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REVIEW

UAV-based inspection of bridge and tunnel structures: an application review

Inspeção de estruturas de pontes e túneis baseada em VANTs: uma revisão das aplicações

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Abstract: Bridges and tunnels are large and complex structures that demand periodic inspections to assess their physical conditions. Although both have different designs and constructions from each other, a common problem they share is the drawbacks that their conventional inspections face. Moreover, conventional procedures not only are laborious, time-consuming, and costly, but also involve high and/or hard-to-reach places, often exposing the specialized inspectors to danger. To overcome these problems, the Unmanned Aerial Vehicle (UAV) is being explored to automate these inspections. Recently, the number of researches employing it within the civil infrastructure condition assessment has been growing in recent years, especially for the inspection of large and complex structures. Unlike the UAV-based bridge inspection that already has some review articles available in the literature, there are none yet for the tunnel inspection, to the best of authors' knowledge. Therefore, this article intends to conduct not only a review of the few UAV-based tunnel inspection researches available in the literature, but also an up-to-date review of UAV-based bridge inspection researches. Finally, the key challenges and future trends of the UAV-based inspection of these two structures are discussed, followed by the review conclusions.

Keywords: unmanned aerial vehicle, bridge, tunnel, inspection, applications.

Resumo: Pontes e túneis são estruturas complexas e largas que exigem inspeções periódicas para avaliar suas condições físicas. Embora ambos possuam projetos e construções diferentes entre si, um problema comum que eles compartilham são as desvantagens que suas inspeções convencionais enfrentam. Além disso, procedimentos convencionais não só são trabalhosos, demorados e dispendiosos, mas também envolvem lugares altos e/ou de difícil acesso, muitas vezes expondo os inspetores especializados a perigos. Para superar estes problemas, o Veículo Aéreo Não Tripulado (VANT) está sendo explorado para automatizar essas inspeções. Recentemente, o número de pesquisas que o empregam na avaliação da condição de infraestruturas civis vem crescendo nos últimos anos, especialmente para a inspeção de estruturas complexas e largas. Ao contrário da inspeção de pontes com VANT que já possui alguns artigos de revisão disponíveis na literatura, não há nenhum ainda para a inspeção de túneis com VANT, até onde os autores saibam. Portanto, este artigo pretende conduzir não somente uma revisão das poucas pesquisas disponíveis na literatura sobre inspeção de túneis com VANT, como também uma revisão atualizada das pesquisas sobre inspeção de pontes com VANT. Finalmente, os principais desafios e as tendências futuras da inspeção com VANT dessas duas estruturas são discutidas, seguidas das conclusões da revisão.

Palavras-chave: veículo aéreo não tripulado, ponte, túnel, inspeção, aplicações.

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1 INTRODUCTION

Bridges and tunnels are often complex large structures that demand specialized inspectors to perform their inspection and assessment in a nondestructive way, which are performed on-site by visual and physical measurement approaches, whose employment depends on the bridge/tunnel type and the material of its structure.

The visual inspection is the predominant non-contact approach used for these structures, as it will at first indicate any visual changes in their surface, such as the crack existence, which is a primary key sign of a structure failure [1], [2]. As its name says, the structure condition is visually reviewed on-site by the inspector, who will register any visual changes with images taken by a camera.

Other approach examples are the acoustic inspection, where hammers or chains are used to detect delamination or hollow areas in concrete components by analyzing the sound changes across its surface; and the infrared (IR)/thermal imaging inspection, or also referred to as infrared thermography (IRT), which may also be used to detect these defects and indicate material degradation by analyzing the infrared radiation changes along the concrete surface, collected by an IR thermal camera.

Regulations and practices vary worldwide, but for example, the manual bridge inspection in the U.S., administered and regulated by Federal Highway Administration (FHWA), usually requires a local traffic control, where the inspectors need to coordinate an inspection date with the traffic controller in order to ensure safety precautions. It is executed by 2 or 3 inspectors on average, depending on the length and complexity of the bridge, where they visually examine all the components by eyesight and prior experience to look for any defects, flaws or potential problem areas that require maintenance [3]. If any of these failures are identified, they are registered by pictures taken during the visual inspection and a physical inspection with equipment or tools is performed afterwards to quantify the damage. The FHWA requires each bridge to be inspected in a biennial routine, unless that the bridge is rated as structurally deficient, then it is recommended at least an annual routine.

This bridge conventional inspection procedure faces some drawbacks, being the main ones listed below:

- existence of inaccessible areas, usually at height;
- high-costly, as generally requires heavy machinery rental (usually aerial work platforms) to provide temporary access to these areas, in addition to affect the local traffic, as it may require lane closures in the highway bridge/tunnel cases;
- laborious, demanding a great effort from the inspectors to get near some hard-to-reach places;
- dangerous, exposing the inspectors to high and complex places, besides the weather conditions and local environment (as gale, dust, and the nearness of water environment, e.g., above lakes and rivers);
- time-consuming task, since these structures are usually large and complex.

In addition, its inspection results are subjective (dependent on the inspector's knowledge and experience), yielding to low reliability due to possible inaccuracies and failing defect detection [4]. It is worth noting that tunnel conventional inspection procedure face pretty much these same drawbacks.

To deal with them, some solutions are being explored in the literature and applied to aid or even replace some manual activities within the conventional inspection. One of them that is getting more attention is the use of Unmanned Aerial Vehicles (UAVs).

Although some reviews involving the UAV-based bridge inspection topic are already available in the literature, some of them explore a wider area within the civil infrastructure. In contrast, this article not only intends to provide an extensive up-to-date survey focused on previous works that explored the use of UAVs for bridge inspection, including both non-contact and contact based methods, but also includes the UAV-based tunnel inspection topic, about which there is no literature review available yet, to the best of authors' knowledge.

Considering all the above statements, the key goals of this review article are as follows:

1. To review the researches of bridge and tunnel inspections using UAVs, where the main applications are identified.
2. To identify the best practices and solutions to address the UAV-based inspection of this kind of structures.
3. To update this topic by presenting emerging commercial off-the-shelf (COTS) UAVs that are promising and have not yet been considered in the literature.
4. To provide both current key challenges and potential future trends of the UAV-based research in bridge and tunnel inspections.

