FAILURE ANALYSIS METHODS IN UNMANNED AERIAL VEHICLE (UAV) APPLICATIONS

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Abstract. *The present work aims at discussing the use of the failure analysis methods in Unmanned Aerial Vehicle (UAV) applications, focusing the design review procedures with Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA). UAV are typically currently unreliable, and lack systems to improve their reliability. It is shown that the use of these tools will lead to reliability improvement by means of the implementation of counter-measures to potential failures as well as to determine the importance of these failures from various perspectives such as cost, reliability and safety. As an example of implementation of such tools, we adapted forms from commercial use for FMECA system for UAV, and a FTA regarding loss of propulsion for a UAV are briefly presented and discussed.*

Keywords*: UAV, FMEA, FTA, CA, loss of propulsion.*

1. INTRODUCTION

An **unmanned aerial vehicle (UAV)** is an aircraft with no onboard pilot. UAVs can be classified according to different criteria such as mission types, mission sensors (type sensor), performance, endurance, and flight control system. UAVs can be remote controlled or fly autonomously based on pre-programmed flight plans. Also, UAVs may be used in many application in which involve high risk such as hazard environment (nuclear, chemical, or biological warfare), and location of difficult access due to the characteristic of the terrain and the presence of obstacle (Clade, 2000); (Pick, 2004); (Robison, 2004); (Heredia, 2004); (Heredia, 2005).

Reliability evaluation is an important and integral feature of the planning, design, manufacture and operation of all engineering systems. The failure of these can often cause effects which range from inconvenience and irritation to severe impact on society and on its environment. In the UAV case, Reliability plays an important role once the use of the same requires the improvement of safety condition in order to allow its routine airspace access. Also, UAV reliability study allow to identify potential means for improvement their mission availability and effectiveness as well as reduces acquisition cost (DoD, 2003).

In addition, reliability evaluation can be used to how a system may fail, the consequences of failures and also to provide information to enable engineers, scientists, researches, managers, and project teams to relate the quality of their systems to economics and capital investment. In so doing it can lead to better and more economic design, and a much improved knowledge of the operation and behavior of a system (Billinton and Allan, 1983).

There are many variations on the definition of reliability but a widely accepted form is as follows: Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered (Kececioglu, 1991); (Dodson and Nolan, 2002). In this paper, we define UAV reliability as the probability that a UAV will operate without failure for the duration (t) of a specified mission profile, given that it was fully operation at time (t=0), as well as during in preflight tests.

According to Department of Defense (DoD, 2003) , attention to reliability must permeate all phases of the UAV life circle beginning with the identification of the requirement, and continues through conceptual, preliminary, and detailed design into production, operating, and retirement. We can categorize the UAV system into five general areas to know:

- Propulsion and Power;
- Flight Control Systems;
- Communication;
- Ground Control Station (Human in loop); and
- Miscellaneous.

By focusing on Propulsion Control System, Flight Control Systems, and Human Factors, which account for approximately 80 % of UAV failures, we can increase reliability (Peck, 2003). Even though UAV cost very little compared to others manned systems, it is desired that the UAV cost should remain as low as possible, as well as UAV be carried out their missions with an acceptable level of safety, mission reliability, operability, and survivability. We can increase UAVs reliability the same the two ways:

- Fault Tolerance is conventionally achieved through the use of hardware redundancy. Such schemes operate in duplicated, triplicated or even quadruplicated redundancy configuration in order to tolerate the failure when it occurs.

- Fault Avoidance can be accomplished by improving reliability of those components that contribute the most to reliability degradation are the most critical for avoidance.

Examples of duplicated redundancy configuration into UAV are data links, propulsion and flight controls. The use of hardware redundancy is not easily added, especially for small UAVs. The major problems encountered with hardware redundancy in UAVs are the extra maintenance cost as well as additional space, weight, and power consumption required accommodating the system. Furthermore, size, weight, and cost are critical factors for operational usage of the UAV. In this case, Fault Avoidance is the better approach.

In literature on Fault Avoidance Methods applied to UAVs is not very detailed and old when compared to Fault Tolerance in UAVs. The first major study has been written by DoD (2003) for Predator, Pioneer, and Hunter UAVs, followed by Noll *et al.* (2004) for Helios UAV, Trotta (2003) for safety assessing in UAV system, Lopez (2003) for avoiding collision, Peck (2004) about reliability of UAVs and others.

In this work, Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), and Criticality Analysis (CA) methods are considered, and as example a propulsion system for a UAV is presented. To analyze these methods and their application in UAVs, the qualitative approach was chosen due to lack of data such as MTBF and Mishap rates, and by the lack of the appropriate level of detail for real propulsion system configuration (RAC, 1993). In Section 2, presents a description of a high level architecture of a low cost UAV system. Section 3, an illustrative example of a FTA for a UAV propulsion system is constructed as a mean of assessing potential faults. Besides the FTA, we adapted FMEA forms based on commercial use's forms for UAV systems, and a CA for the propulsion system is performed, based on our experience and judgment due to lack of tracking by current operators UAVs, where the critical points of the system are highlighted. Section 4 and 5 are devoted to the conclusion and references.

2. HIGH LEVEL ARCHITECTURE FOR UAVS

In general, a high level architecture for a UAV system consists of an Aerial Platform and Ground Control Station (GCS). The aerial platform is the physical structure of the UAV that allow integrating all the necessary system for the mission profile. The GCS may be manned shipboard or land-based station of the UAV system responsible for command, monitor, operate, and support system center.

