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Innovation in precision approach path indicator light calibration using UAS: a comprehensive review

Innovación en la calibración de luces indicadoras de precisión de pendiente de aproximación mediante UAS: una revisión integral

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Abstract: This paper aims to provide a general background on Precision Approach Slope Indicator (PAPI) lights and their relevance in airborne operations. The paper focuses on the calibration of PAPI lights, highlighting the use of Unmanned Aircraft Systems (UAS) as a tool that offers significant advantages. Among these advantages are cost reduction, increased safety, speed and accuracy in calibration. Equipped with sensors and cameras, UAS allow detailed and accurate inspections, even in difficult conditions. In this article, advantages, challenges, procedures and technologies involved in the implementation of UAS for this task are evaluated, comparing traditional methods with modern UAS-based approaches. The results show that the use of UAS considerably improves the calibration of air navigation aid systems, representing an efficient and safe alternative to traditional methods. Emerging trends and research areas are identified that could further optimize this process, highlighting the potential of UAS in the continuous improvement of aviation safety and efficiency.

Keywords: aviation; UAS; GNSS; PAPI lights.

Resumen: Este artículo tiene como objetivo proporcionar un contexto general sobre las Luces Indicadoras de Precisión de Pendiente de Aproximación (P.A.P.I) y su relevancia en las operaciones aéreas. El documento se centra en la calibración de las luces P.A.P.I, destacando el uso de Sistemas de Aeronaves no Tripuladas (UAS) como una herramienta que ofrece ventajas significativas. Entre estas ventajas se encuentran la reducción de costos, mayor seguridad, rapidez y precisión en la calibración. Equipados con sensores y cámaras, los UAS permiten realizar inspecciones detalladas y precisas, incluso en condiciones difíciles. En este artículo, se evalúan ventajas, desafíos, procedimientos y tecnologías involucradas en la implementación de UAS para esta tarea, comparando métodos tradicionales con enfoques modernos basados en UAS. Los resultados muestran que el uso de UAS mejora de manera considerable la calibración de los sistemas de ayuda a la navegación aérea, representando una alternativa eficiente y segura a los métodos tradicionales. Se identifican tendencias emergentes y áreas de investigación que podrían optimizar aún más este proceso, subrayando el potencial de los UAS en la mejora continua de la seguridad y eficiencia en la aviación.

Palabras clave: aviación; UAS; GNSS; luces P.A.P.I.

1. INTRODUCTION

Air navigation is the science that studies the methods and tools used to obtain information about the current position and movement parameters of an aircraft. In addition, it focuses on the methods and tools necessary for navigation, ensuring accuracy in the current position and trajectory of movement in airspace, minimizing uncertainty [1].

In the field of each country's Air Navigation System (ANS), the maintenance of the facilities that support it and its operational verification are essential. Among the components that contribute to the safety of landing operations, the Airport Lighting System (also known as Aerodrome Lighting System) is an essential visual aid. This system assists aircraft during takeoff, landing and taxiing, facilitating their movement in an efficient and safe manner [2] [3].

One of the most prominent elements in airfield lighting is the Precision Approach Path Indicator (PAPI) lights. Designed to provide accurate guidance to pilots during the approach and landing process, PAPI lights define the optimal bank angle, typically around 3 degrees [4], that visually connects the aircraft to the runway [5].

Using a specific formation of lights, this system effectively directs the aircraft to a touchdown zone, ensuring a safe and accurate landing [4]. The accuracy of the aircraft's glide is indicated by the observed distribution of red and white lights, and calibration should be performed periodically [6].

During landing, the pilot observes the airfield lights, the runway and the PAPI system, in addition to the indications of the critical on-board instruments (such as the airspeed indicator). This information allows the pilot to build a mental picture of the situation, covering the state of the aircraft, the glide path and the possible landing point, thus facilitating a correct and safe landing.

In this context, this article aims to analyze the use of UAS for the calibration of air navigation aid systems, specifically PAPI (Precision Approach Path Indicator) lights and radio aids (such as ILS, VOR, DME, among others). Advantages, challenges, procedures and technologies involved in the implementation of UAS for these tasks will be evaluated, comparing traditional methods with modern UAS-based approaches. Additionally, emerging trends and areas of future research that could improve the efficiency, safety and accuracy of calibrations performed with UAS will be identified, emphasizing the potential of UAS in the continuous improvement of safety and efficiency in aviation.