Totally, 142 literature documents (including journal/conference papers, master's/PhD theses, technical reports, to name a few) were compiled (retrieved mainly from Web of Science, ScienceDirect, and Google Scholar databases, considering a publication year period of 2000 to 2021), being 132 related to bridge topic and 10 to tunnel. Their year of publication are gathered in a clustered bar chart (Figure 1), showing that there was a large increase of published documents from 2018 onward, indicating a growing interest on UAV employment for inspection of these large structures and its importance in the civil infrastructure field.

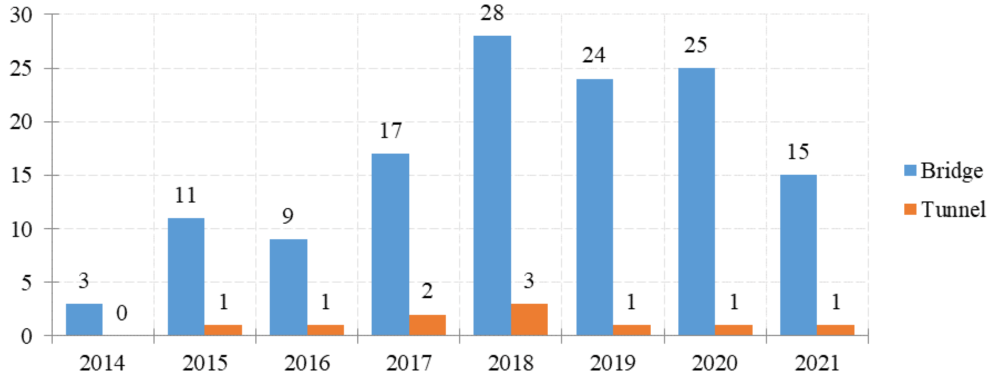

Figure 1. Number of documents published through the years concerning bridge and tunnel inspections using UAVs.

2 UAV EMPLOYMENT IN LARGE STRUCTURE INSPECTIONS

Besides the usual expressions "UAV" and "drone", there are also other correlated expressions found in the literature, as "Micro Aerial Vehicle" (MAV) and "Unmanned Aerial System" (UAS), this latter being usually composed of an UAV with its payload (the equipment it carries) and the ground control system, accordingly to the Unmanned Aerial Vehicle System Association (UAVSA) [5]. These expressions will be used accordingly to those adopted in each cited reference.

The use of UAVs, especially the multi-rotor types, bring some advantages over the conventional inspection procedure:

- it is safer, as the UAV operator control it remotely in a near safe place, together with the specialized inspector that can conduct the inspection by monitoring the UAV video broadcast or by accessing the collected images/videos later on a device (pc, tablet, to name a few);
- offers more accessibility, since the UAV can easily access hard-to-reach places when compared to the conventional procedure;
- has a relatively lower cost, as UAVs are compact, portable, and low-priced devices in contrast to the rented heavy machinery, as well as the indirect savings, such as the cost reduction associated with traffic control (e.g., lessened lane closure during highway bridge/tunnel inspection, especially the high traffic ones);
- yields reduced time inspection, due to the UAVs high mobility.

Although the research publications concerning the use of UAVs for bridge inspection begin in 2014, as stated in Figure 1, there are other few documents that were previously published, e.g.:

- Metni and Hamel [6], in 2007, that was the first step towards the UAV-based bridge inspection. It evaluated an UAV dynamics for structure monitoring and bridge maintenance, where a control scheme was developed for it under some practical restrictions, and validated the concept of inspecting bridge defects with an UAV equipped with a visual device in an on-site experiment using a small helicopter that flew around a viaduct, in France, while taking a video sequence, from which some pictures have been extracted and presented to bridge inspection experts for evaluation;
- and Moller [7], in 2008, that developed a twin-motor aerial robot called "Aerobot" to carry video cameras up to approximately 61m height to perform close inspection of elevated highway structures (including bridges), but due to some implementation issues, the device was not deployed within the schedule and the project was terminated.

Meanwhile, the UAV technology has had a major breakthrough, especially the multi-rotor types, which are more stable and produce less vibration when compared to single-rotor helicopters [8], being them essential features to collect high quality images.

This way, it was in 2014 that Brooks et al. [8] and Hallermann and Morgenthal [9] demonstrated the multi-rotor UAV capability for large structure inspections in civil engineering field, where all the aforementioned advantages (over the conventional procedure) were also stated. Brooks et al. [8] used a 6-rotor UAV (Bergen hexacopter), mounted with a Nikon D800 camera and a FLIR Tau 2 IR camera, to analyze two overpass bridges in Livonia, Michigan, whose presented significant structural defects (i.e., spall, crack, and delamination); and Hallermann and Morgenthal [9] tested an 8-rotor UAV (AscTec Falcon 8), equipped with two cameras (Sony NEX-5 and Panasonic Lumix TZ22), to inspect an 80m long concrete arch bridge, whose arch is approx. 40m high, showing that it was possible to fly at short distance from its structure, even at high heights, although the wind played the major role together with the changing lighting conditions along the structure.

After this, the UAV potential for visual inspection assistance became more and more clear as reported in the literature, e.g., Otero et al. [10] showed that the collected images from the UAS, during field tests, and by inspectors, during previous inspections, were of similar quality, and Seo et al. [11] demonstrated that the UAV-enabled inspection of an arch timber stringer bridge provided results almost identical to the conventional inspection report.

Furthermore, recent researches are also exploring the application of the UAV system for contact based inspection procedures, which brings additional challenges involving the development of inspection devices, and the UAV control, once it might interact with the target structure, generating a complex dynamic for the UAV stabilization.

In the following, all these applications are presented through the reviewed documents, which were separated into the tunnel topic (Section 3) and the bridge topic (Section 4).

3 UAV-BASED TUNNEL INSPECTION

Although UAV application for tunnel inspections is still unusual (due to the main issues of this kind of environment, e.g., lack of both lighting and global positioning system (GPS) signal), as demonstrated by the lower number of published documents, it has potential since it avoids the mobility limitations [12] as recent technology innovations on UAVs and photographic equipment are continuously being introduced to the field [13], allowing a faster inspection performance, which will be required in the future [14].