In general, the UAV mission consists of the following phase, as shown in "Fig. 1". From this way, we can establish an analysis of essential functions which UAVs may be achieve as well as selection factors to hardware and software development. In "Table 1" show an example of analysis of the essential functions for UAVs, and in "Fig. 2" is presented a block functional diagram of a high level architecture for UAVs, as an example.

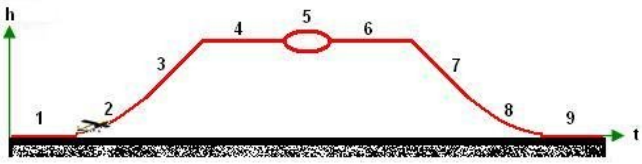


Figure1. Flight Phases

where

1: Start-up, taxi;
2: Take-off;
3: Ascent to desired height
4: Cruise to area of interest;
5: On station;
6: Cruise back to base;
7: Descent to sea level;
8: Land;
9: Taxi of return.

Table 1. Example of analysis of the UAV essential functions

Flight Essential Functions	**Mission Phases**						
	1-2	**3**	**4**	**5**	**6**	**7**	**8-9**
Start-up systems	x						
Structural Integrity	x	x	x	x	x	x	x
Propulsion	x	x	x	x	x	x	x
Power to FCS	x	x	x	x	x	x	x
Power to Mission Sensor			x	x	x	x	x
Power to Communication			x	x	x	x	x
Flight Control System	x	x	x	x	x	x	x
Communication	x	x	x	x	x	x	
Line of Sight (LOS)			x	x	x	x	x
Structural Integrity	x	x	x	x	x	x	x
Withstand Environmental Conditions (turbulence and gusts)			x	x	x		

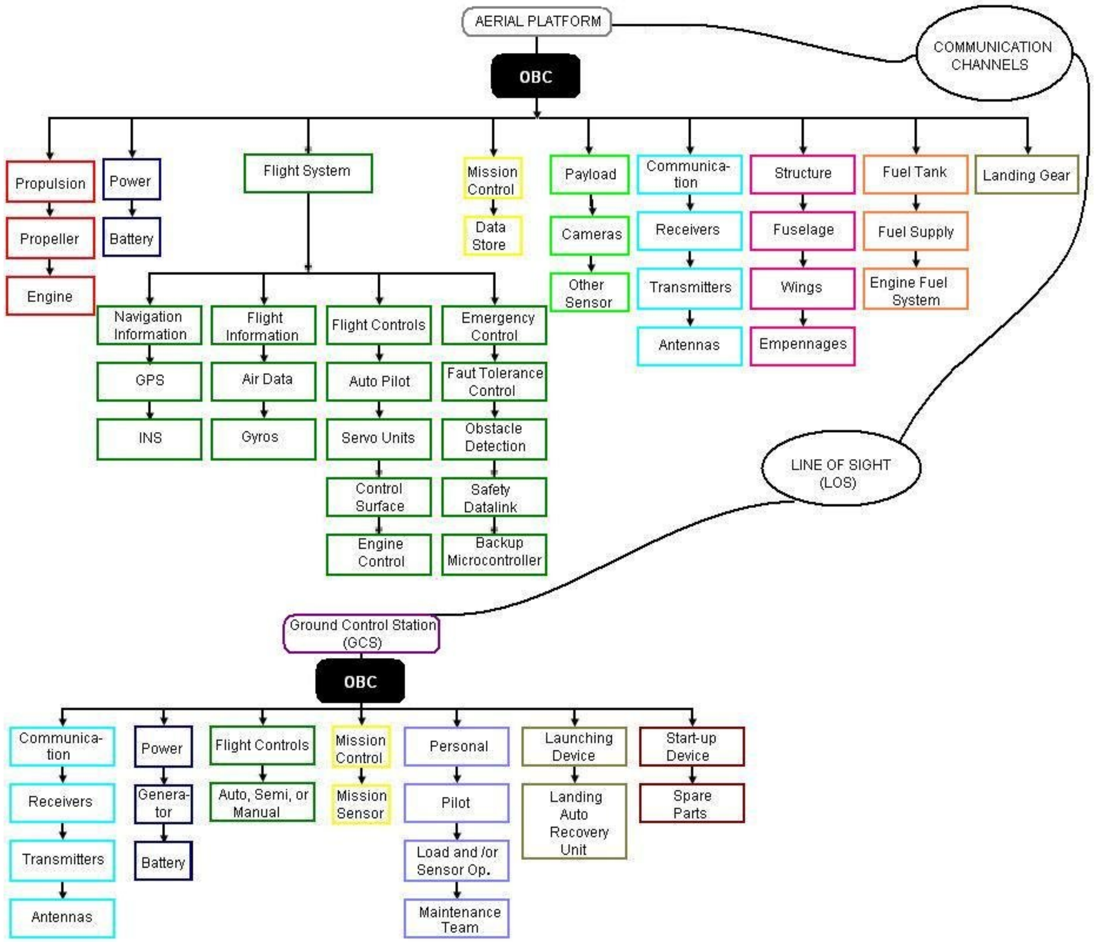


Figure 2. Block Functional Diagram of a High Level Architecture for UAVs.

