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CONTRIBUTION TO R.A.M.S ESTIMATION IN EARLY DESIGN PHASES OF UNMANNED AERIAL VEHICLES – UAVS

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ABSTRACT

The aim of this work is to establish a methodology for assessments of Reliability, Safety and Maintenance features for future UAVs, to be integrated in complex Monitoring Systems, like SMAT System. This paper highlights the high level of complexity connected to this type of assessment. In particular, one of the principal sources of difficulties is the need of estimating RAMS characteristics for a product that is still not known in detailed, like it is usual for airplane in Conceptual Design phase. A further problem concerns the need of dealing with UAVs, i.e. aircraft with strong peculiarities and, due to the very recent development, poor historical data. By the way, referring to a methodology that has been previously developed for manned aircraft (by the research group the authors belong to), a new estimation process applicable to unmanned airplanes is here proposed. At the end, a comparison between the obtained results and few historical data is reported.

Keywords: Reliability, Safety, Maintenance, UAV, Conceptual Design

1 INTRODUCTION

Today, in the Aerospace field, the assessment of Reliability, Safety and Maintenance features of a new System has become a common practice since the earliest design phases [1] [2]. During these preliminary stages, the new System concept is defined, as well as its architecture and its relevant features (not at detailed level). This process is clearly depicted in Ref. [3]. The aforesaid requirements should be considered as guidelines since the very first design phases, even if the approach to Reliability, Safety and Maintenance could be affected by some additional difficulties, mainly due to the lack of definition of detailed features. This implies ad-hoc strategies to be implemented throughout the development of each single product. Moreover, this is a relevant aspect in case the designers face with Unmanned Aerial Systems (UAS), i.e. a System constituted by aircraft without human pilot on board, the so-called Unmanned Air Vehicle (UAV), and related ground infrastructures.

Among all the relevant aspects engineers should take into account, the peculiarity of a GCS-Ground Control Station and of all other support elements (better, the "system support") typical of all other kind of aircraft. Please note that, UASs are becoming more and more relevant, both from the technical and the industrial point of view. As far as the technical point of view is concerned, it can be useful to underline the advantages of UAVs. Indeed, the absence of human pilot allows eliminating many onerous devices, like cockpit and the necessity of defining aircraft shape to conjugate Pilot visibility requirements with aerodynamics, the furnishing or many other elements required to host and support human Pilot, like Environmental Control System, Voice Communications, Displays and Controls. Another more relevant feature is the possibility of avoiding all the constraints related with physiological aspects like time limitations, the lack of attention, tiredness and boredom, and, in general, all the risks that can affect a human life. Obviously, most relevant drawback is the need for a GCS able to perform a part of Human Pilot Tasks and of creating a sort of "Artificial Intelligence" on board. The level of complexity of this sort of intelligence strictly depends on the desired or required autonomy level for the considered UAS. Focusing on the above-mentioned advantages, the success of UAVs is clearly demonstrated by the very high number of models built and currently in-service or in-development phase, as well as the extremely wide spread range of performances, technical characteristics, sizes, architectural solutions, kinds of engines, etc.

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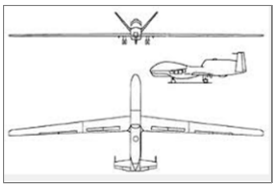
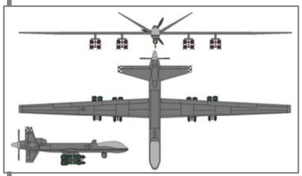
Northrop Grumman RQ-4 Global Hawk



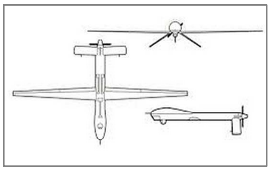

Role:Reconaissance, Surveillance, Monitoring
Lenght 15.40 m
Wing span 35.42 m
Wing Area 50,10 sqm
TOGW 12133 kg
Empty Weight 5100 kg
Power Plant 1 x T.Fan AE3007H - Thrust: 36.8 kN
Speed 640 km/h
Ceiling 19000 m
Range 25000 km

General Atomics MQ-9 Reaper



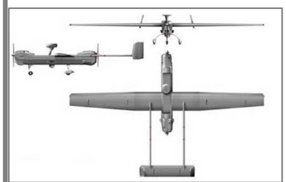

Role: Surveillance, Monitoring & Combat
Lenght 11.00 m
Wing span 20.00 m
Wing Area 20.80 sqm
TOGW 4760 kg
Empty Weight 2223 kg
Power Plant 1xT.Prop TP331-10T – Power: 712 kW
Speed max 480 km/h
Ceiling 15000 m
Endurance 14 – 28 hours

General Atomics RQ-1 Predator



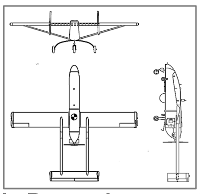

Role: Surveillance, Monitoring & Combat
Lenght 8.22 m
Wing span 14.80 m
Wing Area 11.50 sqm
TOGW 1000 kg
Empty Weight 512 kg
Power Plant 1x4-Piston ROTAX 912 - Power: 72 kW
Speed 218 km/h
Ceiling 7800 m
Endurance 24 hours