A common characteristic found in these few UAV-based tunnel inspection documents is that all of them used custom-built UAVs, needed to overcome the aforementioned issues, e.g., developed UAVs mounted with light detection and ranging (LiDAR), multiple/rotating camera system, lighting source, and GPS-free navigation system. Their information is briefly described in Table 1.

Table 1. UAV-based tunnel inspection research efforts.

Ref.	Custom-built UAV		Application scale	Findings
	(platform)	(payload)		
[15]	4-rotor AscTec Pelican	· 1 Hokuyo LiDAR; · LED lights; · 1 inertial measurement unit (IMU); · 1 1.6 GHz Atom Intel processor.	· published in 2015, was the first literature study (to their knowledge) that focused on UAV localization and autonomous control in featureless three-dimensional (3D) tunnel-like environments; · performed field experiments in three different sites: § in penstocks of both Carter and Allatoona Dams, in Georgia § in a long building hallway at the University of Pennsylvania.	· although a camera was not used in this research, the experimental results showed the feasibility of the UAV-based inspection of tunnel-like environments, making it a reasonable choice for future inspections by equipping the UAV with onboard cameras; · the proposed approach can be used for other tunnels, as those in transportation networks, besides the penstocks in dams and hydroelectric power plants that were explored in the experiments.
[16]	6-rotor KMel Robotics KHex	· 2 Hokuyo UST-20LX 2D LiDARs; · 4 VGA resolution BlueFox cameras; · 8 10W Cree power-LEDs; · 1 IMU; · 1 Intel i7 NUC board; · other sensors.	· proposed a complete system design to collect detailed images of dark, featureless, symmetric and GPS-denied environments (as inside penstocks and tunnels) for their inspection using fully autonomous MAV; · performed field experiments in penstocks of both Carters and Glen Canyon Dams, from which a 360º panoramic image reconstruction and its 3D visualization were obtained.	· the 360º panoramic image reconstruction and its 3D visualization aid for a convenient inspection of inner penstock and tunnel environments; · a safe autonomy was achieved in dark, featureless, symmetric and GPS-denied environment by fusing the data obtained from the four VGA resolution cameras and the two LiDARs.
[17]	6-rotor DJI-F550	· 1 Velodyne Puck LITE LiDAR; · 4 Chameleon3 cameras (each rectified with four Cree XHP-50 high-power LEDs); · 1 PixHawk onboard controller (with IMU); · 1 Intel i7 NUC board.	· presented a new approach to achieve autonomous UAV-based inspection of tunnels and penstocks by addressing the navigation, mapping, estimation, and control problems; · performed field experiments in a penstock of Center Hill Dam, where the autonomous and shared control navigation, environment mapping, and state estimation are demonstrated.	· the autonomous navigation was executed by the onboard controller that receives feedback from the proposed estimator while allowing the shared control navigation with an operator even when the UAV is out of his sight, provided by a visual interface that shows him the UAV sensory data in real-time.

Table 1. Continued...

Ref.	Custom-built UAV (platform)	Custom-built UAV (payload)	Application scale	Findings
[18]	4-rotor DJI-F330	· measurement component (hammering device and microphone); · traversing component (Zumo Robot platform for Arduino); · control component (wireless communication device, DJI Naza-M Lite flight controller, and a microcomputer); · positioning system (camera).	· developed an onboard hammering device for their custom-built UAV to perform tunnel inspection with the impact acoustic method, where the UAV thrust component push it along a concrete wall and the traversing component enable its movement across the structure, while the impact sounds made by the onboard hammering device are acquired by a microphone for later analysis.	· the proposed mechanism was tested in inclined composite panels, achieving free movement in an angle of inclination up to 15º, and its inspection performance was evaluated with experimental results, where the peak frequency of the impact sound (collected by hitting concrete pieces during flight) was successfully detected, validating the proposed mechanism.
[19]	4-rotor custom frame	· 1 LiDAR; · onboard computers; · other components (not specified).	· aimed to develop a railway culvert inspection tool, composed of the custom-built UAV and the developed control algorithm for semi-autonomous navigation and autonomous alignment of the UAV centroid with the culvert cross section center; · performed field experiments in a built 2.4m long small tunnel with an inner rectangular cross section of 1.38m x 1.5m, where the UAV achieved self-stabilization.	· despite some portion of the LiDAR field of view being obstructed by the UAV frame (as it is positioned in the middle of the frame), it had insignificant impact on the overall system performance; · an adjustment on the UAV flight altitude was required during the experiments to avoid the ground effect (an air cushion generated below the UAV), originated while hovering close to the ground, which was aggravated by the confined space and disturbed the UAV stable flight.
[20]	4-rotor custom collision tolerant frame	· 1 Hokuyo UST-20LX 2D LiDAR; · 1 Kodak PIXPRO SP360 4K omnidirectional camera; · 1 high power LED; · 1 StereoLab ZED stereo camera; · 6 TeraRanger One range sensors; · other components.	· attempted to address the inspection problem of human inaccessible tunnels with UAV autonomous navigation and collection of visual data inside these environments; · performed both simulations in gazebo and field experiments in a hydraulic tunnel.	· the autonomous navigation was achieved by using the stereo camera, even when losing communication over long tunnel stretches; · the omnidirectional camera with ultra-wide view angle was able to capture visual image of the inner tunnel wall condition, even inside dark environments.
[21]	4-rotor custom frame	· 1 developed rotating camera system (integrated with high luminance LEDs); · 6 TeraRanger One range sensors; · 1 LightWare SF11/C laser altimeter (down-pointing); · 1 Pixhawk 2.1 flight controller (with IMU); · 1 Intel Edison (as a companion computer); · other sensors.	· designed and developed a novel UAV (called "SWIRL" - Surveyor With Intelligent Rotating Lens) and imaging system for deep tunnel network inspection, where a novel rotating camera system perform spiral panoramic imaging (tested and validated in a field experiment at Connaught Drive underpass, Singapore); · performed both simulations using Gazebo and two field experiments to evaluate the UAV autonomous flight: § in a covered section at Eu Tong Sen Canal (to evaluate the horizontal traveling through a poor illuminated tunnel); § in an entry shaft of the Deep Tunnel Sewerage System in Singapore (to evaluate the vertical traveling in shafts).	· the limited data required by the proposed location method resulted in a relative lower UAV payload and power consumption, yielding to more than 35min of autonomous flight time; · during the field experiment in the entry shaft, its constant high velocity updraft, together with the turbulence generated by its enclosed environment, acted negatively on the UAV flight performance, rising its positioning error.
[22]	4-rotor custom frame	· 1 GoPro Hero4 camera (mounted on a rotating system with light source); · other components (not specified).	· proposed a method that exploits Bundle Adjustment, Structure-from-Motion and available geometry priors to robustly estimate the GoPro Hero4 camera pose, which is rotated 360º around the shaft of the custom-built UAV, to take a sequence of images while the UAV traverses tunnel-like environments, in order to perform panoramic cylindrical views and fully-dense 3D reconstructions; · performed field experiments in an underpass, where the rotating camera system was mounted on a tripod stand and three different datasets were collected to evaluate the proposed method, whose results were compared with the Multi-View Reconstruction Environment method.	· the proposed method allowed the use of as few images as possible to reconstruct a fully-dense 3D scene by using the prior knowledge of local geometry (e.g., the tunnel cross section diameter), enabling this way a pre-configuration of the UAV speed for an efficient image capture.

