Civil RPAS integration in future ATM: avionics system architecture design

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Abstract

This document deals with the description of a proper avionics system architecture to be installed on-board Remotely Piloted Aircraft Systems in order to allow this kind of vehicles to operate within the civil airspace. Starting from the procedure definition, a first set of functional and mission requirements have been elicited. Following a system engineering approach, starting from the functional analysis existing avionics devices have been selected to propose a system avionics architecture.

1. Introduction

Unmanned Aerial Systems (UAS) or Unmanned Aerial Vehicles (UAV) are essentially aircraft with no pilot on-board. An UAV can be controlled remotely from a ground station or can fly autonomously through, for example, pre-programmed routes or more complex dynamic automation systems. The term UAS has been adopted to reflect the fact that these complex systems include ground stations and other elements besides the actual air vehicle. For the purpose of this work, only Remotely Piloted Aircraft Systems (RPAS) have been considered.
RPASs are a particular subcategory of UAS that suppose the presence of a human pilot and non-military purposes for the mission considered. Beside an RPA (Remotely Piloted Aircraft), one or more remote pilot stations have to be available, together with Command and Control (C2) links and any other elements that may be required during flight operations. Among all these physical elements, other features might be included as, for example, software, health monitoring system, ATC (Air Traffic Control) communications equipment, flight termination system and launch and recovery elements [1].
RPAS are generally known for those civil applications that are too dull, dirty or dangerous for manned aircraft: they are considered suitable for those tasks that imply monotony or hazard for the pilot of a manned aircraft. Typical monitoring and surveillance tasks include border and maritime patrol, search and rescue, fishery protection, forest fire detection, natural disaster monitoring, contamination measurement, road traffic surveillance, power and pipeline inspection and earth observation. Moreover, the ability of some UAS to keep station for long period makes them suitable to be used like communication relays. Other UAS are already being exploited for commercial imaging purposes such as aerial photography and video.
In recent years, an increase in the number of operations and applications for RPAS in non-military or civil segments has been observed. Nowadays there are more than 250 RPAS manufacturers involved in designing, developing or producing more than 400 RPAS only in the European Union [2]. However, most of the civil RPAS products are still at prototype levels with a limited production and this is mainly due to the lack of regulations and the difficulties to access the civil airspace.

1.1 Civil UAS Integration into ATM

Adapting RPA to the civil airspace is nowadays an important scope addressed by both European agencies and state agencies (mainly International Civil Aviation Organization also known as ICAO and Eurocontrol). The reason of this increasing interest lays not only in the simplification of monotonous tasks or in the enhancement in some dangerous missions safety, but also in the forecast of a significantly growing number of RPAS operating in the next years [1].
With the same scope, the activity here presented has been dealt with within the framework of SMAT-F2 (Sistema di Monitoraggio Avanzato del Territorio Fase 2– Advanced Territory Monitoring System Phase 2), an Italian project funded by Piedmont Region and Fondo Europeo di Sviluppo Regionale (F.E.S.R.). The main goal of SMAT-F2 is to study and demonstrate an advanced monitoring system able to comply with planned tasks (e.g. traffic monitoring,

pollution monitoring, plantations observation and measurements, etc.) and to prevent and monitor different types of emergency events (e.g. floods, fires, landslips, etc.). Politecnico di Torino is deeply involved in SMAT-F2 project [3] [4]. The purpose of the study performed in this framework is to contribute to the definition of those guidelines that can be followed in order to achieve an integration of UAS aircraft in a non-segregated airspace and in the civil Air Traffic Management (ATM) system. This integration is not easy: many parameters are involved, both for safety reasons and for current airworthiness regulations.

The first regulation about UAS operations was established by ICAO and it is still used as reference [5]. According to this regulation, every aviation safety rule has to be developed in order to protect paying passengers and crews on board, other airspace users with respect to the risk of ground and Mid-Air Collisions (MAC), third parties and properties on ground. As far as RPASs are concerned, the only need is to protect people and properties on ground. Even though from the technological point of view this need could be overcome with the installation of proper systems (e.g. parachutes or emergency routes), nowadays RPAS are often designed to operate in restricted areas, where there is almost no manned traffic, or in not highly populated areas. The reason for this imposition lays in the lack of experience with this kind of vehicles, that are usually small (between 150 and 20000 kg of weight) but with a high level of complexity due, for example, to the automation of some procedures. In order to allow RPAS to fly in non-restricted areas, current regulations have necessarily to be modified, without compromising the safety of these areas. Moreover, the required integration of RPAS in civil airspace shall not imply any impact on other airspace users. According to Eurocontrol [6], in order to overcome this criticality, some requirements have to be defined for RPAS operating in the civil airspace:

- RPAS shall comply with existing or future regulations and procedures;
- RPAS integration shall not compromise existing aviation safety levels: the way RPAS operations are conducted shall be equivalent to manned aircraft, as much as possible;
- RPAS shall comply with the SESAR (Single European Sky ATM Research) trajectory management process;
- RPAS shall be able to comply with ATC rules/procedures;
- RPAS shall comply with the capability requirements applicable within which they are intended to operate.

Supposing to be able to change the current regulations and to allow RPASs to operate in non-segregated areas, RPASs will operate sharing the airspace mainly with civil air traffic: communication, navigation and surveillance systems must be adapted to the ATM rules. This means that an RPAS shall be able to operate under IFR (Instrumental Flight Rule) or VFR (Visual Flight Rule) depending on requirements. The complexity of the application of this requirement is due to the fact that the operations of RPASs involve many different flight profiles. Unlike most civil transport vehicles that perform point-to-point missions with common flight phases (i.e. takeoff, climb, cruise, descent and landing), RPAS have a much wider range of possible operations, from the simplest ones with civil air traffic features to the most complex ones with military features.

In addition to these considerations and as requested by Eurocontrol, SESAR environment shall be considered as reference. Indeed, in the next years, all European ATM will suffer one of the biggest changes ever with the introduction of SESAR, which will introduce a different and evolved way of navigation with the new concept of 4D navigation. Nevertheless, the introduction of SESAR will be a slow process that will take many years: a coexistence with the old ATM system will be required at least in Europe, and this implies that RPAS will have to be able to operate and adapt to both ATM structures. To match these requirements, RPAS must be equipped with the proper avionic suit (communication, navigation and surveillance systems), allowing the 4D navigation but also all old functionalities. At the same time, the regulations and the definitions of flight procedures for RPAS must consider this coexistence. However, if an RPAS is considered airworthy for operating in the SESAR environment, then it should have no problems to perform its mission in the old ATM scenario, due to more demanding requirements of SESAR avionics. Being the SESAR environment the most constraining one, the environment that has been chosen as reference for this work is the I-4D navigation, proposed for the initial phase of SESAR integration. The I-4D navigation is a particular kind of Performance Based Navigation (PBN) procedure [7]. PBN is based on statistical winds that will be used to optimise the route. This concept deals with the definition of a fixed segregated area with an activation and de-activation time. Therefore, the interaction with the civil traffic is between the departure airport and the entrance point of the segregated area and, then, between the exit point of the segregated area and the arrival airport. To this end, every vehicle performance have to be increased in order to support high integrity 4D trajectory management and separation. Pilots, controllers and operations planners will have automated support and management tools bringing safety, environmental and flight efficiency improvements. The systems involved are, again, the Communications, Navigation and Surveillance ones.

