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Survey of Certifiable Air Data Systems for Urban Air Mobility

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***Abstract*—In the near future, vertical take off and landing aircraft of the urban air mobility sector will be integrated into the civil airspace and they will be characterised by several levels of autonomous flying capabilities. Many countries worldwide are funding several researches to identify and develop enabling technologies to make urban air mobility as safe as modern aviation. One of the most critical aspect of those aeroplanes rely on the reduced fuselage dimensions and available space on board to welcome all those safety critical systems commonly used on commercial aviation. The air data system is one of the safety critical system that is equipped with several probes and vanes, protruding externally from the aircraft fuselage, and some of its functionalities are adequately redundant for general aviation and large aeroplanes. Even though an airworthiness standard applicable to urban air mobility is not ready yet, worldwide there are several efforts that will lead to type certification standards in next years. This work presents a brief survey of certified technologies available for sensing solutions feeding air data systems and solutions based on synthetic sensors certifiable in a couple of years. The survey relies on certified and certifiable innovative data sensing units for realistic urban air mobility applications. To this aim, a safety assessment analysis is presented in order to support the validity of the certifiable air data sensing solutions presented in this paper.**

***Index Terms*—synthetic sensors, urban air mobility, air data system, air data probes**

I. INTRODUCTION

The next few years will witness a change of paradigms in urban air mobility (UAM) with ability of manned or unmanned vertical take off and lift (VTOL) air vehicles to fly over populated areas. In fact, a huge growth is expected in the civil market for recreation or people local transportation. For example, the biggest players, AIRBUS and BOEING, are working on UAM projects, CityAirbus and AURORA respectively, that will boost the preparation of dedicated type certificate from EASA and FAA. One of the most recent initiative in the USA involves NASA, the FAA and industry in a UAM Grand Challenge [1] with the aim to stimulate all the involved UAM stake holders.

Generally speaking, with VTOL is intended a "person-carrying vertical take-off and landing (VTOL) heavier-than-air aircraft (A/C) with lift/thrust units used to generate powered lift and control" and optionally with remote piloting capabilities. On the other hand, when an aircraft "is designed to operate with no human pilot on board and which does not carry personnel" we usually refers to unmanned aerial vehicle (UAV) able to fly automatically or to be remotely piloted. For this work, UAM air vehicles are considered to rely on A/C fixed wing configuration during their mission.

As commonly recognised, one of the main problems is the UAM integration within current air traffic [2] and many countries are funding research in several areas to boost achievement of required objectives. Other technical issues related to aircraft systems shall be solved, e.g. those related to safety aspects. In Europe, for instance, EASA has recently published special conditions for VTOL [3] up to $7000\,\mathrm{lb}$ and nine passengers that is under review and should be active in 2023 as applicable standard.

In order to design on board avionic systems for piloted VTOL aviation the applicable standard ARP4761 [4] shall be followed. Speaking of system safety, it shall be demonstrated that the aircraft has an adequate reliability level to guarantee the safety of people on ground at least as the modern civil aviation. Definitions of event severity, probability of occurrence are derived from [5]. For each aircraft type (or category) the applicable airworthiness standards quantify the probability of occurrence in order to give clear target for system reliability/safety analysis. It is obvious that a safety critical system is defined as that system that could lead to catastrophic event and, therefore, its failure shall be classified as extremely improbable. The numerical value of corresponding probability of occurrence per flight hour is related to the aircraft category. In this work, the quantitative values to be allocated to the single event are derived from [3]. Therefore, according to available standards for VTOL, the catastrophic event occurrence shall have the following minimum probabilities per flight hour:

- VTOL Basic (mainly for private use): with catastrophic event with a probability of the order of 1×10^{-7} or less up to 1 passenger, 1×10^{-8} or less up to 6 passengers and 1×10^{-9} or less up to 9 passengers;
- VTOL Enhanced (mainly for civil transportation): with catastrophic event with a probability of the order of 1×10^{-9} or less.

It is worth noting that 1×10^{-9} is the same probability prescribed to large passenger aircraft of the CS25 and FAR25 categories. The chance related to the catastrophic event mainly leads the design of safety-critical systems and subsystems of

VTOL.

In this work, the acronym ADS can be intended as a stand-alone system or as an integral sub-system of a vehicle management system (VMS). For the sake of clarity, without loss of generality the VMS can be replaced by equivalent system such as the flight control system (FCS) or the mission control system (MCS). The ADS is typically equipped with several "sensing units" that are probes and vanes, protruding externally from the aircraft fuselage. With air data sensing suite (ADSS) is intended the group of sensors (e.g. probes and vanes) used to feed the ADS with the necessary air data measurements. Therefore, the ADSS is made up of several line replaceable units (LRUs) [6] able to measure at least: static pressure, total pressure, angle-of-attack and, if necessary, the air temperature. Additionally, the angle-of-sideslip can be required by the automatic control system. For safety reasons, a safety-critical system is never a single point of failure and redundancy is applied in order to be compliant with the applicable safety requirements. In fact, duplex or triplex architectures are typically required.