Table 1. Continued...

Ref.	Custom-built UAV (platform)	Custom-built UAV (payload)	Application scale	Findings
[23]	4-rotor custom frame	· 1 2D rotating RPLIDAR (range measurement); · 1 LIDAR-lite v3 (height measurement); · 1 GoPro Hero7 camera; · 2 10W LED light bars; · 1 PX4Flow optical flow sensor (velocity estimation); · 1 Aaeon UP-Board processing unit (with an Intel Atom x5-Z8350 processor, and ROSflight controller).	· used a ROSflight based custom-built MAV (developed by Luleå University of Technology) to rapidly explore unknown areas while providing feedback to the operator, for which a framework focusing on MAV navigation, control and vision is proposed; · performed field experiments in a dark underground mine in Sweden, located at 790m deep, where three different test cases (in a 150m long tunnel area with a cross section of 6m x 4m) evaluated the feasibility and adaptability of the proposed framework.	· the proposed framework allowed flexibility and modularity on the MAV system by proposing two different approaches for its navigation (one depending on the 2D LiDAR measurements, and the other on the camera image streams), which accomplished the autonomous flight, and by assigning different sensors to the state estimation; · the field experiments demonstrated the capability of low-cost and resource-constrained MAVs to navigate in tunnel confined environments.
[24]	not specified	· 1 high definition camera; · 1 fill light; · other components (not specified).	· presented a real-time defect detection (focused on exposed rebar) of spillway tunnels using UAV and deep learning; · performed field experiments in a spillway tunnel of a hydro-power station in the Minjiang River, where the UAV collected images within a specified area, whose siltation, stagnant water, and light conditions yielded to challenges for image collection.	· the proposed deep learning method allowed a relative reduction of its model size and parameter numbers, yielding to a better real-time performance, which is a key feature for future onboard UAV application.

Among them, only Iwamoto et al. [18] focused their UAV development research for a contact based inspection (impact acoustic method), while the other authors regarded the camera-based visual inspection [16], [20]–[22], [24] and concerned the UAV positioning/localization and/or environment mapping, based on LiDAR [15], [17], [19], [23].

4 UAV-BASED BRIDGE INSPECTION

Regarding now the UAVs used for bridge inspections in the literature, they can be divided into three groups: 1) the literature review articles, 2) the ones that made initial evaluation studies of the topic (or were at early research stage), and 3) the ones that performed case studies with practical tests.

Beginning with the review papers, nine addressed literature reviews involving UAV-based bridge inspections:

- Dorafshan and Maguire [5] presented the state of practice for the U.S. bridge inspection programs, where the autonomous navigation, 3D model reconstruction, and automated damage inspection were some of the covered topics, together with a summary of both U.S. Department of Transportation (DOT) investigations and the Federal Aviation Administration regulations on UASs. It concluded that despite the existing challenges involving UAS-assisted bridge inspections, it has the potential to improve inspection accuracy at a relatively lower cost;
- Duque et al. [25] provided a review on visual inspection, monitoring, and analysis of infrastructure using UAVs, where the bridge inspection topic was also summarized. It concluded from the findings that the UAV results are satisfactory, leading to a more efficient visual inspection in a lower time when compared with the conventional inspection procedure;
- Agnisarman et al. [26] reviewed literature publications that investigated automated visual inspection technologies applied for civil infrastructures, including the UAV-based bridge inspection. It identified that the inspection of bridges is the most frequently addressed domain among the automation-assisted inspection applications (20 of 53 reviewed studies), reflecting the importance of its structure maintenance and repair;
- Greenwood et al. [27] summarized the UAV development efforts on civil infrastructure applications, where one of the discussed topics was the key cases of UAVs being used in bridge inspection and monitoring. It stated that, among the civil infrastructure monitoring, bridge inspection is the most widely approached topic for UAV integration;
- Sony et al. [28] presented a review of next-generation smart sensing technology (such as UAVs, robotic sensors, cameras, and smartphones) applied for structural health monitoring, where the bridge inspection topic was discussed within the UAV-based literature section;
- Ahmed et al. [29] examined recent developments in autonomous robotic platforms for NDE and structural health monitoring of bridges, where UAV-based non-destructive inspections were addressed. It stated that it is a relatively new field of research, where its flexibility and versatility need to be exploited in order to access and monitor the distinct bridge infrastructure parts;

- Outay et al. [30] concerned three major domains of transportation: road safety, traffic monitoring, and highway infrastructure management; where the advancements of key feature extraction from UAV collected images/videos by computer vision algorithms were addressed. Within the highway infrastructure management topic, some research efforts that used UAVs for bridge inspection and monitoring were briefly summarized;
- Jeong et al. [31] summarized the literature central findings on UAV techniques for bridge inspection and damage quantification, where both conventional UAV-enabled visual inspection and damage detection algorithm studies were briefly described. It concluded that UAV can be considered for bridge inspection as a feasible and efficient tool, and a continued interest in it is expected;
- and Feroz and Abu Dabous [32] conducted a review of UAV applications in bridge condition monitoring, based on remote sensing technologies (such as LiDAR, IR and visual imagery, in addition to other sensors), where sixty-five journal and conference papers were compiled and summarized. It concluded that the use of UAVs improved the cost efficiency and accessibility, while reducing safety hazards and avoiding traffic closures during the inspection process.