Northrop Grumman RQ-5 Hunter




Role: Reconnaissance, Target acquisition
Lenght 7.00 m
Wing span 8.90 m
Wing Area 8,00 sqm (estimated)
TOGW 725 kg
Empty Weight 510 kg (estimated)
Power Plant 2 x 2 cylinder – Power:2 x48 kW
Speed 196 km/h
Ceiling 4570 m
Endurance 12 hours

AAI corporation RQ-2 Pioneer




Role:Reconaissance, Surveillance, Monitoring
Lenght 4.00 m
Wing span 5.20 m
Wing Area 50,10 sqm
TOGW 205,00 kg
Empty Weight 155,00 kg (estimated)
Power Plant 1xUEL AR-741 (Wankel eng.) Power:28.3 kW
Speed (max) 200 km/h
Ceiling 4600 m
Endurance 5 hours (at 185 km distance)

Dassault (et alii) nEUROn

Role: Combat (experimental aircraft)
Lenght 9.20 m
Wing span 12.50 m
Wing Area 50,10 sqm
TOGW 6500 kg
Empty Weight 4900 kg
Power Plant 1 x R.R. Adour - Thrust: 40.8 kN
Speed 0.8 Mach
Ceiling 14000 m
Range ? km

Figure 1 Typical UAVs overview

Figure 1 shows typical UAVs models, ranging from a Take Off Gross Weight (TOGW) of more than 10,000 kg (the Northrop-Grumman Global Hawk, with turbofan engine), going from the General Atomics Reaper with turboprop, to the smaller UAVs with reciprocating engines and different roles. Concerning the typical UAV roles, the readers should notice that UAVs could range from the pure Combat task (and in this case they are called UCAV-Unmanned Combat Air Vehicle, of which a clear example is the experimental "nEUROn"), to a wide spread of Reconnaissance, Surveillance, Monitoring and Target Acquisition tasks. Obviously, the difference in roles implies variations in performance and size of the airplane. Even if combat tasks can be performed too (for example see in Fig. 1, the weapons of "MQ-9 Reaper"), UAVs designed for Reconnaissance, Surveillance, Monitoring and Target Acquisition tasks reveal a clear homogeneity. Furthermore, this last group of UAVs has real perspectives to be used in Civilian applications [4]. Thus, in this paper, the Authors will discuss only about this last kind of UAVs, focusing on the way to reach an acceptable capability in terms of Reliability, Availability, Maintainability, Safety (RAMS) assessment. Moreover this paper proposes a possible way to reach an enough high level in the definition of those related requirements since the earliest phases of a new UAV development.

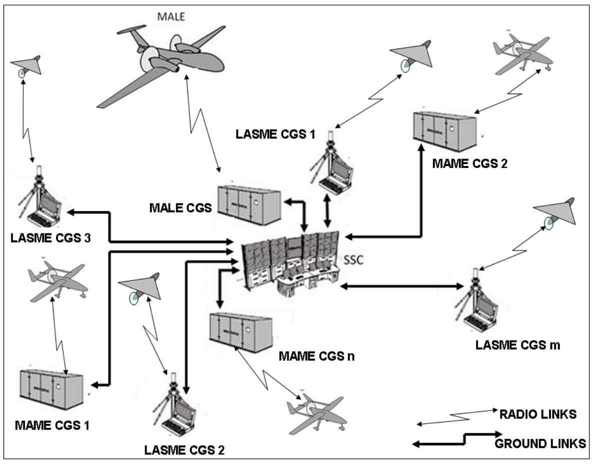


Figure 2 SMAT system configuration

The idea of in-depth studying these RAMS characteristics arose from the participation of the Authors to the Research Program SMAT – *Sistema di Monitoraggio Avanzato del Territorio* (Advanced Land Monitoring System). The Project has been proposed and funded by Regione Piemonte Government and Fondo Sociale Europeo. It hypothesized a Territory Monitoring System, whose configuration is schematically shown in Figure 2. It is based on several kinds of UAS with the aim of controlling and monitoring the entire Piedmont Region or an even wider territory. Indeed, the final target is to define a System able to be offered, in customized configurations, at a higher number of interested Users from all over the word. In Fig. 3 several possible scenarios are illustrated, showing different areas to be covered. In particular, the research focuses on a fleet of several UAVs belonging to different categories (MALE-Medium Altitude Long Endurance, MAME-Medium Altitude Medium Endurance, LASME-Low Altitude–Short/Medium Endurance and Mini and Micro UAVs) and operating from a certain number of possible bases located in Italy. Figure 2, depicts a possible integrated system able to exploit MALE, MAME and LASME. SMAT program has been intended as a way to support the ground operation in both critical, like fire and flood, and nominal situations, as traffic control or thematic mapping.

