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Review article

Inspection of aircrafts and airports using UAS: A review

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ABSTRACT

This review paper examines the use of Unmanned Aircraft Systems (UAS) for inspecting aircraft structures and aeronautical infrastructure as a supplement to traditional methods. The goal is to evaluate the technical and regulatory viability of automated inspections. A systematic review was conducted via Scopus and Google Scholar using terms like aircraft, airport, inspection, UAS, Remotely Piloted Aircraft System (RPAS), Unmanned Aerial Vehicle (UAV), and drone. Research was filtered by engineering, computer science, materials science, energy, decision science, and environmental science, prioritizing studies published in the last decade. The article explores drones commonly used in Structural Health Monitoring (SHM), emphasizing multirotor drones for aircraft structural inspection. It discusses onboard sensors and cameras required for data acquisition, such as Laser Imaging Detection and Ranging (LiDAR) and Infrared Thermography (IR). Deliverables such as 3D models, orthomosaics, Digital Surface Models (DSM), Digital Elevation Models (DEM), and Digital Terrain Models (DTM) are created to identify structural defects such as cracks, delamination, dents, corrosion, and pores. Image post-processing techniques include algorithms like Convolutional Neural Networks (CNN), OpenCV, and Generative Adversarial Networks (GAN), using software such as MATLAB, PIX4DMapper, Agisoft PhotoScan, and FlirTools. The review concludes that drones and UAS can feasibly and effectively supplement conventional aircraft inspections. However, regulatory and operational challenges limit the full automation of the inspection process.

1. Introduction

1.1. Aircraft inspection and maintenance

Aircraft and airport inspections are crucial for the aviation industry, as they are necessary to ensure safe aircraft operation, extend their lifespan, and maintain reliability through sustainable processes that guarantee the efficient use of resources. These inspections involve the periodic review of aircraft [1] and airports [2] to evaluate their condition using non-destructive testing (NDT) techniques. These techniques aim to detect flaws and discontinuities in the materials and components of structures without physically affecting the examined components. The purpose is to subsequently repair and rehabilitate the aircraft, ensuring its continuous operation under safety standards.

Currently, condition assessment is primarily carried out through visual inspection, the most basic of non-destructive testing (NDT) techniques. This method relies on the inspector's sense of sight, aided by tools such as borescopes and high-resolution cameras, to detect variations in physical characteristics, as well as possible surface and subsurface defects and discontinuities in components and structures. Inspectors perform these visual inspections using manual techniques, accessing aircraft and structures via ladders, scaffolds, and vehicles equipped with elevators, as depicted in Fig. 1. This approach can pose significant risks to the inspectors [3]. According to Ref. [4], visual inspections, comprehensive studies, and detailed analyses of the condition of structures are not only costly and complex but also time-consuming.

In terms of aircraft inspection, as outlined by the Federal Aviation Administration (FAA), the pre-flight inspection, also known as a walk-around, involves a comprehensive and systematic visual check. This inspection is performed by flight or maintenance personnel to ensure that the aircraft is airworthy and in a safe operating condition before a flight commences. Technical documents, such as the Pilot Operating

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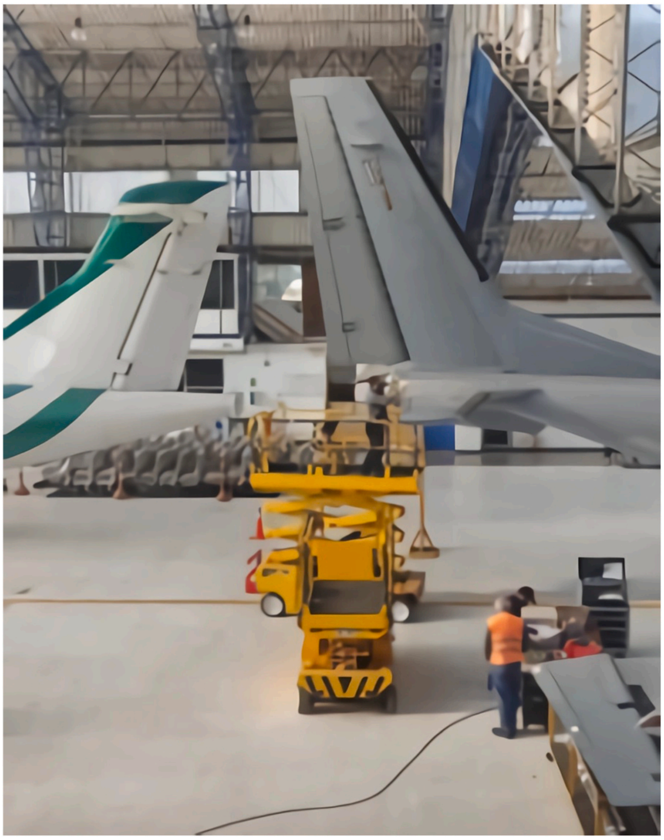

Fig. 1. Aircraft tail inspection operation with a platform, source: Authors.

Handbook (POH) [5], detail the sequence of the walkaround and specify the aircraft areas that must be inspected to confirm their optimal condition for flight. The responsibility for maintaining an airworthy aircraft rests with the operator; accordingly, their maintenance programs incorporate various tasks aimed at assessing the condition of all visible structural elements within a designated zone. These tasks are referred to as zone inspections and must be performed directly on the aircraft. Such inspections are crucial for detecting any damage or missing parts [6]. Maintenance processes are mandatory and governed by the aeronautical regulations of each state. These tasks must be executed by an Approved Maintenance Organization (AMO), which are entities authorized by the state to conduct aircraft maintenance. All maintenance activities must be performed safely, with an assessment and mitigation of risks, as mandated by the Safety Management System (SMS). Given that aircraft typically have a service life of approximately 30 years, it is common for damages or defects, especially on the fuselage skin, to become more frequent and noticeable as the structure ages.

External visual inspections of an aircraft are designed to detect defects such as cracks, corrosion, porosity, delamination, and damage from bird strikes, lightning, and hail. These inspections also target surface and subsurface defects on the aircraft fuselage, which can sometimes result from the aerodynamic forces acting on the structure. To accurately detect these defects, high-resolution images are essential. These images must be taken from a specific distance that depends on both the parameters and characteristics of the cameras and sensors used, as well as on the geometric and physical characteristics of the structure. According to Ref. [7], these factors can sometimes limit, hinder, or prevent inspectors from accessing certain parts of the structure, thereby restricting the quantity, quality, and clarity of the images they can obtain. Given these limitations and difficulties, the use of Unmanned Aircraft Systems (UAS) as platforms for observation and the acquisition of high-resolution data and images is becoming increasingly relevant.

Over the last decade, the use of Unmanned Aircraft Systems (UAS) for structural inspections has grown significantly, establishing this area as a key topic for research and the exploration of potential specific applications. UAS are synergistically integrated with the concepts of Aviation 4.0 [8] and smart hangars [1], which advocate for the automation of maintenance and/or inspection procedures within the framework of the Internet of Things (IoT). This automation is facilitated by machines and/or robots that are capable of communicating, working cooperatively and autonomously, and transmitting information in real-time via Wi-Fi networks. Such capabilities contribute to reducing decision-making time and enhancing the efficiency of processes. UAS are particularly well-suited to this environment as they are a part of aerial robotics; they can operate in conjunction with other machines and relay information instantly through telemetry. Therefore, this article aims to provide valuable insights into UAS, assisting in the selection of suitable equipment and techniques for the inspection and assessment of an aircraft's structural condition.

The methodology proposed in Ref. [9] for aircraft inspection using multirotor drones equipped with high-resolution cameras and thermal cameras allows for the precise detection of surface discontinuities and structural defects. Moreover, the use of advanced algorithms such as Convolutional Neural Networks (CNN) and Generative Adversarial Networks (GAN) offers a novel approach for image classification and pattern identification in components like rivets and screws. Passive and active thermography methods [10] provide innovative non-destructive techniques for assessing impact damage and delaminations in composite materials, while vibrothermography helps detect defects such as 'kiss-bonds' in metal structures. These advanced approaches surpass the state of the art by significantly reducing the time and costs associated with conventional inspections, as demonstrated in the case study of the Zlin Z-142 model, where a surface discontinuity was identified on a wing.

