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Drones as a tool for the sustainable conservation of heritage metal Struc-tures

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Abstract

Historic infrastructure preservation demands innovative and sustainable methodologies that safeguard structural integrity while minimizing environmental impact. This study ex-plores the application of Remotely Piloted Aircraft Systems (RPAS) for the non-invasive inspection of the Requejo Bridge, a centennial metallic arch bridge that spans the Duero River within a protected natural environment in Spain. Through high-resolution aerial surveys, RPAS technology enabled the exhaustive assessment of areas traditionally difficult to access, identifying localized corrosion and material degradation critical for preventive conservation planning. By eliminating the need for scaffolding and heavy machinery—elements that pose significant ecological risks to sensitive landscapes—the drone-based inspections substantially reduced carbon emissions and resource con-sumption, while optimizing operational costs and minimizing workplace hazards. The findings confirm that RPAS not only enhance the accuracy and efficiency of structural diagnostics but also embody a sustainable maintenance strategy aligned with multiple Sustainable Development Goals (SDGs), including climate action, responsible resource use, and occupational safety. This research advocates for the widespread adoption of drone-assisted methodologies in heritage infrastructure management, offering an envi-ronmentally responsible, economically viable, and safer alternative that extends the ser-vice life of historic structures through proactive and minimally invasive interventions.

Keywords: Environmental impact reduction, Heritage management, Occupational safety, Remote inspection, Structural, Sustainable conservation.

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1. Introduction

The Requejo Bridge, also known as the Pino Bridge, is an iconic metallic arch bridge that spans the Duero River in the province of Zamora, Spain. Constructed in the early 20th century, it represents a significant achievement in engineering, combining structural efficiency with aesthetic harmony. Beyond its technical importance, the bridge holds cultural and social value, serving as a crucial link between the regions of Aliste and Sayago and contributing to the historical identity of the area. It is also a key landmark within the Arribes del Duero Natural Park, a protected environment of high ecological and scenic value.

The bridge is located in the position defined by the following coordinates (Figure 1 and Figure 2):

- UTM Coordinates (Zone 29):
- X (UTM): 739,444.16
- Y (UTM): 4,604,980.52

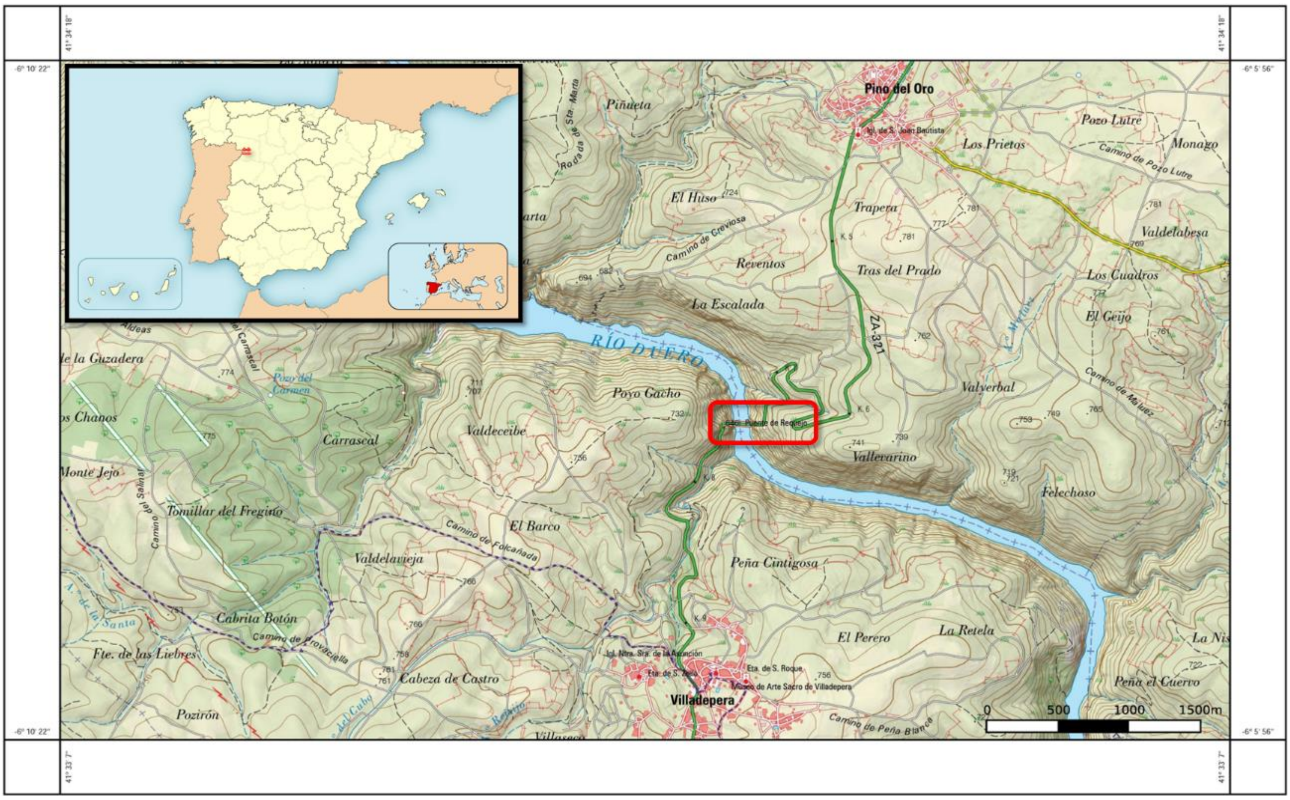

Figure 1.
Location of the Requejo Bridge on the National Topographic Map published by the Spanish National Geographic Institute.

