Airworthiness Process Applied to the Portuguese Remotely Piloted Aircraft Systems

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ABSTRACT

The focus of the Research, Development and Innovation Centre of Portuguese Air Force (CIDIFA) in recent years has been on projects involving Remotely Piloted Aircrafts Systems (RPAS) because of its extensive experience in the development and manufacture of RPAS of Class I. The experience and knowledge accumulated over years in this type of aircraft was transferred to larger aircrafts which are required to be subject to an airworthiness certification process prior to its operation. Due to the absence of a consensual regulatory framework in Europe for certification of RPAS, the regulations applied to manned aircrafts are currently adapted for unmanned aircrafts.

This paper shows the result of the work within the safety assessment, the reliability and the development of the initial maintenance plan of the RPAS manufactured and operated under CIDIFA projects. When developing a new system such as RPAS, there is a lack of information. To overcome this difficulty in development of the initial maintenance plan for this new system, it was settled a methodology based on Morphological Analysis which allowed the determination of the reference failure rates, used to determine the maintenance tasks and intervals through the MSG-3 methodology. It will be presented the methodologies employed to carry out the safety assessment of the RPAS ANTEX (SAE ARP 4761), as well as the tools (FMECA) used to evaluate and classify the identified risks.

The results obtained allowed to identify and define the critical areas and the mitigations actions, that after being implemented allowed to ensure an acceptable level of risk of operations, and continued airworthiness of the RPAS ANTEX systems through the development of the initial maintenance plan within the Regulators.

1.0 INTRODUCTION

The beginning of RPAS activity within the Portuguese Air Force dates to 2009 at the start of the Research and Technology Project in Unmanned Autonomous Aerial Vehicles (PITVANT) of CIDIFA. This project focused primarily on the development of new technologies and new concepts of operation with small remotely piloted aircraft systems, aiming the later transference to larger ones [1]. The entities responsible for the development of the PITVANT project were the Air Force Academy (AFA) and the Faculty of Engineering of University of Porto (FEUP). AFA expertise is in the project area, optimization, and production of remotely piloted aircraft, and FEUP holds the technological knowledge and operational experience in the control of autonomous vehicles [1].

The PITVANT project stood out in the development of several technological areas, namely [1]: i) the design, manufacture and testing of small and medium sized platforms; ii) the cooperative control of several vehicles with mixed initiative; iii) systems interoperability; iv) advanced vision systems, v) data fusion and vi) navigation systems. The objectives of the different areas of this project were achieved through the development of three platforms from two different classes of RPAS for application, testing and demonstration of technologies. The platforms used were: micro-RPAS (weight to 1 kilogram and with a wingspan of 1 meter), ANTEX-X02 (weight from 15 to 25 kilograms and 3 meters wide) and ANTEX - X03 (weight of 110 kilograms and 6 meters wide) [1]. These platforms have been subjected to an extensive testing program encompassing several laboratory tests, demonstrations and evaluations of the employed technologies used in the developed concepts of military operations. Since then, several projects were developed involving RPAS, namely: PERSEUS, SEAGULL, TROANTE and SUNNY.

2.0 CERTIFICATION AND REGULATIONS

In the aeronautic industry, due to the restricted safety requirements there is the need to promote at international level of common standards and rules through the establishment of appropriate cooperation with third parties and international organizations [2]. It should be ensured in aviation, on a permanent basis, a high uniform level of safety to people and operations through the adoption of common standards, safety and environmental protection measures that ensure that products, people and organizations in this sector comply with them [2]. All aircraft, as well as all products, equipment and parts installed must have a type certificate [3]. Similarly, the organizations responsible for the maintenance of products, equipment and parts shall demonstrate their capability and means to perform the tasks related and these capabilities and means shall be recognized through the issuance of a certificate of organization [3]. At present, there isn’t a regulatory framework for RPAS, like the framework that exists for other systems operating in the aeronautical sector.

In 2005, the North Atlantic Treaty Organization (NATO) established the Joint Capability Working Group on UAV (JCGUAV) that is organized into several subgroups and activities. One of the subgroups is the Flight in Non-Segregated Airspace (FINAS), which involves specialists responsible for the definition of airworthiness requirements for RPAS. The most important work of this group was the approval of the first draft of STANAG 4671 dedicated to Unmanned Aerial Vehicles Systems Airworthiness Requirements (USAR) [4]. This publication is applied to all fixed wing systems with a maximum take-off mass of 150 kilograms to 20000 kilograms and was ratified by several member states of NATO, including Portugal. More recently was developed the STANAG 4703 dedicated to the RPAS with "maximum take-off weight" less than 150 kilograms, lying at this moment in the ratification stage. Table 1 shows the RPAS Classification according to the NATO guidelines.