Another significant contribution that surpasses the state of the art is the application of drones in the inspection of airport runways and associated infrastructure. In Ref. [2], cracks, damage, and debris on runways were identified using a combination of techniques such as 3D point clouds generated through photogrammetry and thermal cameras. This approach allows for a rapid and accurate assessment of pavement conditions, preventing potential damage to aircraft. Additionally, the use of applications like Pix4DMapper and the OpenCV library offers a profound methodology for defect detection, providing data that surpasses that obtained with conventional methods. Furthermore, the proposal in Ref. [11] introduces a drone system equipped with high-definition cameras and ultrasound sensors to maintain a safe distance from the surfaces being inspected, thus enabling data capture without the risk of collision. This not only ensures safety but also enhances the consistency and accuracy of the findings by eliminating the subjective factor of human inspection. These advancements consolidate the role of UAS as key tools for structural monitoring, offering a holistic and innovative perspective in the inspection of aircraft and airport infrastructures.

Lastly, the integration of drones and UAS with the concept of 'smart hangars' [1], which incorporates digitization and automation in aircraft maintenance, lays the groundwork for fully automated inspections.

1.2. Classification and types of UAS

According to Ref. [12], the most common term for these vehicles is 'drone,' but over the past 30 years, the term has evolved from UAV to more precise terms such as UAS and RPAS. These terms and acronyms are accepted and adopted by the scientific and academic community, manufacturers, service providers of these vehicles, and international aviation regulatory bodies such as the International Civil Aviation Organization (ICAO) [13], the European Union Aviation Safety Agency (EASA) [14], and the Federal Aviation Administration (FAA) [15]. It is referred to as a system according to Ref. [16] because it consists of three basic subsystems: i) the unmanned aerial vehicle or UAV; ii) the ground control station (CS); and iii) the communication link between the aircraft and the ground station, which are coordinated to allow for controlled and stable autonomous flight [17]. UAS can be remotely controlled by a person on the ground, fly autonomously under computer control, or even combine both methods. According to the National Highway Traffic Safety Administration of the U.S. (NHTSA) [18], UAS can be classified by the levels of automation and operational autonomy, which are differentiated into six levels as listed in Table 1.

UAS can also be classified according to their takeoff and landing methods. The first type, Horizontal Takeoff and Landing (HTOL), is characterized by fixed wings, the ability to cover long distances, and achieving high speeds. The second type, Vertical Takeoff and Landing (VTOL) aircraft, feature one or more propellers with rotary wings [19], enabling them to perform sustained and stable static flight. This capability is particularly advantageous when inspecting aircraft and structures [20]. Although VTOL aircraft are slower than HTOL, they are smaller, lighter, and less expensive. VTOL aircraft are divided into helicopters and multicopters, with the latter being preferred for structural inspections [21] due to their excellent maneuverability and controllability. Multicopters are further classified by the number of motors they possess, as illustrated in Fig. 2: tricopters have three motors, quadcopters four, hexacopters six, and octocopters eight.

1.3. Components of multirotor UAS

According to Ref. [22], multirotors consist of five basic components: (i) a chassis, structure, or frame, which can be made of plastic, carbon fiber, wood, or aluminum; (ii) a motor-propeller assembly where fixed-pitch propellers are coupled with brushless electric motors, located at the ends of the frame's arms; (iii) an Electronic Speed Controller (ESC) that regulates the motor's current according to the Revolutions Per Minute (RPM) required for the operation, controlled by Pulse Width Modulation (PWM); (iv) a Flight Controller (FC), which can be programmed and parameterized [23], sends control signals to the ESC. These signals are generated based on the commands received by the FC through a signal receiver (Rx), transmitted by the ground station (Tx), and from various types of internal and external sensors. The common sensors include gyroscopes for measuring the aircraft's attitude, accelerometers for determining acceleration, velocity, and position, and high-power electrical devices with high energy density [24]; (v) a Lithium Polymer (LiPo) battery powers the UAV's electronic components and includes magnetometers to determine direction and barometers to measure pressure and altitude, supported by a Global Navigation Satellite System (GNSS). Currently, there is a range of commercial and professional drones available on the market at affordable prices, offering stable flight capabilities, efficient navigation, and a favorable cost-benefit ratio. However, some users and companies still opt to build their own drones to provide tailored solutions to very specific problems and needs [25]. While these custom-built drones may have lower performance than commercial ones, their manufacturing costs are significantly lower compared to the acquisition costs of commercial drones, which may incorporate a U.S. Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), or the European navigation and positioning system, Galileo.

Table 1
Levels of UAS automation according to NHTSA.

Level	Characteristics
Level 0	The pilots have manual and full control over the UAS navigation.
Level 1	There is a certain degree of automation applied to two flight modes: the first corresponds to maintaining altitude in dynamic flight, and the second to static and sustained flight.
Level 2	The UAS navigates based on various flight modes programmed by the pilot, autonomously maintaining its route if there is no unexpected change in the flight environment.
Level 3	The UAS understands changes in flight environments and controls flight modes to navigate in the new environment.
Level 4	The UAS can adapt and react when there is a system anomaly, accident, or sudden collision with other objects.
Level 5	The UAS can navigate autonomously in all environments and situations.

1.4. Modeling, control algorithms, and trajectory planning for UAS

The modeling of multirotor UAS motion is performed by formulating differential equations that relate translational movements and model rotational movements [26]. The choice of control techniques depends on whether the system is linear or nonlinear. Non-linear control techniques, although less complex and easier to implement, are very sensitive to disturbances. In contrast, linear controllers for quadrotors typically utilize a Proportional, Integral, and Derivative (PID) controller [27], while non-linear techniques, which are more complex to implement, are less sensitive to disturbances. These advanced techniques, including neural network-based control, adaptive control [28], H control [29], model predictive control, and disturbance observer-based control [30], provide high precision in modeling but increase the complexity of the analysis.

Flight planning is a crucial preliminary step for inspections and determines the quality of images obtained with UAS. Advanced techniques such as Lidar Odometry and Mapping in Real-Time (LOAM) [31,32] and its variation, Simultaneous Localization and Mapping (SLAM) [33], allow for real-time mapping and positioning in unknown environments using laser technology. UAS trajectories can be classified into three types: (i) point-to-point control, which involves traveling from point A to point B regardless of the path's shape; (ii) a trajectory determined by a path defined through intermediate points known as waypoints, which have precise coordinates and a defined altitude; and (iii) a trajectory with defined waypoints and programmed obstacle avoidance.

To plan a mission, several commercial software programs are available, such as Mission Planner [34], Pix4D Capture [35], DroneDeploy [36], and Drone Harmony [37], which are compatible with various drone brands. These programs feature generic connectivity based on the Software Development Kit (SDK) [38], used for drone software development, allowing users to operate the applications with different drone models from various brands. Additionally, there are manufacturer-specific applications, such as DJI Pilot and DJI Ground Station Pro [39], the latter being exclusive to iOS operating systems. Both generic and manufacturer-specific applications provide graphical interfaces for defining trajectories and data acquisition during autonomous flights. It is important to note that while flight trajectories and data acquisition can be conducted manually, this approach imposes a high workload on the pilot, and the quality of the images and information obtained is typically inferior to that achieved through autonomous flights. Key aspects to consider when selecting a flight management application include: (i) the information provided before, during, and after the flight, such as the number of photos, speed, altitude, flight time, required batteries, camera angle, and mission completion mode; (ii) the available configurations for flight plans; (iii) interaction with the drone's original software; and (iv) the stability and support offered by the manufacturer in case of errors.

