QUALITATIVE AND QUANTITATIVE ASSESSMENT OF RISKS ASSOCIATED TO HELIOS HP 03-2 UNMANNED AERIAL VEHICLE DEVELOPED BY NASA

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Anticipating and recognizing the latent (or current) errors or problems of a system is essential for developing a functional strategy for risk management and treatment; secondly, the hierarchy of risks and the prioritization of resources and actions must be considered. Risk assessment tools, which may be probabilistic, aim at identifying and assessing risks specific to different technological systems, such as an UAV developed by NASA. The risk assessment techniques help engineers to discover design/exploitation errors and deficiencies and can also represent a cornerstone for improving system performance and safety levels. Hence, the methods used throughout this paper will provide different perspectives on evaluating risks and at the same time will underlay the models drawbacks or shortcomings.

Keywords: risk assessment, Poisson processes, fault tree analysis, Ishikawa diagram, quality assurance, reliability, UAV

1. Introduction

The instruments for qualitative risk analysis, proposed in the early 1960's are structured to improve safety performance of the system and include the risk matrix, risk probability calculation and its impact, the Ishikawa Diagram (fish bone diagram), Fault tree analysis, etc.

Safety analysis (quantitative or qualitative) is often iterative, so it requires multiple cycles. Safety surveys mainly provide qualitative information; a reliance on more qualitative methods may be needed in the absence of quantitative baseline data [10].

Only a few hazards led to credible analysis just through quantitative methods [13], as the qualitative analysis defines, according to descriptive scales, the probability, the level of risk and consequences, but it cannot numerically aggregate risk interactions or provide sufficient information for a cost-benefit evaluation [2]. Qualitative risk assessment involves analyzing the severity of the consequences and their likelihood of occurrence, while the numerical expression

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which may involve probabilities or frequencies (regarding for example the number of injured persons) defines a quantitative assessment [1].

Risk management methods in combination with probabilistic risk assessment techniques reduce subjective factors in system evaluation. Thus, the authors aim to combine qualitative and quantitative approaches that offer different perspectives for discovering the associated risks defining a remotely piloted aircraft system.

The focus of this report is represented by the second unmanned aerial vehicle configuration developed in 2003 and managed by NASA’s Dryden Flight Research Center [5], which experienced pitch oscillation that led to significant configuration changes, so after a series of control problems, it impacted the water of the Pacific Ocean [14].

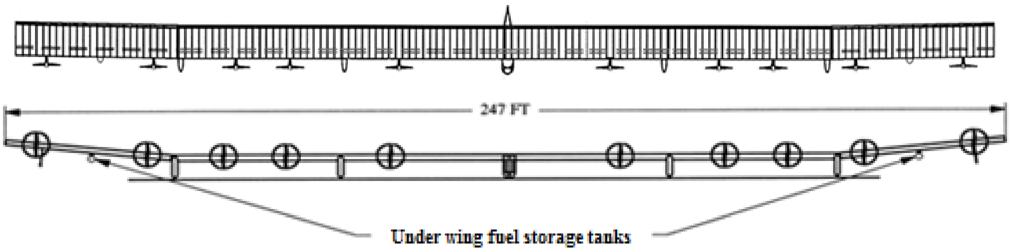

Fig. 1. Helios HP 03-2 configuration [5]

The starting point for the present research considers an important result of Helios accident report which emphasis the fact that the methodologies used for the accident analysis did not take into account the nonlinear control problems; hence linear analysis tools did not consider complex interactions on the vehicle.

The analysis of the root causes of the accident also outlined the inaccurate risk assessment of the effects of configuration changes and a wrong decision to fly an unmanned aircraft highly sensitive to disturbances [5]. Therefore, the range of methods used throughout this paper will provide different perspectives on risks evaluation, outlining the strengths and limitations of the analyzed models whilst quantifying and interpreting the obtained results.

