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SELECTION OF AN UAV CONFIGURATION LAYOUT FOR OPTIMISATION OF TELEDETECTION MISSION USING HYPERSPECTRAL SENSORS

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Abstract

This paper addresses the exploitation of hyperspectral technology on unmanned airborne platforms. In particular, three different Unmanned Aerial Vehicles (UAVs) (Falco, Samonit-1 & Samonit-3) able to accommodate the same hyperspectral sensor (selected as reference) have been analysed and compared using Figure of merits selected among the main performance indexes. In particular, this paper reveals the impact of some configuration characteristics of the UAVs on the performances reached in teledetection activities.

1 Introduction

In the last decade, the development innovative technologies revolutionize teledetection activities pushing the exploitation of small autonomous unmanned aerial vehicles to carry out the missions. Among these innovations, this paper focuses on the hyperspectral technology that in the last few years reached a high Technology Readiness Level (TRL) and, taking advantages of the miniaturization of the electronic components [1], have been envisaged for innovative fields of application. The first applications of the hyperspectral technology go back to the 1980s where the first hyperspectral sensors were applied in the geological field. Today, equipment exploiting this technology is used in various fields allowing solving problems in very different domains, from healthcare [2] to geology [3] [4] [5] and agriculture [6]. Nowadays, the advantages derived from the exploitation of the hyperspectral technology are very well known and therefore, hyperspectral sensors are requested for several kinds of applications in very different fields. This family of sensors was developed starting from already existing and proven multispectral technology, increasing the numbers of bandwidths sensed of orders of magnitude. This achievement had been possible thanks to the miniaturization of electronic devices and to TRL (Technology Readiness Level) enhancements in optical devices. Among the several field of application, aerospace domain played a fundamental role trying to exploit this kind of sensors mainly for monitoring purposes. As far as teledetection activities are concerned, the following considerations should be taken into account:

- a lot of missions could arise as emergency requests and thus unscheduled requests shall be taken into account (search and rescue, incidental area monitoring, etc.);
- some targets could be very difficult to reach because of environmental or man-made obstacles;
- a very high level of danger and risk could characterize some mission scenarios.
- some monitoring activities would be repetitive and boring;

These preliminary considerations make the airborne application the most suitable for monitoring purposes.

In this context, this paper addresses the exploitation of hyperspectral technology on unmanned airborne platforms. In particular, three different UAVs (Falco, Samonit-1 & Samonit-3) able to accommodate the same hyperspectral sensors (selected as reference) have been analysed and compared using key drivers selected among the main performance indexes.

The following section summarizes the main features of missions aimed at performing monitoring activities and provides suggestions for categorization depending on the type of the target. Then, Section 3 provides an overview of the three UAV selected as reference aerial platform and summarizes the main features of the hyperspectral sensor used for comparing their performances. Section 4 enlists the main problems to face with in order to optimize teledetection missions suggesting possible Figures of Merits. In this context, the need of considering the on-board integration of systems and especially the accommodation of the payload should be taken into account since the conceptual design phases. Then, in Section 5, the main results of the comparison are reported and discussed. Eventually, future exploitations of hyperspectral technology are envisaged.

2 Teledetection missions

This kind of unmanned vehicles with hyperspectral sensors on-board is usually employed in monitoring missions for different purposes and depending on the target, three possible monitoring activities have been considered:

- The punctual target: the aircraft performs several loiters to monitor a specific objective;
- The linear target: the aircraft performs round trips to scan it. Typical examples belonging to this family are borders surveillance or highway and railways monitoring activities;
- The area target: the aircraft follows planned trajectories to cover the entire area with the maximum level of efficacy. Monitoring for agricultural or cadaster purposes are typical examples for this type of target.

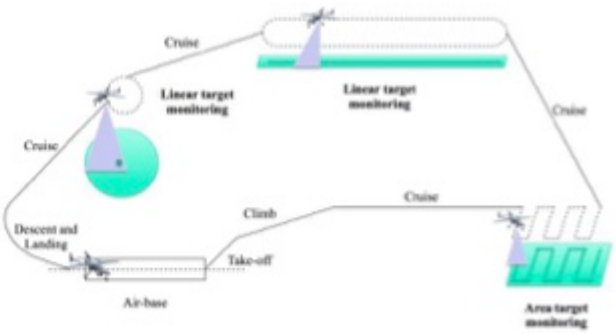

Fig. 1: Example of teledetection mission.