Onboard data processing is developed on a PC based single-board-computer and a microcontroller. The onboard computer is a multitasking real time operating system. The PC is responsible for obtaining data from the flight and communication system as well as sensor's payload. Thus, it computes the flight algorithms, commands the mission sensors, and downlinks store data to the GCS in near real time operating. Already GCS PC is the equivalent of a pilot's cockpit and allows to monitor and / or control the UAV flight and to display in near real time the status of the flying UAV such as speed, attitude, altitude, UAV and GCS position, actual position through an electronic moving map etc.

3. FAULT AVOIDANCE

As seen in the previous section which hardware redundancy is not easily implemented into UAVs due to size, weight, power consumption, and mainly cost associated to its implemention. One of the forms of solving this problem and obtaining a improvement on reliability is using a preventive approach, identifying all the possible ways in which a failure may occurs into system. Tools as FTA, FMEA, and CA quite effectives for this purpose.

3.1. Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a reliability and safety design analysis technique used for complex dynamic systems which provides a graphical representation of the system being studied, and its use often results in discovery of failure combinations that would not have been obvious if others failures identification methods were used. This is an analysis technique which starts from consideration of system failure effects, referred to as "top events", and proceeds by determining how these can be caused by individual or combined lower level failures or events which correspond to a known set of failure modes (RAC, 1990). FTA takes on a deductive approach defining the events and sub events which may cause the top event to occur. The relationship between these events (faults) is governed by their logical relationship to each other. At the top of the tree is the failure, and the various contributing causes are at the bottom branches (basic events) of the tree. These basic events can be the failure modes of components, functions, or even services. FTA is built from events and gates. For more details on the construction of the FTA vide Dodson (2002).

In our example, the propulsion system is equipped with an aviation gasoline engine and a propeller to provide thrust to the UAV platform (KOMATSU, 2006), as shown in "Fig.3".

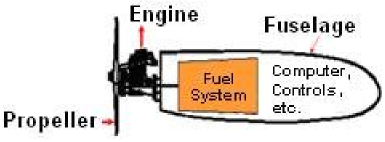


Figure 3. Propulsion System

We consider as top event "Loss of Propulsion" which may be caused by either loss of engine, loss of propeller, or human failure (three input OR gate). The fault trees developed for this example are shown in "Fig. 4-7".