Corroborated by preliminary safety analysis, the main aim of the present work, in fact, is to provide a market survey of the available certified/certifiable sensing units for air data systems for UAM applications. A particular focus will be given to innovative chances arising from the limited use of synthetic sensors that can be certified. For the present study, ADS solutions will be split into three main groups: 1) single-function probe (SFP); 2) multi-function probes (MFP); 3) synthetic sensor (SS) and SFP. In the scenario of integration of UAM into civil airspace, instrument flight rules (IFR) is considered applicable in addition to several levels of autonomous flying capabilities. After an introduction on ADS and its main functionalities in Section II, a market survey of available air data sensing technologies is briefly presented is section III. Considering the ADS current-state-of-the-art technologies and those available in a couple of years (i.e. 2021 in time with UAM operations expected from 2023), airworthiness certification aspects are discussed in Section IV for preliminary safety analysis in order to evaluate reliability of simplex ADS solutions in Section V based on SFP, MFP or innovative synthetic sensor technologies. Comparing ADS reliability characteristics with respect to airworthiness safety objectives, preliminary certification considerations are proposed highlighting advantages and drawbacks of all available ADS technologies before concluding in Section VII.

II. Air Data System

Fig. 1 shows the body reference system ($X_B Y_B Z_B$), the true airspeed vector, V_∞, positive directions of attitude angles (roll, pitch, yaw), body angular rates (p,q,r), body linear velocities (u_B,v_B,w_B) and aerodynamic angles, AoA ($\alpha = \arctan \frac{w_B}{u_B}$) and AoS ($\beta = \arcsin \frac{v_B}{V_\infty}$).

Pilots or VMSs rely on some data that are directly measured from the external environment (e.g. AoA) or derived from them (e.g. Mach number). These data are collected in the common group named air data. Some air data are safety critical (e.g. A/C speed) for the A/C and, therefore, they are crucial for pilots or flight control system for the correct piloting, navigation and control. Usually, air data measures are demanded to the air data system (ADS) that can be interfaced with several systems (e.g. VMS) or displays according to the single A/C requirements.

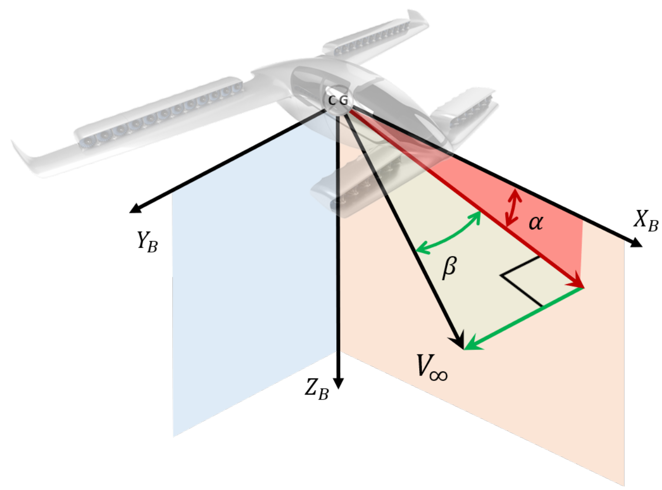


Fig. 1: Description of the aircraft reference system $\{X_B, Y_B, Z_B\}$ and aerodynamic angles, α and β

From a system point of view, ADS is usually based on different probes and vanes (LRUs) that protrude from the A/C fuselage into the external flow field. Generally speaking flow angle vanes and TAT have typically analog/digital outputs whereas each pressure source needs to be connected to a dedicated Air Data Module (ADM) that is able to provide suitable conversion of air pressures into analog/digital signals. In this way, the air data sensing LRUs can be connected to another system (e.g. the VMS) able to implement the necessary air data functions. In recent past years, all transducers were integrated in a single unit, commonly named Air Data Computer (ADC) that has also computational capabilities to calculate derived air data. Anyway, considering the modern integral avionic approach, the air data functions [7] are supposed to be implemented at VMS level.

A. Air Data Functions

In this section equipment specifications of Air Data Computers (ADCs) from the AS8002A [7] are only used to derive the main air data functions (ADF). In order to achieve the minimum performance required for a certified aircraft, at least the following flight data shall be measured or estimated:

- local static pressure, $P_{s,l}$;
- local dynamic pressure, $q_{c,l}$;
- local air temperature, OAT$_l$, or local total air temperature TAT$_l$;
- local Angle of Attack, AoA$_l$ (additional and not mandatory according to [7]);

where "local" refers to measures before application of the free stream calibration. For example, the ETSO-C54 [8]

defines requirements for a stall warning system based on a suitable stall sensor. The stall warning system is always based on AoA senosrs (usually a rotating vane, see Fig. 2c) that inherit stall warning system requirements. As far as the AoS is concerned, the AoS is not required for A/C certification purposes, but it can be required for other A/C operations, e.g. automatic control purposes. In these latter cases, other A/C systems, e.g. VMS, set requirements for the AoS with desired performances. For example, if the AoS is used within a certain flight mechanic control loop, the AoS measure's uncertainty is defined from flight mechanic performances to be achieved. As the UAM will have a certain level of autonomy, the AoS is expected to be used and it is considered in this work.
Among all, ADF shall be able to convert local measurement into freestream ones and, then, to calculate at least the following flight parameters [7]:

1) pressure altitude;
2) vertical Speed, VS;
3) indicated airspeed, IAS;
4) calibrated airspeed, CAS;
5) true airspeed, TAS;
6) mach number, M;
7) air temperature, T;
8) Angle of Attack, AoA (additional and not mandatory);
9) Angle of Sidelip, AoS (not required).