Table 1: RPAS Classification (Adapted from [5]).

Classes (NATO Classification)	Groups (UK CAA Classification)	Mass (kg)	Civil	Military	Civil Authority	Military Authority
Class I (Mass < 150 kg)	1	< 20	Small RPAS	Micro (< 2 kg) Mini (2-20 kg)	National	NA
	2	20-150	Light RPAS	Small	National	NATO
Class II (Mass 150-600 kg)	3	150	RPAS	Tactical	EASA State Aircrafts: National	
Class III (Mass > 600 kg)	3	> 600	RPAS	Strike/Combat Hale/Male	--------	

In 2008, under the aegis of the European Defense Agency (EDA) it was created the European Military Airworthiness Authorities (MAWA) forum, with the purpose of harmonizing a regulatory framework for military airworthiness certification in the European states [6]. The airworthiness certification process integrates both military and civilian RPAS into national airspace demands, and certain requirements must be fulfilled during the development, manufacture and operation of RPAS to demonstrate an Equivalent Level of Safety (ELOS) similar to the existing for manned aircraft, prior to the operation into non-segregated airspace [7].

In Portugal, the responsibility to regulate civilian RPAS weighting less than 150 kilograms belongs to the National Civil Aviation Authority (ANAC), and for those who are employed in military and police assignments responsibility belongs to the National Aviation Authority (NAA). NAA is the entity responsible for the regulation, inspection and supervision of the aeronautics activities within the scope of military assignments [8]. Figure 1 illustrates the process of certification of civilian and military RPAS in Portugal.