2. Risk quantification through different methods. A case study for Helios HP 03-2

2.1. Statistical modeling of accidents

The first step of the present research represents performing statistical modeling of the probability of occurrences for the UAV accident. Secondly, the dependencies of the probability of occurrence on various parameters will be described and analyzed.

Statistical modeling of accidents production uses Poisson processes [3]. The process begins at $t = 0$, events taking place at random moments $t_1, t_2, t_3, \ldots, t_i, \ldots, t_N$. The time intervals between successive events are distributed exponentially; so the events do not depend on the number of previous events or the moment of their occurrence. This is shown in the Poisson process scheme in the figure below.

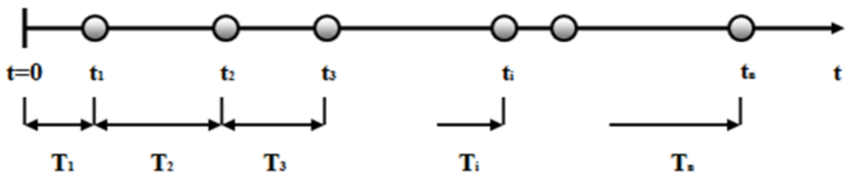

Fig. 2. Poison processes scheme

Assuming that an event occurs in an interval Δt, the probability of its occurrence can be estimated by $\lambda \Delta t$, (where λ represents the average of its failure/occurrence rate), it is proportional to Δt and it is assumed to be constant and equal to [3]:

$$\lambda = \frac{1}{T_a} \tag{1}$$

T_a is the average time intervals between consecutive events

The probability of occurrence of two (or more) events in the Δt interval is considered to be negligible, Δt being a sufficiently small interval.

T is a random variable, considered to be the time between any two consecutive events, and is also exponentially distributed.

The probability that no events occur at time t is:

$$P(T > t) \cong P(X_t = 0) = e^{-\lambda t} \tag{2}$$

X_t is the number of events produced at time t, and λ represents the average accident rate, and the probability of occurrence of at least one event at time t is:

$$P(T \le t) = 1 - P(T > t) = P(X_t \ne 0) = 1 - e^{-\lambda t} \tag{3}$$

In the context of the analysis of Helios HP 03-2 accident through different methods, the Poisson model represents a good analysis tool as it can model the occurrence of rare discrete events.

The last relationship will be considered in the fault tree analysis, to calculate the probability of the primary events in the tree structures to be studied. Thus, reliability and safety analyze will be conducted to describe and quantify failures, calculating the probability of failure of structural elements of the UAV and analyzing combinations of the underlying causes (environmental factors, structure, etc.) through an arborescent failure structure [15].

2.2. Application and critical analysis of Ishikawa Diagram and Fault Tree Analysis

The inputs of the risk analysis for the case studied provide data for the evaluation of fault modes and for estimating the effects of the failures. Analyzing the risks specific to such a UAV configuration requires knowledge of resource variations and system performance.

The Ishikawa Diagram or the Fish Bone diagram represents an analytical tool that provides a systematic way to study the effects and the causal factors that contribute to the effects [1]. The method developed by Kaoru Ishikawa illustrates the main and secondary causes of a particular process-related effect and the link between a consequence and the factors that led to its occurrence by underlying the causes and identifying the areas with insufficient information or the rationales why a process does not proceed as planned; therefore the analysis is performed for each phase and stage [4]. The implications outlined above are imperative for interpreting each process described in the diagram and finalizing the analysis.

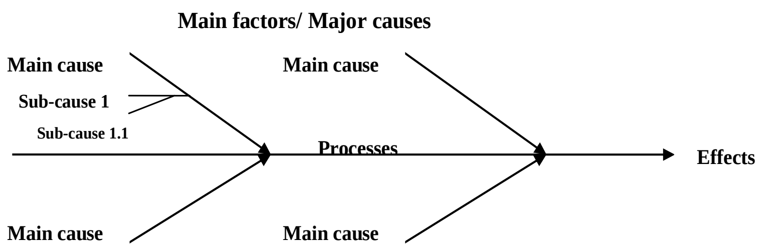

Fig. 3. Scheme of the Fishbone diagram

The method "captures an image" of a given circumstance, creating an overview and highlighting the cause-effect relationships by establishing details of factors that influence processes and areas requiring additional information, indicating thus what can be changed (as identification process and possible treatment of subsequent risk situations).

