MANAGING THE RELIABILITY OF UNMANNED AERIAL SYSTEM

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Abstract. *This paper presents a reliability management system and how it can be applied to Unmanned Aerial System (UAS) over its life cicle, from the elaboration of the UAS specification up to field operation. Reliability is one of the most important aspects for the UAS design because reliability underlies UAS affordability, availability, and acceptance, as well as potential savings by reducing maintenance costs, and increasing safety involving UAS mission. In this paper, a research on main requirements, analysis methods, tools, and good practices applied to managing the reliability over the UAS' life time are considerated, taking into account practical and scientific aspects such reliability metrics, fault classification, fault prediction and removal, as well as FTA, FMEA, FRACAS, and Reliabililty Growth are considerated too.*

Keywords*: Reliability Engineering; Unmanned Aerial System; Fault Analysis; Fault Detection, Isolation and Correction; Reliability Management*

1. INTRODUCTION

The development of successful Unmanned Aerial System (UAS) is linked with the ability to reach longings and desires of many military forces (army, navy, and air force) of big nations that operate UAS in a wide variety of mission profiles, as well as of numerous university research groups around the world that use UAS as test-beds. Several features compose these longings and desires, being that a group of features carries in a deep look of the entire UAS' life cycle and not only in research, design and manufacture, but also flight test and maintenance phase. This group embraces Reliability, Availability and Safety.

The following paper intends to present some directives about reliability management system for UAS, defining the importance of studying the UAS reliability, and answering questions such as why to manage the reliability of UAS, what should be managed over UAS' lifetime, what management tools are relevant to UAS and how they can be implemented in each life cycle phase of an UAS, as well as some practical solutions can be applied to UAS in field, how to manage the reliability of the UAS in field operations and what results are expected to manage UAS reliability. The main goal of this paper aims at guiding these branches of military and research groups that develop UAS, introducing the subject for those who ignore the reliability area or even remember those who have had some knowledge about reliability. The verification and validation of the directives presented will allow to construction of an information system capable to collect, organize, filter, and analyze life data from UAS concerning its Reliability, Availability and Safety.

2. THE IMPORTANCE OF UAS RELIABILITY STUDY

According to OSD (2003) defines UAS reliability study as the ability to assess the risk posed by UAS to persons or property within the civil airspace, identify potential means to improve its reliability, availability, safety and decrease its maintenance costs.

Reliability is determined by the design features that configure its platform and cost to reach such a reliability level. Due to maturing state of the UAS industry is possible to built UAS platform of low cost, using Commercial Off The Shelf (COTS) technology. An UAS is generally composed by airframe, engine, actuators, control surface, electronic devices, and onboard computer system, *i.e.* a variety of COTS components.

Reliability problems in UAS are not intentionally designed in the systems that integrate the UAS. Most of time reliability problems in UAS are discovered after UAS is introduced in field. These problems are caused by failure mechanisms and modes that were not tested or observed during the development of UAS. They happen, however, and due to they happen, must be managed and answered through formal proceedings, in order to discover faults of any nature that could come to affect the UAS mission (Uhlig and Neogi, 2006).

System failures or due to human mistakes increase the maintenance cost and their effects restrict UAS availability, causing delays or unexpected repairs in its systems, or even they can result in total loss or significant damages of its platforms, degrading its role primarily in military applications. Although the costs of operation of the UAS are lower when compared to manned systems, it is essential that UAS has an acceptable reliability level, operability and survivability. In this case, the following principles should be considered in the development of UAS reliable platform (Franco, 2008):

- Obtain information on life data of UAS components; Most of the components used in UAS are COTS. Therefore, a great deal of time should be spend researching COTS components which would result in Reliability and Safety design.
- Define the requirements (viable) to the UAS systems with respect to a goal of reliability (*e.g.* Flight-Mean Time To Failure = 30 h);
- Define the operational environment of the UAS, taking into account aspects such as wind gusts, low temperatures in certain altitudes etc;
- Simplicity of design;
- Establish criteria of comparison with similar UAS, in order to develop information on failure data of COTS components;
- Human Factor Analysis during design, manufacture, operation and maintenance phases of the UAS;
- Run an Environmental Stress Screening (ESS) analysis to detect latent faults in the UAS component which, otherwise, could cause the crash on UAS field;
- Testability of the systems on ground to improve the capacity of prediction and diagnosis;
- Use redundant systems or Fail Safe based on failure mode and effect analysis on UAS mission;
- Check the future availability of components and materials;
- Qualify and monitor procedures for maintaining the UAS systems.