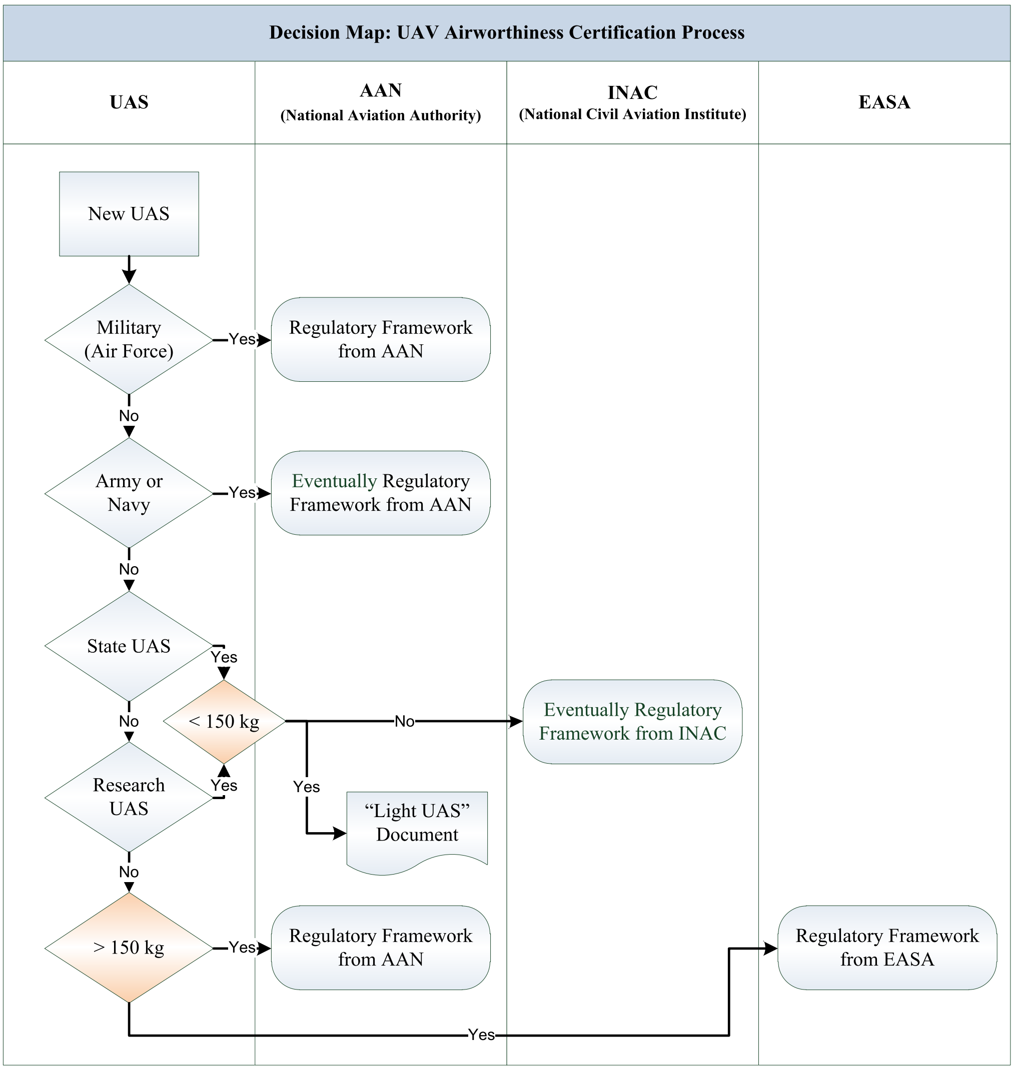

Figure 1 – Flowchart of RPAS Airworthiness Certification Process in Portugal. (Adapted from [9])

The initial maintenance plan methodology developed by CIDIFA fulfilled the requirement established (showed below) by the NAA within the certification procedure. This procedure was implemented through Circular 1/2013, and defines the requirements for issuance of Special Airworthiness Permits (LEA), Permit to Fly, for RPAS operation within National Defense purposes [10]. This license is a document in which the NAA certifies that the RPAS operation complies with certain requirements. The issuance of LEA for a RPAS requires compliance with the following minimum requirements [10]:

(1) RPAS registration at NAA;
(2) Airspace reservation by the entity responsible for the RPAS operation;
(3) Request for issuance of LEA stating the scope or purpose of the flight, duration and location (by the entity responsible for the RPAS operation);
(4) Evidences of existence of RPAS configuration control;
(5) Evidences of existence of historical record from RPAS operation;
(6) Evidences of RPAS technical operating instructions;
(7) Evidences that operation risk or safety analysis were developed;
(8) Evidences that the Continued Airworthiness Instructions were developed.
(9) Evidence of qualifications for the persons responsible to operate and maintain the RPAS;
(10) Evidence of existence of a system to report any accident or incident to NAA.

Currently in Portugal there isn’t a regulatory framework to obtain a Type Certificate, being only issued a Permit to Fly through LEAs [10]. Nevertheless, the implemented procedure requires evidences of development of Continued Airworthiness Instructions, usually materialized among other things in a safety assessment process and maintenance plans. In general, to issue a LEA for platforms with maximum take-off weight up to 25 kilograms, it must simply comply with the requirements defined at Circular 1/2013 of the NAA. However, for platforms with maximum take-off weight greater than 25 kilograms, it is also necessary to establish the certification basis within the STANAG 4703, together with the NAA [10].

3.0 SAFETY ASSESSMENT PROCESS

The Safety Assessment Process is often used to develop and verify the requirements on the design of aircrafts, providing an evaluation of their functions and systems responsible for safety functions. The safety assessment of the RPAS includes more aspects than the aircraft by itself. It should also consider: the ground control station, the data links, the mission planning and type, the autonomy level, the operation environment and flight conditions and the interoperability with ATC and other aircrafts [11]. Safety assessment, which is mostly qualitative, can also be quantitative through a process that encompasses [11]:

- A Functional Hazard Assessment (FHA) – Aircraft functions analysis that allows to identify and classify the potential functional failure conditions according to their severity;
- A Preliminary System Safety Assessment (PSSA) – Systematic evaluation of systems architecture in accordance to its implementation and based on the FHA and classification of failure conditions to verify items’ requirements;
- A System Safety Assessment (SSA) – Systematic evaluation of all systems to verify that the main safety requirements are met.

Several airworthiness military standards (e.g. STANAG 4671, STANAG 4702 and STANAG 4703) indicate the requirements related to safety assessment of RPAS operations in non-segregated airspace. Due to the Maximum Take-off Weight (MTOW), the RPAS ANTEX should comply with Circular 1/2013 and some STANAG 4703 requirements. Based on the results obtained in the RPAS ANTEX Functional Hazardous Assessment, it was developed the PSSA to determine how failures originate the functional risks identified in the RPAS ANTEX FHA, and how the derived requirements could be fulfilled.