In the figure below, a Fishbone analysis will be exemplified, exploring the causal factors that have the effect of failing to control the system; in this case, the study shall cover an unmanned aerial vehicle, designed for remote measurements. In the diagram are presented 4 main causes and their subcategories, listed in the presented ramifications regarding meteorological conditions (turbulence, frost and the incidence of sun rays), erroneous risk assessment of the flight under inadequate conditions (wrong assessment of the risk, which may be: subjective, inappropriate or inadequate), the involvement of the human factor (i.e. inadequate training due to the setting of wrong criteria) and, finally, wrong processes and procedures through inadequate conditions [1].

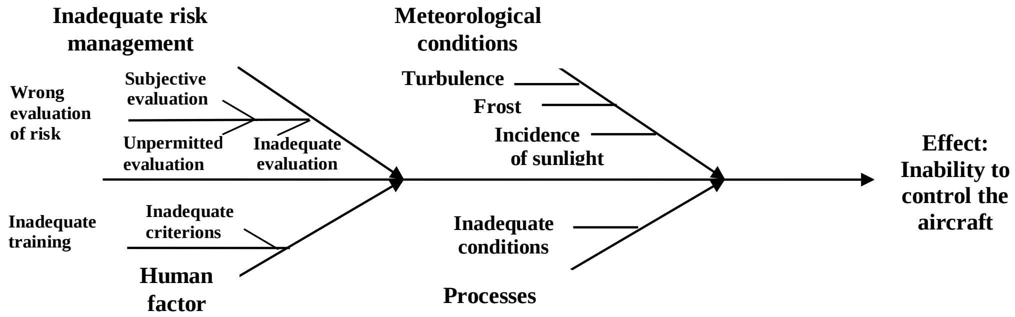

Fig. 4. Fishbone analysis applied for the UAV

Through this graphic method, used especially in quality control studies and processes, one can recognize areas where information is insufficient, but it also highlights the areas where they are repeated.

The confusion created by this representative tool in the field of quality assurance and management aims at treating it as a fault tree analysis; but this approach is incorrect as the FTA uses formal logical symbols to carry out a complex process for analyzing an unwanted event and researching its immediate causes, while the Ishikawa diagram is just a tool for inventory and enumeration of possible causes under the conditions of an unwanted event; but without considering each stage or cause [1]. These fundamental differences between the two methods must be highlighted since the only role of the Ishikawa diagram (as a graphical representation) is to discover and outline the structure and components of the process that compete to identify the risk [1].

Analysis methods built on the cause-effect duo, outline a hierarchical and chronological description of the factors involved, estimate the probability of occurrence of the events (without accurately indicating the moment of occurrence of an error) and in addition, may determine and classify the causes of an accident.

Further, in order to evaluate the causes that determined the UAV crash, a linear method used for probabilistic study of errors will be applied. This will be built through a deductive analysis that will determine a series of processes that preceded the emergence of the Top Event. Consequently, in the fault trees that will be considered for the study of Helios HP 03-2 UAV accident, primary faults (base events) and then, intermediate events will be built up by an inverted logic, in order to frame the scenario of the analyzed event.

The algebra of 0 and 1 (i.e. the Boolean algebra) allows the combination of elementary logical gates in order to build a complex arboreal structure.

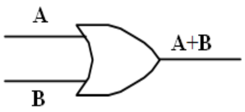

Fig. 5. Result of the logical gate "OR"

The following examples of a fault tree analysis will consider the primary events in an "OR" gate which has the scheme represented above.

Table 1

Truth value for logical operations

Operator	Operation	Operator A	Operator B	Value
OR	Operator A+ Operator B	0	0	0
		0	1	1
		1	0	1
		1	1	1

The following examples can be considered a structure of a fault tree, knowing that if an accident would occur, the probability of the top event (i.e. of a certain event) would have the value 1.