For both autonomous and manual flights, there are flight indicators and parameters to consider. Indicators are quantitative data that can be visualized but not modified, including flight time, number of photographs, covered area, total flight length, final and capture resolution, required batteries, trajectory points and lines, and capture intervals. Conversely, flight parameters, which can be configured and modified, include altitude, camera model, capture angle, capture mode, flight course mode, speed, interval between shots, front overlap, flight trajectory angle, trajectory margin, camera tilt angle, and mission completion actions.

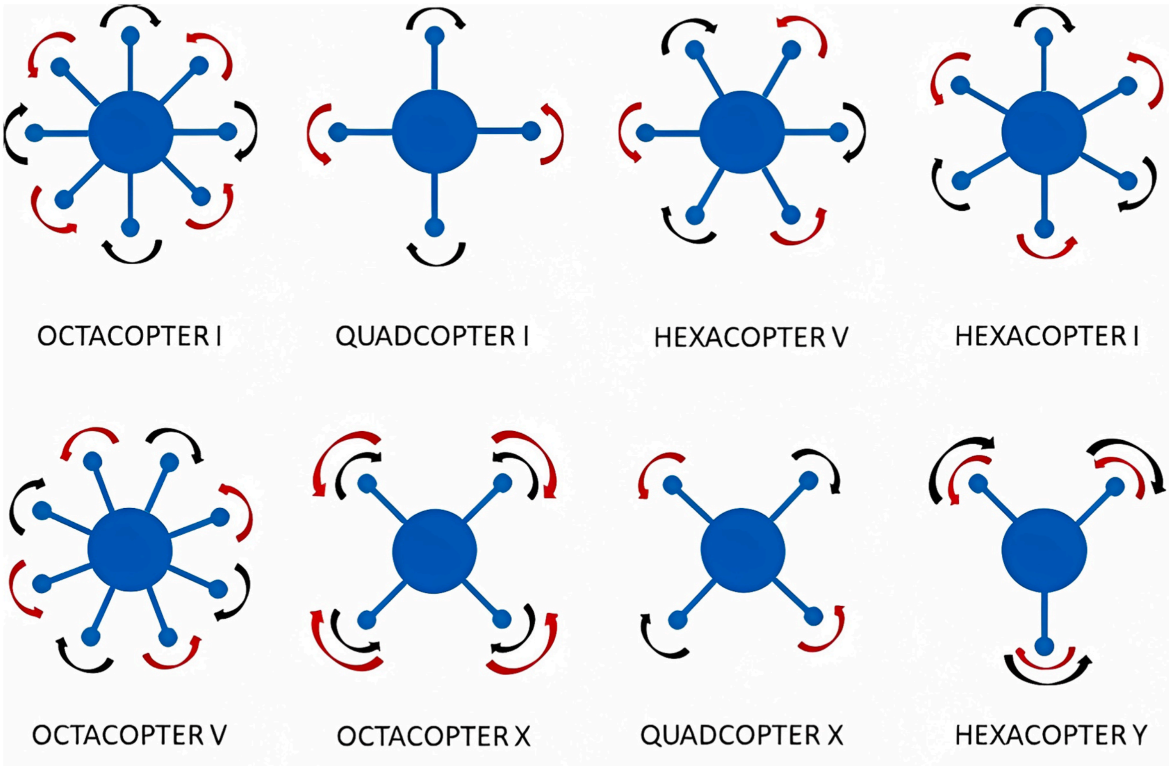

Fig. 2. Types of Multirotor UAS, source: Authors.

1.5. *Application of UAVs in structure inspection*

Among the known uses and applications of UAVs are professional video and photography [40], aerial photogrammetry, precision agriculture [41], surveillance [42], search and rescue [43], mine detection [44], and building, bridge, dam, road, tower, and power grid inspections [45–49], among other structures. One significant advantage that UAVs offer in fracture inspection is their ability to carry various sensors and measuring equipment, including different types of cameras that enhance traditional techniques. These include visual inspection with high-resolution cameras [50], infrared thermography [9,51], and ultrasonic inspection of structures [52]. The objectives of these inspections are to conduct Structural Health Monitoring (SHM) and to detect common surface and subsurface faults in materials and components, such as cracks, pores, delamination, dents, corrosion, moisture leaks, material detachments, missing or damaged screws and rivets, and corrosion caused by environmental factors, fatigue, impact, and mechanical stresses. For structure and object inspection using drones, the generation of 3D models [47] is widely utilized. These models are representations of points obtained by various methods and equipment to form a point cloud. The quality of the model largely depends on the equipment used. Inputs for generating these models typically include georeferenced photographs or data files generated through Laser LIDAR, which contain information for each point regarding location and classification [31]. Although LIDAR visualization is not visually appealing, it is more accurate than models obtained through photographs. Table 2 shows a comparison between the 3D models obtained by the two methods, describing the characteristics, advantages, and disadvantages of each.

Table 2
Comparison of Photographic and LIDAR methods for generating 3D models, source: Authors.

Using Photography	Using LIDAR
Use specialized software that allows for the extraction of necessary information from digital photo files to generate point clouds.	Use specialized software that allows for the processing of large amounts of information to create point clouds based on laser information.
Lightweight models are generated, which can be easily handled on mid-range computers.	The resulting models are large and require high-capacity computers to handle them.
The process requires complex flight plans to ensure sufficient photo overlap.	Complex flight plans are not necessary since the laser has a 360° range.
The models are aesthetically pleasing, as lighting in the photographs allows for color texturing of the generated models.	These models lack color information and are not aesthetically pleasing.
The capacity and range of the models largely depend on the camera used.	Great range due to the ability they have to take a lot of points.
Accessible and low-cost flight applications and data processing software are available	Specialized flight applications and processing software
Low price drones	Medium and high price drones

1.6. *Types of information and final products generated with UAS*

The most common deliverables or products that can be obtained through the two previously mentioned techniques are: (i) point clouds [53], (ii) textured models, (iii) 3D objects, (iv) orthomosaics, (v) Digital Surface Models (DSM) [54], (vi) Digital Elevation Models (DEM) [55], and (vii) Digital Terrain Models (DTM) [56]. These final products can be obtained and analyzed using programs such as PIX4D [57], Metashape [58], and Autodesk InfraWorks [59].

A point cloud is a consolidation of data acquired and processed by photogrammetric methods or a LIDAR device, in which each point is assigned a coordinate, color, and, in some cases, a LIDAR classification that includes six categories of data: 1) default points; 2) terrain; 3) low, medium, or high vegetation; 4) buildings; 5) low points; and 6) model keypoints [60]. It is a key tool for project realization and management, with applications such as generating as-built plans [61], analyzing terrain sections and profiles, calculating volumes of structures and objects, and measuring distances, among others.

A textured model is a type of 3D model where color textures are applied, either from photographs or a LIDAR device. Also known as a textured mesh or simply mesh, it is beneficial because it provides a visually appealing representation of the area or object of interest. Depending on the processing software used, it is possible to observe details of the object or changes in the surveyed terrain and to take measurements on them.

A 3D object is the most basic form of a 3D model. It has a file format compatible with most devices and includes metadata that allows the object to be visualized in various ways. These objects can be 3D printed and used for physical testing or simulations on a scaled basis.

An orthomosaic is the union of multiple photos that have been processed and transformed into an orthogonal representation; it consists of several orthophotos. Orthophotos are photographs with a constant scale, representing an orthogonal projection that was generated from a central projection photograph. The latter has a scale that decreases towards the edges due to Earth's curvature. In orthophotos, objects retain their true positions, although rectification of vertical and horizontal positions is required.

Digital Surface Models (DSM) represent the elevations above sea level of various reflective objects such as vegetation, buildings, light towers, and other structures on the ground. DSM utilizes the full resolution of the camera used in the drone because it processes the return information from each photograph, either through captured light during photography or laser return if LIDAR is used. DSM is useful in fields such as urban planning and building projects, the energy sector for reviewing vegetation obstruction of power lines, aviation to determine obstructions in aircraft approach zones at airports, and environmental impact assessment for infrastructure projects, among others.