Finally, it refers to the costs of investments associated with the increase UAS reliability, as soon as the reliability is associated to the cost that pays for it. The costs to improve the reliability must be economically justified with basis on function and environment for which the UAS is developed to act, e.g., the reliability must be appropriated to the intended use. The relative costs to faults can become expensive UAS, resulting in the need to replace the system or even in UAS mission loss.

3. WHY TO MANAGE THE RELIABILITY OF UAS

Reliability is an UAS feature, equivalent to its integrity, e.g., it is equal to the degree of confidence of which the UAS will accomplish its mission and will not fail in its normal operation. A great deal of the reliability problems in UAS are detected after the system had been introduced in field due to the difficulty of predicting all the faults that can happen to UAS. In other words, reliability is related to the occurrence of failures in the UAS. These faults can take place when the UAS carries out a given mission, driving to a dangerous flight condition.

While developing a management system for the UAS reliability must consider the failure probability of different components of UAS and how these failures affect the overall UAS reliability. Three failure types must be considered when managing the reliability of UAS: hardware, software, and human operator.

A hardware failure (actuator, for example) can generate false signals, which are outside the scope of entries expected by the software of the UAS. On the other hand, a software failure can become UAS operation so unpredictably, resulting in unexpected behavior of the UAS in flight. This behavior can confuse the human operators on ground, driving them to operate or repair the UAS of inadequate way in reaction to failure.

Some basic concepts make possible a better understanding to manage the UAS reliability. They are fault, error and failure within operational context of the UAS. The term "fault" may be used to indicate a malfunction that may be tolerable at its present stage (Hajiyev and Caliskan, 2003). Error is the discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition. The term "failure" suggests complete breakdown of an UAS and whose failure typically results in the loss of the UAS platform or, in the case of sensor, a mission compromised (OSD, 2003) as shown in figure 1.

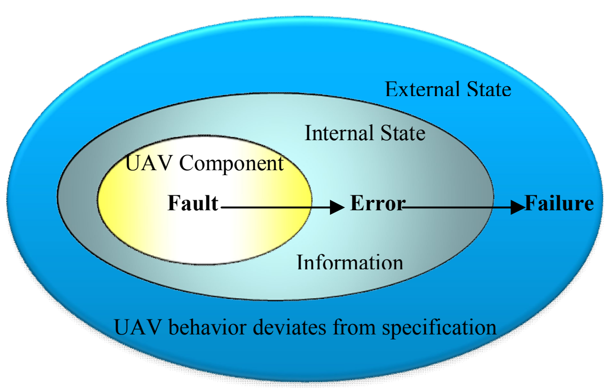


Figure 1. Fault vs. Error vs. Failure

For example, an interaction between human operator on ground and UAV in flight carried out improper manner during UAS mission is a fault. The changed data resultant from fault is an error. When the error produces missed data or error in the value of the UAS variable or in operation time, affecting UAS mission, is considered that a failure is takes places in UAS.

We can also classify flaws in relation to UAS reliability and safety. Flaws that impact the UAS reliability are related to the costs that these flaws cause during the life cycle of the UAS. Any flaw that results in delays or unexpected repairs to the UAS on ground, or when a failure occurs in flight, leading to landing which does not result in severe damage or platform loss of the UAS. These flaws are documented as failures that impact the reliability of the UAS. Already failures related to safety is not necessarily linked to the costs these flaws can cause to UAS, but is related to severe damage of the UAS platform or UAS platform loss due to the UAS impact on ground or collision with another system (manned or unmanned) in flight, as well as severe damage to persons and property on ground.

