplifies, we can generate a complete technical report of the main inspection in the cabinet. In addition, we can also supply the relevant information for its incorporation into a possible management system and obtain the status indices of each element and of the entire construction as a whole. With this, we will be able to assess whether some type of urgent action is necessary or whether, as in this case with practically all the injuries detected, periodic control of the damage detected is sufficient for now.

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