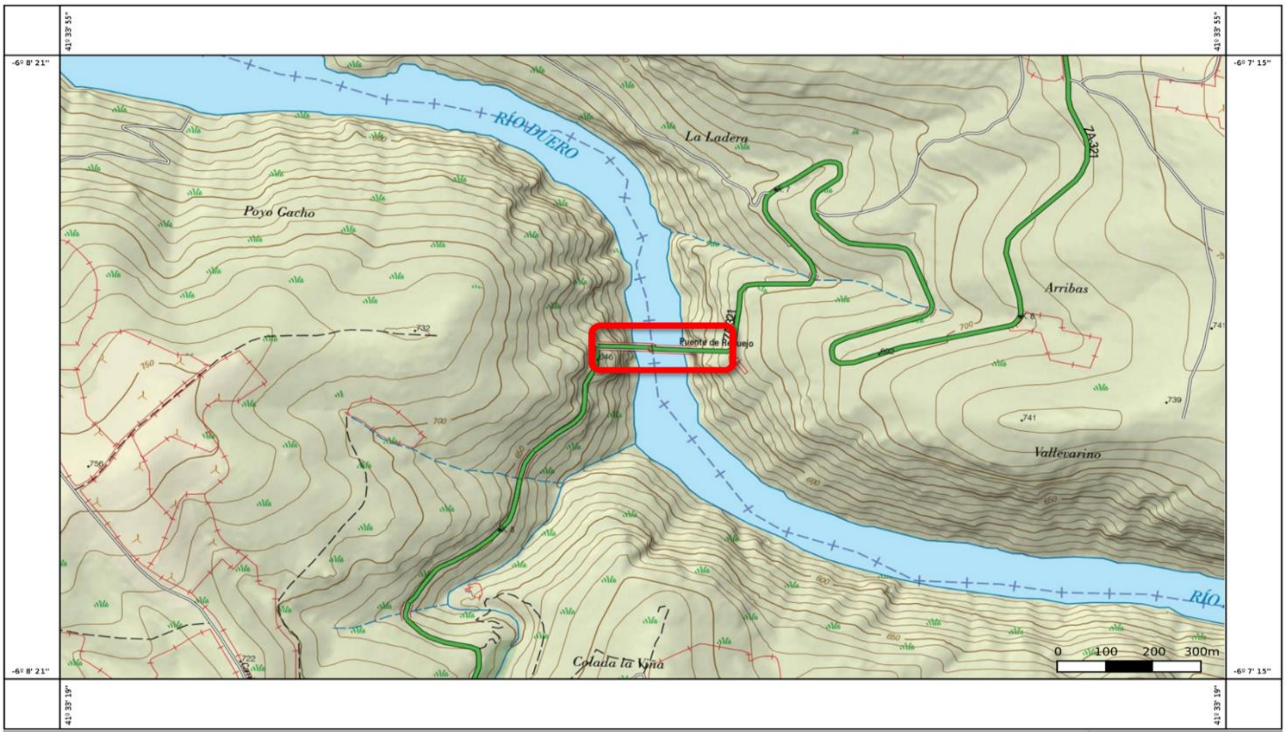

Figure 2.
Location of the Requejo Bridge on the National Topographic Map published by the Spanish National Geographic Institute, represented at a larger scale than the previous plan.

- Geographic Coordinates:

- 41°33'38.42"N
- 6°07'42.92"W

1.1. Historical and Geometric Description of the Bridge

This is a metallic arch bridge, a remarkably innovative structure for the time it was built (Figure 3). Its design harmonizes functionality and aesthetics [1] featuring a striking central arch that supports the deck via metallic uprights.

Figure 3.
General view of the Requejo Bridge, downstream elevation.

The bridge spans a total length of 190 meters, rising more than 90 meters above the Duero riverbed.

Designed in the late 19th century and constructed in the early 20th century, its primary purpose was to facilitate communication between the Zamora regions of Aliste and Sayago, specifically linking the municipalities of Fonfría (located in Aliste, which had 1,347 inhabitants in 1897 [2]) and Fermoselle (located in Sayago, which had 4,569 inhabitants in 1897 [3]).

The bridge was conceived to traverse the Duero's riverbanks in an area characterized by deep canyons and rugged landscapes (Figure 3 and Figure 4). This, coupled with its structural typology and striking beauty, has made the bridge a visual landmark, seamlessly integrating into the Arribes del Duero—a protected area recognized for its high natural and scenic value and significant tourist interest [4].

Figure 4.
Location of the Requejo Bridge on an aerial orthophotograph produced by the Spanish National Geographic Institute.

Before its construction, the only direct connection between the towns near the bridge, Pino del Oro (in the Aliste region) to the north and Villadepera (in the Sayago region) to the south (Figure 1), was a barge that crossed the river using mooring cables [5].

The earliest references to the bridge's planning date back to the mid-19th century. Its first proponent was engineer and future Prime Minister Práxedes Mateo Sagasta, who, upon being elected as a deputy for the Zamora constituency, expressed his commitment to supporting this project [6]. Years later, Eduardo López Navarro evaluated an alternative location, approximately two kilometers downstream from the final site. This proposal featured a significantly lower grade and a construction solution based on two cast-iron spans [7, 8].

Due to the bridge’s strategic importance to the region, all parliamentary candidates pledged to advance its construction. However, it was Federico Requejo Avedillo, a native of Sayago, who, during his tenure at the General Directorate of Public Works [9], secured a feasibility study for a road connecting Fonfría to the Salamanca-Fermoselle highway, incorporating the bridge as part of the project [8]. For this reason, the Pino Bridge is also known as the Requejo Bridge.

The final approved project, designed by engineer [10] faced significant challenges during its execution. Initially, no contractors submitted bids for the initial tenders due to the complexity of the assembly process [10]. The Asturian company Duro Felguera took on the project but encountered difficulties during the bridge's assembly, ultimately transferring the work to another company, Montajes. However, Montajes also had to suspend and abandon the project due to technical complications. The project eventually returned to Duro Felguera, which, under the direction of Galician engineer Robustiano Fernández and with the support of local labor, successfully completed the bridge's construction [4] without any reported incidents or accidents during the arch assembly [8]. The bridge components were manufactured at the company's main plant in La Felguera, in the Principality of Asturias.

The design proposed by Ribera Dutaste [10] envisioned a metallic bridge to span the Duero. As the first steel arch bridge in Spain, upon its inauguration on September 15, 1914, it became the longest-span bridge (120 meters between arch supports) and the highest bridge over a river (90 meters) in the country (Figure 5) [7]. With this project, Ribera challenged Eiffel’s designs by successfully constructing a lowered-arch bridge [8] which was lighter than those designed by the French engineer (Figure 6).

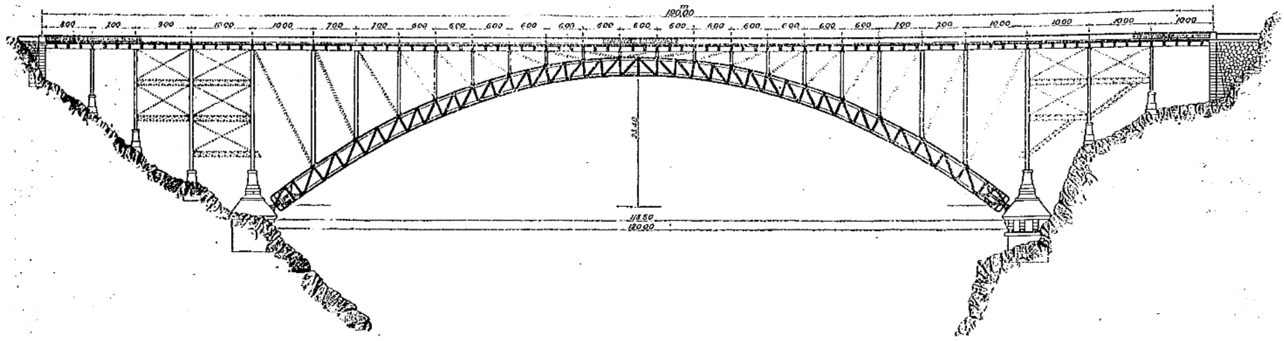

Figure 5.
Elevation of the Requejo Bridge, based on the project by engineer [7].