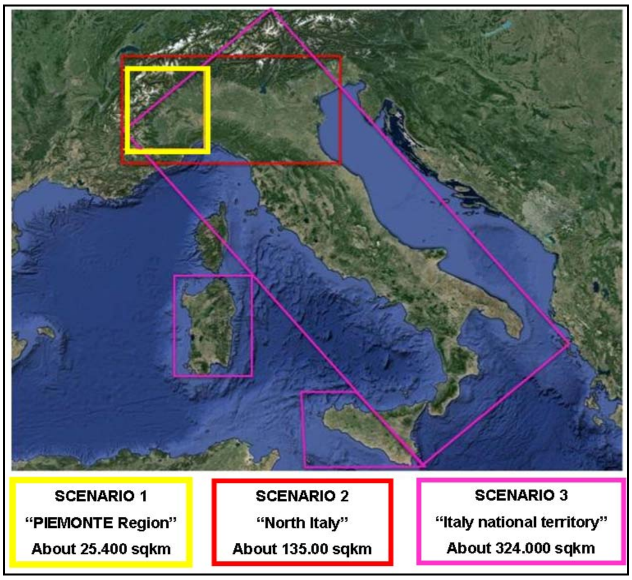


Figure 3 SMAT example of scenarios
with different extension

2 RELIABILITY ASSESSMENT IN EARLY DESIGN PHASE

A system like the one proposed in SMAT project is a clear example of how it is necessary to acquire the capability of assessing reliability and all the other related characteristics, like safety and maintenance features of new aerial systems. Fig. 2 reveals how many constraints on the system efficiency can be related to Reliability and Maintenance features. The variety and the relevance of these constraints are schematically shown in Fig. 4. Moreover, this Figure allows the readers to understand the multiple influences on both the efficacy and on the costs of the system, highlighting the key role played for the success possibility of the System itself. In Fig. 4, maintenance features have been separated into two contributions: the one directly related to the product (i.e. Maintainability, Ref. [5]) and the ones concerning the Maintenance Organization, or, better, to the support system.

For all the above-mentioned reasons it seems to be clear that Reliability characteristics of Sub-Systems and their Maintenance features have to be kept under close control during the development of System and the System Support definition. In particular, in case there would be the wish of integrating already existing UAS in a new Monitoring System, Reliability and Maintenance features of the under-investigation elements are known and it is possible to take them into account. However, it is clear that this is not the more convenient way to develop an optimal system. Indeed, in this case, the designers have to accept not only reliability and maintenance features but also performances and size of the basic components of the system. Conversely, if the system is completely conceived *ex novo*, the engineer should have the possibility of obtaining a really optimal system, perfectly adapted to the considered Scenarios and to all the already existing exploitable like bases infrastructures, maintenance organization characteristics, etc. In this case, reliability and maintenance, as well as all the other UAS characteristics must be defined as specification requirements the system's components must comply with. The relevance of this operation it is well known in case of UAS, in which there isn't a great amount of historical data. The problem is becoming even more difficult, as far as reliability and maintenance features are concerned, because these characteristics are strictly connected to the details of the design. These connections mainly depend on the relevance of these RAMS features in defining a system, in particular a complex and critical one [6], and on the consideration that more advanced system design methodologies [7], forcing us to take into account all relevant features of a new product since from the early Design phases [8]. To this purpose the authors developed a methodology for reliability, safety and maintenance features assessment in aeronautical Conceptual Design Phase [9], but the problematic to apply it to a kind of a quite peculiar airplane with a still short story and not so many historical data available are well kwown

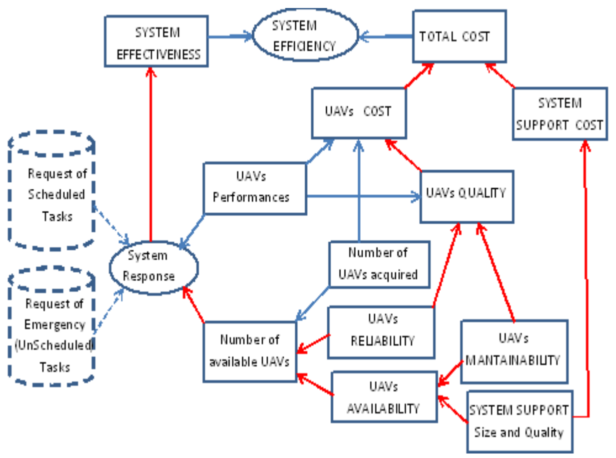


Figure 4 Influence of Reliability and Maintenance features on system efficiency

3 UAV RELIABILITY AND SAFETY ASSESSMENT AT CONCEPTUAL DESIGN LEVEL

In developing the aforesaid methodology for a preliminary estimation of Reliability, Safety and Maintenance features in the Conceptual design phase, the Authors had to face with the lack of detailed data, typical of these phases of the Design. Essentially, they try to solve the problem by using not only technical macro-features already known in early development phases, (such as the vehicle overall weight, and/or indicative main performances) but also compensating the lack of information by introducing qualitative concepts (such as the level of complexity, role, technological age, etc.). These concepts are based on known data of existing airplanes. These aircraft are clearly defined by the point of view of the Complexity level, of the Role, of the Technologies adopted and of the Innovation level. A first estimation attempt for the basic failure rate λ_b is reported n Eq. (1a) and it can be solved using statistical data.

$$\lambda_b = k \cdot \mathrm{MEW} \cdot \mathrm{IR} \cdot \mathrm{IC} \cdot \mathrm{IA} \qquad (1a)$$

where:
MEW = Manufacturer Empty Weight [t];
k = ratio between the failure rate and MEW for a Medium Civil Aircraft, usually equal to 1.8 (failures/1000h)/t;
IR = Index of Role;
IC = Complexity Coefficient;
IA = Technological Age Index.

Some indications are then suggested for the values of the qualitative parameters present in (1a), and this is made in Tables I, II and III, with the warning, already told, that methodology has been developed for Conceptual Design Level of "manned aircraft".