The I-4D concept is based on the addition of a time constrain in the trajectory management. Consequently, the variables to be considered for this kind of navigation are position (i.e. latitude, longitude and height) and time. These operations should be supported by a data link, called 4DTRAD (4D Trajectory Data Link). The idea is to synchronize the information shared by the vehicle and the ground segments to allow a more accurate and efficient route planning. Indeed, Estimated Time of Arrival (ETA) and the future waypoints will be shared by the vehicle with the ground segment. The ground segment will be able to process the information received with the aim of allocating the

trajectory in the dynamic scenario of the SESAR airspace. If this trajectory is found not compatible with the other vehicle trajectories, a negotiation process starts. The future waypoints and time of arrival are negotiated in order to allocate the flight path without creating any conflict. Once the vehicle accepts the new constrains, an evaluation and an update of all information is performed. This iterative process is conducted during the flight in a collaborative way.
Finally, to overcome the limitations associated with the lack of experience with UAS operations in non-segregated airspace is necessary to impose some hypotheses and considerations. Firstly, only medium and heavy UAS are considered (i.e. MAME, Medium Altitude Medium Endurance, and MALE, Medium Altitude Long Endurance): those vehicles are the most constraining ones, not only for their dimensions, but also because they need more support from ground and more extended areas to operate. According to this hypothesis, both takeoff and landing are always performed from an airport, but takeoff and landing phases are not considered, being the cruise phase the most critical for the introduction into the SESAR environment. In addition, as already said, a pilot on ground is considered so only RPAS are evaluated. Taking into account the availability of official regulations from ICAO or EASA (European Aviation Safety Agency), it is possible to validate whether these hypotheses are correct or reconsider them, in a recursive and iterative process.

1.2 Research overview

Taking all previous considerations into account, this work deals with the definition of the avionic system architecture allowing RPAS to be integrated within the civil airspace. Globally this integration would lead to a maximization of the airspace use, avoiding the segregation of huge areas. When a part of the airspace is segregated, all routes expected within this area are deviated and conflicts or congestions can occur. Considering UAS missions and endurances, these segregated areas could last for days. In order to be compliant with other projects with similar purposes currently under-development, SESAR results, Eurocontrol regulations and master plans have been taken into account as reference [7] [8][17]. Due to the lack of regulations and procedures concerning SESAR environment and the future ATM regulations for RPAS, hypotheses of strategies and guidelines for RPAS integration in non-segregated airspace have been made. In particular the concept of DMA (Dynamic Mobile Area) has been used as reference as the most promising strategy to follow [9] [10]. Particularly, DMA are temporary areas placed on the trajectory of the UAV and following it along its mission. This concept, born for military aircraft with limited capacity of integration in the ATM system, implies a dynamic segregation of airspace, which virtually eliminates the need of the generation of static segregated areas. DMA concept would give the opportunity to fly in non-segregated airspace to UAS type of platforms. Moreover, in order to study the best avionic solution, other military references have been taken into account: indeed, usually the RPAS flight profile has similarities with military missions and shall support civil procedures.
The process to determine avionics architecture starts from main requirements definition and proceeds through the Functional Analysis and Concepts of Operations, thus pursuing a typical System Engineering approach. System Engineering tools have been used throughout the design process. Indeed, a first group of requirements derives from the main activities that RPAS have to perform in order to be compliant with SESAR environment and the constraints imposed. On the other hand, a second group of requirements derives from an overview of the airspace organization and air navigation services that set the basis of the operational scenario. This information is complementary to SESAR in order to understand the new features of the future use and organization of the airspace, particularly of I-4D operations and PBN. The efforts are focused on the analysis and the fulfilment of all Communication, Navigation and Surveillance capabilities to ensure a proper integration in civil airspace.
Complementary, a group of MAME and MALE vehicles have been used as reference, in order to consider the actual technology level and be sure both of the feasibility and of suitability of the proposed avionic suit in the current ATM organization. Particular attention has been dedicated to the identification and selection of equipment and components already available on the market. Eventually a possible avionics architecture has been defined through the selection of off-the-shelf components.

2. System engineering approach for an Avionics system architecture definition

As already stated, the main aim of the work is the definition of the avionic system architecture allowing RPAS to be integrated within the civil airspace. The efforts are focused on the analysis and the fulfilment of all the Communication, Navigation and Surveillance capabilities to ensure a proper integration in civil airspace.
The design process starts from main requirements definition, taking into account all main activities that RPASs have to perform to be compliant with SESAR environment as well as the hypotheses and considerations imposed, and an overview of the airspace organization and air navigation services. Then the design proceeds with the Functional Analysis to define Communication, Navigation and Surveillance systems, according to a System Design Methodology [11] [12] [13].

2.1 Design Methodology

Functional Analysis has been used to define both system architecture, specifically the avionic system architecture, and main requirements that drive the system design itself [14]. As far as requirements are concerned, the basic tools of the Functional Analysis are used to derive specific categories of requirements, as shown in Figure 1. Top level requirements, i.e. mission requirements, directly stem out from the mission statement and mission objectives, which address the crucial issue of making the RPAS operative in the future civil aviation ATM. Moreover all the actors involved in this project (defined as Stakeholder [15]) impose additional requirements and constraints.
However, in order to comply with the activities proposed, the functional analysis should be inserted within a framework of other activities aimed to the definition of some top-level requirements and constraints due to the peculiarities of this application.

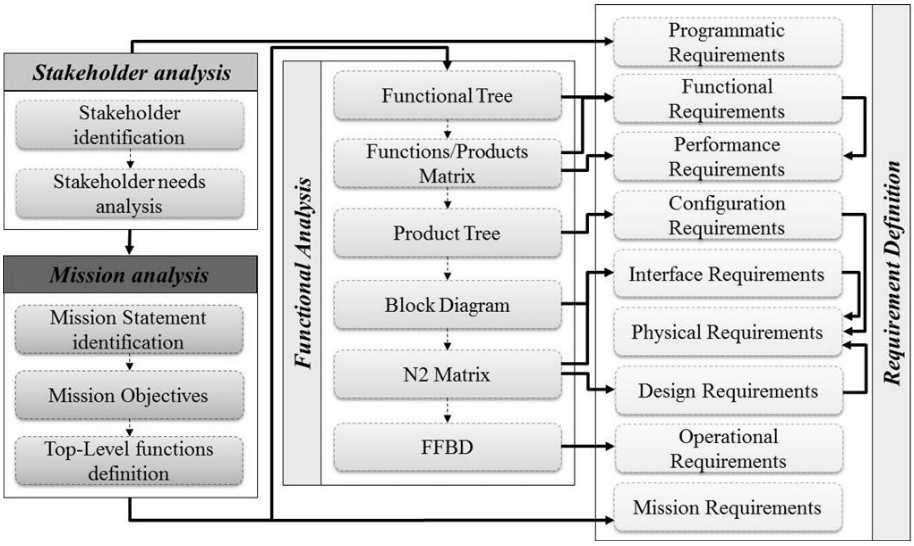

Figure 1: Functional Analysis Methodology overview.

