



An integrated framework for non-destructive evaluation of bridges using UAS: a case study

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Abstract

The following paper proposes an Unmanned Aircraft System (drone) inspection framework for communities where guidelines for this emerging technology have yet to be provided. The framework involves pilot training in an area with similar features to the structure to be inspected, developing best inspection practices for future application, selecting a bridge for detailed inspection using non-destructive testing methods such as visual inspection, and inspecting the bridge using the UAS inspection framework developed for the area. The results of both reviews are compared, and the framework is validated. The final inspection framework is presented in the paper, along with relevant conclusions and future work. The proposed framework can be valuable for infrastructure owners and inspectors to conduct more efficient and cost-effective bridge inspections while ensuring safety in communities with limited UAS guidelines and research work. The structural analysis, qualitative assessment, and load rating of the case study are presented as proof of concept on the effectiveness of the UAS bridge inspection and its advantages.

Keywords Bridges · Non-destructive · UAS · Inspection · Drones

1 Introduction

1.1 The Importance of bridge inspection

Infrastructure inspection is crucial to ensure the safety and reliability of the ever-expanding infrastructure network that connects cities, accommodates people, and serves communities. As the population grows, more infrastructure is built to satisfy their needs, resulting in an ever-increasing inventory of structures that require regular inspection and maintenance [1]. According to recent statistics, in the United States alone, over 617,000 bridges and 48,000 miles of highways are in

operation, and millions rely on these structures daily [2]. In South America, the bridge inventory is 4725 in Brazil [3] and 8000 bridges in Chile [4]. This emphasizes the importance of regular infrastructure inspection to detect defects, deterioration, and potential safety hazards before they escalate into costly and dangerous problems.

Inspection is a crucial aspect of the infrastructure development process. The owner shall guarantee its functionality and the safety of its users from its opening until the structure is decommissioned. This is especially critical as unforeseen extreme events may compromise the structure's safety and the communities it serves [5]. Despite the importance of regular inspection, the mandatory nature of inspection requirements differs depending on location. In some regions of the world, inspection is optional, resulting in owners potentially preceding necessary safety measures that can put lives at risk. In other areas, inspection requirements are enforced differently, leading to inconsistencies in safety standards.

The American Society of Civil Engineers reported that in 2018, out of the 614,387 bridges in the United States, approximately 46,000 were classified as structurally deficient, and 188 million trips were taken across these bridges daily [6]. Furthermore, Muñoz and Valbuena [7] found that 14% of the

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bridges in the national road network of Colombia failed due to structural deficiencies, based on the evaluation of a statistical sample of 63 collapse cases. Therefore, infrastructure inspection and maintenance must be mandatory and consistently enforced across all locations to ensure public safety and avoid potentially catastrophic incidents.

1.2 Traditional bridge inspection

Visual inspection is the oldest method of evaluating bridges. The authors in [8] define visual inspection as a systematic visual investigation of all accessible parts of a structure. The traditional visual inspection is a physical examination method carried out through sight [9]. It includes techniques where all five senses are used with flashlights, sounding hammers, tape measures, and plumb bobs. An excellent visual inspection must also incorporate strategies conceived by the inspector through systematic methods to report findings and recommend further assessments.

1.3 Bridge inspection limitations

Inspection and maintenance practices are often reactive and triggered by previous incidents involving similar infrastructure in other parts of the world. Unfortunately, this approach is only sometimes practical, and the importance of inspection and maintenance can be forgotten as time passes. This can lead to a lack of focus on maintaining infrastructure, increasing the likelihood of catastrophic incidents when the next hazard occurs. Therefore, it is crucial to establish preventative measures for infrastructure inspection and maintenance rather than solely relying on reactionary measures. This approach requires a more proactive and ongoing effort to ensure the infrastructure is continually monitored, maintained, and updated to meet the ever-evolving safety standards [10].

Governments and institutions face several challenges regarding infrastructure inspection, including limited skilled staff, inadequate equipment, and economic constraints. Effective inspection strategies require personnel with the necessary skills to assess structures and determine whether they are fit for service. In addition, equipment is required to conduct inspections in hard-to-reach areas and to perform non-destructive and destructive testing as needed. However, financial limitations often hinder skilled staff and equipment availability, resulting in inadequate inspection practices.

Furthermore, inspections should not only occur after problems arise but also be regularly scheduled to ensure proper maintenance and upkeep of infrastructure. Common inspection schedules include every two years [11], after 25 years of service, and following hazard events. Unfortunately, funding for infrastructure inspection is often a low priority for

governments and institutions, leading to delayed inspections and compromised public safety. To address these challenges, allocating appropriate funding and resources for infrastructure inspection and maintenance is crucial.

1.4 Unmanned aircraft systems in bridge inspection

Unmanned Aircraft Systems (UAS) use for infrastructure inspection has gained significant attention in recent years due to its potential to reduce costs and enhance inspection quality. UAS are remote-controlled systems that do not require a human pilot to fly the aircraft. Typically, UAS has cameras that allow high-quality pictures and videos to be captured during inspection flights. However, recent technological advancements have enabled UAS to perform more complex tasks, such as creating digital twins and 3D models, and reconstructing the inspected structure.

One significant advantage of UAS is its ability to access hard-to-reach areas, which is especially useful for inspecting tall structures or bridges. In addition, UAS can perform inspections faster than traditional methods, reducing the time required to inspect infrastructure and minimizing disruptions to public services. Furthermore, UAS can be equipped with various sensors, such as LiDAR, x-ray, or thermography, that provide additional data and enhance inspection accuracy [12]. Other devices added to UAS can improve its effectiveness in obtaining information from structures and not be limited anymore to visual data.

