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USE OF RPAS (DRONES) FOR OLD BRIDGES INSPECTION: APPLICATION ON PONTE OLVEIRA 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 of a 16th-century bridge, retrofitted to support current road traffic sixty years ago. This inspection was exclusively experimental. With its completion and with the information obtained, we got enough information to assess whether the aircraft can be useful for carrying out these works. We must consider 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, we focus on health andsafety workers and their risk reduction.We must consider safety and risk reduction towards the monument to be inspected, and we must also consider risk reduction for the safety and health of the workers who inspect the monument.

Keywords: Drones, RPAS, Inspection, Structure, Old bridge masonry.

INTRODUCTION

On August 9th and 10th, 2022, the author of this article participated in an old bridge detailed main inspection. with the exclusively experimental purpose of verifying the applicability of drones to carry out this type of inspection. In fact, this intervention was based on the author's 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. An inspection is essentially based on checking, characterizing, and monitoring the structure as a whole and 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. As the inspection was carried out in Spain, the Spanish Minister criteria has been considered (Ministerio de Fomento, 2009; Ministerio de Fomento, 2012). Obviously, there are many other classification criteria followed by many other institutions and organizations that could be applied for this purpose (Ministère des Transports du Québec, 2010; Department of Transportation, 2017; Washington State Department of Transportation, 2022). So, different types of inspection included in the various guides developed by the Spanish Ministry of Public Works (Ministerio de Fomento) to inspect the road network step structure are the following (Ministerio de Fomento, 2009):

1. Routine inspection. It is a basic inspection performed by unqualified personnel. These personnel are usually the structure maintaining workers. According to the Guide, these inspections are carried out on every structures with a span of 1.00 m, or more of course, to properly monitor their condition and thus detect apparent failures as soon as possible. If these faults are not detected on time, they could lead to significant conservation costs or repair costs, if they are not corrected on time.
2. Main inspection. This kind of inspection is deeper than routine inspection; however, it is essentially visual still. It must include every structure visible elements examination. It implies the possible need to use means auxiliary of access. Therefore, depending on its complexity, the main inspection is subdivided in two possible categories (Ministerio de Fomento, 2012):
    a. General main inspection. This inspection consists in a detailed visual observation of every visible elements, without the need to use extraordinary auxiliary means of access. In other words, means more complex and more expensive than, for example, a manual climbing ladder.
    b. Detailed main inspection. In this inspection, unlike the previous one, it is essential to use extraordinary means of access that allow the inspection of all visible parts. In this sense, we have to differentiate between accessible and visible: an element can be visible and not accessible or easily accessible.
3. Special inspection. This kind of inspection, unlike the rest, does not have to be done systematically. This kind of inspection generally arises as a result of damage detected in a main inspection or, exceptionally, as a result of a singular situation. In these inspections, in addition to the visual examination we have previously mentioned, we will need complementary tests and measurements, with special techniques and equipment. This level of recognition requires a plan prior for the inspection, detailing and assessing the aspects will be studied, the techniques and the means to be used as well.

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It should be noted that the previous classification criterion has been extended to more areas than road structures (BoletínOficial del Estado, 2005; ADIF, 2020 a; ADIF, 2020 b). This is the reason why it has been decided to present it here as a starting point.On the other hand, the concept of aircraft without an onboard pilot, Unmanned Aerial vehicle (UAV) or even Remotely Piloted Aircraft System (RPAS) as well emerged a few years ago. All of them are synonyms;

all of them are referred to drones; all of them refer to aircraft that can be controlled by the pilot remotely or that can be programmed, being completely autonomous.The incorporation of some accessories to these aircraft, such as recording cameras or high-resolution image capture, and the development of increasingly precise and affordable micro technology (CuernoRejado, 2015) opened the door to the possibility of incorporating drones to carry out these inspections for some years. In recent times, many advances have been made in civil engineering and this has led to the incorporation of drones to the inspections framed in the previous classification. Thus, to carry out the inspection, a drone was used. In other words, the inspection was exclusively visual, and a drone was used as an auxiliary mean.If we had not used the drone, we would have had to use extraordinary means of access to be able to analyze certain elements of the structure. So, according to the previous classification, the inspection that we are going to present here was a detailed main inspection.