Table I - Index of Role suggestions

Role	IR
Fighter	16.60
Military Transport	2.10
Civil Transport	1

Table II - Complexity Coefficient suggestions

Complexity Level	Complexity Coefficient	Reference Aircraft
Low	0.8	S211
Middle	1.0	AMX
High	1.4	Tornado, Eurofighter EF 2000
Very High	1.6	F-22

Table III, reported from reference [9] shows how (1a) is able to give satisfactory estimation for many kind of manned aircraft, only utilizing few parameters that are easy to fix even in early design phases.

Table III - Technological Age Index suggestions

Technological Age	Age Coefficient	Reference Aircraft
2000	0.66	F-22
1990	1.0	Eurofighter EF 2000
1980	1.5	AMX
1970	2	Tornado
1960	2.5	F104S

Table IV [9] shows how the Eq. (1a) is able to give satisfactory estimations for many kinds of manned aircraft, only utilizing few parameters that are easy to fix also in the earliest design phases. Certainly, the problem becomes even more complex in the case of UAVs, not only for the poor base of historical data, but also for the peculiarities of this type of aircraft.

Table IV - Example of λ_b estimation for manned aircraft, Ref. [9]

Aircraft	k	IR	IC	IA	MEW (ton)	λ_b (failures/1000h)
Eurofighter EF 2000	1.8	16.6	1.4	1	9.6	402
TORNADO	1.8	16.6	1.4	2.0	13.8	1155
AMX	1.8	16.6	1.0	1.5	6	269
JAS 39 GRIPEN	18	16.6	1.4	1.2	6	301
C130	1.8	2.1	1.0	2.5	35	331
A400	1.8	2.1	1.0	0.7	45	119
C17	1.8	2.1	1.4	0.8	120	508
G222	1.8	2.1	1.0	2.0	15	113
A320	1.8	1.0	1.4	1	42	106
B747	1.8	1.0	1.4	2.0	170	857
ATR42	1.8	1.0	1.0	1.5	10	27

Indeed, as far as the "Role Index" is concerned, it is quite sure that UAVs for Monitoring and Surveillance are different both from Fighters and from transport aircraft, considering military and civil applications. However, UAVs with monitoring & surveillance roles canbe considered more similar to fighters, as far as on-board systems are concerned.
This can be justified noticing that they are extremely far from the features of aircraft hosting passengers and that there is the need of taking into account the additional complexity of ground station and the communication links between air and ground segment. By the way, it is also clear that, neglecting Unmanned Combat Air Vehicle (UCAV), the UAVs devoted to the reconnaissance, monitoring, target acquisition do not face with high "g" maneuvers and never utilize weapons and related systems, like Fighters do. Thus, the Authors hypothesize to define an Index Role, see Eq. (2), equal to the 50% of the one defined for fighters, even for present application, limiting the field of application to UAVs with civilian purposes.

$$IR_{UAV} = 8.30 \tag{2}$$

On the contrary it is possible to estimate the other coefficients required by Eq. (1a) applying a similar methodology. With reference to Table II and Figure 1, *ad-hoc* values have been proposed, in order to characterize a group of existing UAVs as it is shown in Table V.

Table V - UAV Example of parameters required for λ_b estimation

UAV	k	IR	IC	IA
Global Hawk	1.8	8.30	1.6	0.66
nEUROn	1.8	8.30	1.6	0.66
Predator RQ-1A	1.8	8.30	1	1
Reaper RQ-1B	1.8	8.30	1	0.8
Pioneer RQ-2B	1.8	8.30	0.6	1.3
Hunter RQ-5	1.8	8.30	1.4	1.3

But some considerations on the UAV peculiarity are certainly necessary and, to this purpose, the Ref. [10] constitutes an optimal data source. In particular, it reveals some strong differences between Fighters and UAVs. For example, in the methodology proposed in Ref. [9], a proportionality between the Basic Failure Rate (which is comprehensive of any kind of failure) and Safety Failure Rate (which takes into account only critical failures) is considered. This has been explicated in Eq. (3).

$$\lambda_s = \frac{\lambda_b}{LR} \tag{3}$$

In Eq. (3) LR is a sort of "role index" and it is different accounting for the several kinds of airplanes. Ref. [9], suggests a value of 10^4 for fighters and of 10^6 for civil transports. These values are related both to the different order of magnitude in the total life flown hours and to the different kind of legal position of a Military Pilot and of a Civilian Passenger, as well as the more stressed technical characteristics of Fighters. In the current assessment, complying with the previous hypothesis of considering UAVs similar to Fighters, the Eq. (3) could be rewritten as presented in Eq. (4a):

$$\lambda_s = \frac{\lambda_b}{10^4} \tag{4a}$$

Please note that this relationship can be useful as a verification with values of "Safety Failure Rates" that are quite strongly fixed (up to now, almost for Manned Aircraft!) due to certification reasons.

Putting aside this method, Unmanned Aerial Vehicles data have to be considered more similar to those to be included in a new System as, for example, SMAT. These data should refer to UAV with a yet considerable number of cumulated flight hours, in order to be relevant from the statistical point of view. In this case, aircraft in service among several U.S.A. Armed Forces Units were considered. These data are provided by Ref. [11] and Table VI summarizes the most relevant ones for our applications. This table provides several considerations. Considering the value of MEW for the selected UAVs, it can be observed that there is a trend to have higher Basic Failure Rates with the decreasing of weight (in particular if the Manufacturer Empty Weight is concerned). This effect is not considered in (1a) but it is clearly shown in Figure 5.