On the other hand, Digital Elevation Models (DEM) represent elevations above sea level but exclude reflective objects like vegetation, buildings, electric towers, and general infrastructure. It is sometimes referred to as 'raw terrain' because it includes only the ground; it is primarily used for measurements based on height and is utilized for the layout of high and medium voltage lines, gas and oil pipelines, tunnels, bridges, and structures at airports. Sometimes, DEM is associated with Digital Terrain Models (DTM), which derive from DEM but provide greater definition of natural peaks and points of terrain failure.

Each of these final products has a file extension and can be opened and manipulated using various specialized software, either free or paid. It is important to understand the types of files generated to select the appropriate software and/or hardware (refer to Table 3).

2. Materials and methods

The systematic literature review was conducted following the methodology described in Ref. [62] using the SCOPUS database. A search was performed using English keywords and acronyms such as aircraft, airport, inspection, UAS, RPAS, UAV, and drone. The search was limited to research articles, conference papers, and review articles, filtering by the fields of engineering, computer science, materials science, energy, decision science, and environmental science, and focusing on publications from the last ten years (2013–2022).

A total of 1050 articles were obtained, which were analyzed using the VOSviewer tool (Fig. 3). This tool enables the determination of the correlation between keywords by assessing the density of articles related to each keyword, graphically represented by the size of each circle. This analysis validated that the articles found were closely related to the review topic.

Additionally, a search was conducted on Google Scholar using the same keywords and acronyms as those used in SCOPUS. From the results, 57 publications, including books, standards, and articles related to the topic, were selected, resulting in a total of 1107 references. These references were characterized, analyzed, and filtered based on the methodology described in Ref. [62] (illustrated in Fig. 4) as well as the authors' expertise and knowledge.

Priority was given to publications from the last 10 years (2013–2022). Based on these criteria, the final 76 references were selected, constituting the relevant academic space (RAS) defined for this review. The percentage distribution of these references by area of knowledge is shown in Fig. 5.

3. Aircraft and airport inspection

3.1. Aircraft inspection with UAS

In [1], the concept of a smart hangar is described, which consists of five measures framed within the IoT philosophy: (i) digitization of the environment; (ii) analysis tools; (iii) automation and robotization of the environment; (iv) intelligent production; and (v) logistics carried out through the just-in-time philosophy. These aspects and parameters are used to digitize all work procedures, enabling the assignment, approval, and monitoring of maintenance tasks online, and allowing for significant analysis of digitized data. This approach enhances the ability to anticipate errors and enables participants in the process to better plan and utilize resources efficiently, relying on UAS and Automated Guided

Table 3
Software and file extensions per deliverable, source: Authors.

Type of Model	Format	Description	Recommended Software	Developer	License
Texturized Model	*rcm	Reality Capture Model	RecapPhoto	Autodesk	Academic/Paid
	*3ds	3D studio Scene	3D max	Autodesk	Academic/Paid
	*vrml	Virtual Reality Modeling Language	Cortona 3D viewer	Microsoft	Free
	*stl	Stereolithography file	Microsoft 3D viewer	Microsoft	Free
	*ply	Polygon Model File	Meshlab	Visual Computing Lab	Free
3D Object	Wavefront Object 3D file	Wavefront 3D Object File	Microsoft 3D viewer	Microsoft	Free
			Adobe Photoshop	Adobe	Paid
			Autodesk Maya	Autodesk	Student/Paid
			Maxon Cinema 4D	Maxon Computer	Paid
			Meshlab	Visual Computing Lab	Free
Point Cloud	*rcp	Reality Capture Project	Recap Pro	Autodesk	Student/Paid
	*rcs	Reality Capture Scan	Recap Pro	Autodesk	Student/Paid
	*pts	Point Cloud Storage	Recap Pro	Autodesk	Student/Paid
	*las	LIDAR data Exchange File	LAS Utility/ArcGis	–	Paid
	*e57	LIDAR Point Cloud Data File	FARO Scene	Faro	Paid
Orthomosaic	*tiff	Tagged Image File Format	Microsoft Photos	Microsoft	Free
	*jpeg	Join Photographic Expert Group	Microsoft Photos	Microsoft	Free
	*ecw	Enhanced Compression Wavelt	ERDAS Imagine/QGIS	HEXAGON/QGIS	Evaluation/Paid
DSM – DTM -DEM	.tiff	Tagged Image File Format	Microsoft Photos	Microsoft	Free
	.jpeg	Join Photographic Expert Group	Microsoft Photos	Microsoft	Free
	.ecw	Enhanced Compression Wavelt	ERDAS Imagine/QGIS	HEXAGON/QGIS	Evaluation/Paid

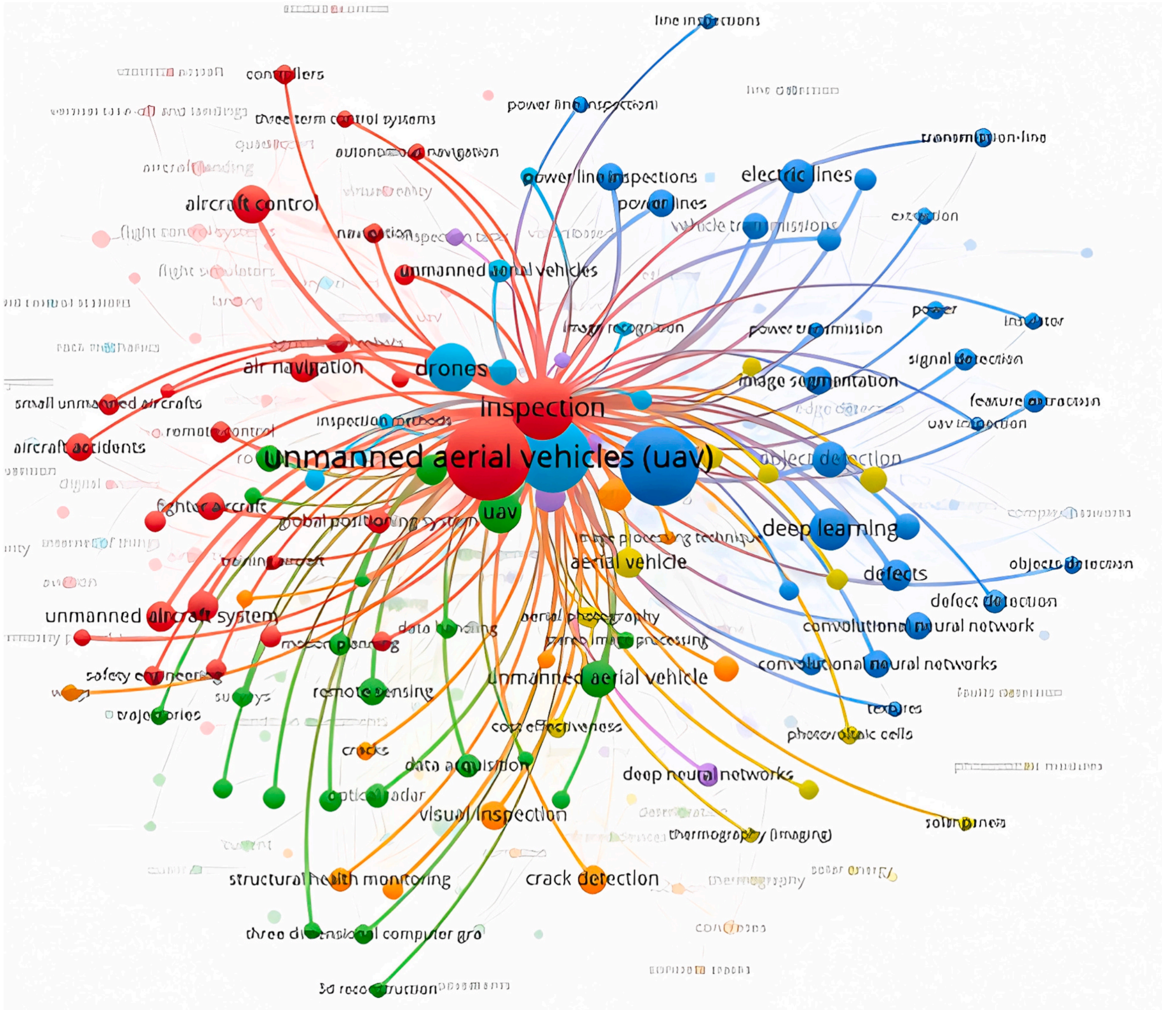

Fig. 3. Correlation analysis of keywords in VOSviewer, source: Authors.