Requirements represent the basis of the whole system design and for this reason they have to be derived with a rational and logical process, in order not to forget any drivers of the design that could eventually lead to an unsuccessful design. In this specific application, requirements have been subdivided into four main categories:

1) Functional requirements. They are statements that define a function that the product shall perform, in order to comply with the needs and requests of the user: they mainly derive from the functional tree and the functions/products matrix that helps better specify them;
2) Interface requirements. They are related to the interconnection or relationship characteristics between the product and other items and include statements describing different types of interfaces: this type of requirements can be derived directly from the block diagram or from the different types of connection matrix, like N2 matrix;
3) Design requirements. They are related to the imposed design and construction standards such as the design standards, selection list of components or materials, interchangeability, safety margins: this family of requirements derives from N2 matrix and block diagram;
4) Configuration requirements. They are related to the composition of the product or to its internal organization: the product tree can be regarded as the main tool to define them.

Before writing down requirements, the first activity to perform is the definition of the main objectives of the project. As suggested in [15] they can be derived analysing the Mission Statement. Primary Mission Objectives are directly derived from the mission statement. Mission Statement and Primary Mission Objectives represent mission foundation, for this reason they cannot be modified during the definition process.
Simultaneously, another important aspect to be accounted is the analysis of needs and expectations of the main stakeholders. This analysis mainly consists of two steps: identifying all the actors and determining their expectations. Consequently, secondary objectives can be derived. The stakeholders can be categorized as sponsors (i.e. those associations or private who establish mission statement and fix bounds on schedule and funds availability), operators (i.e. those people in charge of controlling and maintaining the main systems analyzed), end-users (i.e. those people that receive and use products and capabilities) and customers (i.e. users who pay fees to utilize a specific space mission's product) [15].

Once the main objectives of the project have been derived, the requirement derivation process can start. The typical Functional Analysis tools can be usefully employed in this process. In particular, Functional Tree, Functions/Products Matrix, Product Tree and Block Diagrams are used in this use case, while N2 diagram and Functional Flow Block Diagram are not used at this high definition level but would be exploited in future iterations. The overall process is iterative and recursive, meaning that it shall be repeated starting from the highest level to lower levels, i.e. system level, sub-system level, equipment level, component level.

The Functional Tree is one of the main tools of the Functional Analysis and it allows defining the basic functions that the system shall be able to perform. It is very useful since the very first phases of the design because it gives the opportunity of representing a product by means of a functional view, instead of its more common physical view. In order to split the higher level functions into lower level ones, designers ask themselves “how” that higher level function can be performed. Complementary, as a proof, it is possible to detect the higher level function asking “why” that lower level functions have to be accomplished by the system. It is important to notice that the Functional Tree allows defining functional requirements.

Once the main functions have been derived, it is necessary to map those functions onto the elements able to perform them, thus building up the Functions/Products Matrix. Checked cells of the matrix are used to identify connections between functions and products. Consequently, this tool allows better specifying those functional requirements previously derived. This matrix enables in fact defining the subjects of each function of the functional requirements.

The Product Tree can be drawn up starting from the products of the Functions/Products Matrix. Both the Functions/Products matrix and the Product Tree help define both the system architecture and configuration requirements.

A final System Engineering tool that can be exploited is the Block Diagram. This diagram depicts a graphical representation of the connections among all items at each level. It is very useful because it shows not only which equipment is connected with each other but it highlights the direction and the type of these links (data, electrical power, fluidic and mechanical connections). From these considerations, it is easy to understand that this type of diagram would allow defining interface and design requirements. Figure 2 shows the interactions among the different tools.

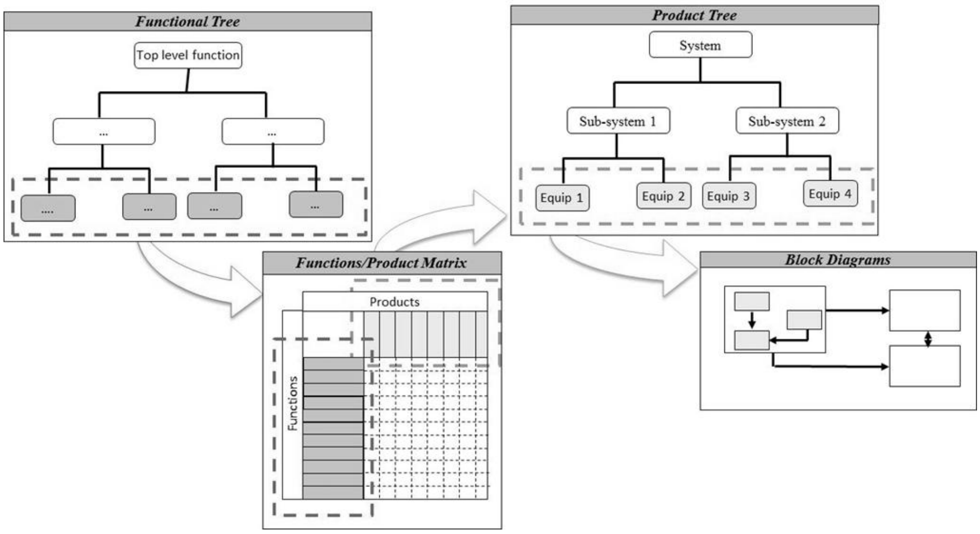

Figure 2: Functional analysis tool chain.

2.2 ATM needs and reference avionic architectures analysis

Regarding RPAS integration, there are different parameters to analyze and to adapt in order to comply with civil ATM requirements. The starting point has to be the analysis of the available avionics, in order to overcome the lack in RPAS regulation for present or future ATM scenarios. Another lack that has to be covered is in the technology readiness of this kind of vehicle. Indeed, the equipments available to operate UASs are generally developed to cover operational requirements for military missions, being this kind of vehicles mainly used and designed for military reason. Those requirements are related to tactical computations, high capacity for data storage, self-protection or military surveillance. So, other aspects such safe operation with nearby traffic or communication of the own position for traffic management are not completely covered with available technologies. Therefore, to implement RPAS in civil environment it is necessary to determine which kind of technology is nowadays available and which gaps shall be covered for a correct integration and safe operation of these aircrafts. Therefore, reference vehicles have been considered [5]:

- General Atomics RQ-1 Predator (Predator A);
- General Atomics MQ-9 Reaper (Predator B);
- Alenia Aermacchi Sky-Y.