Table VI - UAV (currently operating) failure rates (Basic and Safety) comparison

UAV	MTBF [hours]	λ_b [failures/1000h]	λ_s [mishaps/105h]	$\frac{\lambda_s}{\lambda_b}$
Predator RQ-1A	32	31.25	43	$1.38/10^2$
Reaper RQ-1B	55	18	31	$1.7/10^2$
Pioneer RQ-2B	28.6	35	139	$4.0/10^2$
Hunter RQ-5	11.3	88.49	16	$1.6/10^3$

This fact can be explained noticing that, under a certain weight, there is an amplification effect for basic failure rate λ_b due to:

a) higher criticality of micro-components;
b) use of aeromodelling-derived technologies;
c) difficulties in assembly due to reduced size;
d) criticalities due to high density in terms of number of components in a reduced volume;
e) anomalies in aerodynamic behavior due to unusually low Reynolds Number values.

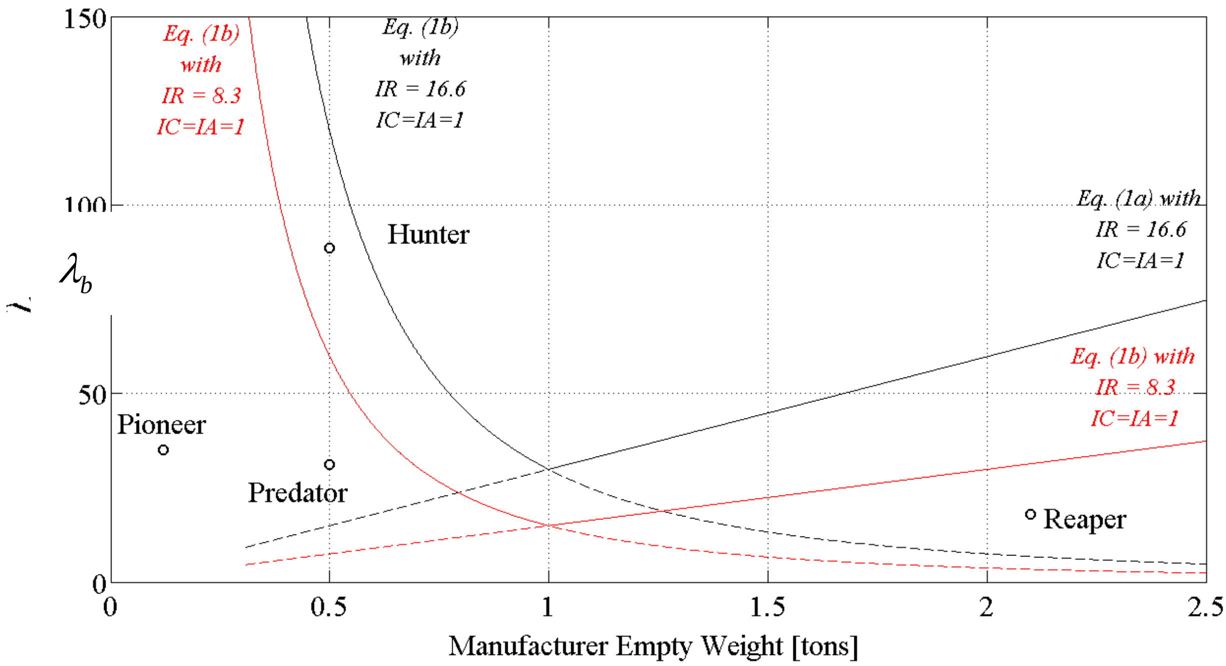


Figure 5 Relationship between λ_b and MEW

Such effect can be modeled by substituting the (1a), for Failure Rate λ_b estimation, only for small UAVs, as follows:

$$\begin{cases} \lambda_b = k \cdot \text{MEW} \cdot \text{IR} \cdot \text{IC} \cdot \text{IA} & \text{for MEW} > 1 \quad (1a) \\ \lambda_b = k \cdot (1/MEW)^2 \cdot \text{IR} \cdot \text{IC} \cdot \text{IA} & \text{for MEW} \leq 1 \quad (1b) \end{cases}$$

The (1b) can replace the (1a) in the range of MEW between 0.1 to 1 [tons], while the (1a) maintains its validity for MEW>1 [ton], as it is shown in Figure 6 by the red curve, obtained from (1b) and (1a) in the aforesaid ranges of MEW values, with IR=8.3 and IA=IC=1.

By introducing, in Table VII a comparison between typical UAVs and typical Fighter Aircraft (as an example, three of the most relevant U.S. Fighters have been considered), "Basic Failure Rate" λ_b seems to be, for UAVs, almost an order of magnitude lower than the Fighters, as shown in the aforesaid Table. This can easily be explained with the generally lower weight (for at least an order of magnitude) for UAVs with respect to the Fighters. Furthermore, it confirms the assumption made for the Index Role.