4. WHAT SHOULD BE MANAGED

In the development of UAS reliability management system, the environment in which the UAS acts and the purpose of its mission must be considered, as well as human operators. There are several measures that can be used in the reliability management, and the most appropriate measure for an UAS depends on the type of system used and mission desired. They are:

Reliability is the ability that UAS has to carry out and to maintain its mission in routine circumstance, as well as to survive in hostile and unexpected environment. In other word, reliability is the probability that UAS can performance correctly its intended mission without loss, defects or flaws during the time of mission (T – flight hours) and under stated operation conditions; given that UAS was fully operating since mission beginning (T0), as well as in pre-flight test where check the readiness of UAS systems (OSD, 2003; Franco, 2008). Reliability can be expressed in terms of Mean Time Between Failure (MTBF - flight hours), failure rate (λ – failure per unit time) or as Mission Reliability (R- expressed as decimal or probability).

$$\mathrm{MTBF} = \frac{\text{total number of flight hours}}{\text{total number of cancellations \& abortions}} \tag{1}$$

$$\lambda = \frac{\text{total number of failures}}{\text{total number of flight hours}} \tag{2}$$

$$R = 1 - \frac{\text{number of canceled missions}}{\text{total number of flights}} \tag{3}$$

Maintainability is a measure of the ease and rapidity of UAS to be retained or restored to a specified condition after failing when maintenance action is performanced by personnel having specified skill level, using prescribed level of maintenance and repair action. Maintainability is usually expressed as Mean Time To Repair (MTTR), Maintenance Man Hour Per Flight Hour (MMF/FH) and Crew Size, *i.e.* average number of individuals required to accomplish the maintenance action (OSD, 2003; Franco, 2008).

$$MTTR = \frac{\sum_{i=1}^{n} \lambda_i \tau_i}{\sum_{i=1}^{n} \lambda_i} \tag{4}$$

Availability describe how a given UAS is able to perform its mission compared to the number of times that is tasked to do, taking into account combined aspects of its reliability, maintainability and logistic support (OSD, 2003; Franco, 2008). There are tree types of availability:

- Inherent Availability (A_I) is the ideal state to check out the UAS availability, representing a function of reliability (MTBF) and maintainability (MTTR). In this type of analysis includes only corrective maintenance actions;

$$A_I = \frac{MTBF}{MTBF + MTTR} \tag{5}$$

• Achieved Availability (A_A) is similar to the Inherent Availability, but includes in its analysis corrective and preventive maintenance actions ($MTTR_A$);

$$A_A = \frac{MTBM}{MTBM + MTTR_A} \quad (6)$$

where MTBM *is Mean Time Between Maintenance*

• Operational Availability (A_O) is the availability of real experiences that takes place with the UAS in the field. In this type of analysis includes corrective and preventive maintenance actions, logistic time, waiting time and administrative time.

$$A_O = \frac{MTBM + RT}{MTBM + RT + MDT} \quad (7)$$

where MDT is *Mean Downtime* (MDT = $MTTR_A$ + mean logistic time + mean administrative time) *and RT is* uptime the *Ready Time*.

A major concern of the scientific community of UAS is related to conditions of potentially dangerous faults that can result in accidents or not, in order to establish their main goal in order to eliminate or mitigate their risks and demonstrate compliance with requirements of the reliability and safety systems with the regulatory authorities for acceptance of UAS in civil airspace. Safety is defined as the absence of mishaps (OSD, 2003; Trotta, 2003; Uhlig and Neogi, 2006; Franco, 2008). Mishaps, in turn, mean significant damage to UAS platform that need actions of extensive repair so that UAS can operate again. Safety is expressed in terms of Mishap Rate (MR) such as:

$$MR = \frac{\text{Classe A}}{\text{flight hours}} \times 100{,}000 hrs \quad (8)$$

$$\mathrm{M}R_A = \frac{\text{accident number}}{\text{flight hours}} \quad (9)$$

$$\mathrm{M}R_{\mathrm{mod}} = \frac{\text{accident number}}{\text{flight hours}} \quad (10)$$

$$\mathrm{M}R_x = \frac{\text{accident number}}{\text{"x" flight hours}} \quad (11)$$

where Class A are those UAS mishaps that result in loss of UAS platform, human life or \$ 1,000,000 in damage. MR_A is the number of mishaps divided by number of flight hours per year. Considering each year UAS suffer a modification in its system, the mishaps can be expressed by MR_{MOD}. Lastly, MR_x is the number of mishaps for the last “x” flight hours.