After the analysis of those vehicles, a research of similar equipment is performed to determine the basic and most relevant features of the available devices. When those features are identified, it is possible to compare the requirement derived with the current avionics and set the way to complete all the functionalities needed. In order to improve the quality of this analysis avionic systems mainly developed for manned aircrafts are also considered, but with weight and performance that can fit with RPAS needs. Following this process, it was possible to determine different devices that can fulfil all the requirements or almost all, and to have a magnitude of the minimum space and weight necessary to operate an RPAS in the non-segregated airspace.

For this search several companies have been considered such as Northrop Grumman, Raytheon Systems, L-3 Systems, Rockwell Collins, Rada Electronic Industries Limited, Thales Avionics and Curtiss-Wright. Other avionics providers have been also considered in a wider research using [2] and [5]. The analysis is divided into three main fields covering Communications, Navigation and Surveillance systems features.

Once the reference vehicles and avionic architectures have been defined and analyzed, whole SESAR scenario is studied, in order to define the main requirements that should be accomplished and which architecture can cover all those necessities. As already explained, this study is based in the SESAR environment but, considering an earlier implementation, also an architecture able to comply with a pre-SESAR environment is considered. The I-4D navigation concept is used as reference. With these hypotheses, additional requirements have been obtained regarding Communication, Navigation and Surveillance systems required capabilities.

3. Avionic system architecture design for civil RPAS integration in ATM

In order to define the main requirements, the first activity to be performed is the definition of the main objectives of the project. For the analyzed case study and the imposed hypothesis and constraints, the Mission Statement can be derived:

To develop a strategy in order to accommodate RPAS into non-segregated ATM environments

From this statement, the Primary Mission Objectives can be listed. In order to consider them in their level of detail and in order to increase the precision of the results obtained, the Primary Mission objectives have been divided into System level Main Objectives and Sub-System level Main Objectives. At System level, the main objectives derived from the mission statements are to design the Avionic System to allow RPAS integration into future ATM and to define flight procedures to allow RPAS integration into future ATM. On the contrary, at Sub-System level three main objectives can be derived:

- To design the Communication Sub-System to allow RPAS integration into future ATM;
- To design the Navigation Sub-System to allow RPAS integration into future ATM;
- To design the Surveillance Sub-System to allow RPAS integration into future ATM.

The following step required by this methodology should be the definition of the possible Stakeholders. In addition to all the Partners and the Stakeholders defined in SMAT-F2 project in [10], for the purposes of this task, all the regulator entities should be take into account. In particular, Eurocontrol, ENAC (Ente Nazionale per l'Aviazione Civile) and ENAV (Ente Nazionale per l'Assistenza al Volo) regulations and intents in order to create a Single European Sky have been considered. To this purpose, the most important functions to be satisfied were written down, concerning present and future regulations. In particular, the major attention has been paid to the integration principles, considering all those functions the RPAS should perform in order to be fully integrated within a future ATM. Therefore, from the stakeholders' analysis two groups of Secondary Mission Objectives can be listed:

- *Integration principles*: to avoid a significant impact on the current users of the airspace, to make the RPAS compliant with existing and future regulations, to make the RPAS compliant with existing and future procedures, to avoid compromising existing avionic safety levels, to avoid increasing avionic risk levels, to create RPAS operation equivalent to manned aircraft, to make the RPAS able to comply with SESAR trajectory management process, to make the RPAS able to comply with ATC rules, to make the RPAS able to comply with ATC procedures, to make the RPAS able to comply with capability requirements applicable to the operative airspace;
- *SESAR compatibility*: to comply with MAP (Missed Approach Point) ATM Master Plan requirements, to comply with SESAR trajectory management for RPAS, to provide capabilities to perform I-4D trajectory based operations, to operate within System Wide Information Management (SWIM, i.e. distributed and

network centric structure to interconnect all actors, to enable a real-time information exchanges), to comply with delegated separation concept.

Once the main objectives of the project have been derived, the requirement derivation process should start. The typical functional analysis tools can be usefully employed in this process. The derived functions for the sub-system level can be directly associated to the three main sub-systems that would compose the entire avionic system: Communication sub-system, Navigation sub-system and Surveillance sub-system. Moreover, a forth-additional function should be inserted in order to guarantee the right connections among these main sub-systems. An iterative process over these functions will lead to higher levels of detail, defining the kind of devices involved. For simplicity and in order to give an example of application, only the system and sub-system level functional analysis will be reported.

Having defined the functions through the Functional Tree (Figure 3), the sub-system level Functions/Products Matrix will shows the main sub-systems required by in order to exploit the bottom level functions reported, (Figure 4). A first attempt of Block Diagrams is reported in Figure 5. It reveals that each main sub-system shall be connected with the data bus sub-system in order to allow the data sharing. Please note that each of the derived function is clearly identified by a unique code that reveal information about the sub-system from which it has been derived and the definition level which it refers to. This type of organization allows a full-level traceability of the derived functions and will be exploited in the requirement definition process.

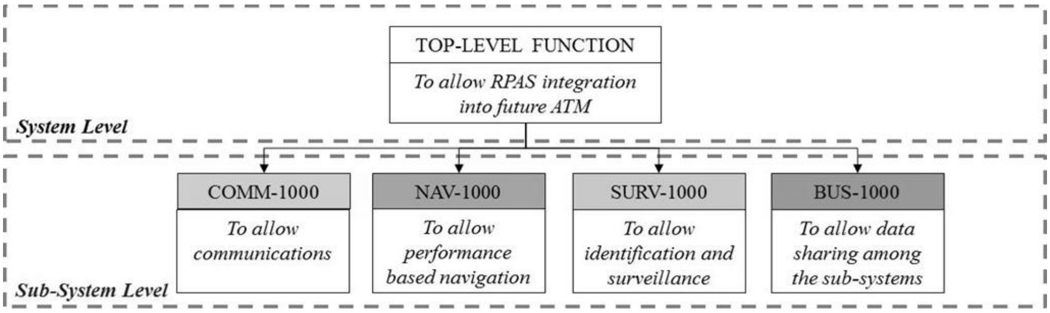

Figure 3: Functional Analysis at sub-system level.

			Sub Systems			
			Communication sub-system	Navigation sub-system	Surveillance sub-system	Data Bus
Functions	COMM-1000	To allow communications	✔			
	NAV-1000	To allow performance based navigation		✔		
	SURV-1000	To allow identification and surveillance			✔	
	BUS-1000	To allow data sharing among the sub-systems				✔

Figure 4: Function Device Matrices at Sub-System level.