2. PRECISION APPROACH PATH INDICATOR LIGHTS (PAPI)

Precision Approach Path Indicator Lights (PAPI) are a visual aid device for landing, regulated by Annex 14 of the International Civil Aviation Organization (ICAO) [7]. It consists of a set of four lights arranged on one side of the runways, generally on the left, at a distance of between 300 and 450 meters from the runway threshold. This arrangement is due to the fact that the pilot is on that side of the aircraft, according to Smith et al. [8] and Celis [9].

The SARPS (Standards and Recommended Practices) for PAPI were adopted in Annex 14, Volume I in 1983 for worldwide application. The PAPI system is now installed at many airports around the world, contributing to safe aircraft operations [10].

It is important to note that the distance between PAPI lights can vary depending on the airport and the type of aircraft being used. In addition, the intensity of the lights can be adjusted to suit different visibility conditions, such as fog or rain, according to Aviation [11].

In Colombia, according to the RAC 14 standard of the Colombian Aeronautical Regulations of the Aerocivil [12] and in accordance with Annex 14 to the Convention on International Civil Aviation [7], the PAPI system must consist of a bar with four luminous elements, placed at equal intervals. This bar is usually installed on the left side of the runway, approximately 300 meters from the landing threshold, unless it is materially impossible, respecting the specified installation tolerances. The components of the light bar must be installed in such a way that, during the approach, the pilot perceives an almost horizontal line.

Fig. 1. *PAPI lights setup*
Source: *Own image*

Each of the lights is mounted at a slightly different angle (20 minutes apart) and emits a high intensity beam of light with a filter showing the upper half white and the lower half red, according to Castle [13]. The ideal approach angle is achieved when the pilot sees the two lights closest to the runway red and the two furthest white, indicating a suitable approach slope. If the aircraft is below the glide slope (below 2° 30'), four red lights are seen, indicating a very low slope. If it is slightly below (between 2° 50' and 2° 30'), the pilot will see three red lights and one white light, indicating that the aircraft is slightly low. Conversely, deviations above the glide slope are adjusted on the same principle.

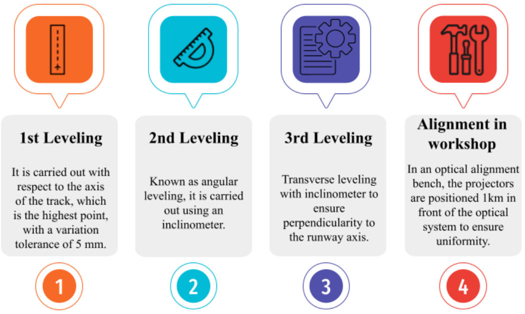
A pinkish color variation can be perceived between the transitions of light hue from white to red, due to the combination of colors in a short angular range before reaching the red hue. These transitions allow the pilot to adjust his position for a proper landing, as mentioned by Anchatipán [14].

PAPI system units must be designed with frangible attachments that allow them to be moved in the event of a collision with an aircraft, minimizing damage. In addition, they must be located as close as possible to the lower edge of the runway and be easily breakable in the event of an impact, ensuring their functionality for both day and night flights [7]. It is essential that these units minimize susceptibility to explosions, thus ensuring greater safety in landing operations [15].

2.1. Calibrationof lights PAPI

Calibration of PAPI lights is crucial to ensure an accurate and safe approach path for pilots. This is critical to avoid errors during approach and reduce the risk of accidents when landing [16]. Calibration ensures that the lights are visible and accessible, especially in low visibility conditions or at night, allowing pilots to adjust their descent angle effectively [17]. Furthermore, calibration is necessary to comply with international regulations of the International Civil Aviation Organization (ICAO), which set rigorous standards for the operation and maintenance of these systems [16]. Through regular calibration, malfunctions or deterioration in the system can be detected and corrected, which not only improves the reliability and accuracy of PAPI lights, but also ensures flight safety by minimizing the risk of technical failures [12].

To ensure that the light signals are optimal, several specific levelings must be carried out. Three levelings are carried out in the field and one in the workshop [16].



1st Leveling
It is carried out with respect to the axis of the track, which is the highest point, with a variation tolerance of 5 mm.

2nd Leveling
Known as angular leveling, it is carried out using an inclinometer.