Human operator can detect input signal, analyze its meaning, make decision on fault, and perform the proper response to eliminate or mitigate its effects on UAS. A careful analysis of human-UAS recognizes both humans and UAS can fail, and what are their effects on UAS mission. Human errors or mistakes cause system failure or increase the risk of failure for the safe operation of UAS. It is possible to construct a set of analogues to reliability parameters for obtaining good UAS design with respect to human mistake, such as:

$$Human\ \ Error = \frac{mistake\ \ number}{number\ \ of\ \ achieved\ \ taks} \quad (12)$$

The availability of life data allows calculating measures to predict the failure probability in order to track the reliability of UAS. However, when only the numbers of flight hours and mishaps are known, we can use these parameters to assess the UAS reliability. The emphasis in each of these parameters may however be different from one UAS to another, depending on the intended mission of the UAS in study.

5. WHAT MANAGEMENT TOOLS ARE RELEVANT AND HOW THEY CAN BE IMPLEMENTED IN UAS' LIFE CYCLE PHASE

Besides what has already been shown, the reliability management in the UAS development consists in performing various tasks at each stage of the life cycle, as shown in table 2, with the purpose to deliver the field team UAS safe and reliable. In table 1 is presented, so short, the tools to manage the reliability of UAS at each stage of its life.

Table 1: Reliability Management over UAV life cycle.

STAGES	TOOLS	APPLICATION IN UAS
DESIGN	FRACAS	Analysis of UAS field data
	FMEA	Aid in choosing the design of the UAV platform
		Aid to validate the design parameters of the UAS
		Failure Modes and Effects Analysis from UAS similar or previous versions
	FTA	Qualification and Validation of the UAS design
	RELIABILITY	Calculate RAMS parameters based on the UAS life data
	FAULT PREDICTION	Estimate the reliability or failures probability in UAS systems via RDB
MANUFACTURE	ESS	Remove latent failures of UAS
	FMEA	Identify faults in the UAS manufacture
OPERATION	FRACAS	Data collection, analysis and corrective actions
	FTA	Highlight critical points that need improvements Assess the impact of changes introduced by UAS hardware and software
		Investigate the causes of field failures, or accidents with UAS
MAINTENANCE	FTA	When we want to focus on a specific system failure
		Assist in management activities for major COTS components of UAS maintenance
	FMEA	Aid the fault diagnosis process
	FRACAS	Record of failure analysis and corrective and/or preventive actions in UAS

To know:

Fault Prediction is a process that can be used to quantitatively estimate the reliability of an UAS design prior to its real operation. Once the UAS platform was designed, we can estimate its reliability and compared it with acceptable reliability levels defined in design. There are several methods for predicting the UAS reliability. In this paper, we used to the number of components, a simplified way, via Reliability Block Diagram (RDB), where reliability is calculated through series and / or parallel systems, using the reliability or failure rate as parameter. Reliability Block Diagram is intended to represent in a logical and visual information flow among the reliability components of a given UAS platform, to identify critical components to the UAS good operation which requires improvements in order to meet the reliability requirements of the UAS design. In this case, reliability can be allocated to UAS components in order to achieve a goal established in design for reliability;

In the reliability study a system in series, represents a scenery in which the successful of the system operation depends on all components are operating without failure (Franco, 2008). In other words, for a system of UAS operating successfully, all components must be operate successfully, as shown in Figure 2.

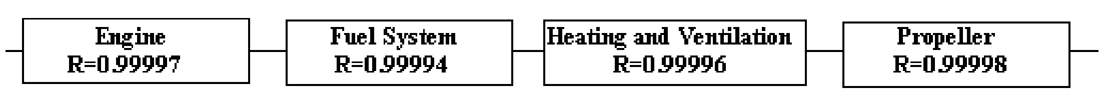


Figure 2: RDB of a system in series.

Figure 2 shows an example of the reliability of an UAS system can be modeled. Each block contains all components that are strictly part of the UAS' power plant system. These include all elements of the engine block, fuel system block, heating and ventilation system block, and propeller block.