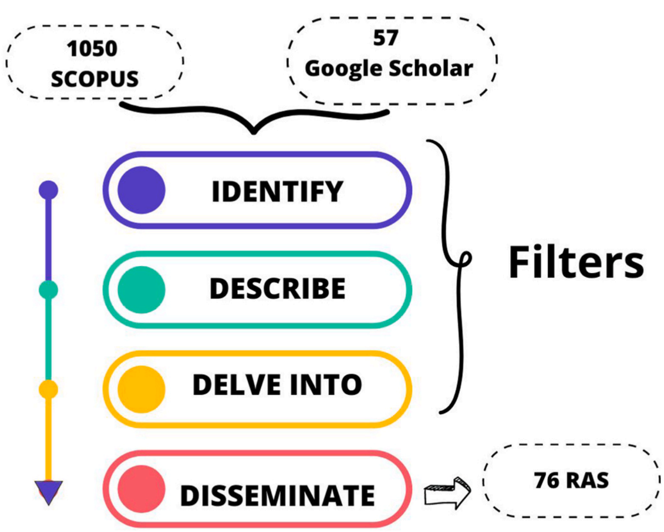

Fig. 4. Article Selection for Review, source: Authors.

Vehicles (AGV) for visual inspections and point-to-point transport of materials and tools before, during, and after maintenance.

The study also describes a partnership between Intel and Airbus to perform external aircraft inspections using UAVs. Intel provides unmanned aerial vehicles equipped with cameras that collect images and data to create detailed 3D models of the aircraft. Similarly, smaller companies such as Ubisense from France, and Canard Drones and MRO Drone from Spain, are offering services and implementing aircraft and airport inspection processes with drones in Europe.

According to Ref. [63], the five major components of a fixed-wing aircraft are the fuselage, wings, tail or empennage, engines, and landing gear. These components can be inspected with the support of a UAS. For example, in the study developed by Ref. [9], a visual inspection was performed using a UAS equipped with a high-resolution camera and an infrared camera to evaluate the condition of the fuselage of a Czechoslovakian-manufactured, two-seat ZLIN Z-142 aircraft, which is used for training new pilots. The methodology involved six steps: (i) image acquisition; (ii) pre-processing; (iii) image segmentation; (iv) feature extraction based on the images; (v) classification and recognition of findings; and (vi) post-processing. Additionally, the authors listed three important aspects to perform an inspection: (i) minimize particles in the inspection environment; (ii) identify the movement of the drone relative to nearby personnel and inform them of the operation; and (iii) ensure that the drone has anti-collision sensors to prevent collisions between the drone and the aircraft. To test their methodology, the authors conducted a test inspection using a DJI Mavic 2 drone equipped with an FC220 optical sensor to capture images. The acquired images were processed using the Matlab tool "Deep Learning and Machine Learning for Computer Vision," which converts an optical image into a numerical data array necessary for subsequent computational analysis.

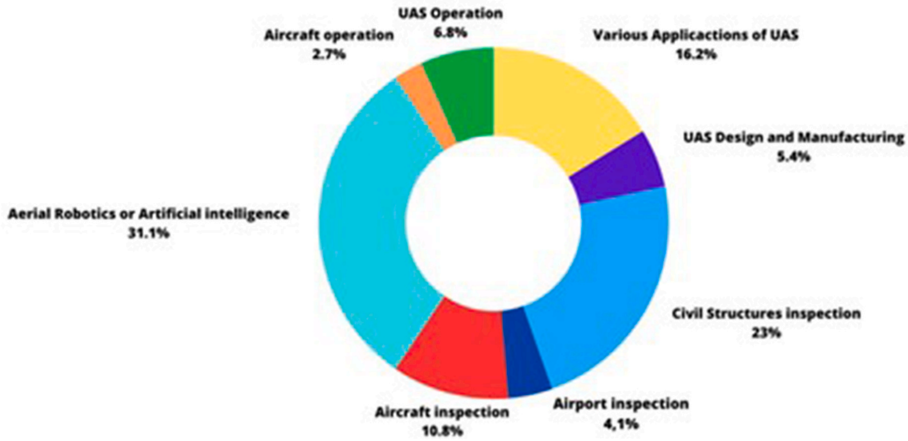

Fig. 5. Percentage distribution by area of knowledge, source: Authors.

During the inspection, a surface discontinuity caused by a dent in the aluminum skin covering the top of the left wing was identified.

In [9], a methodology and workflow are proposed for conducting an inspection using the Mavic Enterprise Dual multirotor drone equipped with a thermographic camera with a thermal resolution of 640 × 512, covering the infrared electromagnetic spectrum bands of IR waves with wavelengths of 8–14 μm, and a high-resolution camera that captures images in the visible light range of the electromagnetic spectrum. This setup allows for multispectral analysis of defects detected in the thermograms and digital images of the elements under inspection. Infrared Thermography (IRT) is a technique that measures the infrared radiation emitted by objects using a thermographic camera. These measurements are converted into digital electrical signals to create a thermogram, which is an image showing thermal gradients that display different temperature gradients present on the object's surface proportional to the infrared radiation. As shown in Fig. 6, which is a thermogram of the control tower of El Dorado Airport in Bogotá, Colombia, obtained with a Flir E5 thermal camera that has a thermal resolution of 120 × 90, images obtained by these cameras can be stored or transmitted in real-time and have the advantage of not being affected by visible light, smoke, or fog. There are two types of thermography: passive and active [64]. Passive thermography does not require the material to be stimulated to generate a response, as the components themselves emit infrared radiation when they operate. This technique is useful in the aeronautical industry for inspecting components, aircraft and helicopter parts, avionics equipment, electrical systems, ground equipment, and structures in general.

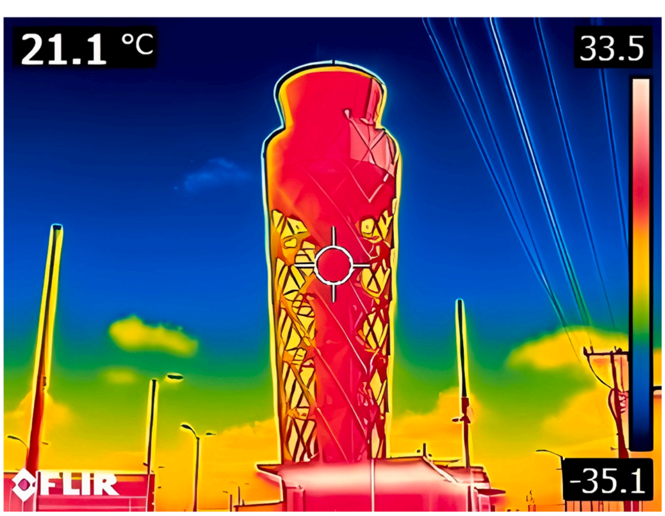

Fig. 6. Infrared thermography applied in control tower, source: Authors.

Active infrared thermography, on the other hand, requires the element under inspection to be stimulated by an external source, such as halogen lamps or current pulses, to force a response in the component to emit more infrared radiation. This technique is used to inspect a variety of materials, such as aluminum, titanium, and composite materials [65]. IRT takes advantage of the fact that there is usually an increase in temperature in components or structures when a fault occurs.