3rd Leveling
Transverse leveling with inclinometer to ensure perpendicularity to the runway axis.

Alignment in workshop
In an optical alignment bench, the projectors are positioned 1km in front of the optical system to ensure uniformity.

Fig. 2: *Specific leveling*
Source: *Barbosa, SI. PAPI Precision Approach Path Indicator. Eletromundo*

The importance of the aircraft entering with the correct approach slope is due to the fact that there must be sufficient distance for it to brake.

2.2. Traditional calibration methods

Procedures for in-flight verification and validation of air navigation aids are defined in ICAO Document 8071 [18] and for in-flight validation of performance-based navigation (PBN) procedures in ICAO Document 9906 [19]. These procedures apply to the different types of flight inspection, of which there are three [20].

- **In-flight inspection:** the commissioning of a NAVAID or PAPI: this is a comprehensive flight inspection that establishes the validity of the radio signals around the service area. It is only after commissioning that the equipment obtains authorization from the National Aeronautical Authorities to transmit.

- **Periodic flight inspection:** verify that the radio signals of the navigation aid are always transmitted in accordance with the regulations. To do this, periodic inspections steal some of the profiles from the commissioning inspection and compare the results with the previous ones. The interval is generally 6 months for ILS/EMD; and 12 months for VOR/DME and PAPI.

- **Special Flight Inspection:** Special flight inspections are required at the request of maintenance personnel or due to the investigation of an incident or accident. In such an inspection, only problematic flight procedures are tested. After any modification of a navigation aid, the periods for periodic inspections are also shortened [20].

In-flight inspection of navigation or landing aids involves comparing the positioning information (azimuth or location) it emits in relation to a given direction with more precise external information, taken as a reference. The in-flight check is performed by a specially trained crew in a specially equipped aircraft with a flight inspection bench [20].

Key participants in this airport operation include the air traffic controller (ATC), who communicates with the pilot of the laboratory aircraft using the tower frequency and conducts a debriefing prior to the start of the operation. Maintenance experts coordinate with the flight inspection engineer via VHF radio, using specific frequencies such as 130.10MHz or 134.65MHz. The flight inspection engineer plays a central role in the operation, communicating with the pilot using a telephone integrated into the aircraft, thus ensuring effective and safe coordination during all phases of the inspection process.

The Flight Inspection Bench is an advanced system comprised of several key elements. It includes a differential GPS-based tracking system for precise localization, receivers that capture beacon and aircraft trajectory data, and a modular FDAU-type acquisition system. It also features a computer system with an intuitive interface for real-time processing, along with portable and desktop workstations. All of this is complemented by specialized software for efficient data acquisition and processing during flights, facilitating detailed and safe inspections in critical air operations.

The calibration method currently used in Colombia requires specific tools and a communication system with the calibration aircraft, in addition to the fact that it is a service provided by the Special Administrative Unit of Civil Aeronautics (Aerocivil), the cost of which is assumed directly by the aerodrome, requires more time and is more expensive for the civil authority department. In addition, if it is out of calibration, the alignment takes even longer [46]. That is to say, these factors involve personnel wear, aerodrome inactivity and consumption of the military air unit's own resources. In addition to the economic costs involved in the current process, it is equally important to highlight the impact involved in the suspension of air operations while this procedure is carried out, particularly in units with a high operational level, an economic and operational factor that is increased, this forces the landing strip to be inoperative during this calibration time, which means modifying the scheduled flight times, with the consequent social and economic inconvenience.

The correct projection of the light beams depends on the periodic calibration process carried out on the system, according to Shaher [21]. Traditionally, calibration was carried out using conventional aircraft, such as single-engine, twin-engine, turboprop or jet, with flight crews and specialized personnel on board. This process represented a significant challenge in terms of obtaining financial resources to cover the operating and maintenance costs of the aeronautical infrastructure and flight equipment, according to Kazda et al [22].

It is important to note that, although the protocol is repetitive, each calibration procedure may involve adjustments due to different parameters, such as the specific topographic and meteorological conditions of the aerodrome. As noted, the correct positioning of aircraft on runways requires precise systems that ensure operational safety in various meteorological conditions. [23], factors that can prolong the suspension of air operations and increase the use of human and material resources. It is crucial to consider the calibration of PAPI lights, whose current methods, although functional, need standardization, updating and technicalization to mitigate operational risks and reduce the execution times of these procedures.