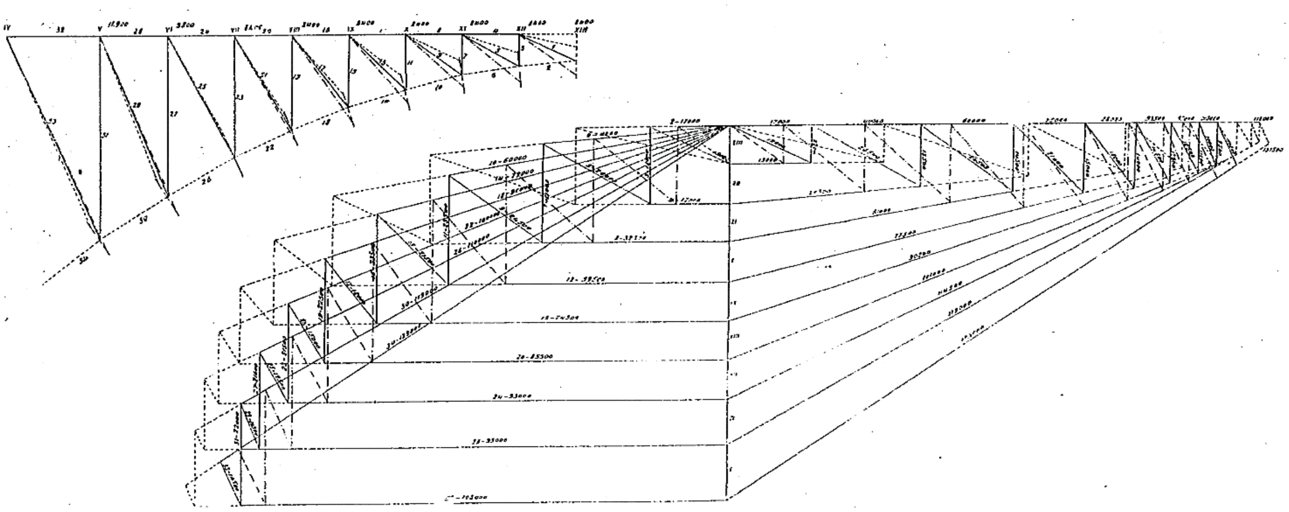

Figure 6.
Graphical calculation of the cantilever assembly of the Requejo Bridge [8].

The bridge accommodates the ZA-321 regional road, enabling vehicles to cross the Duero. The roadway is a two-way single-lane road, with alternating traffic flow not regulated by traffic lights; instead, a priority sign (R-6) is placed at the eastern abutment (Pino del Oro side, right bank of the Duero). At the western abutment (Villadepera side, left bank of the Duero), a priority sign (R-5) is displayed in the opposite direction.

Vehicle weight is restricted to 15 tons, as indicated by multiple signs, and speed limits of 30 km/h are enforced at both bridge approaches (R-301 signs). Pedestrian access is facilitated by sidewalks along both sides of the bridge.

The structure is located within the central basin of the Duero River, which is filled with Cambrian and Precambrian materials [11]. The dominant lithology consists of schists and fine-grained gneisses interspersed with quartzite layers (Figure 7). Prior observations (Figure 3 and Figure 4) provide context for the bridge's integration within the Duero canyon.

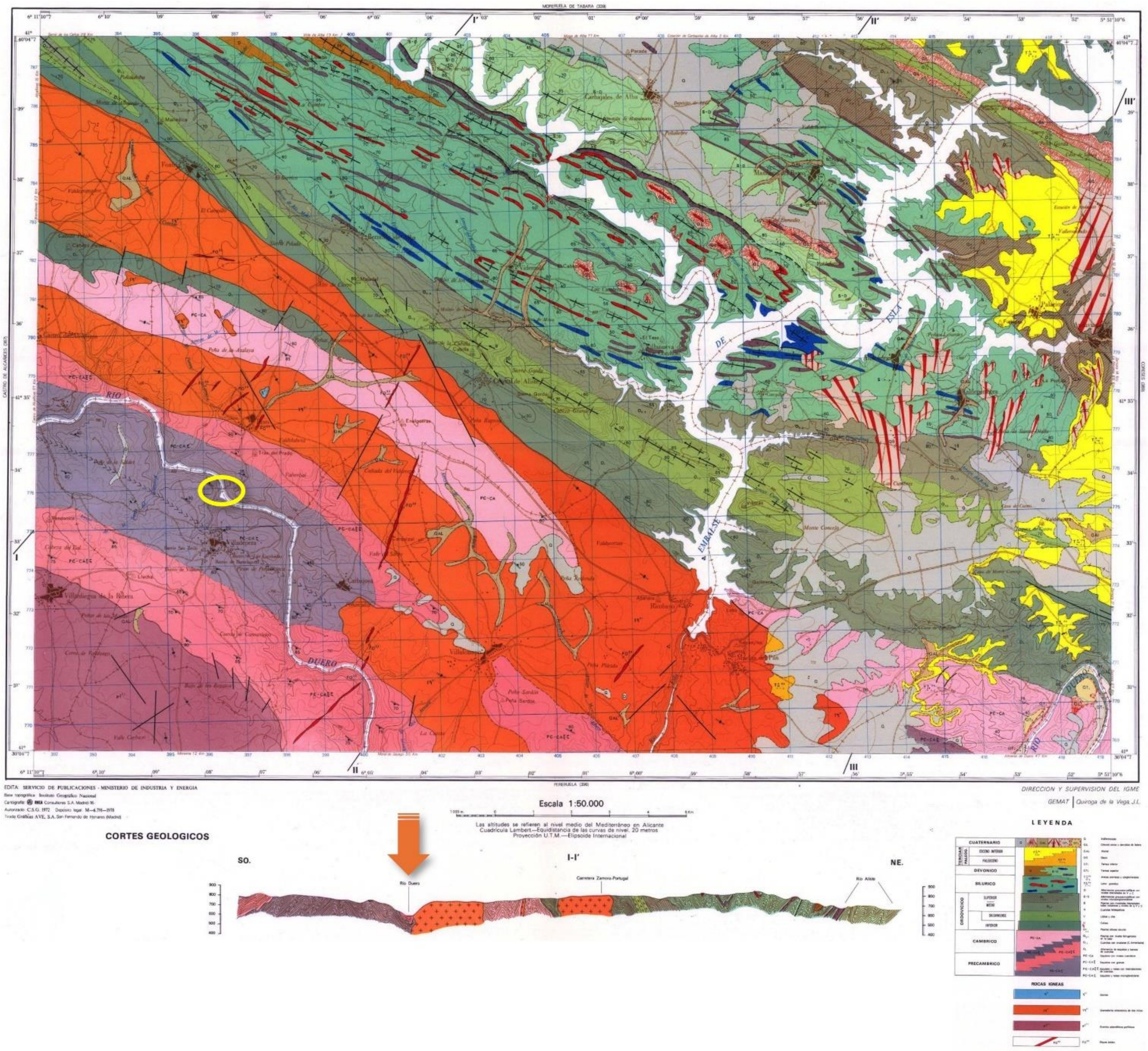

Figure 7.
Geological framework legend, geological map, and cross-section marking the bridge's location.
Source: Geological Sheet 343, 1:50,000 scale, [11].