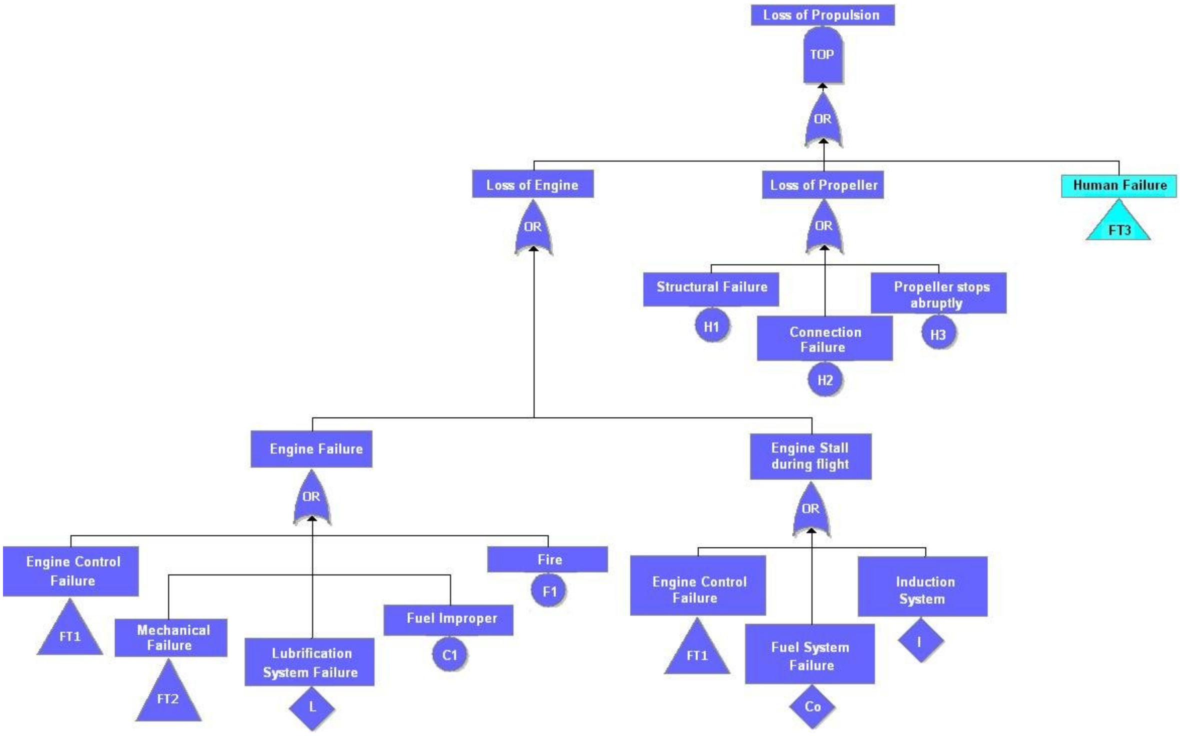


Figure 4. FTA: Loss of Propulsion

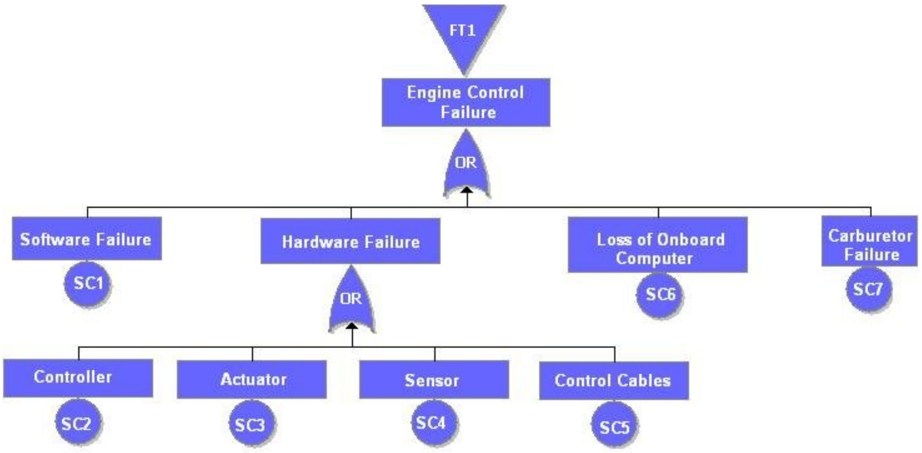


Figure 5. FTA: Engine Control Failure

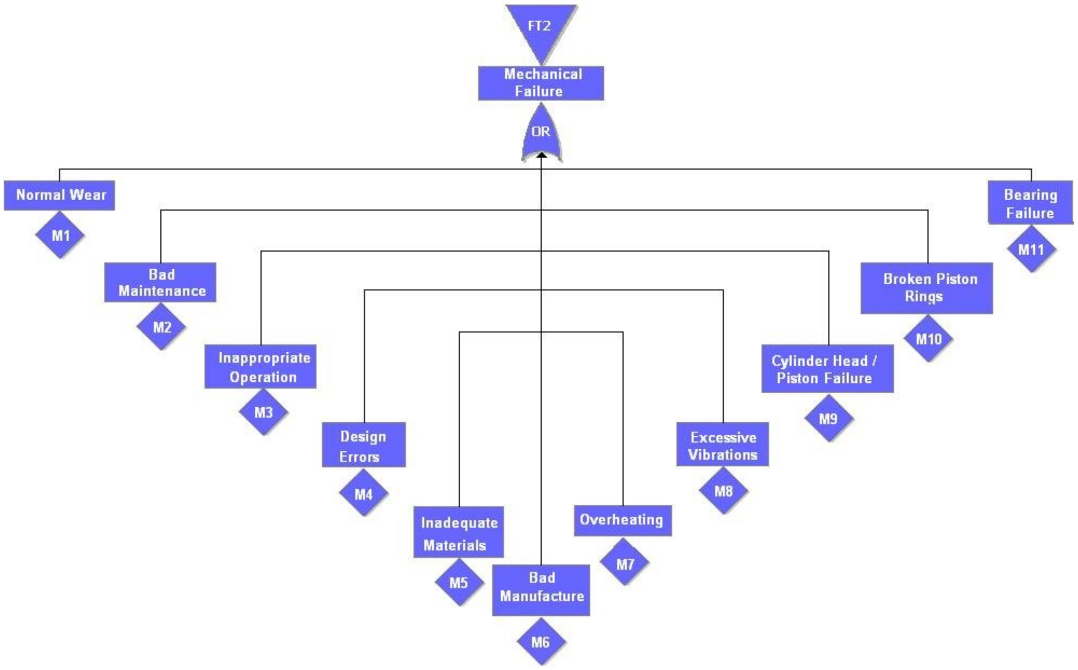


Figure 6. FTA: Mechanical Engine Failure

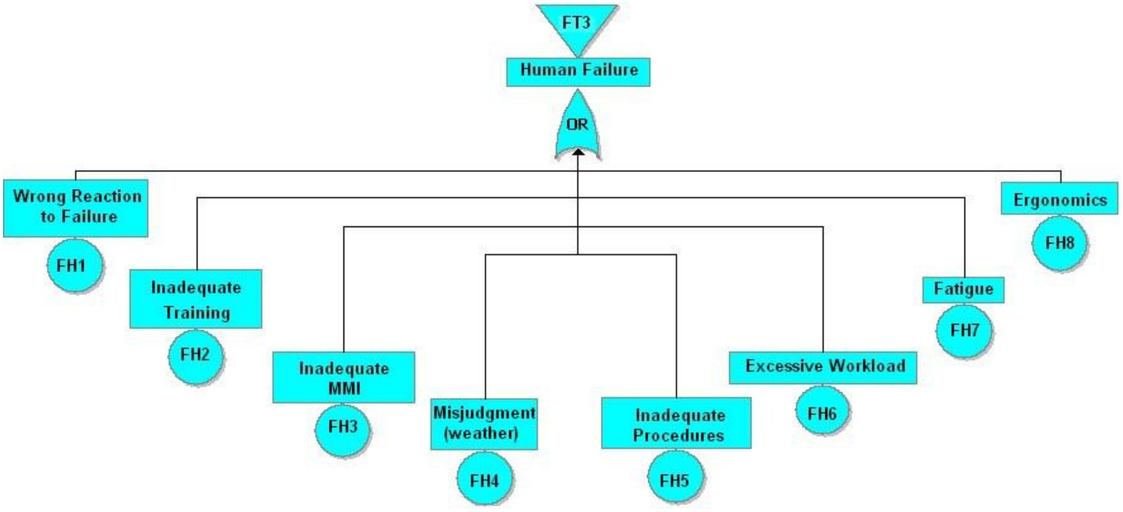


Figure 7.FTA: Human Failure

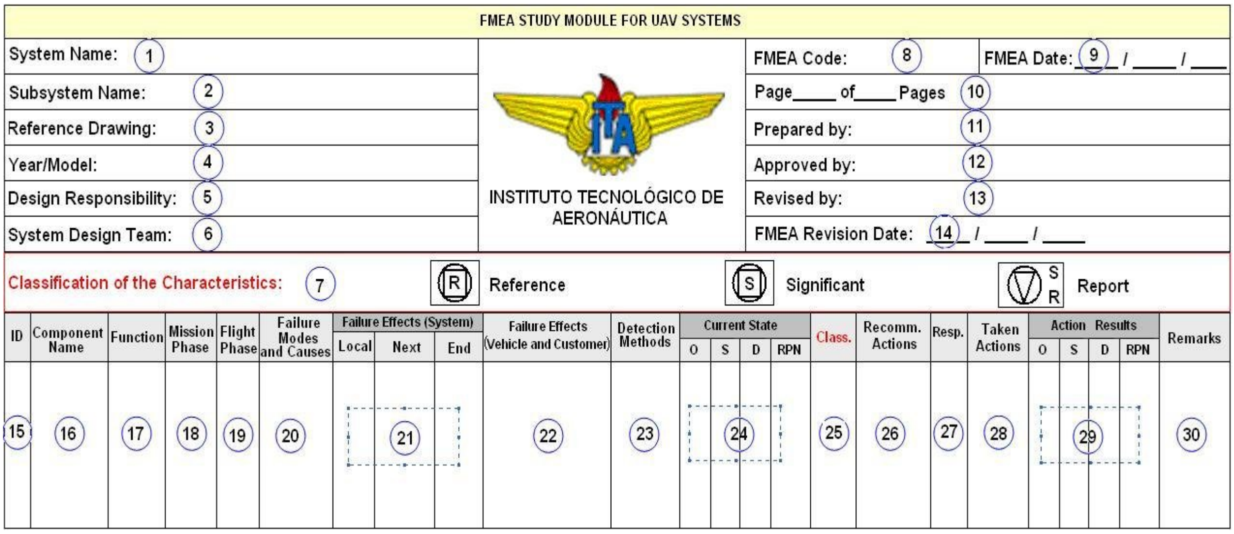
Note that a different FTA will have to be constructed for each defined top event which can be caused by different failure modes or different logical relationship between failure events. For large and complex system, computer programs can be used for generating and evaluating the system as well as cut set analyses. Also, note that FTA can be converted into Reliability Block Diagram (RBD) representation by replacing the Or gates with boxes in series. For a series system to operate successfully, all components must operate successfully, and the most import element for reliability improvement is that one with the lowest reliability.

3.2. Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is one of the most utilized methods for conducting reliability analysis. Like any analytical tool, if used and implemented correctly the FMEA is a powerful design engineering aid, and is used in the aerospace, military, automotive and space sectors. The principle of this method is to consider each failure mode in turn for every component of a system and to ascertain the effects of the failure on the relevant aspects of the system operation in order to determine corrective actions (RAC, 1993).