The mission profile scketched in Fig. 1 has been thought to be the test-bed because it allows to verify the performances of the UAV presented in the next Section in performing puntual, linear or area monitoring activities. In real cases, each mission is composed of different targets put together during the planning activity depending on the endurance and the flying qualities of the vehicle.

The ability of performing the planned mission is only one of the requirements the system shall comply with. Indeed, in order to guarantee a proper service, the system shall respect some operative requirements concerning the cruise altitude, the cruise flight speed, the endurance, and the take-off and landing speeds and distances. Furthermore, the system shall also comply with additional requirements mainly related to the sensor and to its integration like the maximum payload volume, the maximum payload mass and the maximum power consumption. There is also another category of requirements strictly related to the sensor performances. Indeed, we assumed to fix mount the hyperspectral sensor on the aircraft in a proper bay positioned very closed to the centre of gravity in order to diminish the sensitivity of perturbations (both related to gusts or simply to the CG excursions). In this position, the sensor shall guarantee a certain resolution in order to be able to detect objects of a defined sized from its operative altitude.

3 Hyperspectral Technology

The first sensors exploiting hyperspectral technology were used for remote sensing of natural environment, in particular in mineral exploration in the 1980s, highlighting, since the beginning, that the main purpose of systems based on hyperspectral technology is to identify phenomena or targets for which information about shape could be neglected and spectral data are more interesting. It is also worth to remember that hyperspectral sensors have been developed as further improvements of those equipment exploiting the multispectral technology. These enhancements were possible thanks to the main advances in focal-plane technology that allow to overcome the major disadvantages of the previous equipment. The hyperspectral sensor could be defined as a spectrometer [7], [8], consisting of several advanced digital cameras able to gather electromagnetic radiation reflected by the under-observation target and to measure the energy related to each single frequency band. In particular, hyperspectral sensors are designed in order to guarantee the capability of gathering information about a few hundreds of narrow bands. This feature is the most prominent element of distinction among the various existing and under-development remote sensing instruments.

From a scientific perspective, it is obvious that the exploitation of this kind of technology relies upon the assumption that has been verified by optical studies asserting that each material is characterized by its own spectral signature. Each pixel of the acquired picture contains the spectral information of the material. During post-processing activities, spectral signatures shall be analysed and related to a specific material and to this purpose, a database shall be developed and test in advance. Then, data collected during the acquisition process are packaged in to a three-dimensional data structure referred to as *data cube* (Fig. 2).

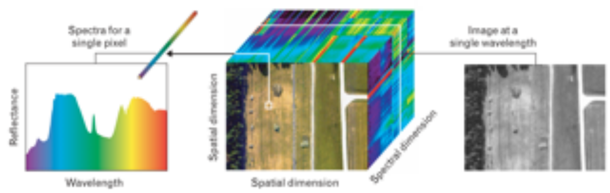

Fig. 2: Data Cube characterization..

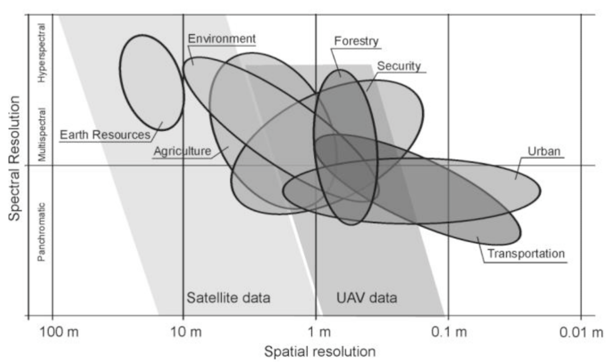

Fig. 3: Spaceborne vs unmanned airborne applications.

Considering the capabilities of this kind of sensors, both spaceborne and airborne applications could be envisaged. Depending on the purpose of the teledetection activities, airborne installation could be more attractive for the spatial and spectral resolutions they are able to guarantee. Fig. 3 summarizes the spatial and spectral resolutions of the most common missions, highlighting the area of exploitation of UAV and space platforms.

3.1.2 Reference hyperspectral sensor

For the application proposed in this paper, the Sphyder® sensor has been selected as reference. The main reason that led the authors to the selection of this specific sensor were first of all its main characteristics (listed in Table 1) and secondly for its previously aeronautical applications for monitoring missions.