Within the group that made initial evaluation studies, composed of [33]–[42], although they were at early stage from a practical point of view, some important details were discussed, such as the necessary specifications and payloads of the UAV, the flight mission planning considerations (including the on-site risk evaluation, the protocols to be followed by the operator, and the bridge data collection), together with the main advantages and challenges of the UAV-based bridge inspection applications.

Lastly, considering the ones that performed practical inspection tests, the used UAVs were identified and listed in Table 2, together with their models, approximate flight time (depending on the UAV series model, its payload, battery lifetime, and environmental conditions, as temperature and weather), and the used cameras.

Table 2. UAVs used for bridge inspection found in the literature.

Model (type)	Cameras (resolution)	Flight time (approx.)	References
SenseFly Albris (4-rotors)	Int.* (38MP /1280x720 video); IR (80x60 video).	up to 22min	[43]–[45]
3DR Iris (4-rotors)	GoPro Hero 3 or 4 Series (5~12MP/ 1080p~4K video).	10~13min	[46]–[49]
DJI Mavic Series (4-rotors)	Int. (12~48MP/ 1080p~4K video).	21~31min	[46]–[56]
DJI Phantom 3 Series (4-rotors)	Int. (12~12.4MP/ 1080p~4K video).	23~25min	[45], [57]–[59]
DJI Phantom 4 Series (4-rotors)	Int. (20MP/ 4K video).	27~30min	[11], [50], [51], [55], [60]–[70]
DJI Inspire Series (4-rotors)	Zenmuse X Series (12.4~24MP/ 4K video); IR - FLIR Vue Pro (640x512 video).	18~27min	[71]–[75]
DJI Matrice 100 Series (4-rotors)	Zenmuse X Series or Zenmuse Z3 (3.5x Optical Zoom).	19~40min	[76], [77]
DJI Matrice 200 Series (4-rotors)	Zenmuse X Series or Zenmuse Z30 (30x Optical Zoom).	13~38min	[78]–[82]
DJI Matrice 600 Series (6-rotors)	Zenmuse X Series; Fujifilm GFX 50S (51.4MP/ 1080p video).	16~40min	[50], [51], [55], [83]–[87]
Bergen Hexacopter (6-rotors)	Nikon D800 (36.3MP/ 1080p video); IR - FLIR Tau 2 (640x512 video).	18~30min	[8], [88], [89]
Intel/AscTec Falcon 8 (8-rotors)	Sony NEX-5 (14.2MP/ 1080i video); Sony Alpha 7R (36.4MP/ 1080p video); Panasonic Lumix TZ22 (14.1MP/ 1080i video).	12~20min	[9], [90], [91]
Other COTS	--------------	--------------	[92]–[104]
Custom-built	--------------	--------------	[10], [47]–[49], [105]–[131]
Not specified	--------------	--------------	[132]–[151]

* IR = infrared camera; Int. = Integrated camera.

One can see from Table 2 that the COTS DJI models [152] are predominant in the applications, together with the custom-built ones, whose were developed by researches within academic institutions or by collaborating companies, not to mention the UAVs that were not specified in their papers.

These UAV applications can be divided into two main groups, the non-contact and contact based methods, described in the sequence.

4.1 Non-contact based inspection applications

The majority of the applications, listed in Table 2, are non-contact based methods, where the predominant one is the visual imagery, which consists in acquiring images, videos, and other visual information. Within it, there are two main approaches: the visual and the infrared inspections.

4.1.1 Visual inspection applications

In the visual inspection, considering the UAV application, the inspector search for any visual structural changes in the images/videos collected by the UAV cameras, either on-site or later in a device. Although this type of application has all the UAV benefits listed in Section 2, the defect detection still relies on the specialized inspectors, whose similar subjective and inaccurate results from the conventional procedure still remain unsolved. Another method used to tackle this problem is the automatic inspection (or the term “vision” is also commonly used), where image processing techniques are specifically developed to detect and/or identify the structural defects in the images/videos collected by the UAV cameras.

All these visual inspection applications are listed in Table 3, where they are separated within the structure material of the bridge and their related defect types.

Table 3. Structural defect detection researches in UAV-based bridge visual inspection applications.

Structure material	Defect type	Inspection type (manual)	Inspection type (automatic)
Concrete	Crack	[10], [11], [43], [45], [54], [58], [62]–[65], [67], [80], [81], [117], [130], [137]	[46]–[48], [50]–[53], [55], [56], [60], [61], [68], [71], [74], [76], [78], [90], [96], [104]–[112], [115], [116], [131]–[136], [143], [150]
	Spalling	[11], [62]–[65], [67], [81]	[60], [61], [105], [106], [108], [115], [132], [134]
	Efflorescence	[10], [11], [43], [45], [54], [58], [62]–[65], [67], [81]	[60], [132]
	Exposed rebar	[11], [62], [64], [65], [67], [70]	[60], [108], [115], [150]
	Generic/others	[10], [11], [54], [62]–[65], [67], [80], [81]	[60], [108], [132], [150]
Steel	Corrosion	[10], [11], [45], [54], [62]–[65], [67], [70], [101], [102]	[96], [100], [109], [138], [147], [150], [151]
	Crack	[49], [54]	[48], [100], [138]
	Paint failure	[45], [80], [149]	[138]

It can be seen that the most explored defect type:

- in concrete structures is the crack, as expected, since it is the main visual warning for a possible failure;
- and in steel structures is the corrosion, as it is one of the main defects that arise in this type of material due to its exposure to environmental conditions (as temperature and humidity, to name a few);

and the most employed technique within the automatic inspection is the deep learning, whose popularity in the literature has been increasing due to its advantages, such as the simultaneous detection of multiple different defect types, e.g., [60], [100], [108], [115], [150].

Despite the defect detection/identification, there are other UAV applications for aiding visual inspection, such as 3D reconstructions [43], [45], [48], [50], [51], [55], [60], [66], [70], [71], [74], [76], [90], [91], [98], [99], [105], [106], [118], [142] and damage quantification [63], [66], [67], [69], [71], [80], [81], [81], [96], [108], [131], [136], [140], [143].