To ensure that UAS technology is used effectively in infrastructure inspection, it is necessary to have a team with different skills and expertise. While some UAS systems promise to simplify complex inspection tasks with minimal effort, the reality is that most high-quality inspections require a skilled inspector, a trained pilot, and a knowledgeable post-processor. The inspector should have expertise in identifying common defects in structures or areas more susceptible to damage. The pilot should be trained to navigate complex geometries and turbulent environments or capture high-quality pictures in open environments. Finally, the post-processor must be able to analyze the data collected and prepare a comprehensive report for the infrastructure owner. It is not always possible for one person to possess all these skills, but in some cases, they do. Regardless, the team shall work together to ensure the proper use of UAS technology in infrastructure inspection.

1.5 UAS bridge inspection in local communities

In recent years, the use of UAS in infrastructure inspection has been steadily increasing worldwide. However, despite its potential benefits, there needs to be more guidance available on the protocols to follow for a successful assessment using UAS. In the case of bridges, the United States often

considered a reference point for other countries, has yet to provide federal guidance for an inspection protocol using UAS [10]. In Latin America, where traditional inspection methods are limited, new technologies such as UAS are falling behind and require prioritization.

Some studies have shown that UAS can reduce inspection costs by up to 50% [13], making it a promising option for infrastructure owners looking to reduce their expenses. As UAS can significantly decrease inspection costs, owners should pay attention to this emerging technology and incorporate it efficiently into their inspection procedures. However, the literature on bridge inspection is limited, and there is a need for guidance to conduct inspections in areas where guidance does not exist or where foreign literature has not been adopted.

The following paper introduces a UAS inspection framework for communities where guidelines for this emerging technology have yet to be provided. The proposed framework involves training in an area with similar features to the structure to be inspected and developing best inspection practices for future application. Then, a bridge is selected for detailed inspection, including non-destructive testing methods such as visual inspection. Finally, the bridge is inspected using the UAS inspection framework developed for the area. The results of both reviews are compared, and the framework is validated. The final inspection framework is presented in the paper, along with relevant conclusions and future work. This study also includes the structural analysis, qualitative assessment, and load rating of the case study as proof of concept on the effectiveness of the UAS bridge inspection and its advantages. The proposed framework can be valuable for infrastructure owners and inspectors to conduct more efficient and cost-effective bridge inspections while ensuring safety in communities with limited UAS guidelines and research work.

2 Materials and methods

2.1 Training and platform preparation

The first step in developing the framework presented in this study involved pilot training. The pilot should be knowledgeable in planning efficient flight routes to maximize image coverage and minimize overlap. The pilot for this study was new to any UAS, and the selection of the appropriate platform to conduct the UAS inspection was reduced to two options: Phantom 4 and Anafi. Both aircraft are equipped with features for photogrammetry and meet the necessary quality standards presented in the literature [14]. Next, the pilot was familiarized with the technical specifications of the equipment and settings to achieve optimal results. The main parameters focused on in this

study were personalized to capture oblique and orthogonal photographs of the surface of any structure.

A walkway-type bridge on the campus of the Pontificia Universidad Javeriana Cali, Colombia, was chosen as a training location for the novice pilot. The area was selected due to its resemblance to some regions of bridge structures, the focus of this study, found in the metal piers and cantilevered slab. The bridge walkway is shown in Fig. 1, where the flight missions in free-flight mode followed practice trajectories: over, under, and perimetrically around the structure to achieve 75% overlap. The model is capable of generating a high-quality 3D model and photographic record of all parts of the structure.

The flight path was automated using PIX4D CAPTURE and CTRL + DJI software. This approach allowed for more comprehensive coverage of the study area and detailed information collection. From the preliminary study, the quality of images and effectiveness of the inspection were improved by generating circular paths with oblique image capture at 30° and double grid with orthographic photos taken at 90° to the terrain surface were the most efficient ways to collect information. Finally, the described approach was applied to the case study and is presented in Fig. 2.

2.2 Traditional inspection methodology: visual inspection

The visual inspection followed the procedure detailed by the national organization where the bridge is located: INVIAS [15]. The inspection started with drawing simple plans of the structure, as presented in Figs. 3 and 4, from surveying dimensions obtained by tape measure and topographic surveying. In addition, a detailed inspection report was prepared to document defects on the bridge, including pictures