MATERIALS AND METHODS

The bridge inspected was the Ponte Olveira Bridge (Fig.1 and Fig.2). The bridge is located at the following coordinates:

- Latitude: 42º 57' 45.5" N
- Longitud: 9º 01' 06.5" W

The bridge is more than four hundred years old: It was built in the 16th century. The bridge has been historically important: it belongs to the Camino de Santiago (Alonso Otero, 2009). In fact, the bridge is probably even older: some medieval texts talk about it (Caucci von Saucken, 1988; NovoaPortela, 2011; Pettini, 2018) The bridge was built with granite masonry. The ashlars are perfect pieces of granite stonework. A river flows under the bridge: the Xallas (Fig. 1, Fig. 2 and Fig. 3). To fulfill this mission, the bridge has three similar semicircular arches, with an arc span bigger than 8 meters, and another semicircular arch smaller, with arc span just 5.00 m. (Fig. 3 and Fig. 4). The height of the bridge reaches 7.00 meters in the highest part (Fig. 4). The bridge has four triangular cutwaters (Fig. 1, Fig. 2 and Fig. 4). These cutwaters are located in favor of the current river and against the current river.The bridge is founded directly over rock (Fig. 7) and it is in a good state of preservation.The bridge was remodeled during the 18th century, in an operation that slightly altered its appearance.The bridge deck is slightly more than 5 meters wide (Fig. 5). Due to its limitations, the original deck was replaced by a new concrete deck in 1962 (Durán Fuentes, 2014). This new deck makes the civil structure very interesting: this new deck made it possible to adapt the bridge to vehicular traffic and to pave the road over it.

Fig. 1: View of the Ponte Olveira Bridge, which was inspected with a drone (Xunta de Galicia, nd).

Fig. 2: View of the Ponte Olveira Bridge, which was inspected with the drone (Xunta de Galicia, nd).

Fig. 3: Intermediate arch vault of the Ponte Olveira Bridge with abundant vegetation on the cutwaters, in a photograph taken by the drone (photo by the author).

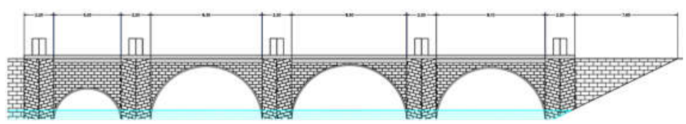

Fig. 4: Ponte Olveira Bridge elevation plan (graphic by the author).

Fig. 5: Current roadway over the Ponte Olveira bridge (photo by the author).

There are many and very diverse types of drones today (Vergouw*et al.,* 2016). 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 (Elijah *et al.,* 2021). 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 (Li & Liu, 2019): they are drones with multiple propellers (always pairs) that take off vertically and can rotate on themselves (Fig. 6). It 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.

Fig. 6: Drone approaching the smaller Ponte Olveira bridge arch vault for its inspection (photograph taken by the author).

The Xallas River water flows under the bridge. This river, the geometric dimensions of the Bridge and the inaccessibility to certain areas of it made the Ponte Olveira Bridge a perfect example. In other words, Ponte Olveira was a perfect structure to verify the validity of the use of a multirotor drone with a camera for the inspection of a heritage construction. Other aspects would remain, such as the beauty of the bridge, the relevance of the bridge and the historical and heritage value of the bridge, which undoubtedly confer added value to the inspection carried out.For this reason, a quadcopter drone was used for the inspection, which was able to approach visible but not accessible areas of the Bridge, making a photographic capture of the most outstanding observations made during the flight. In Fig. 6 we can see the four-propeller drone used, approaching the bridge, to analyze the points of greatest interest in suspension.