The RPAS ANTEX Preliminary System Safety Assessment followed the bellow methodology [4]:

I. Development of a complete list of aircraft and system safety requirements;
II. Assessment whether the RPAS ANTEX system architecture, and the planned design concept, can reasonably be expected to meet the safety requirements and objectives;
III. Derivation of the design safety requirements for: lower level items (hardware and software); aircraft installation, other systems and operations (flight and maintenance tasks).

Thus, in the scope of the safety assessment, the derived operational and safety requirements were listed, and was determined the internal architecture of RPAS ANTEX (Figure 2), which lacks redundant systems.

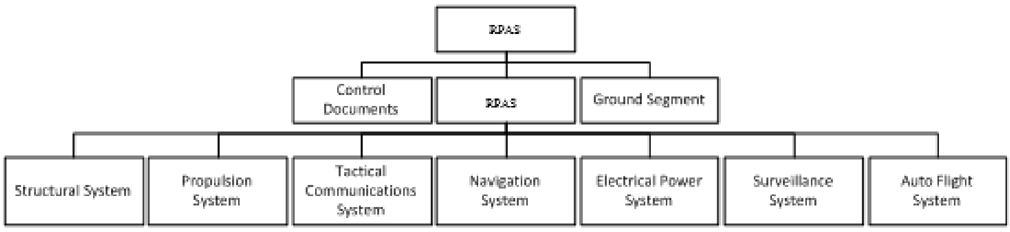

Figure 2: Internal architecture of RPAS ANTEX (adapted from [12]).

The methodology proceeded to the development of Systems Safety Assessment where for each identified system it was allocated their safety requirements and installation, as well as the maintenance tasks that will ensure the preservation of safety conditions. By the conclusion of the Systems Safety Assessment it was possible:

- To verify that the design requirements established in the System Level FHA were met;
- To adjust and validate the classification established for the RPAS failure effects;
- To verify that the safety requirements derived from RPAS for the internal architecture were met.

Performing the Safety Assessment of RPAS ANTEX allowed to demonstrate that, despite possessing an internal architecture with no redundant systems, it complied with the minimum safety requirements defined in STANAG 4703 to operate in segregated airspace [13].

4.0 METHODOLOGY BASED ON MORPHOLOGICAL ANALYSIS

The RPAS ANTEX is an aircraft whose primary mission is the Reconnaissance and Surveillance. It had to undergo an airworthiness certification process before entering service, which included among other things the development of an initial maintenance plan. To do so, it was necessary to know or estimate the failure rates of the systems and components of RPAS ANTEX. However, the development and manufacture of this type of aircraft is very recent in Portugal, and there is insufficient information available related to failure modes or other reliability parameters to develop the initial maintenance plan.

Due to the lack of data available for these systems, associated to the need to certify them, it was developed a method to establish the initial maintenance plan of RPAS ANTEX based on the Morphological Analysis and MSG-3 methodologies, as shown in Figure 3.