The FMEA utilizes inductive logic or bottom up analysis. The purpose of the FMEA is to identify potential hardware design weaknesses including undetectable failure modes and single-point failures. This is done by a thorough, systematic, and documented analysis of the probable ways (failure mode) that a component can fail the causes for each failure mode, and its effects on the operational capabilities of the end system. Each mission phase of the system would normally be taken into consideration. Its primary purpose is the identification of catastrophic and critical failure possibilities so that they can be eliminated or mitigated through design change.

For this analysis, we adapted FMEA Form based on commercial forms for UAV Systems as shown in “Fig. 8”. This form is divided into two parts. The first part with item numbers from 1 to 14 is the introduction part. The second part of the form includes items 14 to 30 which are the body items of any design FMEA.



FMEA STUDY MODULE FOR UAV SYSTEMS

System Name: ①	INSTITUTO TECNOLÓGICO DE AERONÁUTICA	FMEA Code: ⑧ / FMEA Date: ⑨ / ___ / ___
Subsystem Name: ②		Page____ of____ Pages ⑩
Reference Drawing: ③		Prepared by: ⑪
Year/Model: ④		Approved by: ⑫
Design Responsibility: ⑤		Revised by: ⑬
System Design Team: ⑥		FMEA Revision Date: ⑭ / ____ / ____

Classification of the Characteristics: ⑦ R Reference S Significant S R Report

ID	Component Name	Function	Mission Phase	Flight Phase	Failure Modes and Causes	Failure Effects (System)			Failure Effects (Vehicle and Customer)	Detection Methods	Current State				Class.	Recomm. Actions	Resp.	Taken Actions	Action Results				Remarks
						Local	Next	End			O	S	D	RPN					O	S	D	RPN	
⑮	⑯	⑰	⑱	⑲	⑳		㉑		㉒	㉓		㉔			㉕	㉖	㉗	㉘		㉙			㉚