Tab. 1: Reference hyperspectral sensor [9]

	Panchromatic (PAN) camera	Visible Near InfraRed (VNIR) camera	Short Wave InfraRed (SWIR) camera
Spectral range	[450, 800] nm	[400, 1000] nm	[900, 2500] nm
Spectral sampling	-	2.5 nm	6 nm
Spectral bands	1	240	266
Instantaneous Field Of View (IFOV)	0.067 mrad	0.33 mrad	1.0 mrad
Field Of View (FOV)	±14.5°	±14.5°	±10.8°
Ground Sample Distance (GSD) @ 1500 m	0.10 m	0.5 m	1.5 m
Swath @ 1500 m	780 m	780 m	576 m

Tab. 2: Hyperspectral sensor operative modes [9]

	Take off	Climb	Cruise	Descend	Landing
Power off	■			■	■
Initialization		■	■		
Standby		■	■	■	
Calibration		■	■		
Acquisition			■		
Failure	■	■	■	■	■

In addition, table 2 reports the sensor operative modes that are strictly related to the mission phase in which it is supposed to be exploited. Indeed, it is crystal clear that during cruise only, the data acquisition process could be activated. However, the other phases could be exploited in order to perform sensor initialization and calibration. The shift from one operative mode to another one could be remotely addressed by on-ground operators but a complete automation could also be envisaged.

4 Reference airborne platforms

The three reference airborne platforms selected for this case-study are reported in the following subsection. The architecture layout and the main geometrical characteristics are provided. In addition, for each configuration, a proper installation of the sensor would be suggested, based on quality of image acquisition and low sensitivity to perturbation criteria.

4.1 Falco

The first considered platform is a Medium Altitude Medium Endurance UAV (MAME UAV) developed and produced by Finmeccanica, Airborne & Space Systems Division (previously known as Selex ES). Please note that the authors have already performed feasibility studies on sensor integration on-board this platform [9] [10]. In particular, a detailed analysis of flight data analysis and consequent optimization of mission planning have been carried out. As it is clearly visible from Fig. 4 and Fig.5 the hyperspectral sensor is installed in the very proximity of the centre of gravity of the aircraft. This implies the possibility of installing the sensor on the airframe directly, without an interface steerable turret. However, the hypothesis of considering a fixed mounted sensor forces to ad-hoc planning the mission in advance, envisaging attitude variations. In addition, data post processing activities will take longer time due to the non-negligible overlapping phenomena [REF].

Fig. 4: Picture of Falco.

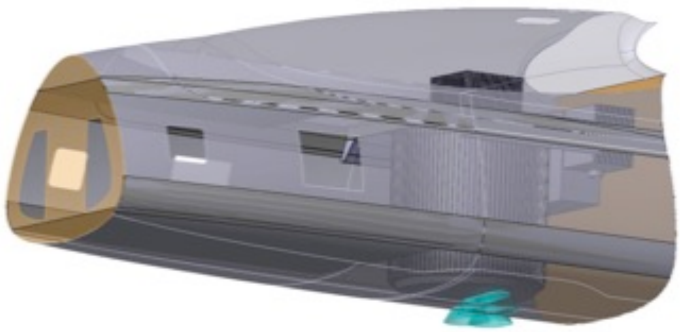

Fig. 5: Sensor integration on-board Falco platform [9].

3.1.2 Samonit 1

Add description of Samonit 1 configuration with special attention devoted to the sensor integration (location wrt CG)

Fig. 6: Samonit 1during a test flight in 2010.

3.1.3 Samonit 3

Fig. 7: Samonit 3 at Minsk Air Show in 2011.