Basically, a complete air data set is derived from direct measurements as reported in table I.

TABLE I: MIDAS ADS function description and allocation

Function ID	Data measured	Required for
ADF1.1	Static pressure	Loss of: pressure altitude, VS, TAS, Mach, T
ADF1.2	Dynamic pressure	Loss of: IAS, CAS, TAS, Mach, T, AoA, AoS
ADF2	OAT or TAT	Loss of: T, TAS
ADF3	AoA	Loss of: angle of attack
ADF4	AoS	Loss of: angle of sideslip

III. Air Data Sensing Survey

As far as the air data sensing LRUs are concerned, this section will give an overview of the current commercial-off-the-shelf products and possible certifiable solutions based on synthetic sensors.
Static and total pressures are measured using Pitot-static tubes or Pitot tubes in addition to static ports. The temperature measures are taken using OAT or TAT probes, several technical solutions can be found for the aerodynamic angles: measure of flow angles or differential pressures.

A. Pressure probes

Conventional pressure probes considered here are Pitot tubes (for the total pressure measurement), Pitot-static probes (for static and total pressure measurements) or static ports (for static pressure measurement).
On modern aircraft Pitot tubes are widely used in addition to static ports, whereas Pitot-static probes are rarely used

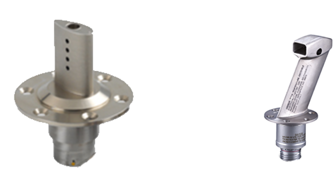
(a) Pitot-static (b) Static port (c) Flow angle vane

Fig. 2: Example of single function probe and vanes for pressure and flow angle measures

because the pressure flow field around the aircraft influences total and static measures in a different way. In fact, the best position to measure the total pressure in the majority of the cases does not correspond to the best position to measure the static pressure. Therefore, using a Pitot/static probe is a little more challenging when considering to remove the classical position errors from the static pressure measures.
In the majority of the examples, the conventional pressure probes are not equipped with pressure transducers, so that they have to be connected pneumatically to dedicated ADMs, ADC or VMC.

B. Temperature probes

As far as low speed air vehicles are concerned, the air temperature is measured with OAT that is able to measure directly the ambient static temperature with a sensing element exposed the external airflow with a suitable shed to prevent ice formation. For this reason adiabatic correction and friction correction are usually applied. When the speed increases over Mach number higher than 0.3, the adiabatic and friction corrections become very important with respect to the temperature measured and, therefore, the OAT is replaced with a TAT probe. The TAT is usually heated to prevent ice formation and, as a consequence, they have several passive or active boundary layer control solutions in order to avoid chocking issues. Some design details can be found in [9].



(a) Outside Air Temperature, OAT (b) Total Air Temperature, TAT

Fig. 3: Example of probes for temperature measures

C. Conventional AoA/AoS vanes

Classical (or conventional) vanes work as weather cocks and they are able to provide direct measure of local flow angles [10], [11]. The vanes are equipped with angular position transducers and their outputs are already analog or digital so that they can be connected the systems housing the ADF. Classical vanes are usually adopted for stall warning purposes and, when needed, for AoS measurement. Other solutions exist, based on slotted cones [12] or cylinders [13], [14], but are rarely adopted on certified aircraft.

D. Multi-function probe

Generally speaking, a multi-function probe (MFP) is a probe with enhanced capabilities able to provide at least two pressure measurements and one flow angle measurement. The pressure measurements are usually refereed to static and total pressures, whereas the flow angle is referred to a local flow angle and only a combination of at least two MFPs can provide both AoA and AoS calculation.
Three main examples exist from only three suppliers: Thales - former GEC-Marconi, Aerosonic (Fig. 4a) and UTC (Fig. 4b). The first one is designed specifically for Eurofighter EF2000 and RAFALE applications and it is made up of a rotating vane provided with static ports and with total pressure tube at the tip. The Aerosonic solution is a rotating cone with several slots for pressure measurement. The UTC MFP is commonly know as SmartProbe® without rotating parts and it is basically 3-hole probe in addition to static holes.

(a) Integrated multi-function probe (IMFP®) (b) SmartProbe®

Fig. 4: Example of multi function probes for pressure and flow angle measures

E. Optical sensor

Basically, optical air data sensors for aeronautical applications transmits an optical laser pulse and interprets the received reflections from microscopic particles in the air (aerosols). The technique allows the measurement of 3-D motion of the air in a certain location around the aircraft, in part by determining the Doppler shift of the collected light. Therefore it is possible to measure relative positions and velocities between the transmitter and the air, which allows measurements of relative wind and of air temperature (because temperature is associated with high-frequency random motions on a molecular level). With a single optical sensor is possible to measure local TAS, AoA, AoS and OAT. The adjective "local" is crucial in this context because it evokes all the drawbacks of the optical sensors due to local airflow measures from aerosols. Turbulence, vortex and wind gusts are three of the main hazardous flight situations. Moreover, the lack of aerosols would limit the use of optical sensors in terms of altitudes.
At time of the work preparation, there is no commercial product that can be used for certified aircraft.