From a geotechnical perspective, the site consists of a plutonic outcrop of gneissic rocks, offering a combination of magmatic, migmatitic, and gneissic formations, which provide favorable lithological conditions. These materials are impermeable, with limited internal drainage due to fracturing and active surface runoff. Consequently, the area exhibits high load-bearing capacity and negligible settlement, making construction conditions generally favorable. Additionally, the region has very low seismic risk [12].

To systematically describe the structural elements of the bridge, this study designates the abutment with the lowest kilometer point—aligned with the kilometer markers of the ZA-321 road that runs over the bridge—as the first abutment. This abutment is closest to the town of Pino de Oro, situated on the right bank of the Duero River (eastern abutment; the left abutment in Figure 3 and Figure 5). The right and left sides of the bridge are defined according to the direction of increasing kilometer points. All referenced subcomponents are numbered from left to right (Figure 3 and Figure 5), following the east-to-west direction of the bridge, from Pino de Oro to Villadepera.

As previously mentioned, the structure is a metallic arch bridge with a deck located above the arch, spanning a total length of 190 meters between abutments (Figure 5). It consists of three distinct sections (Figure 3): a central span, represented by the metallic lattice arch, and two approach spans composed of metallic trestles supporting the metallic deck (Figure 8).

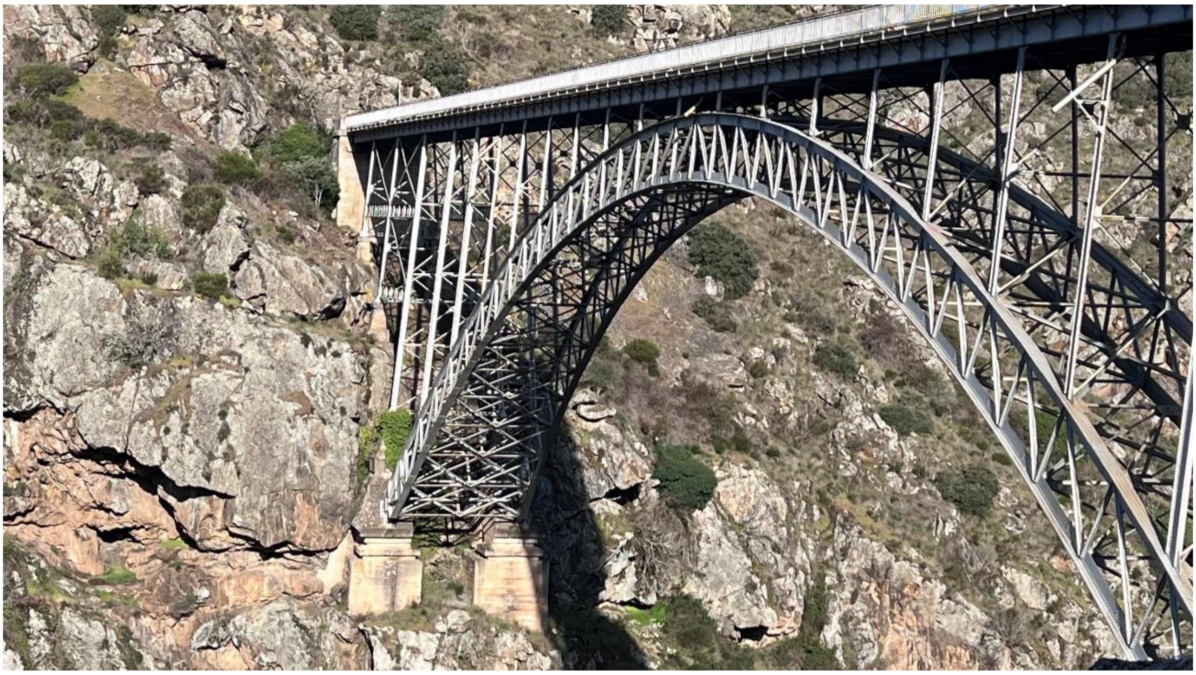

Figure 8.
Partial view of the bridge from the southern side (upstream side), showing the main arch and, in the background, the second abutment with its corresponding support trestles.

In the central section, the deck is supported directly by the arch through metallic uprights of varying height, ranging from 18.50 meters at the ends to 0.95 meters at the center of the arch (Figure 5 and Figure 8). The arch is founded on four concrete footings (Figure 9), with articulations secured by anchoring bars.

The uprights are anchored to the arch using gusset plates fastened with bolts to the main girders of the arch (Figure 10). The arch spans 120 meters between supports, featuring a reduced-rise design with a 23.42-meter rise (Figure 5) and a clearance of 90 meters above the river's water surface. The arch's cross-section varies, with a maximum width of 8.30 meters at the supports, tapering to 4.50 meters at the midspan, and incorporating a 1:12 slope in both arch elevations.

In the approach spans, the deck is supported directly by metallic trestles, which, in turn, rest on concrete foundations (Figure 3, Figure 5 and Figure 8). Similar to the uprights, the trestles are anchored to the concrete foundations using gusset plates secured with four 25-mm diameter bolts.

Figure 9.
Arch supports on direct concrete foundations near the second abutment.

Figure 10.
Examples of upright supports on the arch, using gusset plates fastened with bolts, on the upstream side.

The substructure elements (uprights, trestles, bracing members, and the arch) are composed of L-section steel profiles and steel plates, all meticulously riveted.

The deck has a total width of 6.70 meters and consists of a cambered metallic framework (Figure 11)., topped with a 0.14-meter-thick reinforced concrete layer that forms the alternating one-way traffic lane, which is 4.30 meters wide. This platform was installed in 2013, reducing the overall deck weight by replacing the previous structure, which consisted of a 0.40-meter-thick macadam and asphalt layer [13].
The deck is supported by the concrete abutments through four metallic bearings, each composed of three rollers.

The deck is further extended by cantilevered sections, each 1.00 meter wide, constructed from steel plates forming the sidewalks, which are supported by metallic brackets. The section is completed with steel railings on both deck elevations.

The deck follows a horizontal profile, incorporating a 2% transverse slope for water drainage. The roadway features metallic gutters on both sides to collect runoff water.