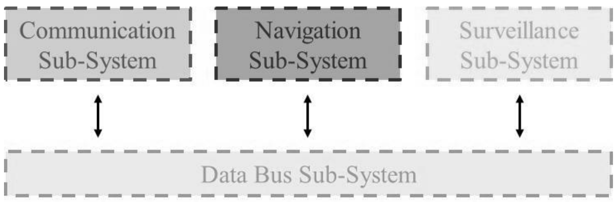

Figure 5: Block diagram at sub-system level.

Table 1: Example of requirements for the Communication sub-system.

Requirement ID	*Requirement*	*Generated Requirements*	*Upper Level*	*Level*	*Method*
		FUNCTIONAL REQUIREMENTS			
COMM-SYS-FUN-1000	Communication Sub-System shall allow communications	COMM-SYS-FUN-1100, COMM-SYS-FUN-1200, COMM-SYS-FUN-1300, COMM-SYS-FUN-1400, COMM-SYS-FUN-1500		Sub-System	Functional Tree
COMM-SYS-FUN-1100	VHF communication unit shall allow VHF communications	COMM-SYS-FUN-1110, COMM-SYS-FUN-1120, COMM-SYS-FUN-1130, COMM-SYS-FUN-1140, COMM-SYS-FUN-1150, COMM-SYS-FUN-1160, COMM-SYS-FUN-1170	COMM-SYS-FUN-1000	Equipment	Functional Tree
COMM-SYS-FUN-1110	VHF antenna shall receive VHF signals		COMM-SYS-FUN-1100	Device	Functional Tree
		INTERFACE REQUIREMENTS			
COMM-SYS-INT-2000	Data Exchange within the communication sub-system shall be guaranteed	COMM-SYS-INT-2100, COMM-SYS-INT-2200, COMM-SYS-INT-2400, COMM-SYS-INT-2400, COMM-SYS-INT-2500, COMM-SYS-INT-2600		Sub-System	Block Diagram
COMM-SYS-INT-2300	HF Communication Unit shall be connected with the Communication Management Unit	COMM-SYS-INT-2310	COMM-SYS-INT-2000	Equipment	Block Diagram
COMM-SYS-INT-2310	Connections shall guarantee data exchange from the HFDL management unit to the Communication Management Unit		COMM-SYS-INT-2300	Devices	Block Diagram
		CONFIGURATION REQUIREMENTS			
COMM-SYS-CONF-1100	The Communication Sub-System shall be composed of a VHF communication unit, a HF communication unit, a SATCOM communication unit and a communication management unit	COMM-SYS-CONF-1110, COMM-SYS-CONF-1120, COMM-SYS-CONF-1130	COMM-SYS-CONF-1000	Sub-System	Block Diagram
COMM-SYS-CONF-1110	The VHF communication unit shall be composed, at least, of a VHF antenna, a VHF transceiver, a VHF radio control unit, an ACARS management unit and an ACARS control unit		COMM-SYS-CONF-1100	Equipment	Block Diagram
COMM-SYS-CONF-1120	TheSATCOM communication unit shall be composed, at least, of a SATCOM antenna, a SATCOM antenna coupling unit, a SATCOM Management Unit, a Satellite Data Unit, and a Radio Frequency Unit		COMM-SYS-CONF-1101	Equipment	Block Diagram

The functional tree reported in Figure 3 should be expanded at lower levels, defining functions, product and interfaces for the Equipment level and the Device level. An iterative process has to be applied. At the end of this process, the main functions and devices for Communication, Navigation and Surveillance sub-systems are clearly defined. This information is then used in order to define the main functional, interface, design and configuration requirements. As it has been mentioned before, the requirements constitute the bases for the design of the system and for this reason they should be written following specific criteria [11] [12] [13]. In Table 1, examples of requirements derived for the communication sub-system are reported. Each requirement is specified through its own unique ID, the statement and all the information that clarifies its hierarchical position. Moreover, an additional column has been used in order to enhance the traceability and connections among tools and requirements derivation process, reporting the name of the tool from which the requirements was derived.

The second procedure used in order to derive all the requirements needed for the avionic architecture definition concerning the SESAR environment analysis and the main current avionic solutions available on the market. Particularly, those requirements derive from an overview of the airspace organization and air navigation services, describing the main concepts of the matter to set the basis of the operational scenario. Once the reference vehicles and avionic architectures have been defined and analyzed, whole SESAR scenario is studied, in order to define the main requirements that should be accomplished and which architecture can cover all those necessities. As already explained, this study is based in the SESAR environment but, considering an earlier implementation, also an architecture able to comply with a pre-SESAR environment is considered. The I-4D navigation concept is used as reference. With these hypotheses, additional requirements have been obtained regarding Communication, Navigation and Surveillance systems required capabilities. For simplicity and in order to give an example of application, only the Communication system results will be reported. The choice to report only these particular sub-system results is also connected to the RPAS features. Indeed, the communication system is the most important system: remembering that the pilot is on ground, an RPAS would not be able to operate without any kind of communications. For this reason, this system is critical for the operation of this kind of vehicle.

The minimum functionalities of the communication system, regarding the integration of an RPAS in the ATM system with all the listed hypothesis and considerations, are here summarized:

1) *To communicate as a manned aircraft:*
   ATC dependences should use different operations between interact with a manned aircraft and unmanned aircraft except when emergency situations, but it has to know if the vehicle it is interacting with is manned or not: this information should be given before the flight beginning or including the word "unmanned" with the first communication.
2) *Permanent data link with ground stations:*
   The system shall be connected with one or more ATM dependences and ground stations during the entire mission, sharing trajectory information (4D information) and trajectory constrains.
3) *Voice communication:*
   The system should have the capability to send and receive voice messages: this communication will be complementary to data link when this is available and the main way to communicate when data link is not available.
4) *Interoperability with radio and satellite communication (SATCOM):*
   When it is possible, the radio communications should be used, but when not possible, other ways to communicate with ground should be considered: the system should connect also by SATCOM to allow the constant monitoring of the trajectory.
5) *Capability to resend messages:*
   To assure the communication between ground dependences (e.g. between pilot and ATC dependences), the UAS communication system should act as radio repeater, when this service is requested.
6) *Capability to inform about lost link with pilot ground station:*
   The system has to inform to ATC dependences when the link with the pilot ground station is lost, communicating a potential risk of collision or the beginning of emergency procedures.
7) *Capability to inform about lost communication with ATC dependences:*
   When the communication between RPAS and ATC dependences is lost, the system should inform the pilot properly, allowing the use of alternative solution in order to restore the connection between ground dependences (e.g. by telephone).
8) *Capability to inform about the total loss of communication:*
   The system should broadcast the lost of communication with all ground dependences (pilot ground station and ATC dependences) if possible. Otherwise, the pilot ground station should identify the lost of communication and inform the ATC dependences with alternative communication solutions.