In this second part, it was necessary to define three important aspects for monitoring the desired parts: (i) define the flight path to monitor the desired parts; (ii) determine the movements and reference points of the drone within the defined path that allow the capture of images of the points of interest; and (iii) define the take-off site and height of each reference point where the images are taken. These three steps determine the duration of the inspection. Using the temperature gradients shown in the thermograms, water ingress into certain areas of the aircraft was detected. The article concludes that the use of UAS reduced inspection time by 60 min compared to traditional visual inspection techniques.

In [10], a study conducted by the University of Laval in Quebec City, Canada, describes two methods of active thermography: Pulsed Thermography (PT) and vibrothermography. The feasibility of implementing these methods in aircraft inspection using an unmanned aerial vehicle equipped with a thermal camera was evaluated. PT is a Non-Destructive Testing (NDT) technique that does not require physical contact with the sample and is used to assess the condition of materials and components. To apply this technique, the sample is subjected to a heating process in the form of pulses spaced over time while images are acquired with a thermal camera. The induced heat is conducted through the material via conduction, and any defects present in the material, whether superficial or subsurface, will affect the heat diffusion. This allows the thermal camera to locate a discontinuity by observing and analyzing the radiation pattern during the cooling phase. It is important to note that surface conditions can affect the results of PT due to variations in emissivity, which is an intrinsic property of materials that determines their ability to emit radiation. This variable must be measured or determined through literature related to the mechanical properties of materials.

For data acquisition in the experiment, three samples of Carbon Fiber Reinforced Polymer (CFRP) composite materials were used: one without defects and two with defects produced by impacts that caused dents. The materials were subjected to a heating process of 2 ms duration using two Balcar xenon flash lamps. As time passed, the heat moved through the samples and decreased uniformly in the sample without defects and non-uniformly in the two samples with impact-induced dents. The thermal response was captured by an infrared camera and recorded on video for subsequent analysis. The acquired data were stored as a 3D matrix with spatial coordinates x-y. MATLAB and software called Ir view from Visiooimage Inc. were used for signal processing.

The other technique used was vibrothermography, which is employed to detect cracks in metallic structures and various types of damage in composite materials. Sonic waves vibrating between 15 Hz and 50 kHz were produced. This inspection technique is slightly faster than PT, which is advantageous because longer inspections increase the probability of sample degradation due to prolonged exposure to heat. The transducer used is a 20 kHz ultrasonic generator, which allowed for the detection of two defects: delamination and kiss-bond. Kiss-bond is characterized by surfaces being in intimate contact with little or very superficial union. Although this method is more efficient, it is difficult to implement on a UAV because the vibrations can affect the measurements of the drone's gyroscope sensors. A way to mitigate this effect is being studied using vibration-dampening pads.

A study conducted in Russia uses a hybrid between an Unmanned Ground Vehicle (UGV) and UAV, called the Robot Complex, to detect damages caused by metal fatigue, lightning strikes, and bird collisions. The UAV and UGV are connected by a gripping mechanism with a rope that unwinds and changes its length as required by the drone, similar to raising a kite. The robot remains in the area where the aircraft will stay overnight or on the ground and, if required, moves to the parking area where the aircraft to be inspected is located. Once there, the UAV takes off and performs the verification, following the trajectory previously programmed by the operator at the ground station. At all times, the UAV and UGV maintain their physical connection through the gripping mechanism, which assists and keeps the drone on its trajectory in case of strong winds, avoiding collisions between the drone and the aircraft [66].

In [11], researchers from the Italian universities of Naples and Campania designed a low-cost UAS equipped with a High-Definition (HD) camera to detect damages in aircraft aluminum panels. They implemented an Ultrasonic Distance Keeper System (UDKS) to avoid obstacles, facilitate trajectory programming, and ensure a fixed safety distance between the UAS and the aircraft to prevent collisions. The study evaluates the efficiency of the drone in detecting panel failures. According to the authors, on average, 68 % of errors in findings obtained through traditional visual inspections of aircraft are due to the subjectivity of human factors, leading to omissions and/or false positives in the detection and classification of defects.

The experimental setup consists of a commercial quadcopter UAV, a ground station (based on a PC), an integrated control system created by the authors and installed in the aircraft fuselage, and a 6-megapixel HD camera for the Raspberry Pi V2. The objective is to perform a General Visual Inspection (GVI) to detect damages caused by hail impacts, bird strikes, and lightning strikes. The drone used was a micro-UAV, the RC EYE One Xtreme, with a length of 23 cm from the tip of one rotor to the tip of the opposite rotor, a height of 8 cm, a total mass of 260 g, a 1150 mAh 7.4 V LiPo battery, and a payload capacity of 150 g. The average flight time is 10 min, the maximum range of the control signal transmitter is approximately 150 m in open fields, and the images are transmitted via Wi-Fi. The UDKS system and the camera were installed in a frame designed and manufactured by the authors using a 3D printer.

Two samples of aluminum sheets were analyzed in the laboratory, one with damage caused by hail and the other with a dent caused by lightning. Image capture was performed using a drone at a height of 1.60 m and a horizontal distance of 1.20 m from the samples. Dents were detected and geometrically characterized in real-time, and the images were sent to the ground station for processing. Based on the results, the article concludes that the use of drones for aircraft inspection has several benefits: i) It reduces the time that the aircraft spends in the hangar and lowers the cost of conventional visual inspection procedures. ii) Visual inspections are expedited and/or facilitated in areas that are difficult to access without compromising the physical integrity of the operator. iii) Specific and reproducible inspection routes can be designed around the aircraft. Images can be captured at a safe distance from the structures and from different points of view, and data can be transmitted through dedicated links to a ground station. iv) Defects can be accurately evaluated by comparing acquired images with 3D structural models of the aircraft. v) Different types of information can be collected by installing optical sensors on the UAV. vi) The quality of inspection reports is improved; maintenance problems and damages can be identified in real-time; and anomalies can be compared with previous inspections. vii) Automatic inspection reports can be generated, and precise inspections can be performed after each flight.

In [67], a study by the Nanjing University of Aeronautics and Astronautics in China developed a methodology to perform visual inspections on civil aircraft using UAS with calibrated routes and ARuco markers to estimate the UAS's position. ARuco markers use square binary markers, which are black and white square images similar to QR codes. The article mentions that traditional visual inspections of the upper and lower parts of the structure can take between 4 and 10 h on a Boeing 737, which has a height of 12.5 m. To compare the manual inspection process with one carried out using UAS, the researchers used a DJI M210 quadrotor multirotor drone, chosen for its ability to carry different types of cameras and its control system that ensures good stability. The inspected aircraft was a Y-7-100 made in China.

The methodology consists of the following steps: i) Geometric dimensioning of the three-dimensional space where the aircraft is located, determining sizes and distances between main components. This involves taking a set of vertical photos from top to bottom, followed by a set of oblique photos at heights of 34, 25, and 15 m at different distances, with a 60 % overlap between each photo. ii) The images are imported into Pix4D Mapper software, a photogrammetry software for image processing that allows generating a 3D model from the mosaic of overlapping photos. This model can be generated manually or automatically by the software, with the latter being preferred despite potential minor errors and slight reductions in precision.