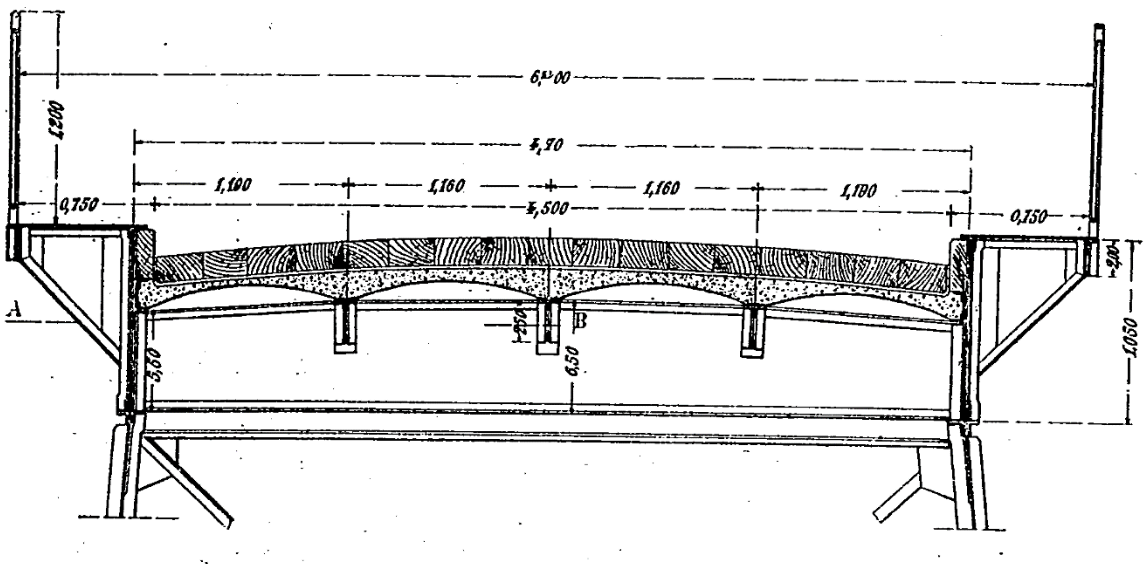

Figure 11.
Cross-section of the Requejo Bridge, corresponding to the design
Source: Ribera Dutaste [7].

At the deck extremities, expansion joints made of reinforced elastomer and four inspection chambers providing access to the deck bearings are installed. Both the expansion joints and the inspection chambers were improvements implemented during the 2013 rehabilitation works [13].

Due to its historical and technical significance, the Requejo Bridge has been recognized as an Industrial Heritage Site in Spain and included in the list of the 100 most important elements of Spanish industrial heritage [14]. Undoubtedly, it represents a historical structure of exceptional heritage value that deserves preservation.

1.2. Literature review and research gap

In recent years, the application of Unmanned Aerial Vehicles (UAVs) for structural inspection has gained considerable attention [15]. Various studies have demonstrated the effectiveness of drones in assessing the condition of heritage bridges [16] allowing for high-resolution visual surveys without the need for direct human intervention [17]. Research by Seo, et al. [18] explored drone-enabled bridge inspection methodologies, highlighting their advantages over traditional manual inspections [18]. Similarly, Nguyen, et al. [19] investigated intelligent path planning for UAV-based civil infrastructure inspection, emphasizing automation and efficiency [19].

Despite these advancements, few studies have specifically addressed the use of drones for heritage metallic bridges. Most existing research focuses on concrete or masonry structures, leaving a gap in the literature regarding the application of UAVs to assess corrosion-related damage in metallic bridges. This study aims to fill this gap by demonstrating how drone technology can effectively detect and document deterioration in a century-old steel arch bridge.

1.3. Objectives

Based on the observations presented, the Requejo Bridge—rising over 90 meters above the Duero River bed and exhibiting a design that restricts access to critical structural areas—represents an optimal and highly relevant case for assessing the effectiveness of drones in the inspection of heritage metallic structures. Beyond the technical challenges, the bridge's historical, cultural, and aesthetic significance further underscores the importance of this inspection.

Accordingly, this study aims to investigate and validate the use of drones as an advanced tool for conducting high-precision visual inspections of heritage metallic structures, with the Requejo Bridge serving as a case study. If its applicability is confirmed, this approach could fundamentally transform the methodology for inspecting complex structures by improving safety, reducing costs, and optimizing execution times.

The primary objective of this research is to evaluate the feasibility of using UAVs for the non-invasive inspection of metallic heritage structures, using the Requejo Bridge as a case study. Specifically, the study aims to:

- Assess the accuracy and reliability of drone-based visual inspections in detecting structural deterioration.
- Compare UAV inspections with traditional methods in terms of efficiency, safety, and sustainability.
- Provide a basis for integrating UAV technology into routine maintenance and conservation strategies for historic bridges.

To achieve these objectives, the study includes an in-depth structural assessment, supported by high-resolution imaging and expert analysis. The findings will contribute to the broader discussion on sustainable heritage management, offering an alternative approach that minimizes environmental impact while ensuring the long-term preservation of infrastructure.

The collected data will facilitate the identification of not only reactive solutions (addressing existing damage) but also preventive strategies that contribute to extending the bridge's service life while safeguarding its historical and functional integrity. This aligns with a broader objective of leveraging advanced microtechnological tools to enhance structural assessment and maintenance protocols.

This case study serves as a pilot test with the potential for application to similar structures. The research seeks to extrapolate insights and methodologies to a broader framework, fostering the integration of drone technology into future inspection practices.

While the study predominantly adopts a technical perspective, it also emphasizes the historical and aesthetic significance of the bridge. It is anticipated that this article will contribute to increasing awareness of the imperative to preserve such structures, positioning them within the framework of cultural and tourism-oriented sustainable development strategies.

Finally, it is important to explicitly highlight the relationship of this research with sustainability, occupational safety, and efficiency in infrastructure management. In particular, this work aligns with the following Sustainable Development Goals (SDGs):

- SDG 9 (Industry, Innovation, and Infrastructure): It promotes innovation in infrastructure inspection and maintenance through the use of drones, optimizing resources and extending the lifespan of structures.
- SDG 11 (Sustainable Cities and Communities): It contributes to the preservation of heritage infrastructure and enhances its maintenance in a sustainable manner.
- SDG 12 (Responsible Consumption and Production): It reduces material waste and the need for additional resources through more efficient inspections.
- SDG 13 (Climate Action): It minimizes the carbon footprint by avoiding more polluting traditional methods for infrastructure inspection and maintenance.
- SDG 8 (Decent Work and Economic Growth): It improves occupational safety by reducing the risks associated with manual inspections in hard-to-reach areas.

2. Methodology

Structural inspection is a fundamental activity in the conservation of any civil engineering structure. Traditionally, this task has focused on assessing, characterizing, and monitoring both the overall construction and its individual components. In some cases, this process is complemented by additional testing to enhance the diagnosis obtained through visual inspection, depending on the type and scope of the analysis.

Recently, the concept of unmanned aerial vehicles (UAVs), commonly known as drones [20] has gained significant popularity. These aircraft, which can be remotely controlled or programmed for autonomous operation, have proven to be highly versatile tools across various fields [21]. Their capabilities have been further enhanced by the integration of advanced accessories such as high-resolution cameras and advancements in increasingly accessible and precise microtechnology. These innovations have facilitated the adoption of drones for structural inspection tasks.

In recent years, the use of drones for structural inspections has made notable advances, yielding highly satisfactory results [15, 16]. This approach has enabled inspections to be conducted more cost-effectively, rapidly, and safely [18]. Consequently, drones are considered a viable option for the inspection of structures such as the Requejo Bridge.

A wide variety of drones are currently available, making the selection of the most suitable model a crucial step based on the specific characteristics of each inspection [22]. One of the key criteria in this selection process is the method of aerial propulsion, which distinguishes between fixed-wing and rotary-wing drones. Although fixed-wing drones are ideal for certain applications, their inability to take off vertically and remain stationary in the air renders them unsuitable for inspecting historical structures [23]. For this reason, rotary-wing drones, particularly multirotor models, are preferred for such tasks. These devices, equipped with multiple propellers, can take off vertically, hover in place, and rotate on their own axis—qualities that make them ideal for vertical inspections and detailed analyses [19].