Add description of Samonit 3 configuration with special attention devoted to the sensor integration (location wrt CG). Differences wrt Samonit 1

5 Trade-off analyses

This section aims at describing the methodology exploited to select the best unmanned airborne platform to host the selected hyperspectral sensor and able to maximize the image acquisition activity.
The proposed approach is a revisited version of the one proposed by the authors in [11] [12] for a different application.
First of all, the main hypotheses and boundary conditions of the problems should be fixed. Then, based on a detailed analysis of the stakeholders' expectations, a list of qualitative aspects to be optimized could be derived. Then, following an iterative and recursive approach, exploiting the quality Functional Deployment Tool, from the list of qualitative high-level product attributes, a list of technical parameters to be maximized can be obtained.
In this way it is possible to derive appropriate Figure of Merits leading the designers to select the best candidate among the options. Please note that in this case, the population of the options is small but this methodology has been conceived to assist in trade off analysis of very high number of possibilities.
Trade-offs are crucial activities of the design process, because they rationally support the choices of the designers. In order to avoid neglecting or deleting some alternatives, it is important to properly evaluate not only the variables and the Figures of Merits, but also the scoring strategy, performing sensitivity analyses, for example. This last consideration is especially true in all high level trade-off where the major difficulty consists in the numerical evaluation of purely qualitative attributes [12].
As far as this specific case is concerned, the first step was to understand the main features required for carrying out a teledetection mission and to this purpose, the main stakeholders (all private and public entities with interest in the product and the service) have been derived. Then, a certain number of top-level stakeholders' expectations have been listed and prioritize through the assignment of weighting factors.
At this level, following the suggestions reported in [12] [13], the following weighting factors can be assigned:

- "0" in case the expectation *is not effective* for the considered technical aspects.
- "3" if the expectation can have a *moderate positive* impact on the considered technical aspects.
- "9" if the expectation could have a *high positive* impact on the technical aspects
- "-3" if the expectation can have a *moderate negative* impact on the considered technical aspects.
- "-9" if the expectation is in contrast with the technical aspects considered.
-

Stakeholders' expectations and relative importance is reported in Table 3. Complementary, Figure 8 is an example of the first iteration of QFD that shows the main technical parameters that can translate in stakeholders' expectations in design variables.

Tab. 3: Stakeholders expectations and relative importance

Stakeholders Expectation	***Importance***
To be exploited for a large number of monitoring scenarios	High (0.3)
Reduced effort in post-data processing	Moderate (0.2)
Short turn-around time	Moderate (0.2)
Repeatability of the acquisition process	High (0.3)

		W	***Vehicle architecture***				***Vehicle performances***						***Sensor characteristics***					***Integration***	
		Importance of Stakeholders expectations	Fuselage diameter	Wing position wrt the fuselage	Empennages surface	Landing gear length	Maximum speed	Stability	Fuel consumption	Maximum range	Maximum endurance	Nominal operative altitude	Field of View	Resolution	Mass	Volume	Power consumption	Displacement wrt the CG location	Steering capability
			△	△	△	△	△	△	▽	△	△	△	△	△	▽	▽	▽	▽	△
Stakeholders expectation	To be exploited for a large number of monitoring scenarios	0,3					3	3		9	9	3	3	3	9	9	9	9	9
	Reduced effort in data post-processing	0,2		3	3			9					3	3				9	9
	Short turn around time	0,2	3			9									3	3			-3
	Repeatability of the acquisition process	0,3						9	9									3	3
		1	0,6	0,6	0,6	1,8	0,9	5,4	2,7	2,7	2,7	0,9	1,5	1,5	3,3	3,3	2,7	5,4	4,8

Fig. 8:Application of the Quality Functional Deployment Tool to our reference case.

It is important to notice that the technical parameters are grouped into main categories:

- vehicle architecture
  - fuselage diameter
  - wing position wrt the fuselage
  - empennages
  - landing gear type
- vehicle performances
  - maximum speed
  - aerodynamic derivatives
  - fuel consumption
  - maximum range
  - maximum endurance
  - nominal operative altitude
- Sensors characteristics
  - field of View
  - resolution
  - mass
  - volume
  - power consumption
- On-board sensor integration
  - displacement wrt the CG location
  - sensor installation type

From the exploitation of QFD, a ranking of the most affecting parameters is derived. Then, in order to compare the three different airborne platforms, these parameters should be combined and Figures of Merit obtained.

The analysis reveals that stability related characteristics are (aerodynamic derivatives, relative distances of the sensor CG and aircraft CG) and mass and volume budgets are the design variables to be properly taken into account during the design process, in order to maximize the identified stakeholders' expectations. Thus it is clear that conceptual design tools like CAD or high level CFD should be exploited in order to obtain a numerical evaluation useful for a trade-off. Moreover, technical performances such as fuel consumption and endurance should also be inserted as parameters of the Figures of Merit.