Conversely, the Mishap Rate of UAVs appears to be at least one order of magnitude higher than the Fighter's one (data reported about λ_s for both UAVs and Fighters are taken from reference [10]). Trying to explain these facts, please note that the safety failure rate, λ_s [Mishaps/hour], seems to be highly variable among all vehicles, Manned or Unmanned (probably with lower, thus better, values for more "mature" vehicles). By the way it is clear that the majority of the considered fighters are compliant with the ratio $\lambda_s/\lambda_b=10^{-4}$, expressed by (4a), whereas, as for UAVs, it is highly necessary to reduce λ_s of 1 or 2 orders of magnitude. In particular, this would became a stringent requirement if it will be necessary to operate on civil field or on highly populated territories, as it is clearly requested for SMAT. For such applications, a target value of λ_s equal to $1 \cdot 10^{-5}$ can be expected, taking as reference Table 8, referring to [11], currently one of the main documents for Safety-related issues. The las column of Table 8 reports the system loss cumulative probabilitiy requirements. This can be assimilated to a mishaps rate not necessary meaning catastrophic events. This value could be further reducedbtaking into account population density, exposition area for vehicle crash, the probability that effects of mishap could be "mitigated", etc…

4 FAILURE RATE AND SAFETY FAILURE RATE PROPOSED FOR SMAT's UAVs

As already said, the UAV in use in SMAT program belongs to three categories: MALE (Figure 6 and Table IX), MAME (Figure 7 and Table X) and LASME (Figure 8 and Table XI). In the following figures and tables the main features of the considered UAV are reported. Starting from the indications provided from AER P2 [11], Table VII suggests that the Safety Failure Rate is the first value to be fixed. This is due to its involvement with an Authorities Approval for operations in Civil Area that is clearly *condicio sine qua non* for the realization of SMAT. Table XII, for three UAVs that will be integrated in SMAT, a proposal of Safety Failure Rate has been formulated. Please note that the rule AER P2 covers only military vehicles and UAVs with a weight larger than 150 kg and created without scientific purpose or for research. For the other vehicles, national rules are allowed. In Italy recently a Rule called "*Regolamento per APR con peso<150 kg*", Ref. [12], has been recently issued by ENAC (Ente Nazionale Aviazione Civile – Italian Authority for Civil Aviation). Given that it is still under discussion the technical Specifications of SMAT's UAVs, it is clear that LASME UAV (also intended as "Light" UAV) could be subjected to different Rules for its definition. Thus, in the following considerations, the attention will focus on MALE and MAME. From the above seen data reporting UAS servicing among USA Military Forces, it can be clearly seen that values of λ_s, for UAVs features, appear worse (or better too high, with values almost between $1/10^3$ and $1/10^4$) and so, not compliant with, for example, the AER P2 regulations.

This is a consequence of the fact that the ratio λ_s/λ_b for UAVs in service appears to be higher than the one which was thought to be assumed by Fighters (please, remember the (4a), i.e. $\lambda_s/\lambda_b=10^{-4}$).

Nevertheless, assuming an improvement of an order of magnitude on λ_s (that appears mandatory for safety reasons) the ratio expressed in (4b) could be adopted, maintaining the current basic reliability values for the components:

$$\lambda_s = \frac{\lambda_b}{10^3} \quad (4b)$$

Table VII - Comparison Basic Failure Rate vs. Safety Failure Rate for Fighters and UAVs

Fighter	λ_b [failures/1000h]	λ_s [mishaps/10^5h]	UAV	λ_b [failures/1000h]	λ_s [mishaps/10^5h]
AV-8	807	10.7	Reaper RQ-1B	18	31
F-16	299	3.35	Pioneer RQ-2B	35	139
F-18	427	3.2	Hunter RQ-5	88,49	16

Table VIII - Cumulated probabilities of failures (Rule AER P2)

Vehicle	Airplane Class	Catastrophic event probability	System loss cumulative probability
Military UAV	(S7) Ultra-light UAV, 20<TOW<150 kg	Catastrophic $\leq 10^{-6}$	System Loss $\leq 5 \cdot 10^{-5}$
	(S8) Light UAV, 150<TOW<500 kg	Catastrophic $\leq 10^{-6}$	System Loss $\leq 3 \cdot 10^{-5}$
	(S9) Medium UAV, 500<TOW<2700 kg	Catastrophic 10^{-6}	System Loss $\leq 10^{-5}$
	(S10) Heavy UAV, TOW>2700 kg	Catastrophic 10^{-7}	System Loss $\leq$ 1-5$\cdot 10^{-6}$

Table IX - Hypothesized Safety Failure Rate of SMAT UAVs

UAV (SMAT)	Weight [kg]	λ_s [mishaps/10^5h]
MALE	4000	$5 \cdot 10^{-6}$
MAME	500	$3 \cdot 10^{-5}$
LASME	150	$3 \cdot 10^{-5}$

This means to adopt an $LR_{UAV}=10^3$. Thus, starting from an order of magnitude of Basic failure rate lower than the one of the Fighters, UAVs have (also taking into account an improvement compared to current situation) λ_s of at least an order of magnitude higher of the Fighters one, the following considerations can be done:

a) There is no crew on board;
b) The fact of having no crew on board reduces the resources to deal with critical situations and emergencies (in other terms, a critical situation has less probabilities to be carried out successfully).

According to these considerations, it is worthwhile to use the methodology proposed in reference [1], adopting an IR=8.3 (as well the 50% of the one of the Fighters) and the other differences already explained for the ratio λ_s/λ_b of UAV in service and for the Role Index, that can be defined LR_{UAV} and that is, as already seen, equal to 10^3.
Nevertheless, to make SMAT UAVs, the “future” vehicles with a strict need of certifications to operate in Civil Field, even on highly populated areas, the Role Index used for Fighters, $LR=10^4$ should be considered valid.
The application of the methodology with the choice of the various factors is reported in the following Table XIII for:

a) UAVs for which real data are available (used for comparison);
b) UAVs included in SMAT system.