Fig. 1 Side view of the corridor at the practice building

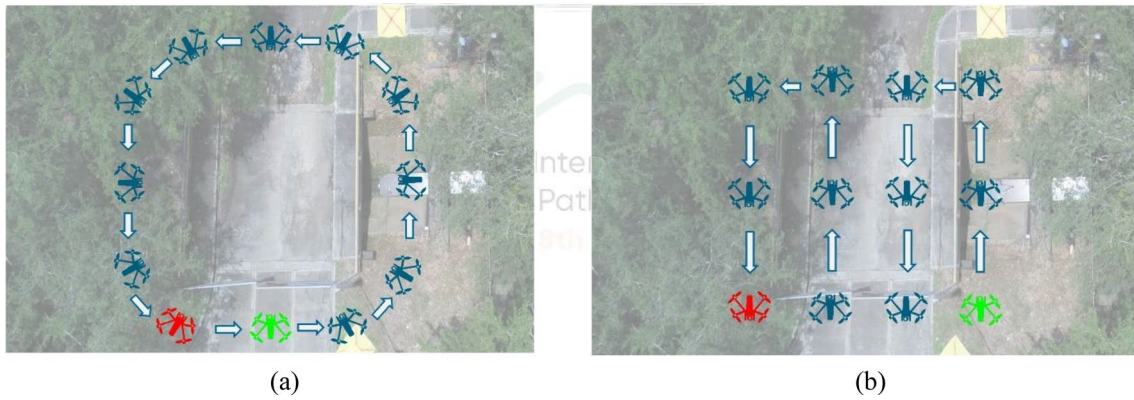


Fig. 2 Automated programmed flights: a Circular paths b Double grid

Fig. 3 Plan view of the bridge

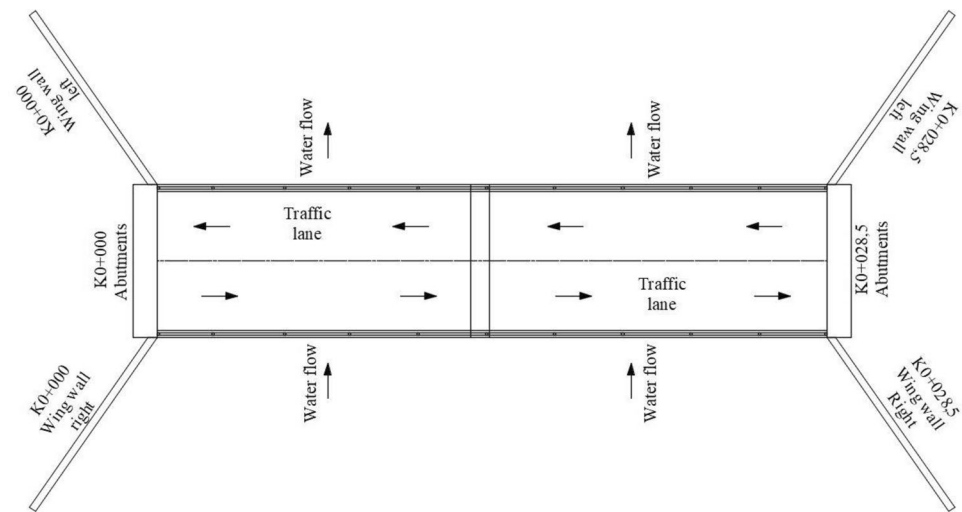
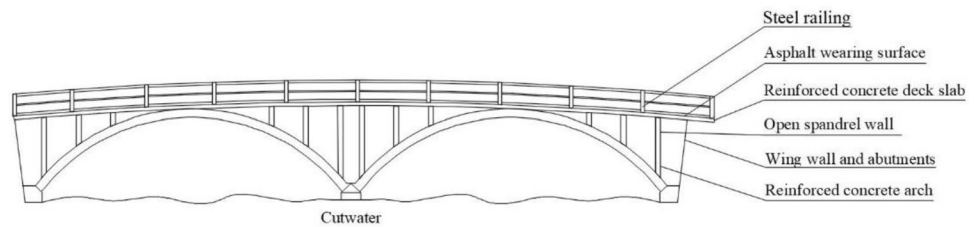


Fig. 4 Elevation view of the bridge



obtained by a camera with a resolution of 16 MP on a mobile device.

2.3 Case study: Río Claro bridge

The bridge selected to prove, develop, and test the effectiveness of the framework proposed by the authors in this study was chosen following criteria that would allow for effective inspection using both the traditional method (visual inspection) and the innovative method (UAS inspection). The requirements are presented below.

1. The bridge construction material is common in the area: reinforced concrete.
2. The bridge was built before implementing the Colombian Bridge Design Standard to guarantee structural damage to report.
3. The bridge presents moderate to severe levels of structural damage to allow better comparison between traditional techniques and UAS applications.
4. The bridge is accessible for both traditional and UAS inspections.

5. The bridge has some technical information to aid inspection.
6. The bridge is located in an area to ensure the safety of the equipment and operators during the inspection process.

The Río Claro Bridge, presented in Fig. 5, complied with the abovementioned criteria and was selected as the case study. The bridge is located on the road connecting the municipality of Jamundí in the Valle del Cauca Department to the municipality of Suárez in the Cauca Department. The bridge has a length of 28.5 m (93.5 feet) and a deck width of 6.58 m (22.47 feet). The bridge comprises a reinforced concrete arch-type system with metal railings, asphalt-type road, deck, and arch-deck with walls, arches, cutwater, abutments, debris fins, and foundations.

2.4 Innovative inspection methodology: UAS inspection

The Unmanned Aerial Vehicle (UAV) selected for this inspection was the Anafi Work with a resolution of 21 MP. The procedure started with a reconnaissance flight, verifying the appropriate height to carry out the missions and the high-risk areas that could cause a UAV collision. Based on

this information, a first “simple grid” flight mission was completed to identify bridge sections and surrounding areas. The mission was conducted 20 m above the bridge deck with the UAV camera oriented at a 90° angle. The total mission time was 2 min at a speed of 2 m/s (4.47 mph). The purpose of this flight was to locate control points using Global Positioning System (GPS) to enable georeferencing pictures.

A free-flight type was performed in the next mission to capture all the bridge components. The free-flight mode allows the pilot to fly the structure freely. The second mission provided enough data to generate a 3D digital model. The model required three control points with latitude, longitude, and altitude information obtained using GPS and presented in Fig. 6. A thorough inspection was achieved using the 3D model to complement dimensions from components not accessible by common equipment in the traditional inspection.