The following table contains a list of the elicited Figures of Merits, related description and suggestions for their numerical evaluations in conceptual and preliminary design phases.

Tab. 4: Selection of the Figures of merit for the Trade-Off analysis

Figure of Merit	***Description***	***How to evaluate parameters***
M_payload*endurance/MTOW	*Unit Productivity* is a Figure of Merit that allows estimating which is the capability of the platform to host heavy payload and flying for long time duration. In this formulation, both the capabilities have the same importance but it could be sufficient to insert other weighting factors to favour one or the other.	All the parameters in the formula could be estimated or assumed in conceptual design or directly extrapolated from datasheet.
Max_range/(DeltaCG_installation * Delta CG_fuel)*Mfuelconsump	This Figure of Merit is strictly related to stability of the integrated platform all along the mission.	The parameters inserted in the formula are strictly related to the fuel consumption that can should be iteratively evaluated exploiting simulation codes. In particular, proper tool has been created on Matlab® platform by the authors of Politecnico di Torino and reported in [10]
T_aquisition/Max endurance	This Figure of Merit is strictly related to acquisition time and maximum endurance	The duration of the acquisition time is strictly related to the interactions of the aircraft performances and the mission profile. Thus, simulation should be preferred.

It is clear that in order to estimate the parameters that are unknown during the conceptual design phase, different analysis had been carried out. In particular, static and dynamic stability has to be taken into account properly (Fig. 11 and 12 show the results relative to Samonit configuration).
Moreover, the evaluation of the total duration o data acquisition during a mission, has been possible exploiting an ad-hoc built-in tool developed within Politecnico di Torino [10] that allow to simulate a teledetection mission, hypothesizing a fixed mounted sensor and taking into account different flight plans.
In particular, considering the results presented in [10], in order to optimize the data acquisition process, minimizing overlapping between a sensor record and the following and minimizing the fuel consumption, a best endurance flight plan performed at fixed altitude has been selected as reference. Moreover, in case terrain profile will be considered, proper corrections to the flight plan or suggestions for the post-processing analysis will be derived by simulations carried out exploiting commercial tools like STK (Systems ToolKit) or ASTOS (AeroSpace Trajectory Optimization Software).

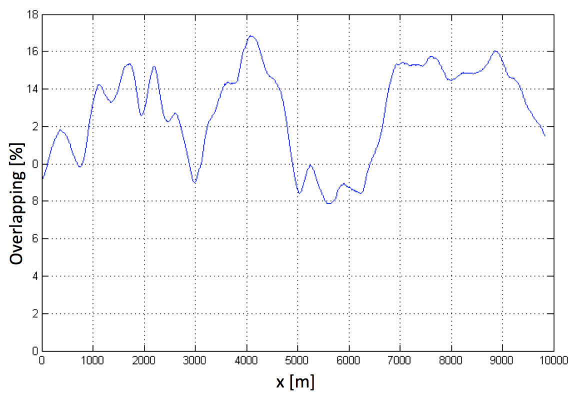

Fig. 9:Example of overlapping during a 10 km acquisition mission with a Falco UAV