To carry out the inspection of the Requejo Bridge, a Parrot Anafi UAV was used. It is a lightweight and highly maneuverable drone well-suited for structural inspections. Key specifications include:

- Weight: 320 g.
- Battery life: Up to 25 minutes per flight.
- Camera resolution: 21 MP with 4K HDR video recording.
- Flight control system: GPS and GLONASS navigation with automated flight path planning.
- Data processing: Compatible with photogrammetry software for 3D modeling and orthophoto generation.

These features allowed for precise and efficient data collection, enabling the detailed documentation of structural defects without requiring scaffolding or other intrusive equipment.

The drone was operated via a Parrot remote control with a mobile phone or tablet attached. For enhanced visual quality, an iPad Pro was used during the inspection process.

As previously mentioned, the strong water flow of the Duero River, combined with the geometric characteristics of the Requejo Bridge—particularly its considerable height above the riverbed and the inaccessibility of many structurally sensitive areas—made this an optimal case study for validating the effectiveness of multirotor drones equipped with high-resolution cameras in the inspection of heritage metallic structures. Additionally, the bridge’s historical significance, cultural value, and remarkable aesthetic appeal provide a unique context that enriches both the results and the overall impact of the analysis.

Figure 12.
Multirotor drone approaching the Requejo Bridge to inspect the trestles of the second abutment from the upstream side.

2.1. Flight Planning

The initial phase of this research consisted of a visual inspection without the aid of auxiliary equipment. However, given the characteristics of the bridge, this inspection proved insufficient. To supplement this initial assessment and accurately determine the existing structural damage, two drone-based inspections were carried out across the entire structure:

1. April 7, 2023 – A drone flight was conducted focusing on the two lateral sections, with particular attention to the trestles and concrete footings.
2. April 30, 2023 – A second drone flight was performed, concentrating on the central span, examining the arch and its uprights, as well as the platform and deck.

On both occasions, flights were conducted on both elevations (upstream and downstream of the bridge), with detailed flights over the trestles, arch, and cantilevered sections to enable an exhaustive examination of nearly the entire structure. Additionally, flights were conducted beneath the deck and cantilevered sections, overcoming the challenge of limited accessibility between structural elements.

To enhance the methodology and ensure robust results, the inspection process incorporated multiple control measures. The drone flights were meticulously planned, employing flight path programming software to ensure full coverage of the structure's critical elements. Automated flight missions were conducted to minimize human error and improve consistency in data collection. Additionally, the drone was equipped with a high-resolution camera and stabilized gimbal system, enabling precise imaging of difficult-to-access zones. To validate the visual data, targeted manual inspections were performed in selected areas to confirm the findings obtained through the drone survey. This combination of automated drone flights and manual verification ensured that potential defects, both evident and less obvious, were identified effectively.

Flight planning was based on a preliminary survey of the environment and the structural characteristics of the bridge. Specific flight routes were defined to cover the following objectives:

- General capture of the bridge from different perspectives (upstream, downstream, and top views).
- Detailed inspection of critical elements: supports, arches, uprights, and the roadway platform.
- Recording of areas susceptible to corrosion and moisture accumulation.

The routes were programmed using autonomous navigation software, allowing precise control of altitude and capture angles. Two main flights were conducted on different dates to ensure full bridge coverage and minimize potential inaccuracies due to adverse weather conditions.

2.2. Data processing

In addition, specialized image processing software was employed to enhance the visual data. This software facilitated the identification of subtle defects such as crevice corrosion, early-stage deformations in metallic profiles, and moisture-induced deterioration in concealed elements. The combination of automated flight planning, precise imaging, and enhanced image analysis represents a methodological improvement that maximized the accuracy of the inspection process.

Photogrammetry software (Agisoft Metashape) and advanced image analysis algorithms were available for processing the collected images, with the capability to generate high-resolution 3D models and orthophotos. These tools were initially considered for detecting structural defects such as:

- Minor deterioration: surface oxidation without structural impact.
- Moderate deterioration: advanced corrosion with material loss.
- Severe deterioration: structurally compromised elements requiring immediate intervention.

However, the damages identified during the drone flights were so evident through direct visual observation that, thanks to the investigator's extensive experience in previous inspections, it was ultimately unnecessary to resort to these advanced processing techniques. The clarity of the observed deterioration allowed for a precise and immediate assessment of the structure's condition, demonstrating the effectiveness of UAV-based inspections even without complex post-processing.

2.3. Validation of the experimental process

To ensure the accuracy of the collected data, the results of the UAV inspection were compared with previous manual inspection reports and on-site observations conducted by structural engineering specialists. It was confirmed that drone technology allowed for the precise detection of corrosion-affected areas, as well as the visualization of zones that previously required the installation of scaffolding or specialized equipment for inspection.

2.4. Innovation and Contribution to the Field

The use of UAVs in the inspection of heritage structures represents an innovative methodology that optimizes analysis time and reduces operational costs. Unlike traditional methods, which require additional infrastructure and pose higher risks to workers, this technology provides a more efficient and safer solution.

From a sustainability perspective, the implementation of drones minimizes CO_2 emissions by eliminating the need for heavy machinery and reducing personnel travel. It also contributes to the preservation of the natural environment by avoiding landscape alterations caused by the installation of scaffolding or temporary structures.

Theoretically, this research reinforces the role of remote inspection as an emerging standard in the conservation of industrial and civil heritage, offering a replicable methodology for other structures of similar typology. Furthermore, the incorporation of advanced image processing techniques opens the possibility of developing predictive models for the early identification of structural pathologies, improving the planning of preventive interventions.

These improvements in methodology, experimental process, and theoretical foundation strengthen the study and position it as a reference in the application of non-invasive technologies for the conservation of metallic heritage.

3. Results

Based on the inspections carried out using a drone, a series of damages have been identified, all of them either of a durable nature or caused by vandalism. Some of these defects are widespread throughout the structure, while others are much more localized and present in a more sporadic manner.

3.1. Identified Structural Deterioration

Every inspection begins with the analysis of the foundation. In this case, it is worth noting that, of the two drone flight operations performed, the first focused on analyzing the concrete footings, the lateral sheet pile walls, and the abutments.

Previous observations (Figure 9) had already indicated that, despite its century-old age, the concrete foundation elements presented a generally acceptable state of conservation, showing slight deterioration related to the material's durability, particularly due to runoff water. The action of runoff water was also the primary pathology observed on the abutment walls, where stains associated with moisture caused by the continuous process of surface runoff sliding down the wall face were detected (Figure 13).

The hinged bearings of the arch displayed an excellent state of conservation, both in terms of the joints and the anchorages. Meanwhile, the roller bearings on the deck exhibited corrosion on the bearing plates, although the rollers themselves showed no significant deterioration, aside from slight corrosion on the body of some of them.

Figure 13.
Wall of the second abutment with runoff water traces.