The same procedure has been used in order to identify the additional capabilities required by Navigation and Surveillance sub-systems. This analysis has allowed the definition of the requirements that the considered sub-systems have to fulfil for the integration in both SESAR environment and in the current ATM system. In addition, a verification of the requirements defined has been performed with the aim of confirm the possibility to select solutions currently available on the market (on the left in Figure 6, [5]). The RQ-1 Predator is a MALE unmanned vehicle, in operation since 1995. It is a military UAS originally designed for surveillance and observation, but later adapted to carry also missiles and munitions. This vehicle is considered the reference aircraft for this study because it is characterized by the typical performances useful and exploitable for civil applications. It also presents a great amount of flight hours that enable this kind of aircraft to be used for military operations that, sometimes, have a profile similar to those hypothesized for civil missions. Analyzing its mass and performance, it is easy to understand that this vehicle has a suitable configuration for the civil operation in non-segregated airspace. It has also to be considered that this UAS dimensions leads to constraints in the takeoff and landing phases that must be performed from airport or aerodrome, and its operation at high altitudes being a potential danger for airliners. All the equipment required for Communication, Navigation and Surveillance sub-systems are so analyzed.

Figure 6: At left, Predator RQ-1K, at right, MQ-9 Reaper.

After the analysis of this vehicle and the other already listed, a research of similar equipment is performed to determine the basic and most relevant features of the available devices. When those features are identified, it is possible to compare the requirement derived (from both functional analysis and the ATM overview) with the current avionics and set the way to complete all the functionalities needed. In order to improve the quality of this analysis avionic systems mainly developed for manned aircrafts are also considered, but with weight and performance that can fit with RPAS needs. Following this process, it was possible to determine different devices that can fulfil all the requirements or almost all, and to have a magnitude of the minimum space and weight necessary to operate an RPAS in the non-segregated airspace.

4. Results

This work deals with the definition of proper avionic system architecture allowing RPAS to be integrated within the civil airspace. The main requirements have been defined in order to select the best avionic solution between those available on the market. These requirements have been elicited from two main procedures. Indeed, a first group of requirements deals with all the main activities that RPAS systems have to perform in order to be compliant with SESAR environment and the hypotheses and considerations imposed. System Engineering tools have been introduced in order to support the results obtained. On the other hand, a second group of requirements derives from an overview of the airspace organization and air navigation services, describing the main concepts of the matter to set the basis of the operational scenario. This information is complementary to SESAR in order to understand the new features of the future airspace use and organization, particularly of I-4D operations and PBN. The efforts are focused on the analysis and the fulfilment of all the Communication, Navigation and Surveillance capabilities to ensure a proper integration in civil airspace. In order to verify all the selected requirements, an avionic architecture is here proposed.

Due to the lack of regulations and procedures concerning SESAR environment and the future ATM regulations for RPAS, proposal for strategies and guidelines for RPAS integration in non-segregated airspace have been considered. Therefore, the concept of DMA has been used as reference as the more promising strategy to follow [9] [10]. The operational scenario is considered composed by fixed segregated areas (Area Reserved or ARES). When the operational scenario evolves, following also the military operations, the ARES change their definition to finally merge with the DMAs. Those DMAs are segregated areas that follow the trajectory of the aircraft to minimize the airspace constrains. This concept, born for military aircraft with limited capacity of integration in the ATM system, implies a dynamic segregation of airspace, which virtually eliminates the need of the generation of static segregated areas. Even if all the elements proposed in this chapter are related with civil missions, assuming that the natural evolution of the UAS is from military applications to civil missions, in this chapter the authors refer to military components. The applicability of these components to civil applications has been verified. Despite of this military origin, civil components will be integrated in this kind of aerial vehicles when the civil use is widely developed. So, initially, military standards are the reference for the study of avionics but future UAS developed exclusively for civil applications will use civil equipment.

The first step for the avionic architecture definition is picturing the main functionalities required in a Functional Block Diagram, able to show clearly the main equipments and their interconnections Figure 7. The discontinuous line in the representation means that the function performed by the depicted block could be included in other device or in a stand-alone equipment, depending on the available technology and on the solution considered. After the Functional Block Diagram, alternatives of devices configuration are also considered selecting the best avionic equipment between those available on the market. In Table 2 data about the final proposed avionic architecture are shown, comparing them with the reference RPAS. For additional information about equipment capabilities see [16].

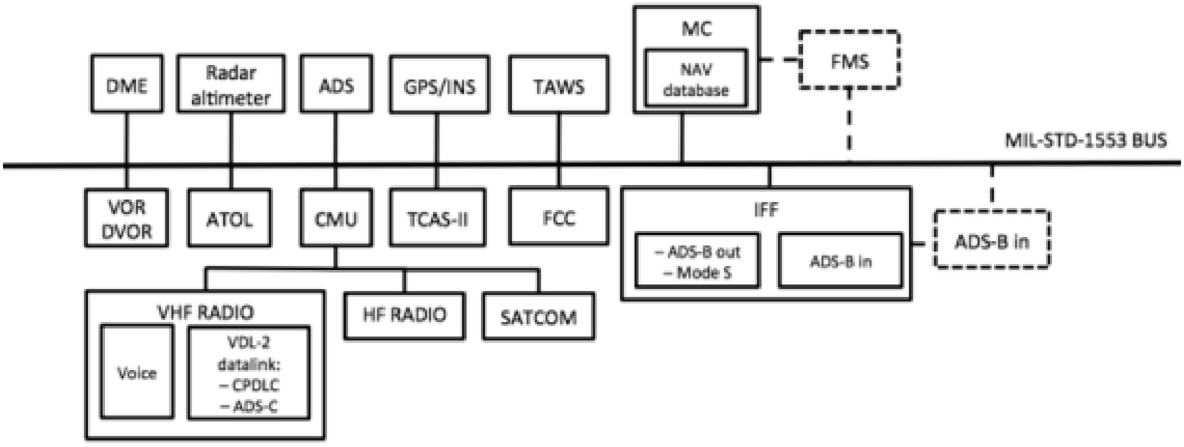

Figure 7: Avionics architecture proposed. With dashed lines those equipment that can be implemented alone or inside other equipment.

Table 2: Proposed solution for the avionic architecture, in comparison with RQ-1K Predator data.