Five free missions were performed, as presented in Fig. 7. Depending on the location of the UAV on the bridge deck, the vertical inclination of the camera was projected to focus on and capture all areas of the components. These inclinations varied from +30° to −90° and changed according to the altitude of the UAV. Additionally, these missions were planned to capture minimum overlaps of 75% since they resulted in a good percentage of the training missions. In



Fig. 5 The Río Claro Bridge: **a** Road view **b** Isometric view

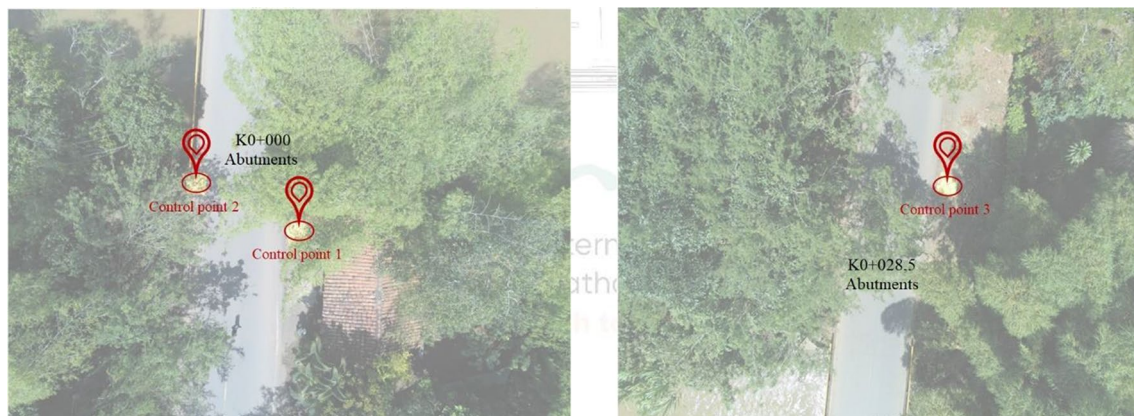


Fig. 6 Plan views of control points near the case study bridge

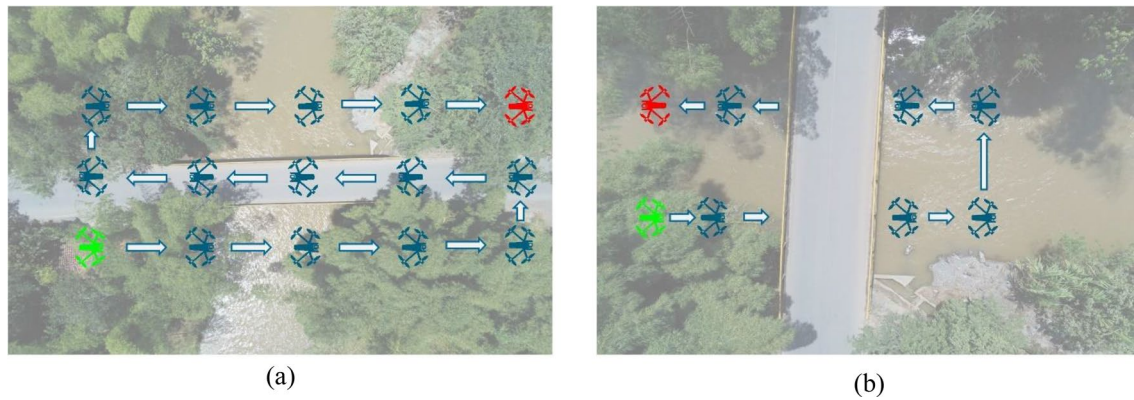


Fig. 7 UAV flight missions: **a** Simple grid type and **b** Free mission

total, 536 photographs were captured with a total flight time of 60 min and using 4 UAV batteries.

2.5 Rating factor

The rating factor is a tool to assess whether a structural element can adequately support live loads, such as a specified truck load, or any other anticipated loads. The assessment of load rating using the rating factor is a crucial aspect of bridge safety and maintenance, as it determines whether a bridge can safely support traffic and other loads [16].

The rating factor considers the effects of bending moment and shear force, and aims to ensure that the load effect being resisted is at least equal to the prevailing load. The ratio of these two effects is known as the rating factor (RF). The bridge can withstand the live load if RF is greater than or equal to 1.0 [17]. The rating factor is calculated using Eq. 1.

$$RF = \frac{[(\phi_c \phi_s \phi_n R_n) - (\gamma_{DC})(DC) - (\gamma_{DW})(DW) \pm (\gamma_P)(P)]}{(\gamma_{LL})(LL)(1 + IM)} \quad (1)$$

where ϕ_c represents condition factor, ϕ_s system factor, ϕ_n resistance factor based on construction material, R_n nominal capacity of a member, γ_{DC} dead load factor for structural components and attachments, γ_{DW} dead load factor for wearing surface and utilities, γ_P load factor for permanent load, γ_{LL} live load factor, and DC, DW, P, LL, and IM provides the dead, live and dynamic loads effect. A detailed description of each parameter is summarized in Table 6 in Appendix A.

3 Application and analysis

3.1 Traditional approach: visual inspection

Table 1 presents the results obtained during the traditional inspection. Notice that the damage was not quantifiable in some parts of this table due to natural obstacles covering important inspection areas. The table follows the methodology presented by INVIAS.

A visual representation of Table 1 is presented in Figs. 8 and 9. Each image contains a number corresponding to the element number in Table 1.

3.2 Innovative approach: UAS inspection

The inspection report generated from UAS information was more complete than the traditional inspections. This is because the inspector could access more information collected by the aircraft in the pre-planned and free flights. The additional visual data comes from areas that were inaccessible to the inspector. In addition, the generated 3D modeling provided other details from defects not captured in the traditional inspection. In fact, some damage captured by the UAS and not determined by the traditional inspection could compromise the bridge's structural integrity if left unattended.

Table 2 summarizes the inspection report prepared with information obtained by the UAS. In addition, Figs. 10 and 11 provide a visual representation of the defects on the case study bridge obtained by UAS inspection. Each image contains a number corresponding to the element number in Table 2.