RESULTS/OBSERVATIONS

Once the inspection had begun, the first thing was, without a doubt, to analyze the foundation. The drone allowed to approach it (Fig. 7). Thus, we have been able to verify that one of the abutments of the bridge rests on a granite base identical to the granite that makes up the ashlars of the bridge. We were also able to partially observe the foundation of the first pier (listing the piers in a south-north direction). We could not see the rest of the foundations because they were submerged, under the waters of the Xallas River.
The visible foundation and the start of the structure (piers and abutments) were in good condition. (Fig. 7). The drone was effective in being able to carry out a detailed visual inspection of the foundation (at least the visible part). In addition, with the incorporated technology, the aircraft can estimate the typology, the dimensions of the foundation element and help other important operations in structures of this type: 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. Thanks to this, we were able to obtain the necessary data to later make a plan of the bridge (Fig. 4) After analyzing the foundation, we continue with the structural inspection of the rest of the elements. One of the most interesting points was the four arch vaults intrados. The vaults intrados are interesting because of the injuries found on them and it is also interesting because of its inaccessibility. In order to carry out a complete visual inspection of any intrados we would need to enter the river, swimming or sailing on a boat. But the level of approximation can in no case reach as far as the drone can go.The constitutive granite of the monument presents, in the intrados, deteriorations due to the synergy of actions of a diverse nature: phenomena of a chemical nature and phenomena of a biological nature. Thus, we observed the formation of various black crusts, especially in the ashlars of the outer zone (Fig. 9 y Fig. 10), presumably linked to the action of contaminating agents and especially to the humidity of the river. We know that this bridge has been restored several times: the use of lime mortar in the last restoration could have increased this damage.Along with the dark crusts we could see spots of dirt (Fig. 9 y Fig. 10). This damage is also characteristic of structural elements exposed to high humidity. These stains result from the joint action of water (humidity), the crystallization of salts provided by contaminating agents and granite masonry (Sweevers & Van Grieken, 1992). The inspection allowed us to locate efflorescence in the central area of the intrados of the vault (Fig. 9 y Fig. 10). Efflorescence's usually appear around areas where there is a high concentration of humidity as well. Obviously, a river like the Xallas River produces this high concentration of humidity. To understand it, we must understand the original construction of the bridge. This bridge was built with large, padded granite ashlars (without mortar in the joints), since that is how ancient bridges were built. Unfortunately, this padding cannot be properly appreciated in many areas due to the mortar used (Fig. 7, Fig. 8, Fig. 9, Fig. 10, Fig. 11 and Fig. 12), to fill the joints, in the subsequent actions.

Fig. 7: Rocky substrate that serves as the foundation for the southern abutment of the Ponte Olveira Bridge (photo taken with the drone).

Fig. 8: Start of the third pier (counting from the south bridge abutment), and its corresponding cutwater, on the Ponte Olveira bridge (photo taken with the drone).

Fig. 9: Image captured with the quadcopter drone at the western start of the vault, where various injuries can be seen, such as dark scabs (photograph by the author).

Fig. 10: Image captured with the quadcopter drone, where various lesions can be observed on the intrados of a vault, such as dark crusts or organic matter (photograph by the author).

Fig. 11: Image captured with the quadcopter drone in the upper part intrados of the second arch vault, where in addition to the previous injuries we can see mortar deterioration (photograph by the author).

Fig. 12: Image captured with the quad copter drone, where you can see rooted vegetation in the joints of the ashlars and in the meeting edges (photograph by the author).