	Proposed avionic architecture	*RQ-1K Predator avionic architecture*
	COMMUNICATION SUB-SYSTEM	
Radio	Rockwell Collins RT-1851A(C)	Rockwell Collins ARC-210 VHF/UHF
CMU	Rockwell Collins CMU-900	Lockheed Martin RQ-1U J-band (14,0-14,5 GHz) SATCOM link / Raytheon Systems UHF SATCOM link
Data Bus	MIL-STD-1553B bus	
	NAVIGATION SUB-SYSTEM	
INS/GPS	Northrop Grumman Litton LN-251	Northrop Grumman Litton LN-100G GPS receiver
Autopilot	Rockwell Collins Athena 311	
Mission computer and FMS	Rockwell Collins FMC-4700/4900	
Radio Altimeter	Thales Communications AHV-2500	
VOR receiver	Rockwell Collins AN/ARN-147(V) VOR/ILS/GS/MB Receiver System	
	SURVEILLANCE SUB-SYSTEM	
IFF transponder ADS-B transponder	BAE systems AN/DPX-7 IFF reduced size transponder	Raytheon APX-100 IFF transponder
ADS-B transponder	BAE systems AN/DPX-7 IFF reduced size transponder	
TCAS II and TAWS	ACSS T2CAS	

In the architecture selected, each data bus consists of two independent pairs of bus lines labelled left and right. Bus communications are controlled by a Bus Controller (BC), which manage the flow of information transmitted across the bus between all the equipment attached to it. The elements connected by data buses are called Remote Terminals (RT), which generate or receive data. The data flow is controlled by the BC that sends specific commands to individual RTs. In addition, all buses have Backup Bus Controllers (BBC) that performs the same functions as the RTs until the BC fails, and when the failure occurs, the BBC assumes the control of the data bus, operating as a BC. An equipment called ACAWS (Advisory, Caution And Warning System) is able to alert the pilot on ground of a BC failure. However, since all buses have BBCs there is possibility of degraded data bus performance in the event of a BC failure. All the buses considered in this architecture are compliant with the standard MIL-1553B, the most common extended military buses. For civil applications, these buses should be substituted with ARINC-A629 or A429 buses that are the most common civil buses nowadays. The common configuration is a dual redundant configuration with two independent lines that allows a backup in case of failure of one line.

One of the sub-systems considered was the Communication one. There are several elements directly involved in communications. In the avionic architecture selected and in order to verify all the requirements defined, the main way to communicate is by radio, using HF (High Frequency) and VHF (Very High Frequency). An additional satellite communications has been selected as support for the radio communication. All those communication systems support the VDL-2 (VHF Digital Link) data link and allow the communication between the aircraft and ground using voice messages or data link information exchange. To manage the transmission mode in VHF (voice or data link), the radio is connected to the bus with the Communications Management Unit. A similar structure is considered when data link is available in HF communications. In conclusion, the following equipment has been selected of the Communication sub-system: Communications Management Unit, VHF radio, HF radio, SATCOM.

The second sub-system considered was the Navigation sub-system. This sub-system is composed by sensors, a Mission Computer and a Flight Management System (FMS).

To provide information to computational equipment there are proposed several sensors, able to give information about flight conditions, surrounding traffic and collision alerts. For the architecture proposed, those sensors are a GPS/INS (Global Positioning System/Inertial Navigation System), an ADS (Air Data System), a VOR/DME (VHF Omni-Range/Distance Measurement unit) and a Radar Altimeter. Even if additional sensors can be considered, assuming space and weight limitations only the most necessary equipment are here selected.

Another Navigation sub-system equipment is the Mission Computer. Generally, military mission computers provide tactical functions, navigation calculations and bus controlling on 1553B buses. For RPAS it is assumed that this structure is also used. Considering that this kind of Mission Computer is included in standard configurations for UAS it is necessary to valuate if this device provides also the capabilities associated to the FMS. If those capabilities are not available shall be studied how to integrate those functions in the Mission Computer. When the computer presents the possibility to update its contents and functionalities, the implementation of new functions usually developed for FMS should be done to save space in the RPAS. If this procedure is not possible, a new MC should be considered to integrate all the functions in only one device. In the worst case, a MC and an independent FMS will be included in the RPAS. Considering this worst condition, two FMS has been selected, using a dual-redundant structure. Both the equipment calculates the navigation solutions independently, comparing their solution in order to increase the results accuracy. The FMS allows the navigation in a 4D route, auto-tuning of frequencies, fuel management and data crosschecking with the navigation database. The preferred format for Navigation Database is ARINC 424. The outputs of the FMS go to the Communications Management Unit, the autopilot and all those other equipment that require input data.

An RPAS using the ARES space division has to include additional functions in the FMS. Indeed, in the navigation database shall be included information about the selected emergency procedure in case of loss connection with pilot ground station. Alternative solutions may be considered in this situation as an autonomous flight re-plan of the route in order to reach the aerodrome. On the other hand when the RPAS use DMA concept to navigate, the functions of the FMS shall be improved due to the dynamism of this kind of area. In this case the functions mentioned before, shall also be available, adding a new algorithm to evaluate the potential conflict point. This algorithm uses the information received from ADS-B (Automatic Dependent Surveillance - Broadcast) and evaluates potential presence of a conflict point between two or more trajectories. When the potential conflict point is confirmed, the FMS shall start a communication by ADS-C (Automatic Dependent Surveillance - Contract) with ATC to obtain information about the real aircraft track, for a more accurate evaluation. If the conflict point is again confirmed, the RPAS speed is redefined to set a minimum separation between every vehicle.

The possibility to use an Autopilot in order to support FMS and on-ground pilots operations has been considered. Autopilot develops the control of the flight attitude considering several inputs from sensors to reduce the workload of the pilots. With all the information received, it provides a solution to maintain the flight conditions in a controlled way. The computer that contains the Autopilot is the Flight Control Computer. Autopilot Flight Director modes considered are the conventional modes available in commercial aircrafts (i.e. Pitch Attitude Hold, Roll Attitude Hold, Heading Hold, Heading Select, Altitude Hold, Altitude Select, IAS Hold, IAS Select, Vertical Speed Hold, Vertical Speed Select, Autothrottle/Speed hold/Speed Adjust, LNAV, VNAV) [16]. Additional required modes that shall be included in the Autopilot database considering the requirement selected are the “4D” Mode and “Return Home” mode. 4D mode is required in order to assure 4D navigation. This new mode shall be developed and integrated in the autopilot system, allowing the possibility to set time constraints on different waypoint and trajectory or velocity constrains. The precision of the time arrival shall be ±30s for en route flights and ±10 seconds for TMA (Terminal Manoeuvring Area or Terminal Control Area, TCA, which manages the traffic departing or arriving to the airport). Finally, the Return Home mode is required in order to increase the safety in RPAS operations. Indeed, this mode shall allow the beginning of a safe procedure to return to the aerodrome, in case the RPAS losses the data link with the pilot ground station and becoming uncontrollable. This procedure shall be properly designed to avoid conflicts with civilian traffic and other RPAS flying in the same area. Specifically, the ATC shall clear the airspace to avoid collisions: the ATC shall be informed about this procedure features before its actuation. A good way to define this emergency procedure is define its waypoints. In addition, when this mode is active, the FMS shall calculate the ETA over the waypoints and communicate it to ATC. When this communication cannot be performed, the ground segment shall provide to ATC an approximate ETA value with alternative methods. Consequently, an automatic way to detect the lost link shall be defined and, when this lost is detected, the Return Home mode shall become active. However, the ground segment shall always notify the situation to ATC. A similar mode is already in use in General Atomics RQ-1 Predator.