Another emerging imaging-based application with UAVs is the displacement/deformation measurement techniques of bridge structure, e.g., photogrammetric computer vision [9], [83], [89], [97], [146] and digital image correlation (DIC) [79], [92]–[95], [148]. Despite these imaging-based techniques, it is also worth mentioning the use of Laser Doppler Vibrometers (LDV) in UAVs as a non-contact sensor to measure bridge displacements [84]–[86].

4.1.2 Infrared inspection applications

Unlike the aforementioned great number of visual applications, the IR inspection is still underexplored within the UAV applications, although IR images of bridge decks are already commonly used during conventional bridge inspections to obtain information on subsurface defects, like concrete delamination [103]. Some few researches that explore this nondestructive method are briefly described below:

- Brooks et al. [8] and Escobar-Wolf et al. [88] used the FLIR Tau 2 IR camera, installed on the Bergen Hexacopter, to detect six delamination areas on the inspected bridge deck, where a total of seven delamination areas (all without visible signs) had been spotted before with a handheld FLIR SC 640 IR camera, whose presence were confirmed with a hammer test, i.e., only one delamination area was not found with the UAV IR imagery. Then, their proposed method improves the classification by also including the images collected by a Nikon D800 camera (also installed on the UAV) in the analysis;
- Zink and Lovelace [103] tested the integrated IR camera from the Aeyron Skyranger UAV in one of the evaluated bridges, where the collected IR images clearly showed the thermal gradient at the deck beam locations;
- Khan et al. [119] and Ellenberg et al. [120] performed experimental investigations on a mock-up concrete bridge, where a hexacopter based on DJI F550 frame (equipped with a GoPro Hero3 camera and a FLIR TAU2 IR camera) was used to map it using a multispectral approach, consisted of visual and IR imaging. While Khan et al. [119] presented the collected UAV images that clearly showed three delaminated regions on the mock-up, Ellenberg et al. [120] used a gradient following algorithm to identify the delaminated regions;
- Ellenberg et al. [141] used a commercially available six-rotor UAV equipped with both GoPro Hero3+ silver edition camera and IR camera (FLIR Tau 2) to collect real-time video imagery from a bridge deck mock-up (an eight inch thick concrete slab, supported by three structural steel I-beams) with multiple pre-manufactured defects (including delamination instances) for field testing, in which the collected IR images/videos were sufficiently clear for their developed image post-processing algorithm to identify the delamination locations;
- Omar and Nehdi [72], [75] mounted an IR camera (FLIR Vue Pro) on a DJI UAV (Inspire 1 Pro) to detect subsurface delamination in concrete bridge decks, where the feasibility of the proposed system was investigated in two full-scale in-service reinforced concrete bridge decks and demonstrated by comparing its results with other nondestructive testing technique results (including hammer sounding and half-cell potential testing), where the defect regions identified by the proposed system were confirmed;
- Wells and Lovelace [44] detected deck delamination with good accuracy in one of the on-field bridge inspections with an onboard thermal sensor of the SenseFly Albris UAV, whose results were validated by comparing them with the ones obtained by a handheld FLIR thermal camera, where the delamination areas were previously located and marked with the chain dragging method;
- Hiasa et al. [57] tested a FLIR T420 IR camera (a handheld IR camera that is not intended for UAV application) attached to a DJI Phantom 3 Advanced UAV using gummed tape, where it was examined if the vibration of the UAV during a hovering flight would affect the images taken from the IR camera (e.g., generate blurred images). They showed that it was possible to capture clearly lattice pattern squares from 1m to 5m range, concluding that if even in this test was possible to capture the target without blurry, then other IR cameras meant for UAV application are also capable, as they are typically used with a gimbal (that mitigates the vibration effects). It is worth noticing that the test was made during hovering flight, i.e., the flying speed during UAV motion may still affect the IRT results, e.g., for a video application;
- Mac et al. [82] conducted experiments on a concrete specimen (emulating a bridge deck surface) with artificial delamination, where two methods were employed to capture its surface temperature: a professional handheld IR camera (FLIR SC660) and a DJI M200 UAV equipped with IR camera (FLIR Zenmuse XT2). A good agreement was observed between their results, which validated the UAV application;
- Jang et al. [153] presented a deep learning based concrete crack detection using hybrid images, where a hybrid image scanning system was developed to combine vision and IRT images for unmanned vehicle, in which an integration with UAVs is in progress by the process of miniaturization and packaging of the developed system to reduce its size and weight for mounting it onto a custom-built sticking-type UAV;
- and Cheng et al. [87] developed a customized deep learning model based on encoder-decoder to segment concrete delamination areas in thermal images at the pixel level. This model is validated with experiments conducted in an in-service concrete bridge, where two UAV configurations were employed to take both thermal and visible images, being the thermal camera (FLIR A8300) mounted on a DJI Matrice 600.

Most of them involved automatic inspection methods, where distinct image processing algorithms were developed to mainly detect the delamination areas, being on the other hand [44], [57], [82], [103], [119] based on manual inspection or other analysis methods.

4.2 Contact based inspection applications

Although UAVs are being widely used for non-contact inspections, especially the image-based ones, as can be noticed above by the number of documents available in the literature, they are also still underexplored for contact inspection tasks. It is mainly due to the challenges that this type of methods involves, requiring specific device developments to be installed onboard the UAV, hampered by its limited payload capacity, along with the requirement of a more sophisticated control algorithm to deal with the complex dynamics derived by the interaction between UAV and target structure.

There is still no COTS UAV available for contact based inspection and both research and development are necessary to overcome these challenges. Thus, there are few documents in the literature that developed custom-built UAVs focused on dealing with this problem.

An example is the displacement or strain measurement application, for which the custom-built UAVs in Sanchez-Cuevas et al. [113], [114] and Jimenez-Cano et al. [122] were developed. Different from the previously visual-based ones, these UAVs rely on a reflector prism (360º miniprisms) installed in their structure, to perform the bridge inspection while in contact with its ceiling, where a total station (Leica Geosystem MS50) continuously tracks the prism position, from which an estimation of the bridge deformation can be obtained. Additionally, the ceiling effect (arisen when the UAV gets close to the bridge ceiling) is exploited to improve the UAV flight performance, where the increment in rotor thrust (derived from this effect) is explored by the developed UAV control while keeping the UAV stable and preventing it from crashing into the ceiling.