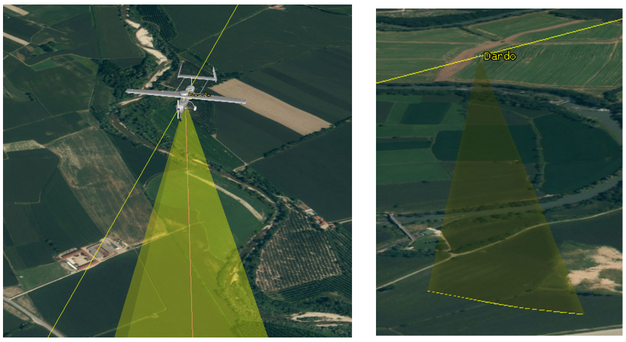

Fig. 10:View of STK simulations

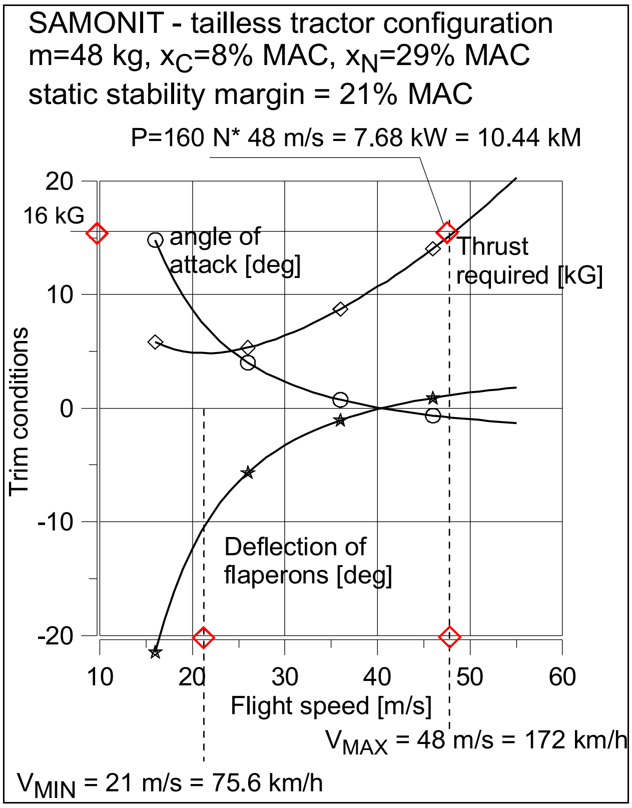

Fig. 11:Samonit trim condition evaluations

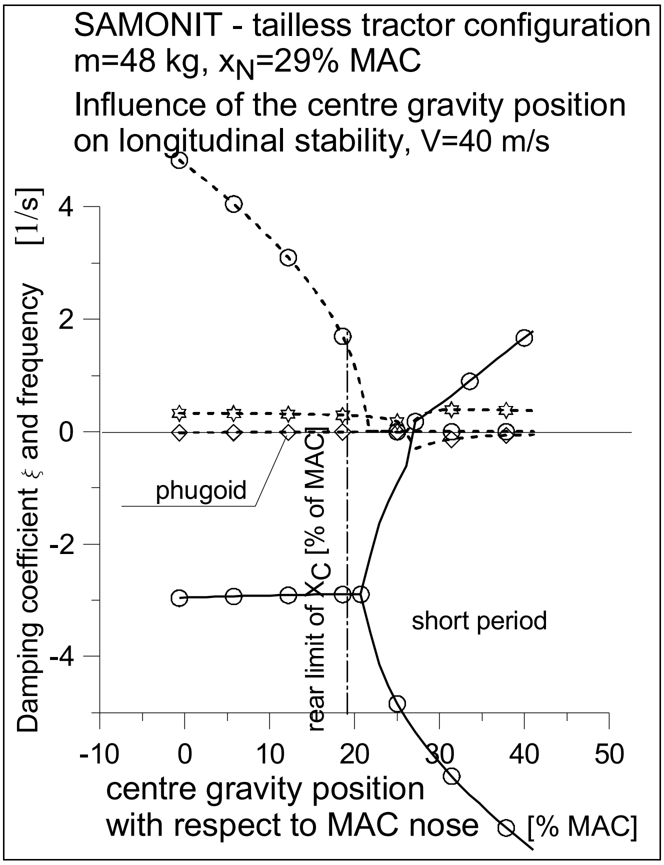

Fig. 12:Samonit effect of CG displacement on longitudinal stability

5 Results and comments

Table 5 shows the numerical evaluation of the Figures of Merit for the selected referece case and Fig. 9 summarizes the results in graphical way.

Tab. 5: Evaluation of the Figures of Merit for the selected reference case

Figure of Merit	***Parameter***	***Falco***	***Samonit 1***	***Samonit 3***
FoM 1	Payload Mass [kg]	70	20	20
	Endurance [h]	14		
	Maximum Take Off Weight [kg]	490		
	Estimation of the FoM	2,00		
FoM 2	Maximum Range (esimated)			
	CG_sensor (estimated)			
	CG_aircraft (estimated)			
	CG_fuel_start (estimated)			
	CG_fuel_end (estimated)			
	Fuel mass consumed (estimated)			
	Estimation of the FoM			
FoM 3	Total duration of the acquisition process (estimated)			
	Endurance	14	0	0
	Estimation of the FoM			

Insert pie chart for the different platform and Select the best one.

Fig. 13:Pie charts summarizing the results of the trade-off analysis

5 Conclusion

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