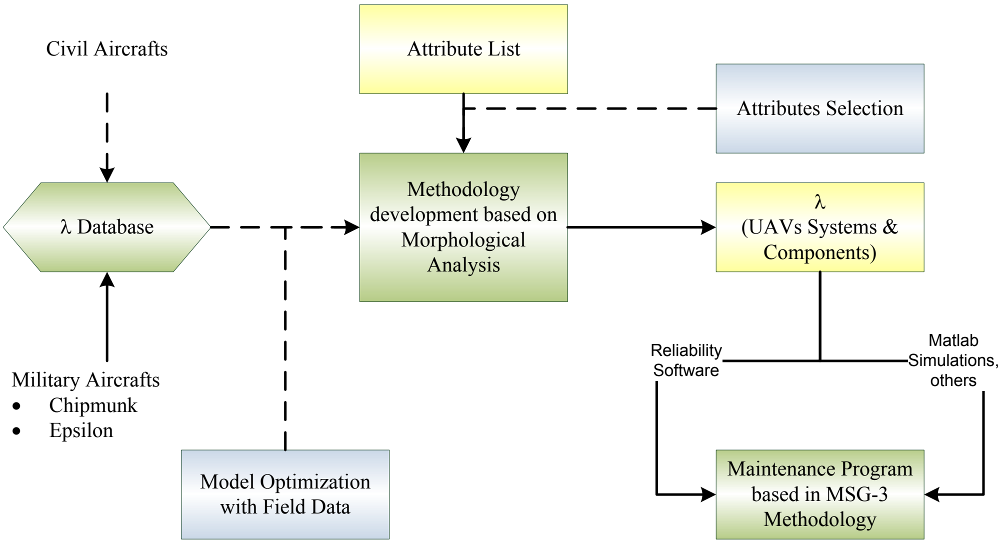

Figure 3: Methodology based on Morphological Analysis to develop the Initial Maintenance Plan.

The Morphological Analysis was used for the determination of initial failure rate for new equipment, as presented by Andrews and Moss [14]. The Morphological Analysis is applied for forecasting new products and services by defining firstly, the critical functions, and then indicating alternative methods to comply with each of these functions. This method is valid whenever there are similar products and services, and is very useful when there is a lack of data available [15]. According to Ayres [16] the Morphological Analysis is a powerful method to synthesize systems in several areas, which would result in a hierarchical framework of systems, separating all the components, functions and attributes of systems in the analysis. According to Ritchey [17] the Morphological Analysis is the method for investigating and identifying the set of configurations and interfaces associated with a given complex problem.

Generically, this analysis includes the identification of similar equipment where failure rate is known and the comparison and quantification of design, operational and environmental conditions, in order to determine the average stress factor of the project, to be applied to the reference failure rate. According to Andrews and Moss [14], to obtain failure data from new systems first of all it must be considered the information published in books or reliability databases. However, for critical assets to safety or production such data could not provide sufficient confidence in the validity of the prediction on failure characteristic the forecasts carried out through generic databases must be adjusted to specific conditions under which the system is expected to operate. The recommended model for estimating the failure rate is based on the following expression [18]:

$$\lambda_{XA} = \lambda_b \alpha_A \prod k_i \qquad (1)$$

Where λ_{XA} is the estimated failure rate of the system X due to failure mode A, λ_b is the failure rate of the known similar system, α_A is the failure portion from mode A, and k_i is stress factor from stress i. Morphological Analysis, as a method of forecasting the failure rate of new equipment and systems, it incorporates the fundamentals of DOE (Design, Operation and Environment). DOE model is based on research and demonstrated that the failure rates from samples of similar control equipment operating at different conditions had a high range of values. There is typically a ratio of 1:10 between the highest and the lowest registered failure rate. The DOE model uses simple linguistic variables such as: high (H), moderate (M) and low (L) having the weighting coefficients (-1), (0) and (+1), respectively. These coefficients are combined into the expected attributes of design, operation and environment, in order to estimate the average weighted (X), which is used as an exponent in the expression for determining the modified factor “k” [19]:

$$k = 2^{X} \tag{2}$$

Where X is the average value of the weights of design, operation and environment attributes.

The allocation of the weights and the determination of the modified “k” factor were performed, and based on them it was possible to establish the development of the initial maintenance plan following the MSG-3 methodology, with determined reference failure rates. The internal architecture, allied with operational and safety requirements, guided the search for systems (equipment) which perform the identified functions of the RPAS. Thus, the systems with known reliability data that enabled the execution of the morphological analysis were identified. The Portuguese Air Force comprises several aircrafts, which in its internal architecture integrates some of the systems that are present in the RPAS ANTEX and for whom there are failure records on the Air Force Integrated Management Support (SIAGFA). For this reason it was chosen failure data from CHIPMUNK MK20 aircraft to develop the RPAS initial maintenance plan. This decision was based on:

- The similarity of operational and environmental conditions to which the aircrafts are subject, which are preponderant factors in the systems failure modes;
- The physical proximity of the research center with the Air Base, where these aircrafts are headquartered.

The data collection process through SIAGFA included the analysis of data related to five CHIPMUNK MK20 aircraft currently in the fleet, and involved the analysis of records on the period from 2005 to 2014, resulting in a total of 7528 work cards. Detailed analysis of the data collected allowed to exclude all work cards related to maintenance actions corresponding to scheduled maintenance tasks, and all work cards related to failures in systems that did not exist in the internal architecture of the RPAS. To determine the initial failure rate of the systems it was considered all failures of similar system. It resulted in the identification of 47 different failure modes, distributed by several systems. Similar analysis was carried out for aircraft systems, identifying those having the greatest influence on the overall reliability of the aircraft, as presented in Figures 4 and 5. The results obtained allowed to foresee which would be the RPAS systems that would be critical, as well as made possible the knowledge of the failure modes to which the systems will be subject in operation.