Table 1 Inspection report based on traditional inspection technique

No	Elements	Defects	Measure	Numerical rating
1	Asphalt wearing surface	Transverse crack	2.45 m	3
2	Asphalt wearing surface	Expansion joint crack	13.16 m	3
3	Steel railing	Painted steel railing	140 m	2
4	Steel railing	Deformations by vehicular impact	19.8 m	4
5	Wing wall and abutments	Vegetation growing	63.73 m ²	2
6	Wing wall and abutments	Inadequate construction joint	7 m	4
7	Wing wall and abutments	Crack due to movement of the abutments wall	9.58 m	4
8	Cutwater	Accumulation of debris	–	–
9	Reinforced concrete deck slab	Exposed reinforcing bars	0.82 m ²	4
10	Reinforced concrete deck slab	Efflorescence	2.98 m ²	3
11	Reinforced concrete deck slab	Inadequate coating thickness	–	–
12	Reinforced concrete deck slab	Honeycombing	0.60 m ²	2
13	Reinforced concrete deck slab	Vegetation growing	8.54 m ²	2
14	Open-spandrel wall	Shear cracks	1.20 m	4
15	Open-spandrel wall	Inadequate construction joint	9.04 m	4
16	Open-spandrel wall	Honeycombing	–	–
17	Reinforced concrete arch	Honeycombing	0.34 m ²	3
18	Reinforced concrete arch	Efflorescence	–	–



Fig. 8 Elevation view of the bridge with defects obtained by traditional inspection

3.3 Innovative approach: 3D modeling

The 3D modeling was performed using ContextCapture software, which employs photogrammetric techniques to produce a model from images provided by the user. The model was georeferenced to the national topographic network of Colombia with UTM 18 (MAGNA-SIRGAS-West) Cartesian coordinates. The three control points established in previous sections were used to complete the geolocation and positioned by dual-frequency Global Navigation Satellite System (GNSS) equipment and real-time adjustments through Real-time Kinematic Positioning (RTK) technology.

The model was generated from 535 aerial photographs taken by a red, green and blue (RGB) camera on board the

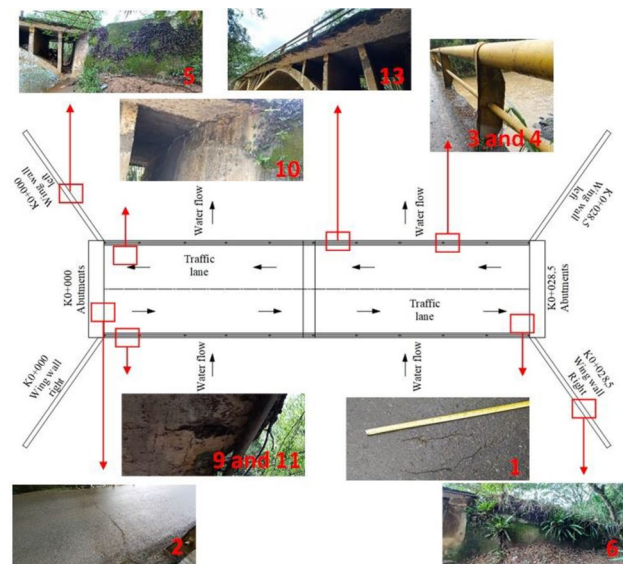


Fig. 9 Plan view of the bridge with defects obtained by traditional inspection

aircraft during UAS inspection. The processing resulted in 56,996 tie points obtained by finding spatial congruence from at least three aerial photographs. This is because a pixel must be present in at least three aerial pictures. This principle is illustrated in Fig. 12 (left), where the colors indicate the number of images used to determine a point with X, Y, and Z coordinates (yellow with 3, green with 4, and blue

Table 2 UAS inspection report

No	Elements	Defects	Measure	Numerical rating
1	Asphalt wearing surface	Transverse crack	2.27 m	3
2	Asphalt wearing surface	Longitudinal crack	0.88 m	3
3	Asphalt wearing surface	Expansion joint crack	12.56 m	3
4	Steel railing	Painted steel railing	118 m	2
5	Steel railing	Deformations by vehicular impact	6.84 m	4
6	Wing wall and abutments	Vegetation growing	68 m ²	2
7	Wing wall and abutments	Inadequate construction joint	13.48 m	4
8	Wing wall and abutments	Crack due to movement of the abutments wall	6.68 m	4
9	Cutwater	Accumulation of debris	3 m ²	3
10	Reinforced concrete deck slab	Exposed reinforcing bars	1.45 m ²	4
11	Reinforced concrete deck slab	Efflorescence	7.98 m ²	3
12	Reinforced concrete deck slab	Inadequate coating thickness	1.20 m ²	3
13	Reinforced concrete deck slab	Honeycombing	0.60 m ²	2
14	Reinforced concrete deck slab	Vegetation growing	8.53 m ²	2
15	Open-spandrel wall	Shear cracks	2.66 m	4
16	Open-spandrel wall	Inadequate construction joint	57.85 m	4
17	Open-spandrel wall	Honeycombing	2.22 m ²	4
18	Reinforced concrete arch	Honeycombing	0.24 m ²	3
19	Reinforced concrete arch	Efflorescence	50 m ²	3

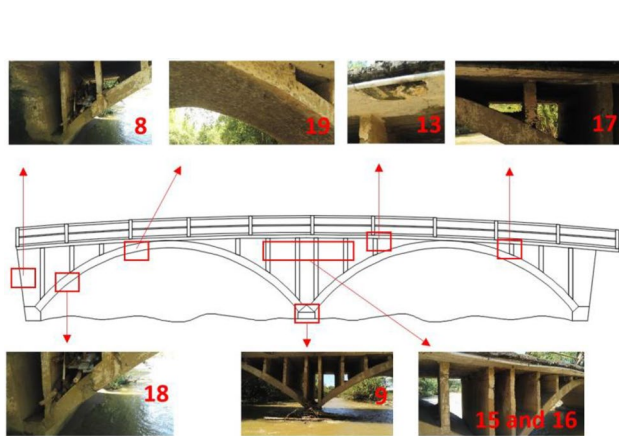


Fig. 10 Bridge elevation view with defects captured by UAS

with five or more photos). As a result, the yellow points in Fig. 12 (left) have a spatial congruence of 3 pictures. In contrast, those in green and blue have an agreement between 4 and 5 photos, producing a model with high precision and resolution.