Values reported in bold font in the previous table, could be therefore indicative of requirements in terms of λ_s/λ_b for the three UAS of SMAT system.

Table X - Failure rates estimated for existing and future UAVs

UAV	k	IR	IC	IA	MEW [t]	Relation. utilized	λ_b [fail/1000h] estimated	λ_b [fail/1000h] known
Predator RQ-1A	1.8	8.3	1.0	1.0	0.5	(1b)	21.13	31.25
Reaper RQ-1B	1.8	8.3	1.0	0.8	2.1	(1a)	25.09	18.00 (25 at specification)
Pioneer RQ-2B	1.8	8.3	0.6	1.3	0.12	(1b)	33.64	35.00
Hunter RQ-5	1.8	8.3	1.4	1.3	0.5	(1b)	38.45	88.49
MALE for SMAT	1.8	8.3	1.1	0.6	2.4	(1a)	23.66	-
MAME for SMAT	1.8	8.3	0.8	0.8	0.3	(1b)	17.45	-
LASME for SMAT	1.8	8.3	0.5	0.7	0.12	(1b)	15.10	-

Table XI - Safety failure rate estimation with Role Index

UAV	λ_s [mishaps/h]
MALE (SMAT)	λ_s = 23.66 10^{-3} 1/LR = 2.4 10^{-6}
MAME (SMAT)	λ_s = 17.45 10^{-3} 1/LR = 1.8 10^{-6}
LASME (SMAT)	λ_s = 15.10 10^{-3} 1/LR = 1.5 10^{-6}

Applying the Role Index LR=10^4 (typical of "Fighters") to the above mentioned values, according to what was previously defined, the Safety Failure Rates reported in the following Table XI can be considered as consistent for the three UAVs considered for SMAT. These values, as it can be easily verified, are fully in agreement with the previously mentioned prescription of AER P2 [11]. These values of λ_s for the three UASs of SMAT system are not in conflict with the need of certification for operations in civil areas, even if highly populated. Moreover, accordingly to the previously explained reasons, are coherent with the estimated values for Basic Failure Rates. By the way, in more long times, another order of magnitude reduction of these λ_s values has to be considered. Obviously, in the same time, the corresponding λ_b values will be confirmed.

5 MISSION RELIABILITY ESTIMATION

This selection deals with the Mission Reliability estimation, that is the probability to successfully complete the mission that each UAS must perform. It can be assumed that the "Mission Failure Rate" (λ_m), that is the failure rate due to failures that cause the abort of a mission, has an intermediate value between those of Basic and Safety Failure Rates, such as:

$$\lambda_b > \lambda_m > \lambda_s \quad (5)$$

Logically, it can be assumed that λ_m has a value with an order of magnitude intermediate between those of λ_b and λ_s, because, luckily, not all the basic failures lead to abort the mission and not all the unsuccessful mission, lead to the loss of the vehicle. This assumption is true for fighters, while for UAVs this value must be considered in a slightly different way, Ref. [10]. Indeed, for UAVs it can be considered, in a more precautionary way, that λ_m has a value closer to λ_b, therefore rather high, mainly due to the already explained reasons of higher λ_s values and due to the fact that having no crew on board leads to an unlikely success when solving anomalies.
As a consequence, in a first approximation, for the three UAVs of the SMAT system, λ_m can be assumed as in Table XII.
As verification, the mission reliability for the three SMAT's UAVs was estimated such as:

$$R = e^{-\lambda_m \cdot t_m} \quad (6)$$

Table XII - Mission failure rates estimation
for SMAT UAVs

UAV	λ_m
MALE	λ_m=2.4 10-3
MAME	λ_m =1.8 10-3
LASME	λ_m=1.5 10-3

The results from (6) are reported in the following Table XVI, considering λ_m from Table XV and different values of mission length (t_m), proper for each of the three platforms considered, according to the foreseen kinds of usage.
In the same Table XV the Reliability values from reference [10] are also reported for the USA Armed Forces UAS already considered. The good concordance with calculated and real values, confirms the methodology validity and in particular the mission reliability values calculated (always in the Table XV) also for the SMAT's UAVs.
Please note that mission reliability values can be quite different, due to the t_m values dispersion, in particular for USA Armed Forces UAS, for which, in the reference, only R_m values have been reported.

Table XIII - Reliability estimate for SMAT UAVs and comparison with USA Armed Forces UASs

UAV		λ_m	t_m [hours]	R_m
SMAT	MALE for SMAT	2.4 10^{-3}	30	1.0
	MAME for SMAT	1.8 10^{-3}	10	0.8
	LASME for SMAT	1.5 10^{-3}	5	1.3
USAF	Predator RQ-1A	/	/	1.3
	Reaper RQ-1B	/	/	0.6
	Pioneer RQ-2B	/	/	0.8
	Hunter RQ-5	/	/	0.7