2.3. Using UAS in PAPI light calibration

The history of unmanned aerial systems (UAS) dates back to the early days of military aviation. [24] The earliest records of unmanned aircraft date back to the use of hot air balloons to bombard Venice in 1849, and later during the American Civil War.

During World War I and II, there were several attempts to use UAS in aerial tactics, albeit with limited results [25].

The term UAS began to be used more frequently from the 2000s onwards, coinciding with the development and integration of complex systems accompanying unmanned aerial vehicles.

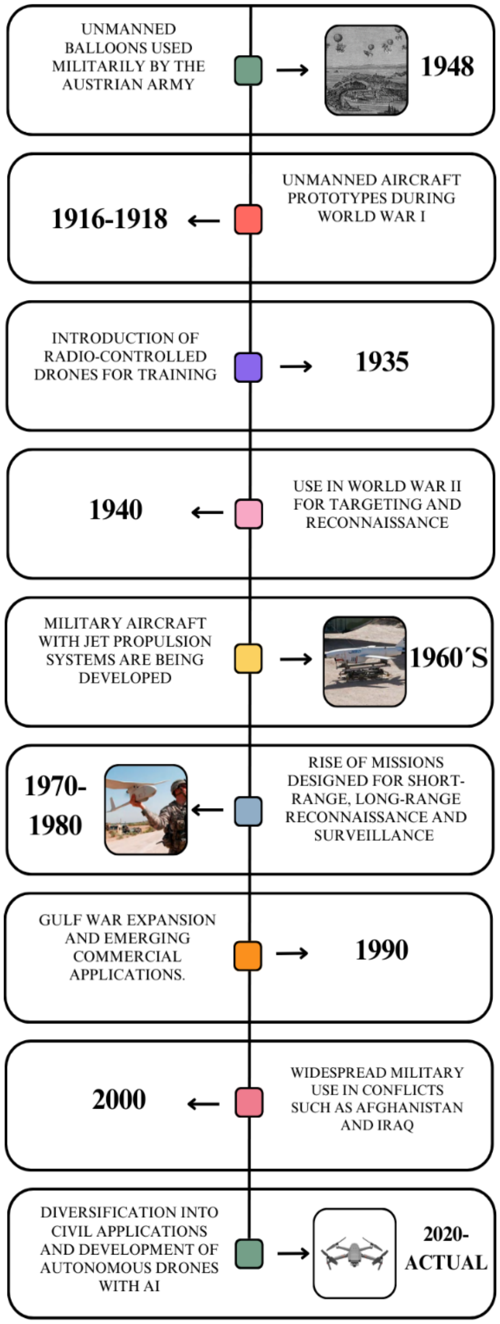


Fig. 3. *UAS Evolution*
Source: *Reuter, F., & Pedenovi, A. (2019). Los UAS y sus aplicaciones a la ingeniería. Facultad deficiencias forestales, 43.- Historia de los UAS. (2016, mayo 29). El UAS.* *http://elUAS.es/historia-de-los-UAS/*

Today, UAS are often considered to be autonomous or semi-autonomous aircraft that are remotely controlled and can replicate the maneuvers of human-piloted aircraft, but without the need for a pilot physically present on board. Most UAS in use today are controlled remotely by pilots located on the ground, either as part of a human-in-the-loop (HITL) system or with a pilot in control with limited autonomous functionality [26].

In a review context, it is essential to understand the essential components that make up an Unmanned Aircraft System (UAS) and their functional integration. Generally, a UAS is composed of several key elements as seen in Figure 4 [20].

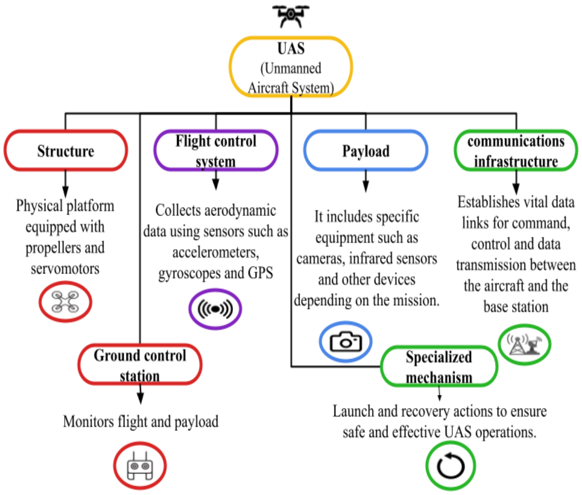


Fig. 4. *UAS Elements.*
Source: *S. Togola., Kiemde, SMA, & Kora, AD (2020). Real Time and Post-Processing Flight Inspection by UAS: A Survey. 2020 43rd International Conference on Telecommunications and Signal Processing (TSP), 399-402.https://doi.org/10.1109/TSP49548.2020.9163498*