The color classification in Fig. 12 (left) indicates that the triangulation generates sub metric pressures by having more than three photos for spatial position calculation. This is a good indicator of different levels of accuracy. Fig. 12 (right) illustrates this principle by showing an error between 0 and 0.006 m corresponding to the purple

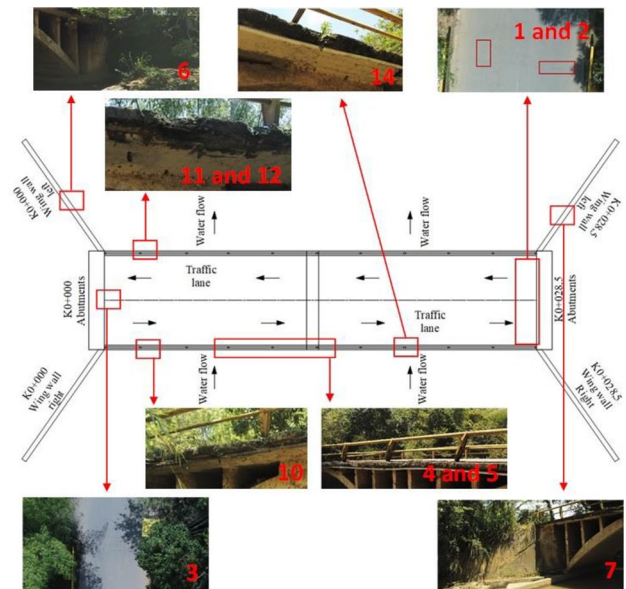


Fig. 11 Bridge plan view with defects captured by UAS

and blue colors on the bridge, providing tremendous confidence in the model. The red color shows errors up to 9 cm on the vegetation in the study area and not the focus of this study.

The final product of this innovative analysis is the 3D model presented in Fig. 13. The model allowed the quantification of previously undetected structural defects using

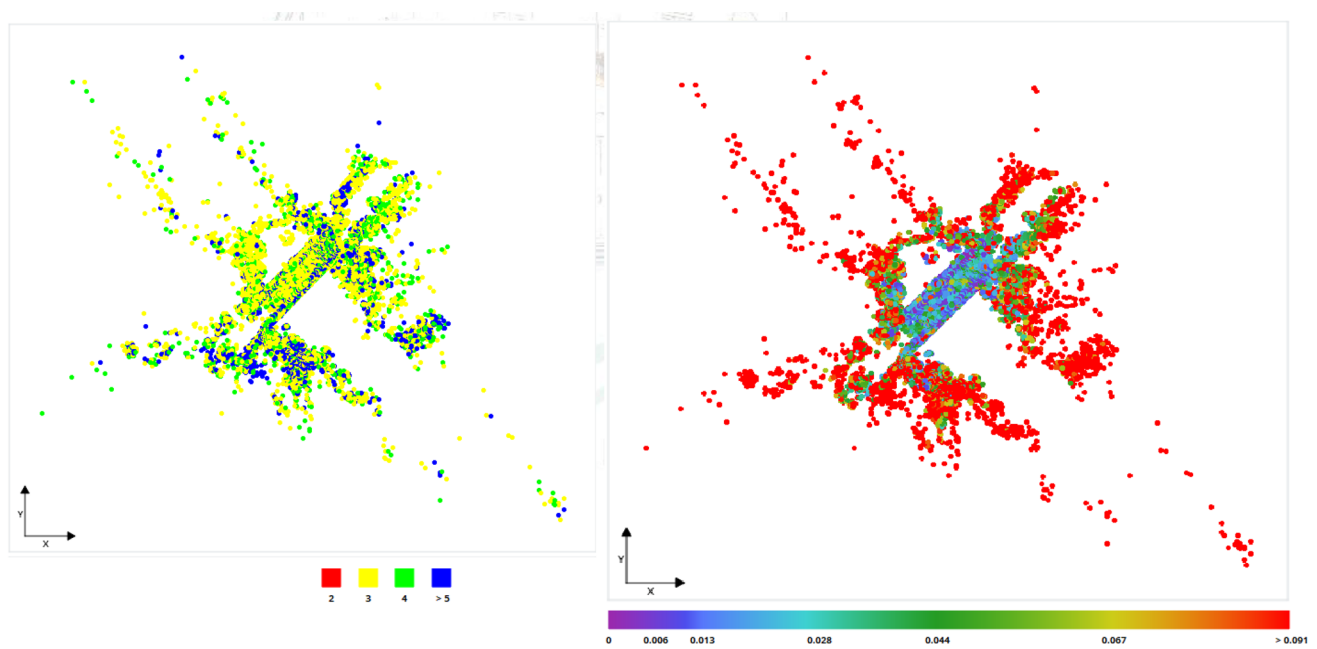


Fig. 12 Number of photos at the link points (left) and position of uncertainty between points in meters (right)