The main deficiencies observed during the inspection were directly related to these restorative actions and to the joints between the ashlars. The use of mortar was the main cause of the efflorescence mentioned. Thus, any micro crack that occurs on the mortar used in the joints is an open door for water access to the interior. Being a humid environment, the amount of water is greater and, therefore, the amount of water that enters the interior of the joint is greater. This entry of water may be prior to subsequent attack by salts and frost (García de Miguel, 2009). The detection of vegetation that has taken root in many points of the bridge joints (Fig. 12) is the best proof that these cracks in the joints mortar exist. Surely this mortar was used to restore to prevent plants from taking root between the ashlars.We must remember that the crusts and especially the efflorescence's are the result of crystallization of salts. These salts tend to agglutinate around points where high concentrations of moisture occur (Sweevers& Van Grieken, 1992). This anomaly is produced by crystallizing the soluble salts, dissolved in the porous system of the granite (García de Miguel, 2009). The drone was effective in detecting efflorescence and detecting possible sources of salt as well. These sources came from the factory itself or from external agents-pollution, materials from previous interventions, etc.In the upper part of the intrados, in addition to the aforementioned damage, we discovered the vesiculation and sanding of several voussoirs (Fig. 11). 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 the internal waterways (from the extrados to the intrados, through the fill, due to poor drainage) with the erosive action of the wind. 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. Also linked to humidity is the proliferation of small black crusts, detected inside the vaults (Fig. 9).In this case, it is carbonation crusts due to, fundamentally, the dissolution of calcium carbonate from the mortar placed between the joints of the ashlars. The dark marks of runoff water, observed at some points on the bridge (Fig. 9), are linked to this process of developing black crusts.Together with these lesions, we observed an abundant presence of biocolonies (plants) and organic matter. The attacks of a biological nature are, along with the above, the most remarkable part of the inspection. When we speak of biological action we refer to the actions of organisms such as bacteria, fungi, lichens (visible at the start of the pier inFig. 8), mosses (visible in some ashlars in Fig. 10 and Fig. 11) and vegetation in general (Fig. 12 and Fig. 13). Damage associated with vegetation is generally related to surface degradation due to chemical alterations (Saiz-Jimenez, 1994; Lisci*et al.,* 2003). We must take them into account because, on occasion, they can cause significant damage. Thus, the pressure exerted by the roots of some plants, for example, can cause breaks in the masonry of some structural element.The life cycle of some bacteria leads to the formation of acids (for example, the case of thiobacilli that generate sulfuric acid from natural sulfides present in the rock itself or from contaminants). Levels above ten thousand individuals per gram can be considered aggressive (Sand & Bock, 1991). The damage associated with this type of action is usually the formation of sulfates and black crusts, like the ones we discovered with the drone (Fig. 9 and Fig. 10). In the case of nitrifying bacteria, nitric acid corrodes the stone without giving rise to the formation of sulphates and black crusts. In this case, the associated damage is superficial deterioration, although the degradation mechanism is still chemical in nature (Sand & Bock, 1991). Other bacteria and fungi generate organic acids with harmful effects for the stone material over time, developing deterioration processes of a chemical nature (Sand & Bock, 1991). It is important to take into account the interaction of the products applied during the various treatments with the existing biological colonizations. The products applied frequently have an organic base and can serve as food for the colonies, thus growing at their expense, increasing injuries and reducing the time and effectiveness of the planned protection (Sand & Bock, 2001; García de Michael, 2009). The lichens that we find on some walls are another aspect that we should not ignore. Lichens usually appear on stone surfaces of a certain age, when the atmosphere is not contaminated (Lisci*et al.,* 2003). They generally produce a decomposition of the outermost layer of the stone (a few millimeters thick). This decomposition is produced by the attack of the oxalic acid that they generate and that can produce calcium oxalate when combined, producing the formation of patinas.Normally the rate of growth of biocolonies is very slow. In addition, there is no consensus on whether it is convenient to remove them or not: on the one hand, they decompose the outer layer of the stone but, on the other hand, the layer that the lichens generate is a protective element from the rest (Warscheid & Braams, 2000 ; Lisci*et al.,* 2003; García de Miguel, 2009). The lichens form a layer of constant humidity and provide a certain hydrophobic effect.As Ponte Olveira is a river bridge, we discover algae and mosses (Fig. 10 and Fig. 11). Algae and mosses need a humid environment for their development (Warscheid&Braams, 2000; Lisci*et al.,* 2003). Although the algae barely produce degradation (they only make the exterior look ugly), mosses in an alkaline environment (such as the environment created by lime or cement) can superficially degrade a centimeter or more of the rock. Lastly, the action of the plants is basically centered on the pressure that their roots produce between the ashlars of the masonry. This pressure can open cracks and even break blocks. In addition to these mechanical damages, plants can also produce chemical damage. In Ponte Olveira, the plants have grown rooting in the joints that are arranged between the ashlars, especially in the joints of angular points (Fig. 12 and Fig. 13). This vegetation enters into feedback with the phenomena of humidity, efflorescence and runoff water, as reflected in the spots observed. Special care must be taken with vegetation, especially the larger ones, due to the action of tree roots and other plantations on the factory. In principle, 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 in the short term; however, they are injuries that can end up in more serious damage if they continue to develop. When we speak of damage related to the durability of the material that makes up an element, we refer to injuries that arise from the interaction of the deteriorated material with the environmental conditions imposed by it. In other words, the durability of the material must be understood as the ability of the material to resist the action of the environment. It includes all chemical, physical, biological attacks, or any other environmental process that tends to deteriorate the material.The discovery of efflorescence implies two important aspects: the first, that in some masonry a process of chemical degradation is taking place, in principle not very dangerous; the second, that, on the other hand, important internal mechanical stresses may be being generated due to the crystallization of the salt, depending on the porous system of the factory The old and heritage buildings that are nearby are made of the same materials. This is due to the limitations of transport that existed in ancient times. The rocky substratum on which the south abutment rests justifies the above: its material is identical to that of the ashlars, although less altered.