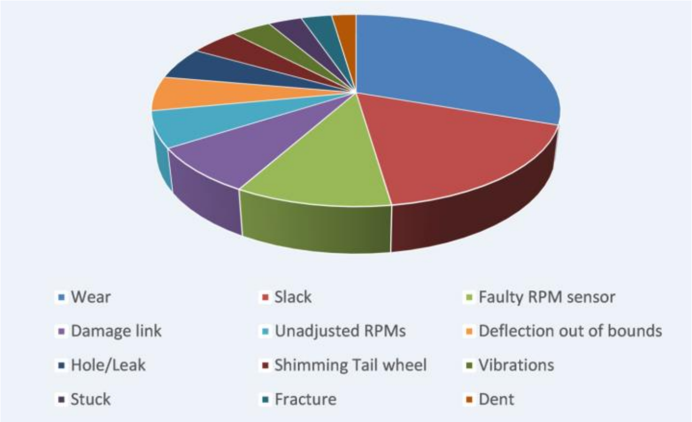

Figure 4: Failure Mode frequency analysis.

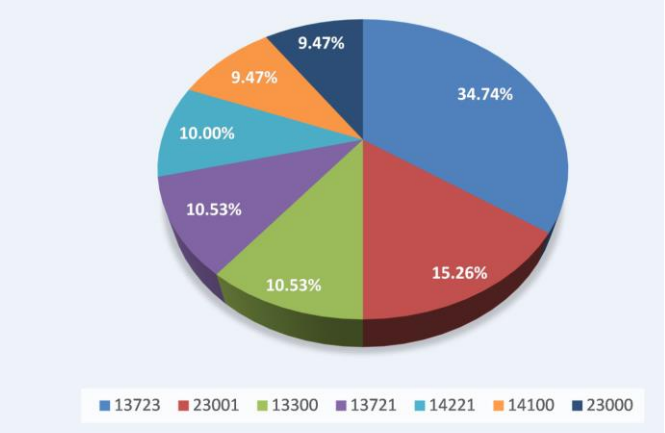

Figure 5: Work Unit Code frequency analysis.

5.0 ANALYSIS MAINTENANCE REQUIREMENTS

Reliability programs are a very valuable mean to achieve better operational performance (through reduction of the maintenance related problems in-service) and increase the flight safety [20]. In aviation is emphasized the use of the Maintenance Steering Group (MSG-3) methodology for development the initial maintenance plans. Thus, it ensures a standardized scheduled maintenance plan, and complies to minimum requirements established by regulatory authorities for instructions for continued airworthiness, as shown in Figure 6.