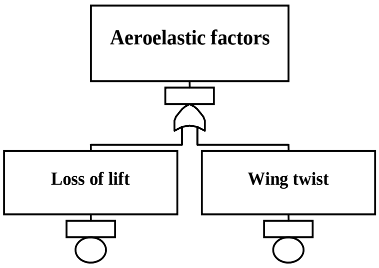

Fig. 6. Fault Tree structure for aeroelastic factors

$$P(\bigcup_{i=1}^{n}(A_i)) = \sum_{i=1}^{n} P(A_i) - \sum_{j=2}^{n}\sum_{i=1}^{j-1} P(A_i \cap A_j) + \sum_{k=3}^{n}\sum_{j=2}^{k-1}\sum_{i=1}^{j-1} P(A_i \cap A_j \cap A_k) + (-1)^{n-1} P(\bigcap_{i=1}^{n}(A_i)) \quad (4)$$

Considering the events: A_1-loss of lift and A_2-wing twist and their probabilities:

$P(A_1) = 1 \cdot 10^{-3}$

$P(A_2) = 3 \cdot 10^{-4}$

The probability for these aeroelastic factors to produce can be calculated:

$$P(A_1 \quad or \quad A_2) = P(A_1) + P(A_2) - P(A_1) \cdot P(A_2) \tag{5}$$

So, for two events, the probability for the OR gate, is:

$$P(OR \quad gate) = P(A_1) + P(A_2) - P(A_1) \cdot P(A_2) =$$
$$= 1 \cdot 10^{-3} + 3 \cdot 10^{-4} - 1 \cdot 10^{-3} \cdot 3 \cdot 10^{-4} =$$
$$= 0.0012997 = 1.2997 \cdot 10^{-3}$$

Another example of a fault tree structure that can be constructed for the Helios HP 03-2 accident will be presented as follows. In this case, the ramifications regarding meteorological conditions (turbulence, frost and the incidence of sun rays) considered in the Ishikawa diagram will be evaluated through a probabilistic approach, using logical gates and imposing the rules of Boolean algebra.

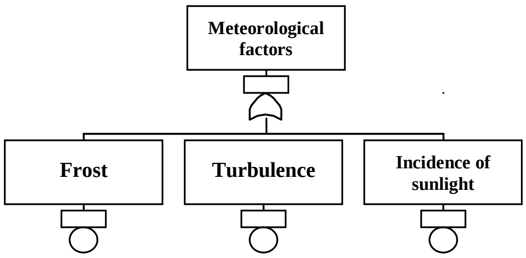

Fig. 7. Fault Tree structure for meteorological factors

Considering the events: B_1-frost, B_2-turbulence and B_3-incidence of sunlight, the probability of an intermediary event (considering meteorological factors) can be calculated as follows:

$$P(B_1) = 2 \cdot 10^{-3}$$
$$P(B_2) = 2 \cdot 10^{-4}$$
$$P(B_3) = 3 \cdot 10^{-5}$$

$$P = (P(B_1) + P(B_2) + P(B_3)) - (P(B_1B_2) + P(B_2B_3) + P(B_1B_3)) + P(B_1B_2B_3) \tag{6}$$

For three events, the probability for the OR gate, is:

$$P(OR \quad gate) = (P(B_1) + P(B_2) + P(B_3)) -$$
$$-(P(B_1B_2) + P(B_2B_3) + P(B_1B_3)) + P(B_1B_2B_3) =$$
$$= (P(B_1) + P(B_2) + P(B_3)) - (P(B_1 \cap B_2) + P(B_2 \cap B_3) + P(B_1 \cap B_3)) +$$
$$+P(B_1 \cap B_2 \cap B_3)$$
$$P(OR \quad gate) =$$
$$= (2 \cdot 10^{-3} + 2 \cdot 10^{-4} + 3 \cdot 10^{-5}) - (4 \cdot 10^{-7} + 6 \cdot 10^{-8} + 6 \cdot 10^{-9}) + 12 \cdot 10^{-12} =$$
$$= 0.002229534012 = 2.229524012 \cdot 10^{-3}$$

In the context of linear accident methods, the fault tree analysis quantitative and qualitative aspects make it not only a descriptive sequential model, but a good tool to explore and quantify risks. By developing the above analysis, the basic assumptions of errors were considered and described through an expository tool, but also evaluated using logical equations.