Fault Removal: Fault Removal Method used in this paper aims at testing the behavior of the UAS before it is put in real operation, in order to detect and remove - through corrective actions, hard failure, latent, incipient, or intermittent flaws or defects which would cause UAS failure in its operational environment. The fault removal method treated in this paper is Environmental Stress Screening (ESS). ESS is a process involving the application of a combination or sequences of environmental stimuli such as thermal cycling, random vibration, electrical stress etc. The main goal ESS is to expose, identify and eliminate weak components, workmanship defects, flaws or defects, and other conformance anomalies which cannot be detected and removed by visual inspection or electrical testing but which will cause UAS failures in the field. O purpose of ESS is to compress a system's early mortality period and reduce its failure rate to acceptable level as quickly as possible, as shown in figure 3 (Franco, 2008).

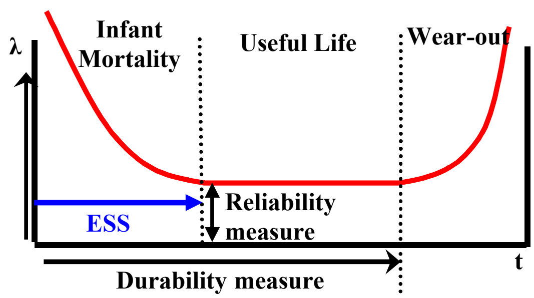


Figure3: Bathtube Curve for UAS electronic items

In the case of unmanned systems, the testing program should cover a wide range of operating conditions that these systems will face during its mission in order to stimulate the occurrence of latent failures in the UAS so that they can be eliminated, otherwise, they could do with UAS crash on the field [80]. Readers interested in the subject of ESS are encouraged to refer to Kececioglu and Sun (1997).

Fault Prevention: The study of the failure prevention aims at preventing or minimizing the failure occurrence in the system during the UAS development and operation, and avoiding fault reoccurrence in field, driving to an improvement of UAS reliability and safety. Fault Prevent in the development of UAS operational / maintenance proceeding implies an economy of resources, improves reliability and minimizes potential damage to the UAS. Among the tools that can be used in this area, are:

- **Fault Tree Analysis (FTA)** is a preventive method of reliability analysis that can be used to highlight weaknesses in the UAS that need to be improved, assess the changes introduced in the UAS system, identify events that could drive the UAS to a dangerous flight condition, as well as qualify and validate UAS design, operation, and maintenance in order to ensure the reliability and, consequently, its certification. FTA is a graphical representation of the faults, critical failures, loss, or accidents associated with UAV, as shown in figure 4, in order to find out primary events that result in the occurrence of a specified system level event of a UAV (Franco, 2008).

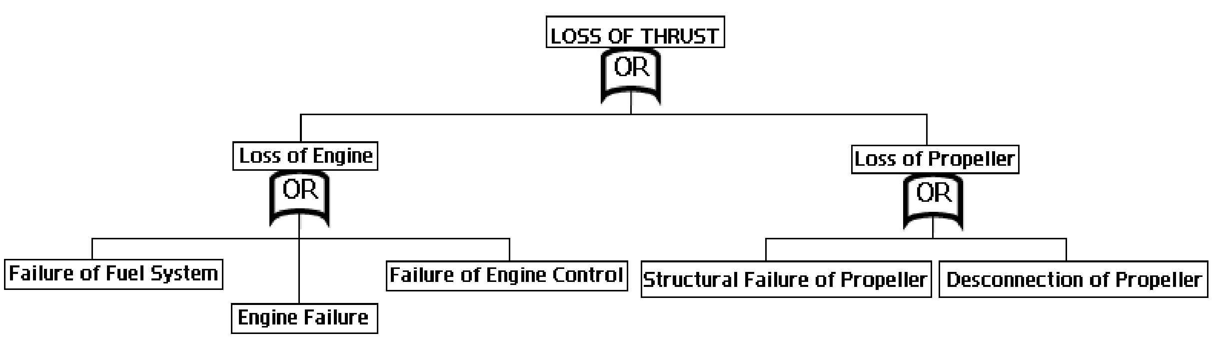


Figura 4: Loss of Thrust FTA

FTA is a top-down structured way of representing causes for an UAS undesirable event. FTA allows multiple cause for an specified event and use "and" and "or" gates to distinguish different event that can occur to UAS.

Failure Mode and Effect Analysis (FMEA) is one of the tools frequently used to improve reliability of an UAS. FMEA is an analysis that originally was intended as bottom-up approach where UAS components were analyzed for the manner in which they might fail, and the failure effects were investigated to measure the risk to UAS mission, as shown in figure 5.