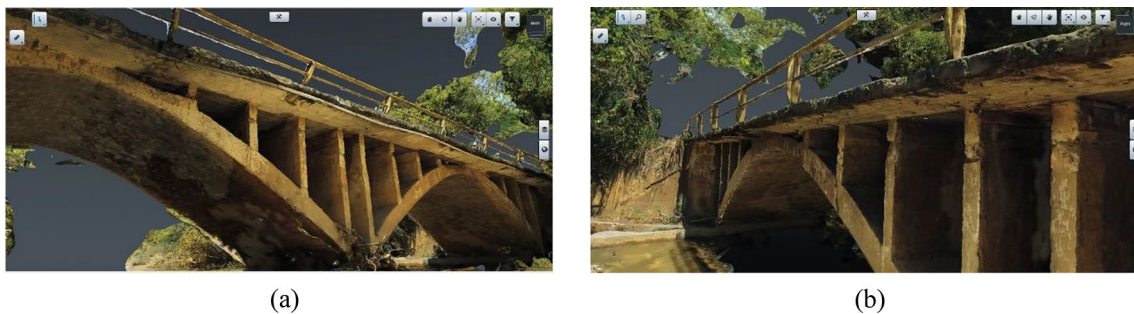


Fig. 13 3D model of the case study bridge: **a** upstream view and **b** downstream view

traditional inspection. Defects determined from the 3D model include cracks, joint damage, fissures, efflorescence, segregation, and defects in the arches, slab, and railings.

3.4 Holistic structural evaluation: traditional and innovative inspections

3.4.1 Qualitative analysis

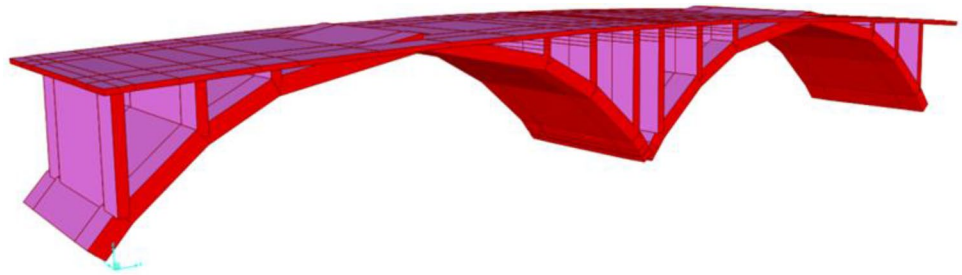
The damages in the inspection reports were used to apply the status correlation procedure by element and numerical qualification presented in [18]. From the analysis, 12.5% of the components are in good condition, 37.5% are in fair condition, and 50% are in bad condition. The retaining walls, spandrel walls, and wings walls suffered the most severe and extensive damage, receiving a quantitative rating of 4,

which, according to the Administrative System of Bridges in Colombia [15], indicates severe damage that requires immediate repair. The bridge received the structural state of 'bad' by selecting the highest result from the sum and weighting of the numerical qualification and its equivalent in a descriptive capability.

3.4.2 Structural modeling and rating factor

The structural analysis was conducted following the methodology proposed by [17], which allows an evaluation of the wall-type component supporting the predominant vehicular load from the internal shear forces and bending moments. The bridge was analyzed under the geometric conditions during the inspection and the load requirements according to [19]. The structural model was developed in the CSIbridge v24.0.0 software [20]. The bridge geometry was defined

Fig. 14 3D structural model



from the 3D modeling obtained using the images captured by the UAS. The components were assigned a shell-type configuration in the software and support as either pinned or fixed, as presented in Fig. 14.

The compressive strength of the concrete used in the model was determined through the non-destructive hammer impact test by the provisions of [21]. The minimum allowed yield strength of the reinforcing steel was assigned by [19]. Table 4 in Appendix A presents the mechanical properties of the materials used in the model.

The loads considered in the model were:

- Dead load due to structural components and attachments (DC).
- Dead load due to wearing surface and utilities (DW).
- Live load effect (LL), design tandem, consisting of 125 kN axles spaced 1.20 m apart and with a transversal spacing of the wheels of 1.80 m.
- Design Lane load (LL), consisting of 10.3 kN/m load, uniformly distributed in the longitudinal direction of the bridge.

The structural modeling aided in calculating a rating factor focused on the bridge spandrel wall since this element presented the most structural concern. In addition, the model provided shear forces generated by the different loads (DC, DW, and LL). The maximum internal shear forces for the spandrel wall are presented in Table 5 in Appendix A.

The rating factor is calculated using Eq. 1 considering the loads presented above and the parameters summarized in Table 6 in Appendix A. The rating factor obtained following the methodology and using Eq. 1 is **RF = 0.95**. A rating factor less than 1.00 implies that the structure in its current state cannot carry the design loads. Furthermore, the rating factor confirms the qualitative results obtained through the visual information captured by the traditional visual inspection methodology and UAS inspection. Therefore, quantitative and qualitative analysis confirms the poor condition of the bridge selected for the study case.

3.5 Comparison of inspection by traditional and innovative approaches

Traditional and innovative approaches were compared to analyze the advantages and disadvantages of each methodology. Table 3 summarizes relevant characteristics when conducting a bridge inspection.


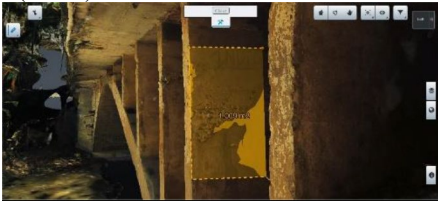



3.6 Framework: proposed methodology

The following paper has shared a practical work framework when implementing UAS technology in traditional bridge inspection where limited specifications and training are available. The framework distinguishes from others in the literature because it is suitable for novice and expert users of this technology. The framework also focuses its application in communities where UAS applications are not prevalent and UAS procedures are limited.