2.3. A probabilistic approach on the reliability of the UAV structure

Determining a product's compliance with technical standards by meeting certain conditions is a matter of quality assurance, otherwise, in the contrary case it may result in failure.

Table 2

Characteristics of faults and non-compliance

Category	Characteristics
Fault	Failure to comply with conditions/usability
Non compliance	Failure to comply with specifications

As a quality assurance aspect, the focus on the internal variations of the UAV, the decrease of efficiency and the modification of system characteristics should have been used and implemented as a way of controlling/minimizing the occurrence of failures.

The materials, production and technological process are elements that have influenced the moment of occurrence of the faults and their nature, so the notion of quality cannot be separated from the technical framework. The decision to fly in an inappropriate configuration was determined by the fact that the HP03-2 configuration was adapted from the HP01 that was able to fly at altitudes above 30 km due to a budget cut in NASA's ERAST project [11].

The Helios HP03-2 Prototype was designed for long-duration flight and used efficient photovoltaic cells disposed on the upper surface of the wing to power the vehicle's electric motors and it's subsystems during the day [6].

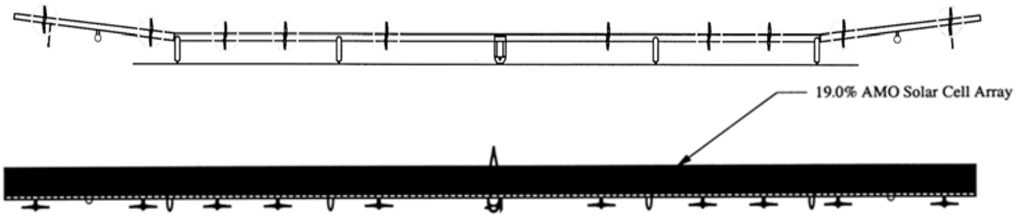

Fig. 8. Helios HP 03-2 solar cell array [5]

The batteries for photovoltaic systems have a limited life of service and their efficiency depends on temperature, the cycles of loading/unloading and in addition, extra use and aging causes gradual depletion so the result is the need for battery replacement [7].

Table 3

Fault criterions and manifestation

Criterion	Fault	Manifestation
Occurrence	Progressive	Anticipated on the basis of observations/analyzes
	Instantaneous	Cannot be anticipated

The probability of failure of these batteries can be calculated as a forecasting model taking into account the set of components subject to observation that have the condition to belong to a homogeneous domain and the studied set must be sufficiently large.

$$P_f = \frac{n_f}{t_i \cdot \sum_1^N i} \tag{7}$$

P_f - probability of failure

n_f - number of failures

t_i – operating time

N - number of analyzed components

The method is important as a general preliminary analysis in a specific study (in this case for the Helios HP 03-2 UAV), more so if the considered set is a poorly homogeneous one [9]. Forecasting estimates for different levels of a system allow for a qualitative functioning analysis from the design stage, calculating the probability of failure and highlighting possible weaknesses, this being a starting point for improving the safety level.