Failure Mode and its Cause	Failure Effect
Loss of Communication in Real Time between Ground Station Control and UAV due to fault network.	UAV can lose the course or drive it to an accident.

Figure 5 Failure Mode and Effect Analysis

The FMEA can be used to evaluate system failures related to the UAS systems, when the definition of its roles in the early stages of design or to evaluate failures related to UAS components, when of the validation design parameters. We can use the FMEA, still in the design phase, to investigate the failure modes and their effects of the UAS similar or previous versions in order to pass experience to UAS team.

The FMEA has three processes of analysis, as shown in figure 6. The first is a failure study which evaluates the function, the task to be performed during UAS operation and in what flight phases it act, as well as possible failure modes that can come to fail to perform its function, and what are the effects and consequences of this failure mode for the UAS operation. The second refers to the risk of each identified failure mode, checking whether is or is not acceptable for the safe and reliable operation of UAS. The third and last process refers to UAS continuous improvement where UAS component reliability is conquered. In this case, the actions are assessed for ensuring the reliability of the component analysis, and identifying the responsible for implementation of the actions (Franco, 2008).

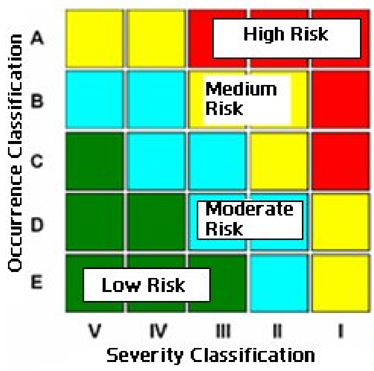
FMEA

☐ System ☐ Subsystem ☐ Component	INSTITUTO TECNOLÓGICO DE AERONÁUTICA	Date FMEA : Page :
Code of Reference FMEA:		Prepared for
Number of Reference FMEA :		Approved for

Component	Function	Failure Mode	Failure Cause	Effect Failure			Severity	Fault Detection	Actions Recommended
				Local	Next	Final			
Identification of the analysed item	Short description of the analysed item's function	How the item can come to fail	Description of the causes-roots of the failure mode	Description of the effects what the failure mode can cause in the eventuality of the fault incident			The consequences for the UAS reliability and safety For example: Catastrophic	How can be detected.	How can be corrected or prevented

Figura 6: FMEA de um UAS

- **Critically Analysis (CA)** is a method of reliability and safety analysis that allows the UAS development team has a visual representation of the critical areas of the UAS system that require immediate attention and action. Figure 7 shows the matrix of criticality where the axis of abscissa indicates the severity and the axis of the ordered indicates the frequency of failure occurrence. The intersection of X with Y focuses and prioritizes the actions required in order to improve UAS reliability. The portions in red, yellow, blue and green indicate high risk, medium risk, moderate risk and low risk respectively, to demonstrate the critical failure, as well as the preventive or corrective action must be taken.



OCCURRENCE	DESCRIPTION
A - FREQUENT	Likely to occur frequently.
B – PROBABLE	Will occur several times in life of an UAS
C - OCCASIONAL	Likely to occur sometime in life of an UAS
D – REMOTE	Unlike, but possible to occur in life of the UAS
E - IMPROBABLE	So unlikely, it can be assumed occurrence may not be experienced

Severity	DESCRIPTION
I - CATASTROFIC	Uncontrolled UAS landing, loss of UAS platform or crash another sytem
II - CRITICAL	Failure conditions which result loss of mission or cause system severe damage or injuries.
III - MARGINAL	A fault that causes less damages to the UAS resulting in a degradation of the mission
IV - MINOR	The fault is perceptible but it does not cause notable degradation of a mission
V - NEGLIGIBLE	Imperceptible fault

HAZARD RISK	ACTION REQUESTED
HIGH RISK	UNACCEPTABLE
MEDIUM RISK	UNDESIRABLE. Managing activity decision required
MODERATE RISK	ACCEPTABLE with managing activity review
LOW RISK	ACCEPTABLE without review.

Figure 7: CA applied to UAS

where

- Risk is based on the failure probability (occurrence) and its severity.
- Severity is an assessment of the impact of an event on UAS;
- Occurrence is the likelihood of a fault occurring.