To define the trajectory, an Android application called Mobile Software Development Kit (MSDK) was developed, allowing the transmission of the trajectory to be followed by the drone. The application has the trajectory parameterized for a Y-7-100 aircraft, as shown in Fig. 7, but it can be adapted for A320, A330, A350, B737, B747, and B777 aircraft. The trajectory allows inspection of empennages, fuselage, engines, and landing gear. Through the graphical interface of the application, technicians and engineers can choose the inspection to be performed from a visual menu. The obtained images can provide information by transitioning from a 2D to a 3D space. Given that customizing the trajectory for each aircraft model is a daunting task, ARuco markers are used to facilitate inspection, helping the UAS maintain the trajectory and not deviate due to environmental, mechanical, or electromagnetic disturbances. For image acquisition and analysis, the researchers relied on the Open-Source Computer Vision (OpenCV) library, which is widely used in academic and commercial environments. OpenCV contains more than 2500 algorithms that allow identifying objects and faces, classifying human activities in video, tracking the movement of objects, extracting 3D models, finding similar images, recognizing scenarios, monitoring equipment, assisting in robot navigation, and inspecting barcodes and QR codes of components and products. It is written in C++ and has interfaces for Python, Java, and MATLAB, and it works on Windows, Linux, Android, and macOS. The research concludes that with the use of UAS, the inspection task takes only 6–10 min.

In an investigation conducted in Toulouse, France [68], the inspection of screws and rivets in an aircraft fuselage was completed using UAS. These components are responsible for keeping the parts of this section of the aircraft together. To analyze and classify images from the Zones of Interest (ZOI), a Convolutional Neural Network (CNN) was used, which offers the ability for robotic systems to analyze images in a manner similar to human vision. Specifically, a subtype of the CNN algorithm called Single Shot MultiBox Detector (SSD) was used, which can detect components as small as 1 % of the size of the acquired image. Screws and rivets are the most common components on the surface, and the algorithm can recognize and classify dozens of objects, including screws and various defects associated with them. The algorithm is robust

Fig. 7. Drone inspection trajectory for an aircraft, source: Authors.

and considers variable lighting conditions, low light, and specular reflections due to polished and shiny surfaces, such as aircraft skin. Additionally, a Digital Mockup (DMU) model combined with a Generative Adversarial Network (GAN) model was used to detect the exact position of the screws in the generated 3D model. This approach allows for the identification of patterns in images of screws and rivets, serving as a reference for comparison with subsequent measurements to detect the absence of screws and rivets or identify defective ones. The system was tested on an A320 aircraft and was able to detect patterns of five screws in the rear area of the empennage, even when the drone took images at difficult angles and in low light. To generate the trajectory, a navigation algorithm based on laser technology was created to avoid collisions between the drone and the aircraft, as it is not possible to use a satellite navigation system in the confined indoor space where the experiment was conducted.

3.2. Airport inspection

In the study [69], a drone is used to monitor areas of interest on an airport runway to detect cracks, potholes, roughness, damage or fading of markings, and Foreign Object Debris (FOD), which can cause damage to aircraft during takeoff and landing. This inspection is carried out by traversing the runway at least four times a day and obtaining images for subsequent processing. The article also describes other benefits of using UAS at airports, such as increasing airport security and surveillance, and collecting data on the airspace and operations. This data can be used by airport ground officials to acquire weather information, predict microclimates at the airport location, reduce the requirement for human resources, and optimize risks and costs. The article proposes the use of UAS for bird control at airports to avoid delays, accidents, and damage to wildlife during take-off and landing. It also mentions that UAS can be used to mitigate or eliminate fog by spraying certain gases designed for this purpose. Another aspect mentioned is that different environmental factors affect the design of airport drones: i) The size of airports will determine the required flight autonomy in minutes for the UAS and consequently the size and type of UAS; ii) The altitude of the aerodrome and surrounding climate will determine the type of motors and batteries required; iii) The cameras and sensors onboard the drone will depend on the type of operation and airport category. As part of the study, a hexacopter multirotor was fabricated on an F550 frame using a Raspberry Pi development board as the flight controller and a GoPro HD camera. Seven images were taken in seven different zones of the runway, five of which showed cracks and/or potholes. These defects were characterized in the post-processing of the images using artificial intelligence algorithms implemented in Python, which detected cracks in five images by differentiating pixels corresponding to a crack from pixels in unaffected areas using statistical methods.

Additionally, for efficient inspection, autonomous trajectory designs are required, such as those described in Ref. [70], which details the use of computer vision algorithms to detect contours and reference marks for better navigation and flight over asphalt paths or routes, such as runways and taxiways at airports. In Ref. [2], two field tests were carried out on an airport runway in Georgia, USA, using three different drones: the DJI Matrice 100, the DJI Phantom 4 Pro, and the Yuneec Typhoon H. The methodology employed was as follows: i) Collection of 2D and infrared images using the UAS cameras; ii) Execution of photogrammetry to create a 3D model from a point cloud; iii) Measurement and analysis using a process called Point Cloud Library (PCL). With the methodology used, 101 digital images were taken with a 12.4-megapixel camera and 24 thermal images. The digital images were analyzed with Agisoft PhotoScan software, which detected cracks and wear on the runway. It was also possible to measure the growth of nearby trees by comparing the obtained images with those from a manual study conducted years ago. Subsequently, thermal gradients and patterns were generated using thermograms obtained with thermal cameras. These patterns serve as a reference for further analysis [2].

In [71], a methodology is proposed for the inclusion of drones in airport operations and the inspection of airport infrastructure. To achieve this, airport operators, airlines, and Approved Maintenance Organizations (AMOs) will need to coordinate and track drone operations along with all other vehicles such as aircraft and ground support vehicles. This methodology is named the Design of a Local Area Integrated Drone, Aircraft, Vehicle, and Asset Management System (LAIDAVAMS).

Coordination and tracking can be achieved thanks to recent changes in drone standards that require these aerial vehicles to be equipped with receivers to transmit location and other information using a standard communication protocol specified in the ASTM F3411-19 Standard Specification for Remote ID and Tracking (AST). This protocol will allow drones to be synchronized with ground support vehicles, other electronic equipment used for logistics, and other aircraft, with the purpose of improving airport productivity, efficiency, and safety. This operation must comply with airspace operation procedures determined by the Air Navigation Service Provider (ANSP), Universal Traffic Management (UTM), and Low Altitude Authorization and Notification Capability (LAANC) standards.

LAIDAVAMS is designed to provide the airport operator with detailed information, data processing and storage, data analysis, visualization, and reporting. It can also be configured for obstacle detection and avoidance during operations. LAIDAVAMS is carried out in three phases: i) Approval and Registration Process; ii) Day of Operations; and iii) Monthly/Quarterly/Annual Report Registration Process, which has four steps for implementation: i) The company operating at the airport decides to use drones in some of its operations; ii) The interested company sends a request to the airport operator detailing the type of drone, flight plan, operation time, location, etc.; iii) The airport operator evaluates the request based on regulations and operational rules; and iv) The airport operator registers the drone as an asset in the LAIDAVAMS system.

The Day of Operations has seven steps: i) The drone operator prepares the flight plan; ii) The operator registers the vehicle and flight plan in LAIDAVAMS; iii) The LAIDAVAMS processing module submits the LAANC request to the FAA; iv) LAIDAVAMS approves the operational plan; v) The drone operator initiates it and LAIDAVAMS recognizes the tracking; vi) The drone operator performs the mission; and vii) LAIDAVAMS provides the airport operator and drone operator with the means to track operations and provide an alert if necessary.

Reports have two steps: i) LAIDAVAMS provides the drone operator and airport operator with a monthly, quarterly, or annual operational and statistical report. It also identifies and provides precautions and warnings related to safety, and ii) the airport operator and drone operator adjust appropriate procedures to enhance safety.

The debate on the use of drones in airport and aircraft inspections extends to several studies showing their effectiveness in infrastructure inspection and maintenance. Table 4 provides a comparison of these studies, highlighting the damage assessed, the UAS and cameras used, the techniques employed, the software and algorithms for image control and processing, as well as the type of aircraft or component inspected.