F. Synthetic sensor

Within the ADS market, in recent decades we have witnessed of a proficient academic and industrial research for use of innovative techniques for air data calculation.
The estimators are basically of two types: i) model-based [15]; ii) model-learned [16], [17]. There are several estimators able to provide one or more air data parameters. Synthetic sensors are usually developed for several purposes (estimation, analytical redundancy, failure identification, etc.). According to their final operative task, they will have more or less relaxed performance requirements. In recent years many solutions have been published dedicated to several scopes and based on several techniques. The main aim is to estimate at least one air data parameter exploiting both model-based or model-learnt solutions. The model-learned group exploits several technologies, such as machine learning, fuzzy-logic, etc. to estimate air data.
Among all possible solutions, some have been extensively tested with flight tests. For example, solutions aiming to estimate aircraft airspeed [18] are more oriented towards failure identification because the estimation uncertainties are well beyond the limits imposed by the current airworthiness regulations [7]. On this topic, therefore, using a classical source of total and static pressures (e.g. with a Pitot/static probe) seems to be mandatory. There are no relevant work for estimation air temperature using synthetic sensors. Whereas, there are several examples of synthetic sensors for AoA and AoS [19] with acceptable performance to be used in place of common vanes [20]. As it will be shown in Section V, using estimators for both aerodynamic angles will give the chance to enormously simplify the ADS architecture.
Certification issues should be taken into account when considering to design air data sensing architecture partially based on synthetic sensors for small air vehicles certifiable in a couple of years. From this point of view, one of the most promising solutions with the highest technology readiness level (TRL, defined in [21]) is the MIDAS solution, funded within the Horizon 2020 frame, that will be certifiable in 2021 within the MIDAS project [22]. The solution is basically a state variable observer where the A/C flight dynamic model is replaced by a model based on neural networks [23]. Therefore, the focus is shifted from the probe/vane to flight mechanics using machine learning techniques and flight data already available on board through the Smart-ADAHRS technology [24], [25]. In order to have a certifiable synthetic sensor/s able to provide AoA and AoS within 2021, this work will consider only AoA and AoS synthetic estimation within the air data sensing solutions. Therefore, apart the selected technology and considering the current state-of-the-art, the best compromise for ADS that exploits synthetic sensor(s) is to consider:

- measure of static and total pressure (e.g. using a Pitot/static probe);
- measure of static and dynamic pressure (e.g. using a TAT or OAT;

- estimation of AoA and AoS (e.g. using analytical estimators);

where only AoA and AoS vanes are replaced with synthetic sensors because of low criticality level (as it will be shown with FHA tables in Section V). In this work, the MIDAS solution will be considered as reference solution for synthetic air data sensors as it is the most promising for civil applications. According to [26], the estimators will be fed with direct measure of dynamic pressure, static pressure and inertial data. The latter are provided by the VMS. Therefore, the synthetic sensor considered in this survey estimates aerodynamic angles (AoA and AoS) as an indirect measure by means of data fusion between measured air data available and inertial data [26]. A well documented proof of the concept can be found in previous works [27] even though several architectural solutions can be adopted to satisfy the particular A/C application.

IV. Air data system unit qualification

The air data system is made up of several LRUs and each of them shall satisfy unit-level aerospace standards to be compliant with system-level standards. For example, the ADS shall be verified in several environmental conditions (e.g. as required by the DO-160 [28]) that are applicable at system level. In order to satisfy those requirements, each LRU shall have a minimum set of performances that are listed in other standards that are applicable at unit level. For civil applications (as UAM), in order to certify the A/C the flying vehicle should satisfy the applicable airworthiness standard [3] and, therefore, each system shall satisfy subpart F (systems and equipment) of [3]. Each system will comply with the subpart F if designed according to civil equipment specifications:

- pitot-static probe - AS8006 [29]
- temperature probe - AS793A [30]
- AoA (for stall warning) - AS403A [31]
- AoS - N/A

As far as the synthetic sensor (based on neural network) is concerned, there is a guideline from the FAA [32].

Flight in icing conditions may not be applicable to UAM. Nevertheless, for IFR the airworthiness regulators requires that airspeed system and static pressure system must have a heated pitot tube and static port respectively or equivalent means of preventing malfunction due to icing. The current state-of-the-art of anti-icing systems for ADS probes and vanes are based on heated solutions. For this reason, in this work heated ADS probes and vanes are considered.

Air data sensing items available on the market with corresponding mean time before failure data (MTBF) derived from literature data [33] are grouped in TABLE II. All values reported in TABLE II shall be considered average values and any detailed design shall refer to the selected manufacturer's data.

Dealing with air data systems, other two main segments shall be considered: the computing and displaying (if piloted). In this work, it is acceptable to consider that both the computing (at VMS level) and the display (integrated in cockpits) already meet the airworthiness regulations with necessary redundancy. For the latter reason, they are not treated in this work as part of the safety analysis process.