In other worlds, CA aim at ranking each failure mode as identified in the FMEA or FTA in accordance with failure modes' severity and its occurrence probability in order to assess those UAS mission critical component that cause potential faults, errors, failure, weakness, mission cancellation and mishap.

Failures that cause the loss of UAS (hazard risk with high cost) must be considered in order to determine how failures can cause the hazard identified by CA and the ways to correct them. Failures that cause UAS collision in flight with other UAS or collision on ground over population area (high risk) must be included in this analysis. Failures involve both medium and moderate risk require a revision of UAS activities, taking into account the UAS operative environment in which failures take place.

To reduce the risks presented in figure 7, some action can be performance in order to minimize its effects on UAS mission, such as UAS redesign, incorporate safety devices and warning devices inside UAS, as well as apply procedures or training to UAS human operators (Trotta, 2003).

- **Failure Reporting and Corrective Action System (FRACAS)** determines the failure causes associated to UAS life cycle and provides a closed-loop analysis in order to implement corrective actions. The purpose of FRACAS is to collect failure data, provide procedures to identify failure cause and to document corrective actions taken during design, manufacture, test, and field deployment phases of UAS.

The FRACAS concept suggests a closed loop system, as illustrated in Figure 8, where the real information derived from analysis of data collected in the field are confronted with the desired parameters for the UAS reliability. If there is a discrepancy between these data, one set of preventive and corrective actions are put into practice in order to achieve the continuous improvement of these UAS (Franco, 2008).

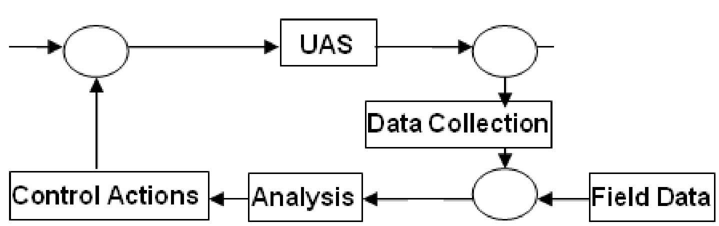


Figure 8: FRACAS applied to UAS

6. SOME PRACTICAL SOLUTIONS APPLIED IN A REAL UAS

An issue that may be raised in this paper is how these tools can be used in practice. To answer this question, we can consider the following sceneries (Franco, 2008):

- A major failure of an UAS system occurred or is occurring in the field, driving to its unavailability to accomplish a given mission or that results in UAS platform loss. So, we can analyze what caused or what is causing a system failure during the UAS operation. In this case, we can use the FTA to investigate all possible combinations of events (root causes) that eventually result in system failure (event-top) of the UAS;
- We can use also the FTA when changes are made in the UAS systems in order to highlight potential faults of operation, identifying critical paths that a system failure can result in an accident with the UAS;
- We can use FMEA when want to identify critical faults in each component of the UAS, its causes and consequences before occurring in the field if no action is taken.
- Analyze the criticality failure modes enable the UAS team to structure and prioritize actions needed to improve the UAS reliability and avoid potential accidents or incidents related to its operation, aiding the team decide how to focus the resources available and necessary for overcome those events that are most critical to the mission and operation of UAS.
- Collect real data from UAS will form a database for quantitative analysis of reliability. One tool that can be used to obtain this information is a FRACAS program to collect and record fault from the field, implement and track corrective actions to optimize existing processes to improve reliability of existing and future UAS and can be used during the design, operation and maintenance phase of the UAS.

In table 2 shows how combine these tools in the reliability management of UAS in field **(**Krouwer, 2008**)**.

Table 2. Use of FTA, FMEA and FRACAS to detect fault in field.

	FMEA	**FRACAS**
General	**"proactive"**	**"reactive"**
Purpose	**affect the design before launch**	**correct problems after launch**
Errors	**may occur – the potential errors must be enumerated**	**have occurred – observed errors are simply counted**
Error rate	**is assumed**	**is measured**
Issues with technique	**Is it complete? Models can be wrong.**	**All errors counted? Culture inhibits reporting errors.**
Can be combined with	**FTA**	**FTA**
Evaluate quality of the technique	**difficult – completeness, reasonableness of mitigations is qualitative**	**simple - measure error rate**

FMEA and FTA are compatible tools of UAS risk analysis, being that the choice of proper tool depends on risk nature to be evaluated. However, FMEA considers only single failure in its analysis while FTA considers multiples failures, requiring a greater skill level than FMEA. When an UAS is designed, the modes it might fail can be captured in a FTA and FMEA. After the UAS is launched to field operation, the modes in which the UAS has failed can be captured through FRACAS and this knowledge can be used to update the FTA of the UAS in study **(**Krouwer, 2008**)**.