In the age of remote engineering and automation, aerial inspection UAS have emerged as indispensable tools for the assessment and maintenance of a wide range of facilities and structures. Equipped with a variety of sensors, cameras, and imaging technologies, these unmanned aerial vehicles (UAVs) are capable of performing detailed inspections and troubleshooting in remote and hard-to-reach locations. From power lines to wind turbines, oil rigs to dams, aerial inspection UAS are transforming the way maintenance challenges are addressed on large-scale projects. This approach not only reduces operational costs by minimizing the need for human personnel on the ground, but also ensures a level of detailed inspection that meets the highest standards of safety and due diligence [27].

Unmanned units are ideal devices for patrolling large areas, so they can be used to protect property and guard state borders. They will also be able to take aerial photographs used for geodesy, archaeological purposes, advertising, etc. With their small dimensions and high maneuverability, they can fly between obstacles, buildings and even fly into rooms, through gates, windows and open doors. Models equipped with thermal and night vision cameras can be used as prospecting machines in rescue operations, with daily patrol of the chosen area and can operate 24 hours a day over wooded areas [28]. They transmit an image in real time allowing an immediate reaction from the relevant services in the event of an emergency, accident or crisis situation requiring intervention [29].

One of the main advantages of UAVs compared to traditional aircraft are the following: much lower fuel consumption, much lower design, manufacturing, maintenance and operation costs. They do not require pilots, they are generally small and manufacturing and material costs are very low; in case of collision they are very resistant, accidents with them being rare and without tragic consequences; they can operate several things without a pilot, without costs, without risks, with results superior to those of classic aviation [30].

Unmanned aircraft systems have proven to be much more efficient than traditional methods, such as flight laboratories, for the inspection of lighting systems at airports. Moreover, the use of these commercially available systems can lead to considerable cost savings in the long term, allowing for more efficient use of resources in this task. Inspections carried out with unmanned aircraft systems at the small uncontrolled Vysoké Mýto airport showed acceptable accuracy, confirming the accuracy and reliability of these systems in assessing airport lighting systems [28].

The use of Unmanned Aerial Vehicles (UAVs) offers significant benefits in several areas of flight inspection operations. These vehicles can effectively mitigate the risks associated with manned aircraft, reducing operational costs such as maintenance, fuel and overhead. By employing UAVs, the impact on air traffic during flight calibration is minimized, thereby improving operational efficiency. In addition, they decrease the workload for technical personnel and contribute to environmental conservation by reducing air pollution and noise. The integration of navigation aids into ground checks reduces human and system errors, improving aviation safety. Looking to the future, there is the potential for UAVs to influence the evolution of International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPs), supporting and expanding their role in flight inspection operations [31].

According to document 9157, a typical Unmanned Aircraft System (UAS) includes several essential components: an unmanned aircraft (UA), a control station or remote pilot station (RPS), a data link (C2 Link) between the UA and its control station/RPS to manage the flight, and possibly other elements such as launch and recovery equipment, as well as a ground processing unit to download the measurement data. To achieve high dimensional accuracy, a real-time kinematic (RTK) base station is required [15].

Using the UAS´s method for measuring Precision Visual Approach System (PAPI) angle adjustments requires a visible spectrum camera or sensor that is operationally validated for overall perceived image quality [15].

Camera sensing must be equivalent to that of the human eye, for example, with respect to angular resolution, dynamic light capability, and susceptibility to the frequency spectrum of PAPI LEDs [32].

It must also be able to hover in front of the PAPI system, making measurements and checks easier. This improves the accuracy of inspections.