Vegetation and organic matter, primarily moss, were found on some of the support footings of the sheet pile walls, with the sixth sheet pile, near the second abutment, being particularly affected (Figure 14). The presence of vegetation on concrete elements always indicates suboptimal maintenance. Deterioration of concrete caused by vegetation constitutes a form of chemical attack induced by living organisms. In the case of higher plants, this effect combines both mechanical and chemical actions, as roots exert pressure on joints or cracks where they take hold, while simultaneously retaining moisture, thereby exacerbating the damage.

The sheet pile walls exhibited widespread deterioration of the corrosion protection system. This damage was more severe on the end walls: the first sheet pile wall on the downstream side and the seventh sheet pile wall, also on the downstream side (Figure 15). Additionally, localized corrosion of components was observed at the ends of the sheet piles, attributed to the tendency of these areas to accumulate moisture.

Slight deformations in the L-shaped profiles were also observed, associated with crevice corrosion caused by moisture penetration between the profiles, leading to the deformation of the elements as their volume increased due to corrosion.

Figure 14.
Presence of organic matter and vegetation on the concrete footing of sheet pile wall 6, downstream side.

Figure 15.
Corrosion on sheet pile wall number 7, the one closest to the second abutment, downstream side.

In the case of the last sheet pile wall, the seventh one, the drone inspection revealed the loss of the head of one of the anchor bars on the downstream support (Figure 16). This loss appeared to be linked to the corrosion present on the bar, which likely caused its eventual breakage.

Figure 16.
Loss of an anchor head on sheet pile wall 7, downstream side.

The analysis of the ends concluded with the detection of localized corrosion on some of the braces, which was more pronounced near the second abutment (Figure 17). This deterioration is undoubtedly the result of the combined action of atmospheric oxygen and humidity, exacerbated by the lack of an adequate protective surface treatment on the metal elements.

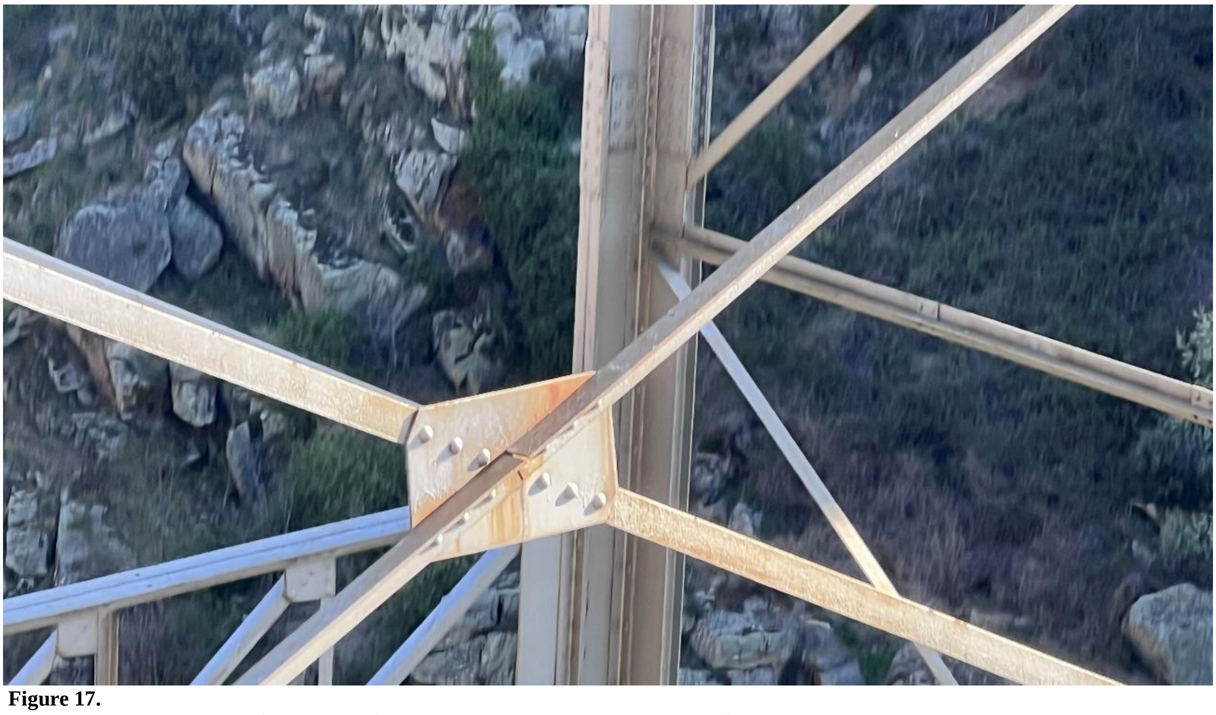

Figure 17.
Localized corrosion on one of the braces of the sheet pile walls at the western end of the bridge, upstream side.

Continuing with the inspection, the second drone flight focused on identifying damage on the arch (Figure 18) and the deck.

Figure 18.
Bottom view of the arch from the downstream side.

During the inspection, the arch only showed deterioration due to the aging of the corrosion protection system (Figure 19), with patches of rust visible on the upper part of the heads of the lateral beams forming the arch, as well as localized rust at connection points between elements (Figure 20).

Figure 19.
General state of the arch, in a section between support uprights.

Figure 20.
Detailed view of an arch section with localized corrosion at connection points.

Stains produced by the discharge of water and other liquids through the drainpipes were also observed. At the time of the visit, these pipes were not long enough to discharge water away from the arch (a pipe can be seen in the center of the arch in Figure 8 and Figure 18).

The uprights on the arch exhibited widespread deterioration of the corrosion protection system due to aging. Corrosion spots were observed between elements comprising the uprights, such as plates and L-shaped profiles (Figure 21).

Figure 21.
Detail of corrosion on one of the uprights over the arch.

Atop the arch lay the deck, which also exhibited localized corrosion at numerous points along its entire length and width (Figure 22). A closer examination confirmed that corrosion was particularly concentrated at the connections between stringers and the slab, as well as at the connections between transverse beams and the X-shaped cross braces (Figure 23).

Notably, the transverse beams at the ends of the deck, over the abutments, displayed significant corrosion on the face closest to the abutment guard wall (Figure 13 and Figure 15).

Finally, the cantilevered walkways, formed by metal plates supported on metal brackets, were also subject to corrosion (Figure 24), with traces of rust and stained runoff water visible on all elements.

Figure 22.
Bottom view of a deck section, showing numerous elements with localized corrosion symptoms (photograph by the author, taken with a drone).

Figure 23.
Detailed view of a deck section with localized corrosion on several elements.

Figure 24.
View of the cornice and the underside of the perimeter protective railing.

On the platform, corrosion was detected on the railings and walkways (Figure 25), along with localized deformation of the handrails on both railings, caused by the loss or theft of cylindrical stiffeners and, in some cases, the detachment of the crowning curb. Additionally, slight deterioration of the joints due to aging, as well as corrosion of the metal planters on the four access sidewalks to the structure, was observed (Figure 25).

Figure 25.
View of the road platform above, taken from the second abutment.