Figure 8. UAVs FMEA Form

The process for conducting an FMEA is straightforward, and main steps are outlined below:

- **Function:** A brief statement about the objective function of the design;
- **Mission Phase:** a brief statement about the item’s objective or task to be carried out inside the functioning of the system;
- **Flight Phase:** vide section 2;
- **Failure Mode and Cause:** All probable failure modes for each item under analysis. A failure mode is defined as the manner in which a component, subsystem, or system could potentially fail to meet the system intent. A failure cause is defined as a system or design weakness that may result in a failure. An example of potential failure modes and causes for carburetor failure are improper adjustment, throttle failure, and others;
- **Failure Effects on System:** These are the consequences of each assumed failure mode on item operation. The failure under consideration may impact the several indenture levels, from Local Effects, Next Higher Level Effects and End System Effects. Examples of failure effects for the case carburetor are:
    - **Local Effect:** Engine cannot be controlled;

  - **Next Higher Level Effect:** Loss of Engine;
  - **End Effects on System:** Loss of Propulsion.
- **Failure Effects on Vehicle or Customer:** It evaluates the effect in the failure mode will be able to cause in the vehicle in activity and for the final customer in the eventuality of the occurrence of the fault;
- **Failure Detection:** A description of the way(s) by which a failure can be detected;
- **Risk Priority Numbers (RPN):** The Risk Priority Number is a mathematical product of the numerical Severity (S), Occurrence (O), and Detection (D) ratings. The RPN is used to prioritize items than require additional quality planning or action;
- **Classification (Class)**: Symbol that represents the class of the characteristic of the operation of the item under analysis;
- **Recommended Action(s):** Recommended actions intend to reduce the RPN for the different failure modes;
- **Taken Action(s):** This is about the follow-up actions;
- **Action Results:** After these actions have been taken, reassess the severity, probability and detection and review the revised RPN's;
- **Remarks**: Any pertinent remarks pertaining to and clarifying any other column in the worksheet line shall be noted.

From this way, FMEA looks to avoid or to minimize through the fault analysis, its effects and causes, as well as improvement actions for faults that come to take place in the system.

3.3 Criticality Analysis (CA)

Criticality Analysis (CA) ranks each failure mode according to each failure mode's severity of the failure effect and its probability of occurrence. The result of the CA will leads itself to the development of a Criticality Matrix which provides a visual representation of the critical areas of the system (RAC, 1993). According to MIL-STD 1629, each failure mode can be classified, as shown in “Tab. 3” and “Tab. 4”.

Table 3. Classification of Failures According To Severity

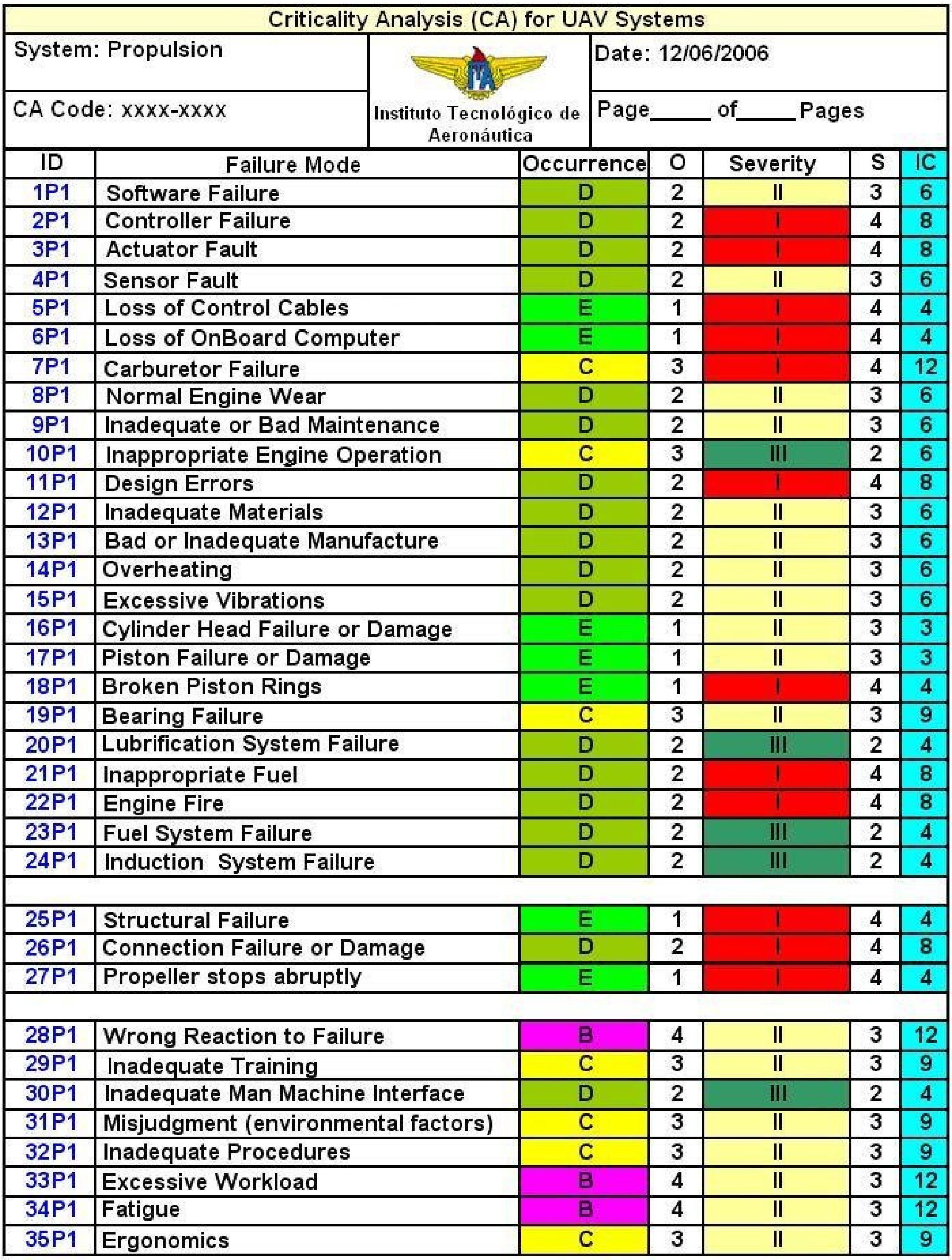
Category	Description	Mishap Definition
I	Catastrophic	A failure which may cause System ou UAV Platform loss
II	Critical	A failure which may cause major system damage which will result in a UAV mission loss.
III	Marginal	A failure which may cause minor system damage which will result in a delay or loss of availability or mission degradation.
IV	Minor	A failure not serious enough to cause system damage, but which will result in unscheduled maintenance or repair.