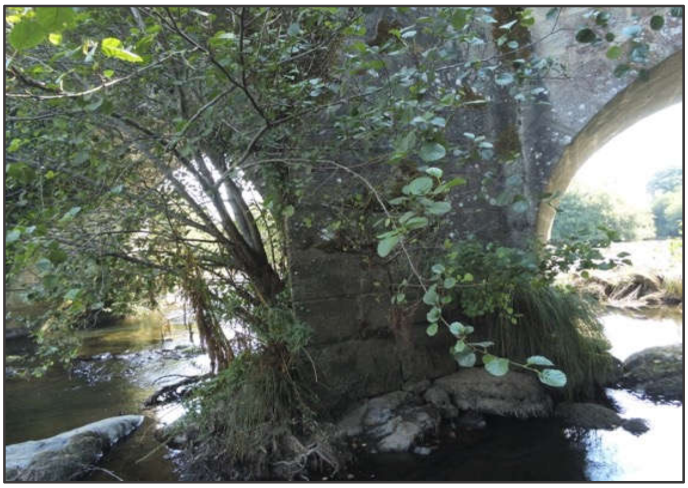

Fig. 13: Image captured with the quadcopter drone, where we can see abundant vegetation rooted on the firstpier (photograph by the author).

DISCUSSION

Despite the fact that none of the damage compromised the safety of the monument, the drone allowed the location and diagnosis of such damages. We must not forget that many damages were invisible to a person. In addition, the inspection with the unmanned aircraft made it possible to have 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 restoration intervention.The previous sections have exposed the carrying out of a reconnaissance technical inspection on Ponte Olveira, an old 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. 14). The previous sections have exposed the carrying out of a reconnaissance technical inspection on a old 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 parts. 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 has to use them or climb on them in order to access those parts of the structure 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.

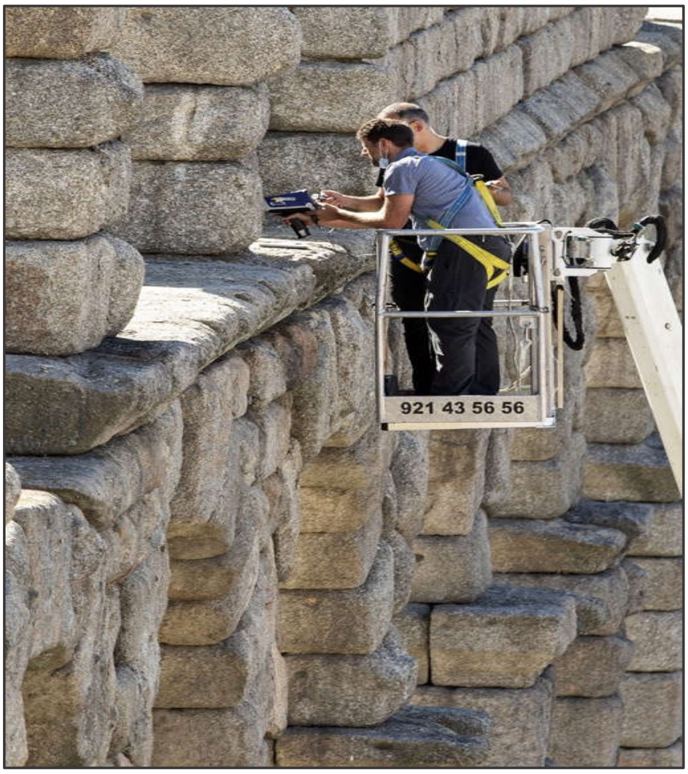

Fig. 14: Image of a check-up inspection (special inspection) of the Segovia Aqueduct: two workers from the Spanish Geological and Mining Institute (IGME) take data from granite that makes up the stone ashlars for its geochemical characterization (photograph by Rosa Blanco (VVAA, 2020)).

Needless to say that the experience of the experimental inspection carried out for the elaboration of this article can be extrapolated to many other identical nature works: inspection of buildings, old structures, industrial constructions or energy facilities, which opens up an infinite range of opportunities for these small ingenuities that, without a doubt, have come to stay and change our lives.

CONCLUSIONS

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 structure. 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 structure. 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 element, accessible and non-accessible, that form a big old construction, such as Ponte Olveira Bridge. 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:

1. The drone simplifies planning work, because it reduces the planning and acquisition of auxiliary means of access.
2. The drone simplifies field work, for the identification and assessment of deterioration of each of the constituent elements of the structure.
3. We can work faster thanks to the two previous simplifications.
4. 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.
5. 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, a complete technical report of the main inspection can be generated in the cabinet, in addition to supplying the relevant information for its incorporation into a management system and obtaining the indexes of condition, of each one of the elements and of the structure as a whole, to assess whether some type of urgent action is necessary or whether, as in this case occurs with practically all the injuries detected, a periodic check of the detected lesions. All of the above is just only one of the many possibilities that these small devices offer. There are many other possibilities, many others may be the functions that they satisfy... Many others are, therefore, the future lines of research that open up with these small and intelligent tools.

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