TABLE II: MIDAS ADS function description and allocation

ADS unit	MTBF
Pitot and TAT probe	$> 1 \times 10^5$ h
Pitot and TAT heater	$> 1 \times 10^4$ h
TAT sensing element	$< 1 \times 10^5$ h
ADC	$> 1 \times 10^6$ h

As can be seen from TABLE II the most critical component is the heating element that drastically reduces the MTBF of the single LRUs less than 10 000 flight hours.

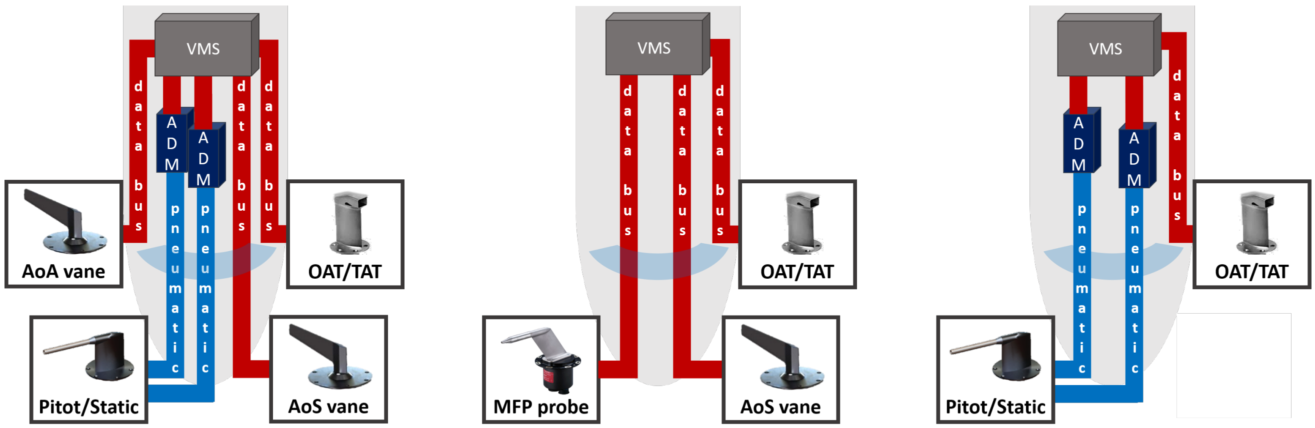
A. Safety Analysis Approach

The safety analysis is performed following common guidelines [4] and considering a generic application to a small aircraft belonging to the UAM community. The aim is to provide preliminary design considerations for a certifiable air data sensing solution emphasising those partially based on synthetic sensors.

Firstly a system level Functional Hazard Assessment (FHA) is performed in order to identify failure conditions and classify them at aircraft level in agreement with possible severity from previous industrial project's experience. Classification of the failure conditions establishes the safety requirements (or objectives) that the operative ADS shall meet. As an example, possible loss of the air data function related to airspeed calculation will be evaluated and classified in accordance with its effect at aircraft level.

The second step is the Preliminary System Safety Assessment (PSSA) with the allocation of system function (from the FHA safety objectives) to system parts (or components) and then single part safety requirements will be allocated to a lower level (hardware and software). This allocation to system items is performed using the Fault Tree Analysis (FTA) method and it will determine part reliability requirements. As an example, from the PSSA, safety requirements will be allocated to the single parts of an air data sensing unit.

These two steps, FHA and PSSA, represent a standard *top-down* approach: from the safety requirements at system level (FHA), several safety objectives are derived for the single system parts. On the other hand, there is a *bottom-up* analysis, the system safety assessment (SSA) that, exploiting the FTA method, verifies if the selected system architecture meets the safety requirements as defined in the FHA. The SSA exploits results of other analysis, such as the Failure Modes and Effect Analysis (FMEA), able to identify failure modes and rates of the system items and their effect at higher level. As an example, the FMEA could provide very low level analysis of how the failure rate of a single sub-part is derived, while the FTA of SSA will propagate those characteristics to higher level (e.g. unit) and again to system functions (e.g.



(a) SFP-based (b) MFP-based (c) SS and SFP-based

Fig. 5: Generic three realistic simplex air data sensing architectures able to provide a complete set of air data. The red lines represent data bus connections, the blue lines the pneumatic connections.

ADF1.1 airpseed calculation).
As final step, SSA results are compared with PSSA objectives in order to evaluate possible re-design at system level (e.g. select different LRU) or at aircraft level (e.g. redundancy).