The most ideal UAS for PAPI light inspection include multi-rotors and fixed-wing UAS. Multi-rotors are perfect for their ability to remain stable in the air, allowing them to carry heavy equipment and high-precision sensors. On the other hand, fixed-wing UAS are suitable for covering large areas thanks to their efficiency in long flights and over large areas.

According to Patent ES2687869A1, 2023, the aircraft in charge of these tasks can be an unmanned vehicle that has the ability to carry out detailed explorations both vertically and horizontally. Ideally, a UAS, also known as UAV, would be preferable due to its simple handling and its ability to adapt to different types of flights required. This vehicle can be controlled remotely from the ground, either by a human operator or by an automatic system, or it can fly autonomously [33].

2.3.1. Calibration procedure

In a standard operation, the UAS is placed at least 300 meters in front of the PAPI system. The vertical scanning performed by the UAS allows the operator to measure the heights h1 and h2, which represent the upper and lower limits of the red-to-white transition zone. Using this data, the angle of adjustment of the light unit can be calculated using a specific formula [15].

$$\theta = \tan^{-1}\frac{(h1 + h2)}{2d}$$

where:

h1, h2 are the upper and lower limits of the transition zone; and d is the horizontal distance from the AU to the PAPI.

The calibration process involves determining the pitch angle required for each unit of the PAPI system. This is achieved by identifying the altitude at which the transition from red to pink light occurs, and then from pink to white, and obtaining the corresponding angles for these altitudes. During this process, the aircraft can move in any direction to locate exactly where these transitions occur and thus determine their precise positions [33].

2.4. Practical applications

In the aviation industry, leveraging emerging technologies such as UAS is seen as crucial. These systems are not only more efficient and ergonomic, but also economically viable. Implementing these advances would not only ensure greater accuracy in the calibration of equipment such as PAPI lights, but would also contribute significantly to ICAO's strategic objectives, especially in terms of improving operational safety and the efficiency of the global air navigation system [34].

In particular, innovative alternatives to the traditional calibration method are being introduced, such as Canard UAS [35]. These UAS are specifically designed to assess and calibrate PAPI lights at airports. Equipped with high-resolution cameras and specialized sensors, these UAS can assess the intensity and alignment of PAPI lights from various angles and altitudes accurately and efficiently. The process involves flying the UAS along the runway approach path, recording essential data to ensure the correct configuration of the lights, which is crucial for safety during airport operations. Landing and takeoff [36] [37].

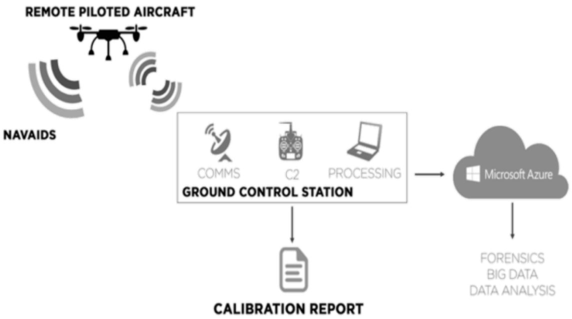


***Fig.** 5Canard UAS architecture.*
***Source:** Aeriaa. (2017). Canard UAS – Beyond a disruptive platform for safety.Aeriaa.https://aeriaa.com/canard-UAS-beyond-a-disruptive-platform-for-safety/*

In addition to PAPI light calibration, UAS are also used in the inspection of radio navigation aids, as described in the study by Horapong et al. (2017). These unmanned aerial systems allow for preliminary validation of radio navigation aids, reducing the need for actual flight inspections during ground-based facility maintenance. This not only saves time and financial costs, but also improves operational efficiency [41].

The benefits of using UAS (Unmanned Aerial Systems) in the inspection of air navigation facilities have also been highlighted by Barrado et al. (2013). Compared to traditional inspections using manned aircraft, the use of UAS offers a significant reduction in costs and the ability to carry out assessments even in adverse weather conditions. This approach underlines the potential of unmanned aircraft to improve efficiency and safety in the inspection of air navigation facilities, establishing itself as a promising alternative to conventional methods [42].

The UAS application research team [43] in China has been developing a leading and practical PAPI light inspection technology based on proven multi-rotor UAS and high-end imaging payload. This technology was proven through test flights at airports on both plains and plateaus. Its advantages were clearly demonstrated in terms of environmental benefits, safety, economy, efficiency and labor saving. Although there are still areas for improvement, UAS-based PAPI light inspection technology has great potential to benefit both flight inspection service providers and airports when applied correctly.