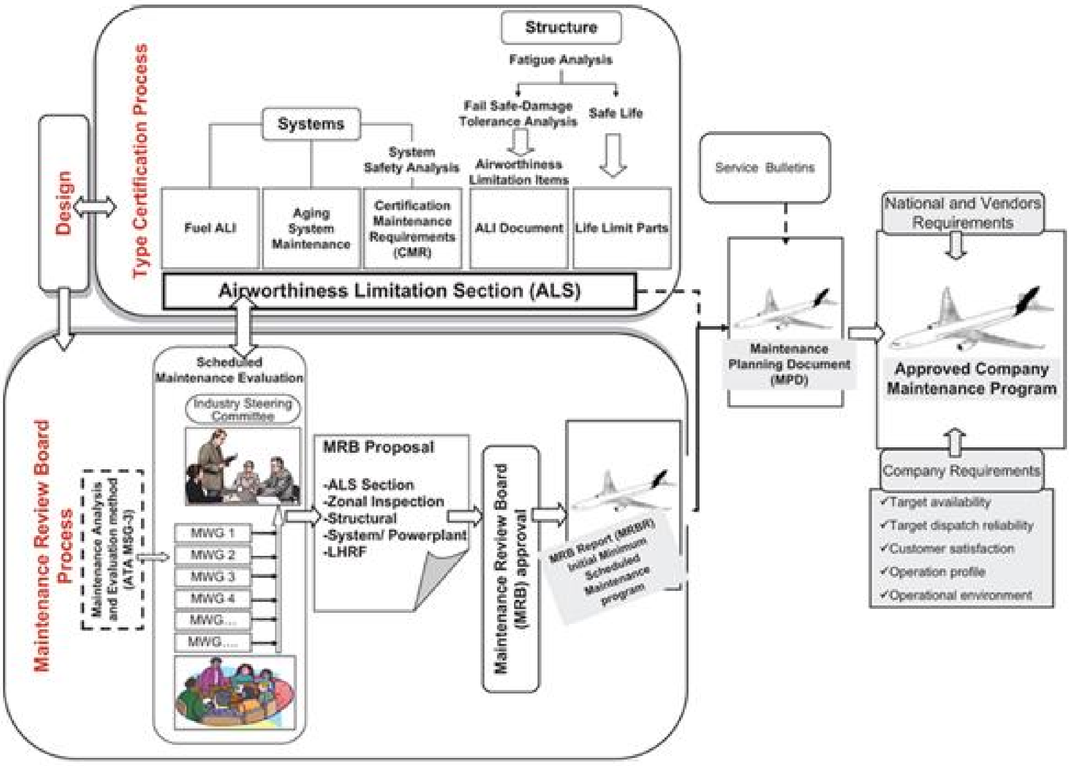

Figure 6: Maintenance Plan Development Process through the MSG-3 methodology (Adapted from [21]).

The MSG-3 describes the general organization and the decision process to determine the requirements for scheduled maintenance initially designed to preserve the life of the aircraft and its systems, in order to maintain inherent levels of safety and reliability. This methodology divides its analysis and recommended procedures into: Aircraft Systems and Engine, Aircraft Structures and Zonal Inspections. According to Air Transport Association (ATA) the objectives of an effective scheduled maintenance of aircraft include [22]:

- Ensuring the levels of inherent safety and reliability of the aircraft;
- Restore the safety and reliability to their inherent levels when their degradation occurs;
- Get the information needed to improve the design of items whose inherent reliability proves inadequate;
- Achieving the purposes at the minimum total cost, including maintenance costs.

These objectives are materialized by conducting different analysis comprising several steps on systems, structures and zones of the aircraft. The MSG-3 methodology applied to aircraft systems consists in several steps, including [22]:

1. Selection of Maintenance Significant Items (MSI);
2. The analysis process of MSI (identification of functions, functional failures, failure effects, and failure causes);
3. Selection of maintenance actions using a decision logic, which includes:
    - Evaluation of the consequences of failure;
    - The selection of the task(s) in accordance with the result of a failure.

The implementation of MSG-3 methodology to aircraft systems and components was done using a set of questions designed to determine if the item's function is critical. The questions determine whether the loss of function (failure) has impacts on safety, operation or economics, and whenever a response to any of the questions were positive, the item was considered critical. The analysis of the Functional Failures determines the category of each item failure effect. In other words, it allowed the knowledge of the impact on safety, operation and economics, and the classification in terms of safety and whether the failure is evident or hidden to the RPAS crew. There are five categories of failure effect: Evident Safety, Operational Evident, Evident Economic, Hidden Safety and Hidden Non-safety. The Failure Cause analysis permitted the selection of the type of maintenance tasks. At this point it was also defined the concept of fault tolerant system, such as systems comprising redundant components that may fail without affecting the safety or the operational capability, and for those weren't required forward analysis. The maintenance tasks resulting from safety, operation and economic criteria are Lubrication or Servicing, Operational or Visual Check, Inspection or Functional Check, Restoration, Discard or a task combination [22]. Further were established the parameters for determining the scheduled maintenance tasks intervals, which should consider the information the technical analysis, testing, manufacturer's recommendations, customer or operator requirements, field experience in operation of similar subsystems or compatible equipment and on "best engineering judgments"[22]. The maintenance task intervals defined were on a calendar basis, flight hours and flight cycles.

The MSG-3 methodology applied to aircraft structures also consists of several steps, the first was the classification of all aircraft structural components as: critical structures (Structure Significant Item - SSI), which may be classified as main structural elements (Principal Structure Element - PSE), or as other structures (Other Structure) [22]. The aircraft structures include: the wings, the fuselage, the vertical empennage, the engines mounts, the landing gear, the flight control surfaces and all connection points [22].