Finally, the third sub-system considered is the Surveillance sub-system. This particular sub-system is required for RPAS because the surveillance phases could include large areas with different terrain profiles. In addition, takeoff and landing phases are performed in non-segregated airspace and the performances assured in these areas have to be the same of a commercial flight also for an RPAS. The Surveillance sub-system is composed by interconnected and collaborative systems that are always active on the background. When a potential collision is detected, these systems are able to alert the pilot or the autopilot. The main systems are TCAS-II (Traffic Collision Avoidance System), the IFF (Identifier Friend or Foe) and TAWS (Terrain Awareness And Warning System).

In addition, in order to increase RPAS automation, an Automatic TakeOff and Landing (ATOL) system shall be included. The ATOL system is able to cooperate with GPS and other kind of visual systems (e.g. laser measurements).

In conclusion, a solution to fulfil all the functionalities described and respecting the architecture proposed (Figure 7) is defined elaborating a list of available equipment to be carried in a RPAS. Indeed, each sub-system includes different functionalities that are satisfied by different equipment: there exist different devices and possible configurations to satisfy the requirements. Every existing configuration has been analyzed and the optimal solution has been selected (Table 2). Once all the devices have been selected, an evaluation of the preliminary mass, volume and power budgets is performed in order to validate the avionic architecture selected comparing the results with General Atomics RQ-1 Predator performances (Table 3, [5]). The budgets evaluation is useful not only in order to validate the solution proposed, but also for its optimization. Indeed, the devices with the most elevate contributions can be determined and replaced, when feasible an in accordance with the magnitude of this contribution and its relevance in the achievement of the requirements. In case of missing information, estimations are reported, using as reference other devices with similar dimensions and functions and considering a safety factor, in order to be conservative.

Table 3: Mass, volume and power budgets for the selected equipment, (*) indicates approximated values. RQ-1K Predator mass and electric power specifications are reported.

	Mass		**Volume**		**Power**	
Device	*kg*	*%*	*dm^3*	*%*	*W*	*%*
Radio	4,8	12	3,96	9	23	4
CMU	5,5	14	7,72	18	35	5
GPS/INS	5,8	15	7,00	16	30	5
MC/FMS	7(*)	18	7,72	18	250	39
Radio altimeter	1,8	5	1,62	4	16	2
VOR receiver	3,6	9	4,06	9	45	7
DME receiver	1,27	3	1,45	3	100	15
IFF/ADS-B	2,72	7	1,89	4	80(*)	12
TCAS-II/TAWS	6,68	17	7,72	18	70	11
TOTAL	**39,17 kg**		**43,16 dm^3**		**649 W**	
RQ-1 Predator	*204 kg*				*3000 W*	

Finally, the total mass is approximately 40 kg, with 44 litres of volume and a power consume of 649 W. These values are a small percentage of weight and power considering the maximum weight and power required by a MAME or MALE RPAS: General Atomics RQ-1 Predator budgets, the results obtained are only 19% for the total mass and 21% of the total electric power. Even if no comparison is possible for the volume budget results, the value obtained as results is considered reasonable. Firstly, the percentages of total weight and power are considerably small (i.e. around 20% of the total RPAS capacity). Secondly, the selected devices are designed not only for the same RPAS applications here considered, but also with compact formats. Thanks to all these considerations, the equipments selected are compatible with the use of other onboard payload (e.g. cameras or spectrometers).

5. Conclusions

The aim of this work is to define an avionic architecture able to allow the integration of RPAS in the civil airspace, considering SESAR results and Eurocontrol regulations and master plans. Currently, all the effort in the market are focused in the increasing the RPAS features able to assure a coexistence of those unmanned vehicles with the manned ones in civil missions. Behind these efforts is hidden a potential increase in the number of UAS operations, considering all the advantages that are connected with it in term of cost reduction, risk reduction and long mission endurance. This market increase is also reflected in the avionics market. Indeed, there are an increasing number of companies that propose miniaturized avionic solutions for UAS applications without decrease the quality of the final product. This increasing number of avionics for UAS applications is a positive aspect for their integration in a controlled airspace. Indeed, this integration is completely dependent on Communication, Navigation and Surveillance sub-systems capabilities considering the introduction of PBN rules. Consequently, a wider range of products is useful in order to satisfy all the requirements defined in order to assure safe operations with other manned or unmanned vehicles.

The process to determine an optimal avionic architecture has to start with the main requirements definition. These requirements have been defined through two main procedures. A first group of requirements deals with all the main activities that RPAS systems have to perform in order to be compliant with ATM environment. System Engineering tools have been used in this phase of the work. In addition, a second group of requirements derives from an overview of airspace organization and air navigation services. All these requirements are compliant to SESAR in order to understand the new features of the future airspace use and organization, particularly of I-4D operations and PBN. The efforts are focused on the analysis and the fulfilment of all the Communication, Navigation and Surveillance capabilities to ensure a proper integration in civil airspace. Complementary, a group of MAME and MALE vehicles have been used as reference, in order to consider the actual technology level and be sure both of the feasibility of the avionic proposed and of its suitability in the current ATM organization. All these vehicles have been analyzed from the avionics point of view with a special attention to look for those equipment and components already available in the market. Accordingly to the state of the art of the technologies involved and the hypothesized operational scenarios, iteration on the obtained requirements has been performed. Finally, to conclude the study, possible avionics architecture has been defined through the selection of off-the-shelf components. Certainly, the avionic architecture selected has to be the first step in an iterative process with the objective of determining the optimal onboard equipment for RPAS civil applications in a controlled airspace. The next iteration must perform a more detailed analysis in specific ATM features to assure the complete compatibility of the whole network with the equipments selected. In addition, it is also important to validate all the compatibility between the different functions identified and the equipments selected in order to assure also the compliance with ICAO annexes.

Considering safety regulations, different problems have to be highlighted. Generally, UAS regulations are not defined and in many cases, reference to manned aircraft regulation (especially military ones) has to be considered. In order to increase the applicability of the analysis performed, the functions selected are both a combination of ICAO regulations for manned aircrafts and hypotheses able to assure safer operations. Moreover, UAS mainly come from military technology. In that way, UAS designed for civil operations have to be considered as a hybrid between of military and civil systems. Hence, in order to overcome the difficulty to manage this new kind of aircraft in a complex scenario, both military and civil rules have to be used as reference.

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