In collaboration between the Flight Control Unit (CEV) of the Department of Technology and Innovation (DTI) of the French DSNA (Directorate of Air Navigation Services) and the Defense Calibration Center (CCD), they developed the CAVOC method (Calibration of Visual Aids by Colorimetric Objectivity), which aims to measure the elevation angle of the PAPI lights, according to the report [48] it is a measurement system that is easy and quick to implement (general installation), allowing a reduction in runway occupancy time (time required to install the 4 PAPI units estimated at 20 minutes) [40].

The comparison of PAPI light calibration using UAS versus traditional methods reveals notable advantages in several critical aspects. UAS equipped with high-resolution cameras and specialized sensors provide superior accuracy and a more consistent assessment of PAPI light intensity and alignment from multiple angles and altitudes. This not only improves calibration quality, but also increases operational efficiency by significantly reducing the time and costs associated with inspections. Furthermore, the flexibility and accessibility of UAS [38] allow these tasks to be performed in adverse conditions and difficult-to-access areas, optimizing safety and regulatory compliance without disrupting airport operations. Taken together, the adoption of UAS for PAPI light calibration represents a significant improvement in terms of accuracy, efficiency, and costs, positioning itself as an advanced and effective alternative in the management of air navigation facilities [39].

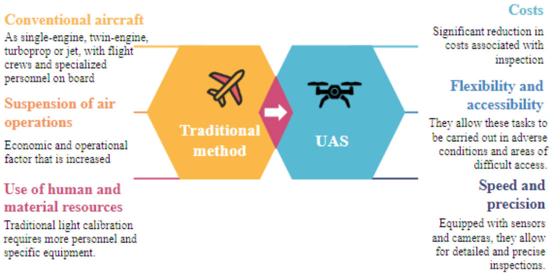


Fig. 6: *Comparative advantages of UAS over the traditional PAPI light calibration method*
Source: *Own elaboration*

2.5. Regulations

The use of UAS such as maintenance and calibration of PAPI lights is essential to ensure operational safety at airports and the surrounding airspace, therefore, the regulations governing these aspects play a fundamental role.

The Civil Airworthiness Regulation (RAC) constitutes the legal framework that regulates the airworthiness of aircraft registered in our country, in order to guarantee operational safety, structural integrity and the correct operation of on-board systems. The RAC 100 [45] regulation on the operation of Unmanned Aircraft Systems (UAS) establishes aspects such as airworthiness certification, technical requirements for aircraft and equipment, risk management and operational safety, staff training, regulatory compliance and audits, as well as continuous monitoring and improvement of the operational safety system. Its main objective is to ensure that aircraft comply with the established safety standards to protect the life and integrity of people on board and on the ground.

Likewise, the RACAE 210 Standard [46], also known as "Requirements for Remotely Piloted Aircraft (RPAS) Operations", establishes the requirements and procedures for the safe and legal operation of remotely piloted aircraft (RPAS) in Colombian airspace. In summary, this regulation defines the technical requirements for the aircraft, the operating procedures, the training and certification of personnel, the required documentation, the flight restrictions and the security measures necessary to protect the integrity of people and property on the ground. Its main objective is to regulate the use of RPAS to guarantee operational safety and the protection of Colombian airspace.

Similarly, the Colombian Civil Aeronautics establishes the provisions for the registration and operation of unmanned aerial systems (UAS) in Colombia through resolution 4201 of December 27, 2018 [47]. This resolution defines the requirements for the registration of UAS, the certification of pilots, the permitted operating zones, flight restrictions, and sanctions for non-compliance. It also establishes measures to guarantee operational safety and the protection of privacy and public safety during the use of UAS in Colombian airspace.

Compliance with PAPI (Precision Approach Path Indicator) lights is essential to ensure safety and precision in aircraft approach and landing operations. PAPI lights provide crucial visual guidance to pilots, ensuring they maintain the correct approach path, and must therefore comply with operational safety and air navigation standards set by civil aviation authorities.