In addition to the previous classification, the structures were also evaluated for applicability and effectiveness of different methods to prevent, control and detect structural damage or degradation: Fail-Safe structure, Safe Life structure, metallic and non-metallic structures, as well as the materials in which they are manufactured [22]. The structures designated as Fail-Safe are damage tolerant, and they are able to withstand the damage ensuring that the remaining structures reasonably support the loads application until the damage is detected at next scheduled maintenance or inspection defined in the maintenance program [22]. The structures designated as Safe Life are structures where it isn't feasible to develop a maintenance program. Its reliability is ensured by replacing the components before the expected appearance of cracks. The non-metallic structures were analysed in terms of effects as: Accidental Damage (AD), Environmental Degradation (ED), Fatigue Damage (FD) and Aging Deterioration. However, metal structures should be analysed for Accidental Damage, and Environmental Degradation, caused by corrosion [21]. The maintenance tasks or techniques applied to structures were: General Visual Inspection (GVI); Detailed Inspection (DET), and Special Detailed Inspection (SDI). The decision logic of this method considers the location and the size of the damage, the inspection type, and the accessibility [22]. The structures designated as "Other Structures" were analysed in a different analysis, and were the basis to the zonal inspection program.

The analysis procedure for aircraft zones according to MSG-3 methodology allowed the determination of the inspections zones, and it was preceded by the systems and structure analysis. The MSG-3 methodology applied to aircraft zones implied the following logical sequence for developing the inspection zone program [22]:

- Aircraft breakdown in internal and external zones;
- Identification for each zone: the location, access, size, types of systems and components installed;
- Determination of zone inspection intervals, through development of classification tables from likelihood of damage versus density of equipment installed;
- Identification of zones that contain both electrical wires and potential combustible materials;
- Zonal analysis to determine the inspections and maintenance tasks which mitigate the potential damages identified.

The maintenance tasks used in the zonal inspection program were: General Visual Inspection (GVI), Detailed Inspection (DET), Restoration (RST) and Functional Check (FNC). The maintenance task intervals of zonal inspection programs are based on the equipment susceptibility to damage, the volume of work in the zone and the operator and manufacturer experience on similar systems or structures. The inspection frequency is inversely proportional to the need of accesses, in other words, the greater the need for accesses, the lower must be the frequency of inspection [22]. The tasks developed, as well as their intervals provided the basis for the development of the initial maintenance plan. With the increase of operational experience, further adjustments may be carried out in order to optimize the scheduled maintenance.

6.0 CONCLUSIONS

The extensive employment of RPAS in several business areas caused a tremendous evolution in the aeronautical sector. However, this leads to several safety related issues arising from the inherent specificities of operations from this type of aircraft.

The RPAS ANTEX had to comply with the requirements defined in STANAG 4703, and thus a Safety Assessment process was conducted. Through the development of Functional Hazard Assessment and Preliminary System Safety Assessment it was possible to identify the functions that the RPAS ANTEX would have to perform, and evaluate their failure conditions and the associated operational effects. These assessments resulted in the identification of operational and safety requirements for the operation of the RPAS ANTEX, as well as the development of the internal systems architecture. Each system was analysed, and their functional failures and their effects were evaluated in terms of severity. The analysis resulted in the development and implementation of mitigation actions and processes, as well as the development of maintenance tasks that ensure the preservation of the required safety level on RPAS ANTEX operations. The execution of RPAS ANTEX Safety Assessment allowed to demonstrate that despite possessing an internal architecture lacking redundant systems, it was possible to comply with the minimum safety requirements defined in STANAG 4703 to operate in segregated airspace.

Several difficulties were experienced due to the lack of data to perform systems reliability analysis for further development of RPAS ANTEX Initial Maintenance Plan required by NAA. It was decided to use the MSG-3 methodology to develop the Initial Maintenance Plan, because it is widely employed in aeronautic industry to ensure the compliance with safety requirements in the airworthiness certification process. However, the MSG-3 methodology requires the knowledge of items failure rate. So, to overcome this problem, it was developed a methodology based on Morphological Analysis allowing the determination of failure rates based on similar known systems.

This methodology was implemented in Portugal under the PITVANT research project. Improvements were introduced in accordance to new qualitative and quantitative data that were collected from the operational field. All the experience and know-how are currently applied in the various RPAS in operation under the framework of different projects, namely: the SUNNY Project, the TROANTE Project and the RPASMAR Project.

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