Table 4. Classification of Failures According To Occurrence (MIL-STD 1629A)

Level	Occurrence	Probability
A	Frequent	O > 0.2
B	Reasonable probable	0.10 > O > 0.2
C	Occasional probability	0.01 >O > 0.10
D	Remote probability	0.001 > O > 0.1
E	Extremely unlikely probability	O < 0.001

In “Table 5”, a Criticality Analysis (CA) for the propulsion system is performed, based on our experience and judgment due to lack of tracking by current operators UAVs, where the critical points of the system are highlighted.

Table 5. Criticality Analysis for Loss of Propulsion



Criticality Analysis (CA) for UAV Systems

System: Propulsion

Date: 12/06/2006

CA Code: xxxx-xxxx

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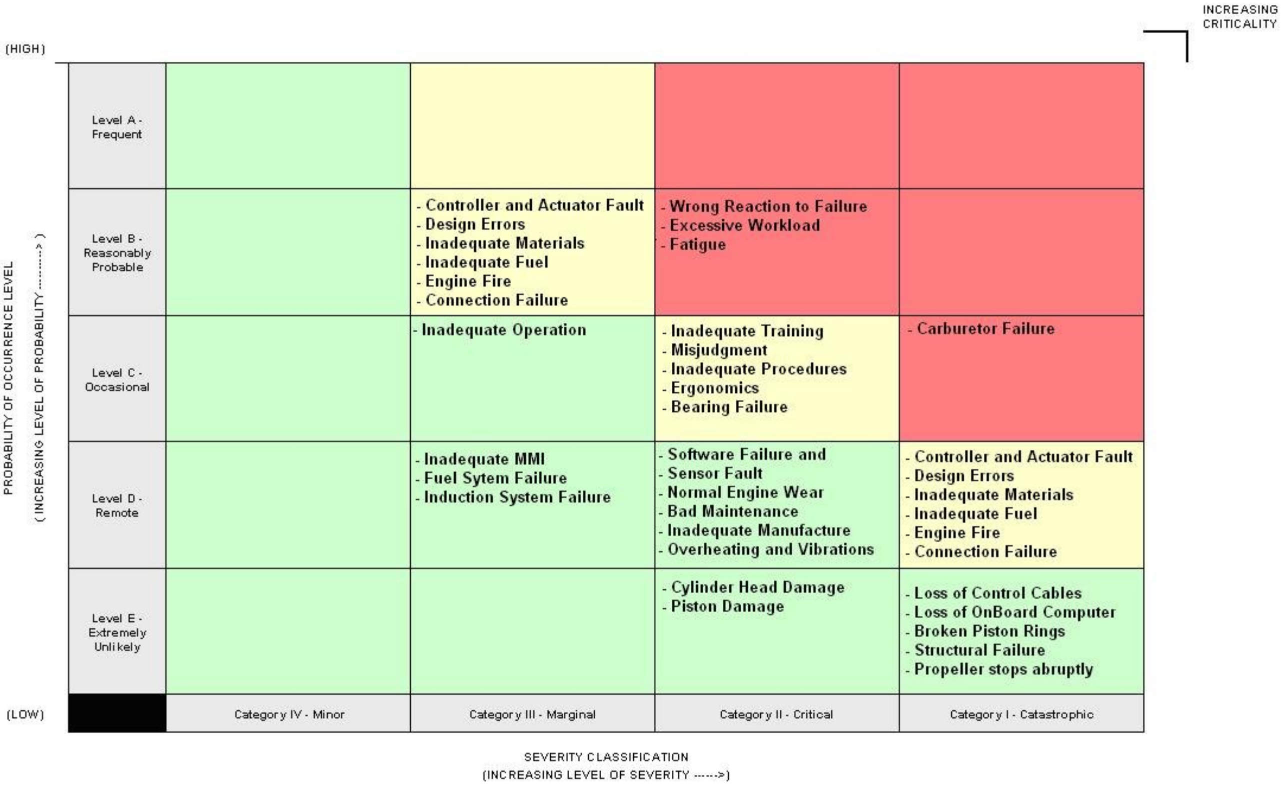
Page_____ of_____ Pages