V. Simplex ADSS for UAM application

In this section three possible simplex air data sensing architectures will be presented in order to provide a complete set of data (reported in TABLE I) to perform a system safety analysis for UAM air data sensing units.
For the sake of generality, the ADSS is considered to communicate with the VMS environment over a generic data bus. Three realistic simplex solutions are schematically represented in figure 5. In this work, the following definitions apply: 1) single-function probe (SFP) basically designed with commercial off-the-shelf (COTS) probes and vanes able to sense a single kind of air data from the external environment; 2) multi-function probe (MFP) able to sense more than one single kind of air data; 3) the synthetic sensor (SS) able to estimate one or more air data by means of processing other flight data already available on board with adequate sensor fusion techniques.
The following realistic hypothesis are assumed in this work: 2) all ADFs are implemented at VMS level; 2) only the in-flight phase will be considered in this work because it is the most critical mission phase and will set the safety objectives; 3) probe/vane heaters are considered embedded in the corresponding LRU; 4) cabling and/or pneumatic connections are not considered because they usually have an MTBF much higher with respect to all other components.
In this work for page limit, the PSSA and SSA are limited to ADF1 for SFP and MFP-based ADS, whereas also ADF3 is considered for ADS solutions partially based on SS.

A. Failure Hazard Analysis

An example of FHA performed for the ADF3 at aircraft level is reported in TABLE III. The same approach is used for all other functionalities not reported here for page limit. The worst cases (leading to catastrophic events) are summarised in TABLE IV. From analysis of the worst cases, the unannuciated loss emerges, of course, as the worst possible event for a simplex ADS. In fact, for ADF1, 3, 4 the unannuciated loss shall have the lowest probability of occurrence (extremely improbable), whereas the air temperature function ADF2 can be relaxed to extremely remote. Quantification of probability occurrence are used as input for the PSSA for the three simplex air data sensing architectures considered here.

B. ADS based on synthetic sensors and SFP probes

The main advantage of an ADS based on synthetic sensors (or estimator) for AoA and AoS is the reduced number of LRUs and the chance of using SFP probes available from several worldwide manufacturers/sellers for Pitot/static and temperature probes. The simplex ADS architecture (Fig. 5) can be based on Pitot/static probe is devoted to ADF1, measure of total and static pressure, the TAT is used to measure air temperature (ADF2) and the synthetic sensors are devoted to estimate AoA and AoS, respectively ADF3,4.
In table V we should consider also a sensor fusion technique that exploits both air data measured from ADF1 and other data already available at VMC level. As the VMC and its sub-systems (such as AHRS) are considered to meet already the safety requirements for safety-critical systems, a reliability of $< 1E-9$ will be considered for inertial data sources.
The TABLE V collects the decomposition of the main virtual sensor-based ADS function with corresponding allocation to the single LRUs.
The loss of total or static pressure implies that the AoA and AoS cannot be estimated, as reported in TABLE V. As said before, the ADF3, 4 are supposed to be implemented at the VMS level.

ot reported in the reference of the TABLE V because they should be implemented in the VMS, but they are in the failure effect column.

TABLE III: Example of FHA performed for ADF3

Function (FHA Ref.)	Failure Condition (Hazard Description)	Phase	Effect of failure condition on aircraft/crew	Classification	Remarks / mitigation
Angle of attack	Total loss of capability to measure AoA. Possible system fail: AoA sensor (SFP/MFP ADSS) ADF1+VMC (SS and SFP ADSS)	All	No AoA Limited flight envelop Mission may be aborted A/C may be lost	see below	
ADF3.a	a. Unannuciated loss	in-flight	Piloted: Crew is able to control/pilot the A/C correctly. Mission may be aborted. AutoPilot: AP is unable to control/pilot the A/C correctly. If the crew does not disengage the AP, A/C may be lost.	Piloted: Hazardous AP: Catastrophic	If AP is engaged, the unannuciated loss may be detected by the crew by non-coherence between airspeed and AoA
ADF3.b	b. Annunciated loss	in-flight	Crew (or AP) can rely on other subsystem to cope with loss of AoA. Limited flight envelope. Mission may be aborted.	Major	
ADF3.c	c. Unannuciated loss	T/O ground	Crew (or AP) will not abort the take-off. Piloted: Crew is able to control/pilot the A/C correctly. Mission may be aborted. AutoPilot: AP is unable to control/pilot the A/C correctly. If the crew does not disengage the AP, A/C may be lost.	Piloted: Major AP: Catastrophic	If AP is engaged, the unannuciated loss may be detected by the crew by non-coherence between airspeed and AoA
ADF3.d	d. Unannuciated loss	LAND ground	AoA not crucial. Mission completed	/	Once the weight is on wheels, the AoA shall be not considered.
ADF3.e	e. Annunciated loss	ground	T/O: mission aborted, LAND: mission completed	Minor	

TABLE IV: The most critical functions with corresponding safety objectives emerging from the FHA

Function ID	Worst classificat.	Occurrence probability	PSSA
ADF1.1	Catastrophic	Extremely improbable	$< 1 \times 10^{-9}$
ADF1.2	Catastrophic	Extremely improbable	$< 1 \times 10^{-9}$
ADF2	Major	Extremely remote	$< 1 \times 10^{-5}$
ADF3	Catastrophic	Extremely improbable	$< 1 \times 10^{-9}$
ADF4	Catastrophic	Extremely improbable	$< 1 \times 10^{-9}$

TABLE V: ADS decomposition and functional requirement allocation to LRUs for ADS based on SS and SFP

Air Data System		Air Data Function				
Unit	Part	1.1	1.2	2	3	4
Pitot probe	Probe	X	X	X	X	X
	Heater	X	X	X	X	X
TAT probe	Probe			X		
	Heater			X		
	Sensing			X		
FCC data (input to SS)	/				X	X

1) Preliminary System Safety Assessment: Starting from TABLE IV several FTAs are defined in order to identify safety objectives for ADS parts. An example is reported in Fig. 6b for ADF3, where at the junction (“AND”, “OR”) the contributions of lower-level events are equally distributed towards the higher-level event failure probability. Following the example, from the PSSA of ADF3 it is clear that heater and the Pitot probe should have high reliability characteristics (about 1.7×10^{-9}) in order to satisfy the safety objectives coming from the FHA analysis.