6 MAINTENANCE MAN HOURS/FLIGHT HOURS ESTIMATION

Complementary, it is also necessary to estimate how many efforts will be necessary to support the operations of future UAVs. This estimation could be done both from the point of view of entity of “Down Time” (i.e. the amount of time for which the System could not operate as it is under Maintenance or waiting for that) and the contribution of Maintenance to the Life Cycle Cost. A very good index for these purposes seems to be the “Maintenance Man Hours / Flight Hours” (MMH/FH). By hypothesizing the number of Maintainers that at the same time will work on the System, it is possible to deduce the “Down Time” and, then, the “System Availability” [9]. Based on Maintenance Man Hours an estimation of Maintenance cost can be derived. Based on such considerations, using the methodology for Reliability, Safety and Maintenance features assessment in aeronautical Conceptual Design Phase, already applied to the UAV as to Reliability (Basic and Mission) and Safety [9], an estimation strategy for MMH/FH has been developed for the Airplane Conceptual Design Phase, and it is based on the relationship:

$$MMH / FH = IRM \cdot CDTM \cdot IC \cdot IA \cdot MEW^{0.25} \quad (7)$$

where:

- MEW [tons], IC and IA are the same already utilized for the (1a) and (1b);
- IRM is an “Index Role for Maintenance”, defined in Table 14;
- CDTM is a coefficient, taking into account how much the RAMS Techniques, in particular the ones influencing maintenance, have been considered in design phase; suggestions for the values are given in Table XVIII.

The following Table, reporting data from reference [9] shows how the (7) is able to give satisfactory estimation of MMH/FH for many kinds of manned aircraft, only utilizing few parameters that is easy to fix even in early design phases; please note that in such a Table all values utilized to calculate MMH/FH are reported as well as the calculated values that are compared with known ones, showing a very good realism of the estimations. So it was decided to apply also this part of Methodology to UAVs, in particular to the three models considered in this paper for the integration in SMAT System. Please note the following considerations:

Table XIV - Role Index of Maintenance Values for different kind of Aircraft

“Index Role” for Maintenance”	Fighters	Military Transport Vehicles	Civil Transport Vehicles
IRM	IRM=4.4	IRM=3.0	IRM=1.5

Table XV - Role Index of Maintenance Values for different kind of Aircraft

Influence level of maintenance in the design	Maintenance nearly not considered in the design	Early attempts to consider maintenance in the design	RAMS disciplines considered as design requirements	Testability and integrated logistic support considered since early design phases
CDTM Coefficient of influence of maintenance in the design	2.1	1.5	1.2	1.0

Table XVI - MMH/FH estimate examples for manned aircraft, Ref. [9]

Aircraft	IRM	CDTM	IA	IC	MEW [t]	MMH/FH, (calculated)	MMH/FH (known value)	Source Data
TORNADO	4.50	1.10	2.00	1.40	13.80	26.71	24.30	-
AMX	4.50	1.00	1.50	1.00	6.00	10.56	11.02	-
Eurofighter EF2000	4.50	0.90	1.00	1.40	9.60	9.98	9.67	-
SCALT	4.50	0.80	0.90	1.20	4.20	5.57	-	DIASP
F104	4.50	1.50	2.50	1.00	8.00	28.38	27.70	-
FIAT G91	4.50	2.10	3.00	0.60	3.50	23.27	25.50	-
C130	3.00	1.10	2.50	1.00	35.00	20.07	19.60	-
G222	3.00	1.10	2.00	1.00	15.00	12.99	-	-
ATR42	1.50	1.00	1.50	1.00	10.00	4.00	3.64	ATR
A320	1.50	1.00	1.00	1.50	42.00	5.73	-	-
B747	1.50	1.00	2.00	1.40	170.00	15.17	14.50	Roskam

On the basis of some considerations previously made, about the λ_b estimate, the Index of Role for Maintenance adopted for UAVs is the same of Fighters, i.e. IRM=4.4, as the similarity aspects have been considered prevalent.
Please note that a judgment on MMH/FH estimate will be, at the moment, only qualitative, as in reference [9] data the MMH/FH for UAVs of USA Armed Forces are not reported apart the Availability values. Unlikely Availability is a concept that requests more parameters to be defined and it is not reported in Ref. [10], so the values given are only indicative.
The presence in Eq. (7) of a MEW=0.25, i.e. with an exponent <1, seems a good interpretation of the contraction caused by the lower values of MEW, thinking that an UAV with high empty weight will probably have more component and so more maintenance operations but an easier work for Maintainers. Conversely, a reduced empty weight will probably have a greater number of unrepairable components that have to be directly replaced, compensating the difficulties of work for the reduced dimensions and the trend to a greater defectiveness seen about λ_b estimation.
By the way, the application of (7), with all assumed values, is reported for the three SMAT UAVs in Table 20 and the results, at a first glance, seem consistent.

Table XVII - MMH/FH estimated for SMAT UAVs

UAV	MEW [t]	IC	IA	IRM	CDTM	MMH/FH
MALE for SMAT	2.40	1.1	0.6	4.4	0.8	2.9
MAME for SMAT	0.30	0,8	0.8	4.4	0.8	1.7.
LASME for SMAT	0.12	0.5	0.7	4.4	0.8	0.75

7 CONCLUSIONS

The previously defined methodology for estimation of Reliability, Safety and Maintenance features in Conceptual Design Phase, even if developed for manned aircraft, has been adapted to the case of Monitoring and Surveillance of UAVs in order to study their integration in a complex Monitoring System, like SMAT. In the study, the very few available data for existing UAVs have been utilized. In this way, an assessment methodology has been established and some first almost indicative values of wanted features have been defined and found applicable.

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