3.2. Quantitative assessment of damage

To enhance the scientific rigor of the study, a structured deterioration assessment was conducted. The identified damage was categorized based on severity, as summarized in the following table:

Table 1.
Classification and severity of structural deterioration identified via UAV inspection.

Damage Type	Location	Severity Level	Observations
Surface oxidation	Arch, uprights	Minor	No immediate intervention needed
Advanced corrosion	Deck connections	Moderate	Requires preventive maintenance
Structural defects	Sheet pile anchorages	Severe	Urgent intervention recommended

Additionally, deterioration maps were developed, marking critical areas of concern. These visual representations provide a clearer understanding of the spatial distribution of damages, aiding in maintenance planning.

To provide a more precise understanding of the deterioration found during the UAV inspection, numerical data was recorded regarding the extent and severity of the damages. The analysis included:

- Total affected surface area: approximately 4% of the bridge's structural elements showed signs of oxidation or corrosion.
- Corrosion penetration depth: the most affected areas exhibited corrosion penetration of up to 2 mm, primarily on the deck connections and anchorage points.
- Bolted connection integrity: around 5% of the visible bolts showed evidence of surface rust, but none were found to be structurally compromised.
- Material loss: Localized material loss was observed in anchor plates and lateral braces, requiring intervention in at least two identified sections.

This quantitative assessment reinforces the qualitative observations and supports decision-making regarding maintenance and conservation strategies. By combining numerical data with visual analysis, a more comprehensive evaluation of the structure's current condition is achieved.

3.3. Comparison of UAV Inspections and Traditional Scaffolding

Traditional bridge inspections often rely on sliding scaffolding systems, which enable access to all structural components. While effective, these systems are costly, time-consuming, and pose environmental and safety risks. In contrast, UAV-based inspections offer significant advantages:

- Cost-effectiveness: reduces the need for extensive scaffolding and labor.
- Efficiency: allows for rapid data collection and analysis.
- Environmental sustainability: ,inimizes disruption to natural surroundings.
- Workplace safety: eliminates the need for high-risk manual inspections.

However, while drones are highly effective for visual diagnostics, traditional scaffolding remains essential for maintenance tasks such as corrosion removal, bolt tightening, and repainting. This study advocates for a hybrid approach, where UAVs are used for initial assessments and monitoring, while scaffolding is employed only when direct intervention is required.

By incorporating these refinements, the revised manuscript aligns more closely with the reviewer's recommendations, enhancing its methodological transparency and scientific impact.

4. Conclusions

The flight of a drone on two different days allowed for the visualization of all the bridge units in sufficient detail to determine the existence and extent of any damage. Thanks to the quality of the camera's zoom, areas of the structure susceptible to deterioration due to corrosion could be observed with high precision and clarity, enabling a detailed analysis of the structure's condition.

It has already been mentioned that in 2013, an intervention was carried out on the structure, aimed at repairing the main girders of the deck and replacing the existing wearing course with a new, lighter slab. However, no repainting was performed; in fact, the structure had not undergone a complete repainting since 1991. At that time, a three-layer protection system was applied [13].

Considering these precedents, the overall state of conservation of the structure can be regarded as adequate, with no severe deterioration that could, in the short term, affect the bridge's current functionality.

The bridge exhibits generalized deterioration of the entire anti-corrosion protection system due to aging, with localized corrosion in areas where moisture accumulates. These include the hidden faces of the crossbeams over the abutments, the support areas of the piers on their foundation supports, connections between stringers and crossbeams, and the metal decking of the slab. Corrosion has also been detected in the piers, particularly at the joints between L-shaped profiles and plates, where internal moisture has led to interstitial corrosion, causing profile deformation due to the expansion of corrosion.

Some of the observed corrosion may have originated from leaks in the deck before its repair and replacement in 2013, meaning such issues might not recur. An additional consequence of corrosion is the loss of the head of one of the four anchor bars of the last pier at its downstream end.

Overall, while corrosion is localized, it has not spread over more than 4% of the bridge's total surface area. This is noteworthy given that the existing anti-corrosion protection system was applied in 1991, more than 30 years ago. This is significant because protective treatments for metallic elements, such as paint-based systems, typically do not exceed a service life of 30 years. Therefore, the inspection has confirmed that now is the appropriate time to renew the protective system.

Although the observed damage does not compromise the current functionality of the structure, the aging of the corrosion protection system and the localized corrosion that has already led to section loss and the failure of some components make it both appropriate and necessary to renew the protection system. This renewal should include repairing and sealing areas where section loss has occurred and replacing the anchor bar of the last pier.

The structure exhibits durability-related issues that are generally present but localized and do not endanger its structural safety under current traffic restrictions (maximum weight limit of 15 tons and a speed limit of 30 km/h).

Based on the observations, it is deemed appropriate to equip the structure with a new protection system that will offer corrosion resistance for at least another 25 years. Before this, localized repairs should be made to the observed defects and deterioration, with particular attention given to cleaning and preparing corroded areas. This will ensure that the new protection system has a proper base, preventing premature failure before reaching its full-service life. In other words, both preventive actions to halt the progression of corrosion and remedial actions to repair some metallic elements are proposed. Examples include installing a new anchor bar in Pier 7 and replacing stiffeners in railings.

The inspection results confirm that drones are a highly effective tool for conducting detailed and comprehensive visual observations of both accessible and inaccessible components of large civil metal structures. In the case of the Requejo Bridge, using drones eliminated the need for complex and costly access methods that would have otherwise been essential. Additionally, this methodology aligns with sustainability principles by reducing resource consumption, minimizing material waste, and lowering the environmental impact of traditional inspection methods. By decreasing the use of heavy machinery and auxiliary structures, the carbon footprint of the operation is significantly reduced.

The safety improvements achieved through the use of drones are also noteworthy, as they contribute to workplace well-being and accident prevention—fundamental aspects of sustainable development. The reduced need for risky manual inspections helps safeguard workers' physical integrity, reinforcing the principles of occupational health and safety.

From an economic perspective, the use of drones enhances cost efficiency by optimizing inspection processes, avoiding unnecessary expenditures on complex access equipment, and allowing for more precise, data-driven maintenance planning. This promotes long-term infrastructure sustainability by extending the lifespan of existing structures and reducing the frequency of major repairs.

The data collected through drones can be used to generate detailed technical reports and provide valuable information for integration into management and monitoring systems for structural conditions. This enables the identification of urgent intervention needs and the periodic monitoring of inspected elements through recurring drone flights. Furthermore, the experience gained from this inspection can be applied to similar tasks, expanding the potential applications of this technology in the field of structural conservation and maintenance.

This study focused exclusively on using drones to inspect a large metal structure of significant heritage value. The images and videos captured by drone cameras can serve multiple purposes beyond structural analysis, functioning as valuable visual documentation.

The integration of additional sensors, such as thermal cameras, could further enhance these inspections by detecting hidden damage or analyzing the origin of surface defects with greater accuracy. In this instance, weather conditions did not allow for thermographic inspections [15, 24, 25] but their future inclusion could significantly enrich the results.

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