Obviously, the PSSA is performed for all worst cases of TABLE IV with most severe reliability objectives collected here:

- Pitot probe, heater element: $< 0.17 \times 10^{-9}$;
- TAT probe, heater, sensing element: $< 0.33 \times 10^{-5}$;
- ADM: $< 0.5 \times 10^{-9}$;
- VMC: $< 0.33 \times 10^{-9}$;

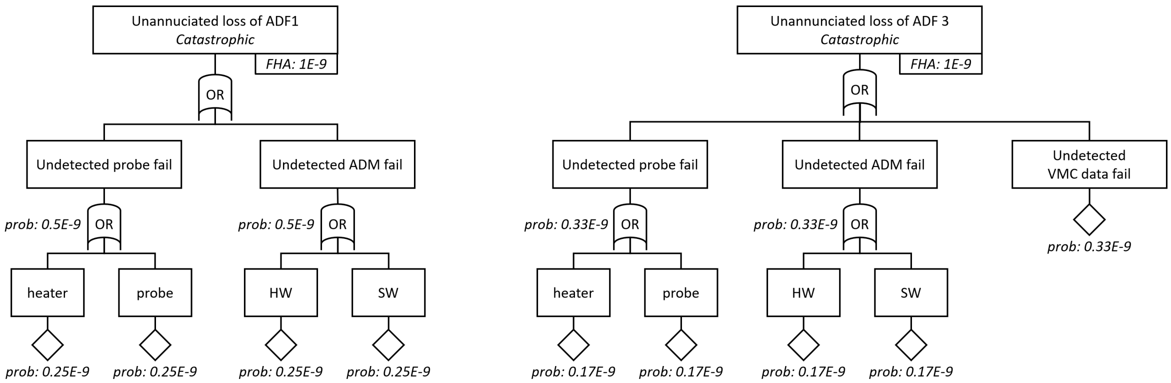
Another important aspect emerged from the PSSA analysis for the worst cases of the FHA. Data from the FCC, used as input to synthetic sensors, shall guarantee data loss at least every 3.3 billion flight hours. This safety target can be satisfied by the A/C integrator, for instance, with a triplex redundancy of the vehicle management computer (VMC) and related sub-systems.

2) System Safety Assessment: Starting from Table II it is possible to evaluate several FTAs identifying safety performance calculated for any MIDAS ADFs.

An example is reported in Fig. 7b where the contributions of lower-level events are summed towards the higher-level event at the “OR” nodes. According to item selected and related MTBF, it can be noted that the unannuciated loss of ADF3 can occur more than once over 10 000 flight hours. This result is much lower than the safety objective (once loss over 10 000 000 flight hours) reported in TABLE IV.

C. ADS based on SFP

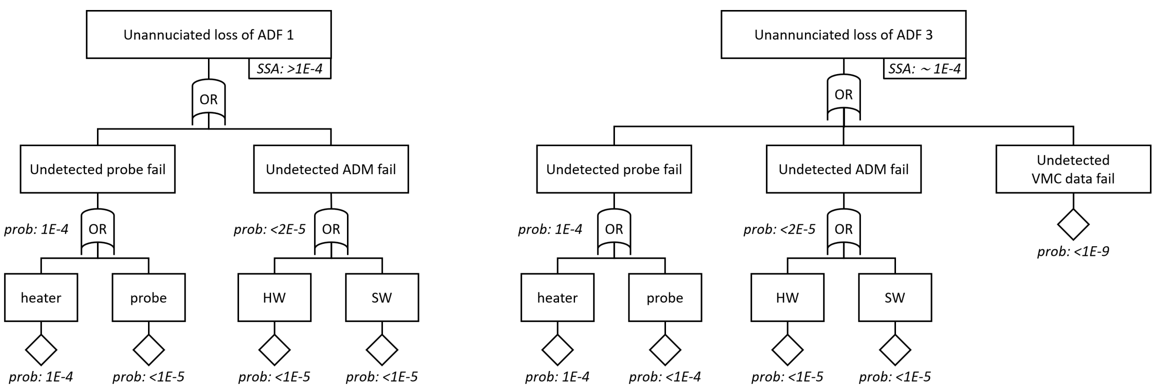
An ADS based on SFP LRUs is based on the use of mature technologies available from several worldwide manufacturers/sellers. On the contrary, this solution leads to a high



(a) PSSA for ADF1

(b) PSSA for ADF3

Fig. 6: Example of preliminary system safety assessment (PSSA) using the fault tree analysis (FTA) method



(a) SSA for ADF1

(b) SSA for ADF3

Fig. 7: Example of system safety assessment (SSA) using the fault tree analysis (FTA) method

number of LRUs to be installed protruding outside from the A/C fuselage as schematically represented in Fig. 5a with consequent increase of weight and power. For the sake of simplicity we consider that the Pitot/static probe is devoted to ADF1, measure of total and static pressure, the TAT is used to measure air temperature (ADF3), a vane is used to measure the AoA (ADF2) and the other one to measure the AoS (ADF4).