The framework is summarized in the following section:

1. *UAS self-training*: Familiarize with the UAS in a controlled environment, precisely capture images that suit the project's needs, and develop skills to navigate near structures. Ideal structures are the ones with geometries similar to bridges. Important skills to learn and train are: remote control settings, battery charging and flight time allocation, flight configuration for pre-planned missions, satellite map, GPS availability and positioning, flight speed, and mission path shape (e.g., polygon, grid, double grid, or free flight) come into play. At least 50 h of flight time is recommended to achieve proficiency for novices. Pilots with less than 50 h of flight time should conduct inspection operations with caution.
2. *Reconnaissance flight*: a flight covering the entire inspection area is recommended before collecting the inspection information. This flight should allow the inspector to identify appropriate heights of structural elements, high-risk collision areas, and the preliminary regions where dedicated inspection may be needed.

Table 3 Comparison between traditional and UAS inspection

Feature	Traditional inspection	UAS inspection
Fieldwork time	240 min	60 min
Office work time	Three days	Four days
Equipment	Camera/flash Measuring tape Flashlight Inspection forms Computer	Unmanned Aerial Vehicle GPS FOIF A90 Computer
Picture files	237	665
Percentage of access to the bridge	80%	100%
Accuracy in the damage quantification for elements with difficult access	Medium: e.g., a measure of honeycombing in the reinforced concrete arch (0.34 m ²) presented in the figure 	High: e.g., a measure of honeycombing in the reinforced concrete arch (0.244 m ²) presented in the figure 
Accuracy in the damage quantification of elements with limited access	Not possible	High: e.g., honeycombing in an open spandrel wall (1.0 m ²) 
Level of effort to obtain images for an accurate 3D model	Very high	Very low
Ability to obtain pictures from multiple angles	Low 	High 
Requirement of special equipment: boat, snooper truck, or scaffold	Yes	No
Inspector Safety	Low 	High 

3. *UAS inspection flight*: apply lessons learned from the training conducted in the initial phase and collect information on the structure's integrity to prepare an inspection report. Depending on the complexity of the structure or the level of overlap the inspector wants to achieve, the flight mission may be pre-planned or free-flight. At this step, the inspector should provide GPS control points to georeference the future 3D model. The inspector should revise the methodology at any point during the inspection, perform safe operations, and, if necessary, prepare additional practice in the training structure before performing challenging tasks.
4. *Supplemental visual inspection*: verify the structure has been inspected and significant defects are documented or recorded for future analysis. The instructor is responsible for guaranteeing the accuracy of the results obtained during the inspection, either by UAS or traditional techniques.
5. *Build a 3D model*: use images captured in the flight missions to generate a 3D model with GPS information. The model measures defects and structural elements of the bridge inspected.
6. *Post-processing and inspection report*: an inspection report collecting significant findings is presented to the owner or the agency in charge of the structure. The report may additionally include a structural analysis of the current status of the structure, a qualitative assessment of the condition, and a load rating analysis.

4 Conclusions

The following paper presents an inspection framework using Unmanned Aerial Systems for bridges in communities without specific guidelines for this technology. The framework involves training a pilot in an area with similar features to the structure to be inspected, developing best inspection practices, and selecting a bridge for detailed inspection using both UAS and traditional methods. The results of both inspections are compared, and the framework is validated. The proposed framework is valuable for infrastructure owners and inspectors to conduct more efficient and cost-effective bridge inspections while ensuring safety in communities with limited UAS guidelines and research work. The UAS inspection framework is expected to contribute to safer and more cost-effective bridge inspections in the future.

The effectiveness of the UAS bridge inspection is demonstrated through a case study conducted on the Río Claro bridge in Colombia. The results of the UAS inspection were compared to the traditional visual inspection, and the framework proved to be effective. The UAS inspection methodology identified additional defects not found through visual inspection, and it was possible to obtain

high-quality images of the bridge's structure. The UAS inspection allowed for better coverage of the bridge, increased safety of the inspection personnel, and reduced the time and cost of the inspection. Therefore, the UAS inspection framework proposed in this study can be used to identify defects at an early stage, enabling timely repairs, and, ultimately, extending the life of the bridge.

Finally, the UAS inspection framework can also reduce the cost of bridge inspections, especially for bridges in remote areas, which are often expensive to inspect. The proposed framework can be modified and adapted to other types of structures, such as dams, tunnels, and buildings, to ensure their safety and extend their life cycle. The authors recognize the initial investment required to acquire a UAS but emphasize the benefits and applications. The results of this study provide valuable information to infrastructure owners and inspectors, enabling them to make informed decisions about the maintenance and repair of their infrastructure.

Appendix

Appendix A—Structural analysis information

See tables 4, 5, 6

Table 4 Mechanical properties of materials

Property	Strength
Compressive strength of concrete $F'c$ (MPa)	28
Elastic modulus of concrete E_c (MPa)	20,637
Yield Stress of reinforcing steel F_y (MPa)	420
Elastic modulus of reinforcing steel E_s (MPa)	200,000

Table 5 Maximum shear force at the open spandrel wall critical section

Element	Type	Prevailing load	Force type	Values of force (kN)
Open-spandrel wall	Shell	DC	Shear	23
Open-spandrel wall	Shell	DW	Shear	8.62
Open-spandrel wall	Shell	LL	Shear	100.32

Table 6 Parameters for the rating equation

Parameters	Defined values	Description
\emptyset_c	0.85	Condition structure: poor
\emptyset_s	1.00	All other girder and slab
\emptyset_n	0.90	For shear and torsion
R_n (kN)	346.16	Nominal shear resistance
γ_{DC}	1.25	Dead load factor
γ_{DW}	1.50	Dead load factor
γ_{LL}	1.75	Live load factor
DC (kN)	23	Dead load effect
DW (kN)	8.62	Dead load effect
LL (kN)	100.32	Live load effect
IM (%)	33	Dynamic load effect

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Declarations

Conflict of interest The authors declare no conflict of interest.

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