ID	Failure Mode	Occurrence	O	Severity	S	IC
1P1	Software Failure	D	2	II	3	6
2P1	Controller Failure	D	2	I	4	8
3P1	Actuator Fault	D	2	I	4	8
4P1	Sensor Fault	D	2	II	3	6
5P1	Loss of Control Cables	E	1	I	4	4
6P1	Loss of OnBoard Computer	E	1	I	4	4
7P1	Carburetor Failure	C	3	I	4	12
8P1	Normal Engine Wear	D	2	II	3	6
9P1	Inadequate or Bad Maintenance	D	2	II	3	6
10P1	Inappropriate Engine Operation	C	3	III	2	6
11P1	Design Errors	D	2	I	4	8
12P1	Inadequate Materials	D	2	II	3	6
13P1	Bad or Inadequate Manufacture	D	2	II	3	6
14P1	Overheating	D	2	II	3	6
15P1	Excessive Vibrations	D	2	II	3	6
16P1	Cylinder Head Failure or Damage	E	1	II	3	3
17P1	Piston Failure or Damage	E	1	II	3	3
18P1	Broken Piston Rings	E	1	I	4	4
19P1	Bearing Failure	C	3	II	3	9
20P1	Lubrification System Failure	D	2	III	2	4
21P1	Inappropriate Fuel	D	2	I	4	8
22P1	Engine Fire	D	2	I	4	8
23P1	Fuel System Failure	D	2	III	2	4
24P1	Induction System Failure	D	2	III	2	4
25P1	Structural Failure	E	1	I	4	4
26P1	Connection Failure or Damage	D	2	I	4	8
27P1	Propeller stops abruptly	E	1	I	4	4
28P1	Wrong Reaction to Failure	B	4	II	3	12
29P1	Inadequate Training	C	3	II	3	9
30P1	Inadequate Man Machine Interface	D	2	III	2	4
31P1	Misjudgment (environmental factors)	C	3	II	3	9
32P1	Inadequate Procedures	C	3	II	3	9
33P1	Excessive Workload	B	4	II	3	12
34P1	Fatigue	B	4	II	3	12
35P1	Ergonomics	C	3	II	3	9

For our previous analysis for loss of propulsion, we can construct a criticality matrix, as noted in “Fig. 9” below.



	Category IV - Minor	Category III - Marginal	Category II - Critical	Category I - Catastrophic
Level A - Frequent				
Level B - Reasonably Probable		- Controller and Actuator Fault - Design Errors - Inadequate Materials - Inadequate Fuel - Engine Fire - Connection Failure	- Wrong Reaction to Failure - Excessive Workload - Fatigue	
Level C - Occasional		- Inadequate Operation	- Inadequate Training - Misjudgment - Inadequate Procedures - Ergonomics - Bearing Failure	- Carburetor Failure
Level D - Remote		- Inadequate MMI - Fuel Sytem Failure - Induction System Failure	- Software Failure and - Sensor Fault - Normal Engine Wear - Bad Maintenance - Inadequate Manufacture - Overheating and Vibrations	- Controller and Actuator Fault - Design Errors - Inadequate Materials - Inadequate Fuel - Engine Fire - Connection Failure
Level E - Extremely Unlikely			- Cylinder Head Damage - Piston Damage	- Loss of Control Cables - Loss of OnBoard Computer - Broken Piston Rings - Structural Failure - Propeller stops abruptly

Figure 9. Criticality Matrix for Loss of Propulsion

Criticality matrix displays the distribution of the all the failure mode according to severity category and its occurrence. From the above, it is obvious how important the human factor is for the propulsion system. The way how user operates and / or maintains the systems are also among the critical factors for propulsion failure mode. The importance of the carburetor, in our analysis, is also shown, constituting the hardware component the most critical among all the parts composing the propulsion system.

4. CONCLUSION

The use of UAVs in many civilian applications requires the improvement of safety conditions to avoid potential accidents. Reliability Methods plays an important role in this context. This paper has been presented the FTA, FMEA, and CA methods applied for UAV propulsion system. FTA is frequently used a qualitative evaluation method in order to assist the designer, planner or operator in deciding how a system may fail and what remedies may be used to overcome the causes of failure. The FTA always supplements the FMEA. Already the principle of FMEA is to consider each failure mode of every component of a system and to ascertain the effects on system operation of the each failure mode in turn. The FMEA is generally viewed as an analysis, which should be implemented during the design phase, to have maximum influence and impact on the final design. After the failure modes have been identified by the FTA or FMEA, the CA is performed to rank each failure mode according to the criticality and its occurrence. Its purpose is to identify all catastrophic and critical failure probabilities so they can be eliminated or mitigated as early as possible. Reliability Methods presented may be used for almost any kind of reliability analysis for UAVs such as Flight Control System, Power, Communication, and others. Here reliability cost, and benefits are like an investment, thus one truly gets what one pays for.

5. ACKNOWLEDGEMENTS

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