TABLE VI collects the decomposition of the main ADS function with corresponding allocation to the single LRUs.

Starting from TABLE VI it is possible to evaluate the PSSA identifying safety performance calculated for any air data items. An example of FTA developed for the PSSA is reported in Fig. 6a for ADF1.

On the other hand, MTBF of the sensing element of the SFP-based ADS are used to derive the ADS reliability using a *bottom-up* approach as reported in Fig. 7a.

D. ADS based on MFP

The main advantage of an ADS based on MFP is the reduced number of LRUs and the absence of pneumatic tubes as represented in Fig. 5b. On the contrary, the main drawback is that MFPs are not available worldwide but only from very few manufacturers as stated before.

When an ADS is based on MFPs, air temeprature probe (OAT or TAT) and an AoS vane should be added to provide the complete air data set of TABLE I.

In order to calculate the system reliability of the ADS based on MFP, the same approach of section V-B is followed. Considering the preliminary outcomes of the present work, a conservative approach will be considered and the same MTBF of the Pitot probe (as reported in TABLE II) are allocated to the MFP parts.

TABLE VI collects the decomposition of the main ADS function with corresponding allocation to the single LRUs.

As can be seen from TABLE VII, the measures of total and static pressures have a direct influence on local flow angle measurements for MFPs. Example results of PSSA and SSA are reported in Fig. 6a and Fig. 7a respectively for ADF1.

VI. Certification considerations

As far as all three ADSS of Fig. 5 are concerned and based on modern UAV air data sensing solutions, safety requirements of ADF2 and ADF4 could be relaxed according to the A/C integrator considerations about the authority of autopilot modes or flight envelop protection rules. This would make the simplex solution may meet the safety objectives for ADF2, 4. On the other side, all other functions are safety-critical for UAM

TABLE VI: ADS decomposition and functional requirement allocation to main components for ADS based on SFP probes

Air Data System		Air Data Function				
Unit	Part	1.1	1.2	2	3	4
Pitot/static (or Pitot + static port)	Static holes	X				
	Total tube	X				
	Heater	X				
	ADM	X				
Temperature	Probe		X			
	Heater		X			
	Sensing element		X			
AoA	Vane			X		
	Heater			X		
	Encoder			X		
AoS	Vane				X	
	Heater				X	
	Encoder				X	

TABLE VII: ADS decomposition and functional requirement allocation to LRUs for MFP-based ADS

Air Data System		Air Data Function				
Unit	Part	1.1	1.2	2	3	4
MFP probe	Static holes	X		X		
	Total tube	X				
	Heater	X		X		
	Integrated ADM	X		X		
Temperature probe	Probe		X			
	Heater		X			
	Sensing element		X			
AoS	Vane				X	
	Heater				X	
	Encoder				X	

applications and, therefore, they require redundant solutions to be compliant with airworthiness regulations. Therefore, at this very preliminary stage, a triplex solution for ADF1, 3 seems to be the target for VTOL of the UAM category.

VII. Conclusion

Air data sensing is a safety-critical segment of UAM avionics and its sensors contribute to the overall ADS safety. The sensing units are probes and/or vanes protruding from the aircraft fuselage that are typically redundant to achieve the safety objectives of the aircraft type. This paper presents a brief overview of state-of-the-art probes and vanes suitable for UAM applications in addition to innovative synthetic sensors that can be beneficial to overcome some issues that emerge when dealing with reduced aircraft fuselage size. The MIDAS project is presented as the first example of safety-critical ADS partially based on synthetic sensors able to obtain certification for civil applications.

In order to evaluate possible ADS sensing architectures for VTOL applications, the work proposes to group all possible solutions into three main categories: SFP-based, MFP-based and partially based on SS. The solutions are presented and they are studied from a safety point of view highlighting the advantages and drawbacks for UAM applications. Each ADS is decomposed in functions and items to define a functional allocation matrix. From early FHA the worst operational conditions are derived. It emerged that there are several air data functions (related to sensing units) that can lead to catastrophic events. Considering the special condition for VTOL issued by EASA in 2019, those critical events are quantified in 1×10^{-9} per flight hour. From PSSA, the safety objectives are split to safety requirements for each ADS parts.

The SSA is performed to evaluate if the simplex air data sensing suite can satisfy the safety requirements allocated to each ADF established with the FHA. Preliminary analysis shows that simplex ADSS architectures are not adequate for all air data functions and, as expected, redundant solutions are required. In fact, the functions ADF1 and ADF3 are the most critical and redundancy is necessary. Whereas a simplex architecture for air data sensors involved in ADF2 and ADF4 could satisfy safety objectives if some failure classifications can be relaxed by the A/C integrator.

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