As regards the regulations governing PAPI lights, it is important to mention ICAO Doc 9157 [15], also known as the Aerodrome Design Manual, which is a publication of the International Civil Aviation Organization (ICAO) that provides detailed guidelines for the design and planning of aerodromes. In summary, this manual addresses a wide range of topics related to aerodrome design, including site selection, runway and taxiway geometry, lighting, drainage systems, visual signals and markers, planning of the surrounding airspace, and operational safety procedures. The objective of the document is to provide planners, designers and civil aviation authorities with the necessary tools to develop and maintain aerodromes that meet safety and efficiency standards.

The International Civil Aviation Organization (ICAO) "Manual on Testing of Radio Navigation Aids, Volume I (Doc 8071)" [18] provides detailed guidelines and procedures for testing and testing radio navigation aids systems used in air navigation. From technical definitions to general standards and specific procedures for testing different types of radio navigation aids such as VOR, ILS, DME and NDB, this manual comprehensively addresses all stages of the testing process. In addition, it provides guidelines on documentation and reporting to ensure clarity and accuracy in communicating results. In summary, the manual sets standards to ensure the accuracy and reliability of radio navigation aids, thus contributing to the safety and efficiency of air navigation.

2.6. Technical challenges

Some of the challenges that may arise along the way are: the possible difference in color changes detected between the camera and the human eye. This can lead to biases in the final PAPI assessment. This leads us to two further directions: investigating the difference and how to correct it, establishing a reasonable tolerance when using camera-based technology.

Similarly, Togola et al., 2020 discusses the environmental impacts of UAS as aerial inspection using UAS is changing the landscape in terms of energy consumption and greenhouse gas emissions compared to traditional fuels such as diesel and gasoline. Despite being a cleaner option, UAS are not exempt from significant environmental impacts. From the environmental footprint of the energy sources used to charge them, which varies by region and can include everything from natural gas to electricity, to the effects derived from the manufacturing and extraction of materials for the lithium-ion batteries that power most civil UAS, each phase of the life cycle of these devices has important environmental implications [20].

Electric UAS, while promising in terms of reducing direct emissions, face inherent challenges, especially regarding the energy required for their manufacture and operation. Lithium-ion batteries, essential for UAS' autonomy and flight efficiency, are associated with the exploitation of natural resources and high energy consumption during their production. This underlines the importance of comprehensively assessing the environmental impacts of UAS, not only during their active use, but throughout their entire life cycle [20].

2.7. Future directions and innovations

To envision a future where inspection procedures are more efficient and sustainable, it is essential to explore emerging technological trends and priority areas for research and development. Innovations such as advances in high-precision sensors, the development of artificial intelligence-based image processing algorithms, and improved autonomy and energy efficiency of UAS are critical to optimizing the accuracy and reliability of measurements during calibration operations. Furthermore, areas of future research include the integration of faster and more secure communication technologies, the design of systems robust against electromagnetic interference, and the exploration of adaptive and automatic calibration methods that reduce human intervention and maximize accuracy. These advances not only improve the effectiveness of calibration operations, but also pave the way for broader applications in fields such as precision agriculture, environmental monitoring, and critical infrastructure management [48].

3. CONCLUSIONS

For all the above, calibration is necessary to ensure the accuracy of these lights, following international ICAO standards. Traditional methods, such as in-flight inspection by manned aircraft, are costly, time-consuming and can disrupt airport operations, facing challenges due to meteorological and topographical conditions. Instead, UAS offer significant advantages, such as cost reduction, increased safety, speed and accuracy in calibration. Equipped with sensors and cameras, UAS allow for detailed and precise inspections, even in difficult conditions. In addition, UAS can patrol large areas, take aerial photographs and participate in rescue operations. In conclusion, the use of UAS significantly improves the calibration of air navigation aid systems, representing an efficient and safe alternative to traditional methods, with emerging trends and research areas that can further optimize this process.

It is important to note that although the current procedure is at a basic stage, with the help of new technologies it can be made much more efficient, reducing interaction with personnel to a minimum. This will allow calibration to be carried out in an automated manner, not just as a mere requirement, but also providing updated parameters that reflect the real state of air safety elements at airports and airfields, regardless of their size and location. In addition, this automation will contribute to greater accuracy and consistency in measurements, optimizing response times and facilitating the identification and correction of possible deviations in the system while minimizing human error. Ultimately, the integration of these advanced technologies will ensure that air operations are carried out with the highest standards of safety and efficiency, quickly adapting to the changes and needs of the operating environment.

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