Another example is the acoustic inspection application, performed by the custom-built UAVs developed in Chun et al. [109], Mason et al. [144], and Moreu et al. [145], whose onboard hammering device systems were developed to perform both impact and sound recording for post-processing analyses of concrete structure assessment. Besides that, the implementation of onboard manipulators on UAVs, both 1 Degree-of-Freedom (DoF) ones (explored in Ikeda et al. [124] and Ichikawa et al. [126]) and 3 DoF ones (in Jimenez-Cano et al. [123] and Ikeda et al. [125]), may not only be employed for this kind of test, but also for other contact based inspection applications, where a specific device may be manipulated by these UAVs.

5 DISCUSSION OF THE REVIEWED LITERATURE

Following the above description of UAV-based application researches for bridge and tunnel inspection, it would be interesting to have an overview of these main applications. To aid this, the following pie charts (Figure 2) are presented.

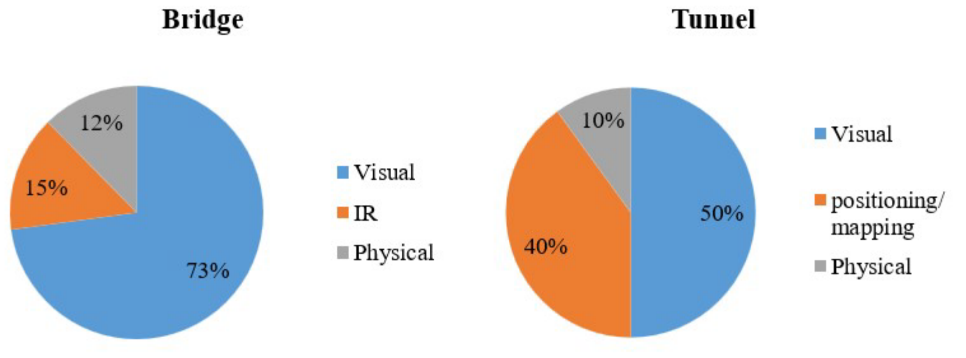

Figure 2. Percentage of the main UAV-based applications for bridge and tunnel inspection.

It is evident that the most employed application is the visual inspection, corroborating with the statements made previously in Subsection 4.1. It was expected since this is also the main employed method in the conventional procedure and the availability of lightweight high-definition cameras (especially the on-board/integrated ones on COTS UAV platforms) enable a good quality inspection. Although in the tunnel case it is not as expressive as in the bridge case, the visual inspection still represents half of UAV-based tunnel applications, followed by the ones focused on LiDAR-based UAV positioning/localization and/or environment mapping, since the lack of GPS signal in this environment is still a main challenge.

Note that, within all the UAV-based inspection applications, it was employed either manual or automatic flight navigation, where in the former the operator manually controls the UAV position during the inspection process, and in the latter a pre-determined trajectory is programmed and uploaded in the UAV, so that it can automatically navigate on-site, where the operator supervise it during all the inspection and may intervene it by taking the UAV control, if any unexpected external event occurs.

It is worth emphasizing the difference between automatic and autonomous flight navigation. While the former is developed to reduce the human intervention during its operation to a minimum, the latter does not allow any human intervention during its flight mission, being independent and self-governing while coping with all unforeseen and unpredictable situations that may happen during its navigation. Currently, UAV regulations of many countries do not allow autonomous flight navigation in open airspace since it is still immature and may pose risk to itself and to all of its surroundings. However, this may change as this development becomes more mature and ensures more security during its operation.

Despite the flight navigation mode, it was shown in Section 2 that UAVs provide several advantages over the conventional inspection of bridge and tunnel structures, overcoming the main drawbacks related to their procedures (described in Section 1), e.g., the UAV enable the access and assess of dangerous and/or tight spots that are inaccessible to humans [20], [130].

However, the use of this type of technology also brings some challenges, as described in the following.

5.1 Key challenges

The use of UAVs presents some challenges/limitations as:

- the flight planning, which requires a specialized UAV operator (who needs to be trained and certified to ensure a safe UAV operation) to conduct a manual flight or even to attend an automatic flight (which requires a previously developed path planning) to inspect the on-site structure, along with the evaluation of the environment and weather conditions, which may preclude the flight mission, e.g., gale and heavy rain;
- limited flight time and payload capacity, which varies for each UAV platform, requiring some extra batteries for long structure inspections;
- the noise on collected images, derived mainly from the local conditions, e.g., dust, changing lighting conditions along the structure, and wind disturbances during UAV flight (that may lead to blurry images);
- the existence of GPS-denied areas, whose hinder the UAV navigation, precluding the inspection of structure components at these areas, e.g., at tunnel environments and underneath large bridges;
- and the regulations of governing authorities for UAV operation, which varies from country to country [34].

However, they are continuously being dealt with by the researchers of the area, as the research and development of autonomous flight that provide high accuracy positioning to collect images without blurry effects, along with the UAV technology advancement (e.g., energy-efficient UAV platform designs, enhanced batteries, and GPS-free flight capability) and also the regulations improvement by the associated government agencies in charge.

Concerning the UAV-based tunnel inspection, as stated in Section 2, the major challenges are the lack of both light and GPS-signal, which were mainly overcome by custom-built UAVs developed in the few literature documents (see Table 1), besides some of them being inaccessible by humans, where the UAV must do its inspection out of the operator view, making the task even more challenging (e.g., problem tackled by Özaslan et al. [17] and Hongyu [20]).

Likewise, among the main challenges of UAV-based bridge inspection, the underside deck can be mentioned, which is one of the most problematic areas to perform the inspection by an UAV. Some few examples that designed UAVs to overcome this problem are Sanchez-Cuevas et al. [113], [114] and Jimenez-Cano et al. [122], whose UAV platforms explore the ceiling effect when in contact with it in a fixed position during an under-bridge inspection, and Wang et al. [112], whose tethered creeping UAV platform ensures the distance between the camera and the bottom of the bridge for an accurate crack detection. Other examples related to this problem are Yang et al. [117] and Peng et al. [131] that mounted a camera in an upward gimbal on the top of their UAVs (solution that are also being provided by some specific COTS UAVs, mentioned in Subsection 5.2).