4. Discussion of results

The systematic literature review clearly shows how UAS have significantly improved the inspection of aircraft and airport infrastructure compared to conventional methods. In Ref. [1], the concept of "smart hangars" highlights the integration of UAS in the automation and digitization of maintenance processes. In this framework, automated guided vehicles (AGVs) and drones work together to streamline the transport of tools and materials, optimizing efficiency and reducing downtime. In Ref. [2], the utility of thermal cameras and photogrammetry to detect cracks and debris on airport runways is demonstrated, improving effectiveness compared to manual methods [69]. also highlights the capability of UAS to identify foreign object debris (FOD) on runways, reducing risks for aircraft during takeoff and landing. In Ref. [71], the LAIDAVAMS system is proposed, which coordinates the operation of drones with ground vehicles and aircraft, enhancing airport productivity and safety.

Regarding the detection of structural defects in aircraft [9], implements a methodology with multirotor drones equipped with thermal cameras, effectively identifying discontinuities in composite materials and insulation areas. This effectiveness is also reflected in Ref. [11], which incorporates an ultrasonic distance system to maintain a safe separation between the drone and the inspected surface, ensuring the quality of the captured data. [68], in turn, uses convolutional neural networks (CNNs) and GAN models to detect defects in rivets and screws on fuselages, achieving a level of detail impossible to reach through manual inspection.

For the inspection of airport structures [47], employs 3D models generated with drones to assess the integrity of a dam. Additionally [67], uses ARuco markers combined with photogrammetric techniques to inspect the structure of an aircraft, providing a high level of accuracy in pattern identification.

Finally, the ability of UAS to create 3D point clouds and orthomosaics has been used to inspect various structural elements [66]. implements a hybrid robot between UGV and UAS to detect fatigue damage in metallic materials, and [65] explores active thermography and vibrothermography methods to identify defects in composite materials.

5. Limitations

Currently, several limitations prevent the development of fully automated UAS inspections, primarily due to regulatory aspects that prohibit the use of UAS in controlled airspace near airports, as described in FAA and AESA regulations. Additionally, technical limitations hinder the generation of 100 % reliable trajectories and anti-collision systems in the vicinity of aircraft due to atmospheric factors such as winds and failures in existing communication links and control trajectories. Although effective, these systems are still in the research and development stage. Another obstacle is the loss of satellite signal in enclosed indoor environments such as hangars. For this reason, UAS perform these trajectories using LIDAR technology and other ultrasound sensors to provide a sufficiently precise route while avoiding collisions with objects and obstacles.

Enhancing the power and efficiency of GPS navigation systems is a challenge, and there is a need to develop simple and portable alternative methods to address the loss of satellite signal. Therefore, it is essential to identify whether the use of unmanned aerial vehicles will be in enclosed spaces or for outdoor inspections. It is also necessary to determine the

Table 4
Comparison of characteristics and parameters of the studies, source: Authors.

Reference	Assessed damages	Used UAS and camera	Used technique	Software and algorithms for image control and processing	Type of aircraft or component inspected
[9]	Cracks, failures in water-resistant insulation seals of the aircraft	Mavic 2 with FC20 optical sensor and Mavic Dual Enterprise with thermographic camera.	Visual inspection and infrared thermography.	Matlab, ToolBox “deep a machine learning tool for computer vision”.	Zlin Z 142 two-seater aircraft and Piper PA 34–220T Seneca.
[65]	Delaminations in composite material joints	FLIR Phoenix thermographic camera, with inSb sensor material, 3–5 mm, 640 × 512 pixels.	Pulsed thermography PT and vibrothermography (VT)	Matlab and Ir_view from Visiooimage Inc.	Testing of 3 composite material samples.
[66]	Sheet metal buckling due to hail impact and lightning strikes in aircraft	RC EYE One Xtreme equipped with a 6-megapixel Rasberry Pi camera module V2.	Visual inspection.	Matlab, LabView, Filtro de Kalman.	Samples in a laboratory.
[11]	Methodology confirmed, no defects found	DJI M210.	Visual inspection.	Pix4D Mapper, Arco markes, open cv.	Aircraft Xian Y7-100.
[67]	Damage to fuselage screws and rivets in the aircraft	Donecle UAV	RGB images. 3D reconstruction.	GAN. Pix4D Mapper, Autocad 3D 2017, Convolutional Neural Network (CNN),	Aircraft A320.
[2]	Cracks on the airport runway	DJI Matrice 100 -, DJI Phamton 4 Yuneec Thyphoon H	Infrared thermography; point cloud generation.	Agisof PhotoScan	Airport runway.
[68]	Cracks, potholes and/or roughness	drone built by the authors on a F550 frame, with a GoPro camera and Rasberry Pi.	Digital RGB image analysis.	Not specified.	Airport runway.

size of the aircraft for which the use of a UAS for inspection is relevant, as its use may not be necessary for small aircraft.

Lighting conditions are another important factor to consider, as dark conditions often present in enclosed spaces can reduce fault detectability and the proximity distances between the drone and structures, requiring the use of external artificial lighting for the UAS. This poses a significant challenge as autonomous lighting systems generate additional power consumption, which reduces flight time. Another aspect that limits the use of UAS for inspection imaging is the electrical noise produced by the drone and its components, which can result in blurry images. Fortunately, there are algorithms that allow for noise correction or mitigation [72] and image enhancement [73,74]; however, these algorithms require high computational processing power [75], obtained through high-speed computing equipment with 3.2 GHz dual-core processors, 8–16 GB RAM, high-performance video cards, and large storage with at least one terabyte of space, due to the number of overlapping images required to create a 3D model [75]. It should be noted that in the future, online image classification and management alternatives are being envisioned, as described in Ref. [76], and methods for ensuring intellectual property through the inclusion of invisible watermarks in images are proposed, as described in Ref. [77].

Another significant limitation of UAS operations is the short flight time, which ranges from 15 to 30 min, allowing for only short operating periods. This requires the use of several batteries to carry out an inspection, increasing costs and inspection times, as battery charging times are 2–4 h. Therefore, it is pertinent to develop alternative or complementary power sources to the LiPo batteries currently used to power UAS, as this is one of the most promising research areas in this field.

6. Future challenges

Further research is needed to address technical issues such as battery life and weather conditions that may affect UAS performance. In addition, a regulatory framework must be established to ensure the safe deployment of UAS in aerial inspection operations. The implementation of real-time processing algorithms integrated with artificial intelligence can streamline decision-making during inspections. Addressing these challenges will ensure a more efficient and safer integration of UAS in the aviation industry, thereby driving the digital transformation of maintenance and inspection.

7. Conclusions

The use of UAS in aircraft inspection complements traditional visual inspections of aircraft and aeronautical infrastructure, as well as some non-contact NDT techniques such as infrared thermography. It is a plausible prospect for the development of fully autonomous aircraft inspection within the framework of aviation 4.0 and the Internet of Things (IoT). Among the advantages and contributions of UAS in these inspections are the significant reduction in time, which can be quantified in minutes or even hours, the decrease in costs by reducing the personnel required to carry out the inspection, and the mitigation of risks associated with working at heights. Additionally, the wide range of sensors and cameras that can be installed on a drone has increased the effectiveness and efficiency when applying various NDT techniques that traditionally require contact, such as ultrasound or eddy currents.

UAS can also improve the accuracy and consistency of inspections. They can capture high-resolution images and video of aircraft structures and aviation infrastructure, which can be analyzed using machine learning algorithms to detect defects and anomalies. Furthermore, UAS can provide access to hard-to-reach areas of aircraft structures and aviation infrastructure, such as wingtips or tails. This allows for comprehensive inspections and reduces the need for scaffolding or other equipment. Overall, the use of drones in aircraft inspections has the potential to revolutionize the aviation industry by improving safety, efficiency, and cost-effectiveness.

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CRediT authorship contribution statement

Didier Aldana Rodríguez: Writing – review & editing, Writing – original draft, Investigation. **Cristian Lozano Tafur:** Writing – review & editing, Writing – original draft, Investigation. **Pedro Fernando Melo Daza:** Writing – review & editing, Writing – original draft, Formal analysis. **Jorge Armando Villalba Vidales:** Writing – review & editing. **Juan Carlos Daza Rincón:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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