Statistic control and reliability studies show that batteries used in overheat conditions present faults in the case of 6.948 of the batteries from 10^6 analyzed [7], [8]. Thus, the absolute risk of battery malfunction or failure in the above mentioned circumstance (i.e. overheat) can be calculated as following, considering the events [7]:

A_1 -overheat and A_2 -battery failure

$$P(A_2 \mid A_1) = \frac{P(A_1 \cap A_2)}{P(A_1)} = \frac{P(A_1, A_2)}{P(A_1)} \tag{8}$$

$$P(A_2 \mid A_1) = \frac{6.948}{10^6} = 6.948 \cdot 10^{-6} \tag{9}$$

As previously stated, for Helios HP 03-2, a flight decision under adverse weather conditions in conjunction with other factors (e.g. aeroelastic), has led to the production of an accident. The discovered faults are influenced by prior states of the system, so in order to determine their causes and influences, the following factors have to be analyzed: the moment, type, location, intensity and failure modes.

Table 4

Causes and manifestation of faults

Criterion	Fault	Manifestation
Cause	Improper use	Reported to undetermined design errors
	Deficiencies	Stress exciding admissible limits
	Wear	Probability increased over time

At the entrance of the aircraft in a turbulent area, the structure of the UAV has been deformed, this being determined by an erroneous design of a configuration sensitive to turbulence. Consequently, the large dihedral angle caused instability on the OY axis, the dynamic pressure has increased, and the aircraft has disintegrated.

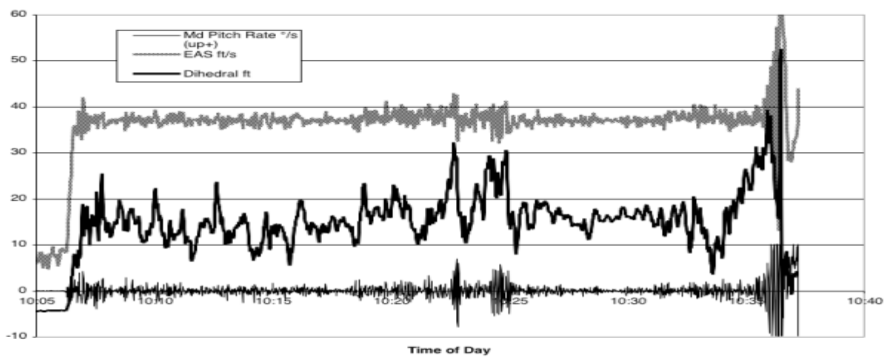

Fig. 9. Wing Dihedral, Pitch Rate, and Airspeed History for Flight HP03-2 [5]

In addition to the points outlined above, the financial implications are important. Also, it is essential to underline the impact on the manufacturer that made the decision to design a configuration with a deforming structure.

The probability of this event was calculated using the Fault tree analysis and has the value $3.8 \cdot 10^{-3}$ [12]. The calculation of the costs corresponding to the caused damage was estimated to be \$ 20 million, so the expected value of risk (i.e. $EV(a)$) can be calculated.

$$P(a) = 3.8 \cdot 10^{-3};$$

$$E(a) = 20000000\ \$\ ;$$
$$EV(a) = P(a) \cdot E(a)\ ; \qquad (10)$$
$$EV(a) = 3.8 \cdot 10^{-3} \cdot 20000000 = 76000\ \$$$

Validated mathematical models that support risk analyzes can exclude such situations, and consequently the consequences/impact of an accident, regardless of their nature. Numerical risk estimates are possible if data needed to calculate the likelihood of occurrence are available.

3. Conclusions

The analysis conducted throughout this paper became a matter of identifying critical elements that either have not been considered in the design phases or can have significant financial (or other) implications on the decision not to develop another configuration of this kind (i.e. NASA'S Helios HP03 UAV).

Through various analysis tools, the retrospective research on the UAV crash has implemented qualitative and quantitative models in order to describe and explore the interaction of accident contributing factors. This way, a better comprehension of the determinant factors that influenced the likelihood of the event has also been acquired.

For the risk control stage, the information on the risk management processes which involved the follow up of specific risks was to be considered; followed by a quantitative evaluation of the consequences of the different scenarios. Early detection of risks by identifying and collecting data from multiple sources and the configuration of parameters associated with hazards, vulnerabilities and threats, as well as through proactive observations and approach might have represented a solution for avoiding the production of Helios HP-03 accident.

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