7. HOW TO MANAGE THE RELIABILITY OF FIELD IN UAS

Managing the UAS Reliability in field operation aim to identify, locate, implement, and verify corrective actions, and document undesirable events on ground and flight to prevent the recurrence of them. Below are presented a number of directives that can used to manage the reliability of UAS in the field operation (Franco, 2008).

7.1 Conduct an ESS to accelerate component and workmanship imperfections, to discover hidden faults or weaknesses of design that could be dangerous for the safe operation of UAS;

7.2 Perform a FMEA or FTA dedicated to the UAS operation or maintenance phases in order to identify activities of greater risk to the UAS;
7.3 Development of manuals for UAS operators and maintainers to ensure that the information is centralized and are used in due time;
7.4 Check and calibrate all instruments of the UAS in order to reduce possible errors;
7.5 Record failure data, maintenance data, exchange of components and subsystems, including overstress condition or unfavorable weather condition in which occurred to fault, as well as operator or procedural errors etc. This step can be performed driving to FRACAS to record these data.
7.6 Assess the satisfaction of the UAS team during the flight test phase;
7.7 After failures were identified and actions taken to correct them is necessary verify whether UAS reliability improved or not over time. This analysis corresponds to the UAS *Grouth Reliability Analysis*. This can be done using Duane Model to analyze data from fields such as MTBF and Availability Achieved, seeking to check out the reliability of UAS over time.
7.8 Finally, a program to track the actions that improve existing processes with the purpose of improving the UAS reliability in field and of future versions should be implemented, coordinated and approved by UAS developers and reliability engineer in cooperation with the field team of UAS. Thus, it will be possible to evaluate the effectiveness of actions taken based on procedures related to each failure mode in order to achieve the continuous improvement of these systems.

8. WHAT RESULTS ARE EXPECTED TO RELIABILITY MANAGEMENT IN UAS

In the present paper it was possible to introduce concepts about reliability management applied to the process of decision in the design, operation, and maintenance phases for UAS team, starting from an overview of the system up to an analysis more specific of the system. Obviously, the presented directives will have resulted different depending on the type of analyzed UAS, especially for parameters of Reliability, Availability and Safety. The reliability management tools presented in this paper has been reported in several academic papers. However, complete reliability management systems that use theses tools applied to UAS' life cycle have been reported in few papers with real results. These directives aim at increasing the reliability, safety and readiness of the UAS, reducing fault costs, minimizing its recurrence in field, and monitoring the responses of the improvement actions throughout UAS' life cycle. It is expected great most of UAS developers will be able benefit with the directives presented in this paper, considering the impact of reliability in the design, development, operation and maintenance of UAS.

9. REFERENCES

Dodson, B.; Nolan, D. (2003). *Reliability engineering Handbook*. Tucson: Q.A. Pub., 601p. (Quality and Reliability, 56)

Franco, B. J. O. M. (2008). *Métodos de Análise de Falhas e suas aplicações em Veículos Aéreos Não-Tripulados*. Tese de Mestrado em Sistemas Aeroespaciais e Mecatrônica – Instituto Tecnológico de Aeronáutica, São José dos Campos. 205p.

Hajiyev, C; Caliskan, F. (2003) *Fault diagnosis and reconfiguration in flight control system***.** Boston: Kluwer, 2003.

Kececioglu, D; Sun, F.B (1997). *Environmental Stress Screening – Its quantification, optimization and Management*, Prentice-Hall PTR, New Jersey.

Krouwer, J. (2008). *FMEA vs. FRACAS vs. RCA*. Available at: http://krouwerconsulting.com/Essays/FMEAFracas.htm

Office of the Secretary of Defense – OSD (2003). *Unmanned Aerial Vehicle Reliability Study*. February, 2003. 80p.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.