However, its main issue is again the lack of GPS signal, especially at large bridges. Dorafshan et al. [48] not only summarized some instances during state DOT missions, but also underwent it during their field experiments, where though the built-in sonar sensors, installed on the bottom of their DJI Mavic, allowed the operator to substantially control it while flying under the bridge (in absence of GPS signal), some instability occurred when flying over the river, precluding the under-bridge inspection over this region. Other authors have also reported this issue, e.g., [5], [103], [113], [117], [127], [128], for which an auxiliary positioning system is required, such as other position estimation approaches (as optical flow and visual odometry techniques) and/or other technologies (as LiDARs and image based navigational sensors).

At last, but not least, the success of the UAV-based inspection task rely on the UAV flight parameters (e.g., the distance between the UAV and the structure), the payload choice (the sensors and instruments carried by the UAV) and their parameter configuration (e.g., the high definition camera settings, as the shutter speed, aperture, and ISO), which may be cumbersome even for experienced UAV operators.

5.2 Future trends

Throughout the survey, an identified trend regarding the UAV-based inspection of both tunnels and bridges is the development of automatic flights and even semi-autonomous navigation that are being explored by some of the research studies. This will lead to a future trend of completely autonomous UAV navigation, which will play an important role to enable the automation of the inspection procedure.

Seeing this and the rapid advance on UAV and remote sensing technologies, together with the development of advanced control and navigation, another expected future trend is the multi-UAV cooperation, whose collected multi-data will not only improve the efficiency and performance of the inspection, but also decrease the execution time.

Before this, a trend provided by the rapid advancement of UAV technology is the emerging of COTS models focused on inspection tasks, which are probably already being used in current researches of UAV-based inspection of this kind of structures. Some examples of these 4-rotors UAVs are:

- the DJI Mavic 2 Enterprise Series (launched on October 29, 2018) [154], which is based on the Mavic 2 flight platform (with same 31min flight time), but with new features, as the modular accessories (spotlight, speaker, and beacon), the camera upgrades (in which the IR camera addition, available in Dual and Advanced series, is highlighted here), and the add-on Real Time Kinematics (RTK) module for the Advanced series only;
- the collision-resistant Flyability Elios 2 (launched on April 29, 2019) [155] (with up to 10min flight time) that has a protective frame as a distinctive feature (a carbon fiber spherical cage that encloses the UAV, protecting it from collisions up to 1.5 m/s), in addition to embeds both 12.3MP camera (that records 4K videos) and Lepton 3.5 FLIR IR camera (160x120 video), together with onboard LEDs that provide 10K lumens of light with a remotely adjustable intensity;
- and the DJI Matrice 300 Series (launched on May 7, 2020) [156] (with up to 55min flight time), compatible with more Zenmuse Series cameras (including powerful full-frame, optical zoom, and IR options) and supporting an upward gimbal, in addition to have the RTK module available.

Although some UAV model comparatives were made in the literature, e.g., [5], [25], [51], the aforementioned models had not been released yet.

Considering all the presented UAV models (Table 2 and the aforementioned ones), the authors highlight here two of them: the DJI Matrice 210 RTK V2 and the DJI Matrice 300 RTK, since they support not only both IR camera and RTK module (which are desirable features for this kind of inspection), but also an upward gimbal, which is a highly recommended feature for both tunnel and underside bridge deck inspections. Although DJI Mavic 2 Enterprise Advanced also provide both IR camera and RTK module, it does not offer the upward gimbal option, but its relative lower price makes it a good alternative. At last, but not least, it is worth mentioning the Flyability Elios 2, whose protective frame and GPS-free flight capability are strong features to also inspect complex and confined indoor spaces, being a great option especially for tunnel inspections.

The IR camera availability is emphasized since the use of hybrid image processing (in this case, the fusion of infrared and visible images) will provide more information to the inspection process, where their individual advantages can be explored to improve the defect detection. Moreover, other sensors may also be explored in this kind of approach, such as the ultrasonic displacement sensor (to provide a distance measurement from the target structure) [157].

6 CONCLUSIONS

There has been a rapid increase in the number of researches on UAV-based inspection applications in civil infrastructure field, especially for large and complex structures, promoted by the fast advancing electronics technology that is aiding the development of powerful custom-built UAV platforms and also enabling the emergence of COTS UAV solutions focused on inspection tasks. They bring several benefits over the conventional procedures of bridge and tunnel inspection, such as more accessibility and safety, along with a reduced cost and inspection time, overcoming the main drawbacks faced by them, which are practically the same for both.

This review article has gathered and surveyed both UAV-based inspection researches of bridges and tunnels, and the main applications have been identified, whose relevant information were summarized in detailed tables to provide a convenient overview of their state-of-art. This includes the several identified COTS UAV platforms that were employed for bridge visual inspection and the diverse custom-built UAVs developed specifically for tunnel inspection.

Although the challenges for both bridge and tunnel UAV-based inspections are practically the same, it is worth to emphasize that the lack of lighting and GPS signal in tunnel environments are far more critical when compared to the bridge case, as in the latter these regions are relatively smaller (usually under its deck), where it is still possible to collect images with some UAV platforms that can point the camera in an angular way towards the bottom of the deck. Consequently, the percentage of researches focusing on positioning and mapping in tunnel environments is still expressive (see Figure 2).

It also has shown that the current main employed application is the visual inspection, boosted by the great number of available lightweight high-definition cameras, especially the on-board/integrated ones on COTS UAV platforms, which provide high quality images and enable an inspection result of similar quality from the conventional procedures.

Despite the still existence of some limitations that hinder the applications of UAV-based inspection of large structures, such as the existence of diverse UAV regulations that vary for each country and the weather conditions that may preclude and delay the on-site inspection execution, some other challenges are being overcome by the fast advancing of UAV and remote sensing technologies, together with the development of advanced control and navigation, which may enable some new future possibilities such as the automatic condition monitoring of these structures, where an UAV will autonomously execute a periodic inspection with a precise positioning during the path-planned trajectory, and the collected data from different sensors will be evaluated and compared with the previous ones, yielding to a shorter-time assessment and a better maintenance management.

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