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ALTAIR - Design & Progress on the Space Launch Vehicle Design

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Abstract

ALTAIR is an innovative air-launch system consisting of a reusable unmanned aircraft carrier, an expendable launch vehicle and a cost-effective ground segment. The autonomous aircraft brings the launcher at altitude; following the release, the launcher boosts the payload to the intended orbit. This paper presents the launcher design at the project mid-term. Primary aims of the development are risk mitigation, cost savings, reliability and high performance. The project leverages collaborative engineering, design-to-cost techniques and multidisciplinary design optimization strategies. The resulting design utilizes low-cost hybrid propulsion, lightweight composite structures, innovative avionics and a smart multi-mission upper-stage to simultaneously attain all goals.

1. Introduction

The market of satellite launches will drastically change in the coming decade. While being nowadays monopolised by the needs of massive and expensive satellites, requiring heavy launchers of the size of the Proton M, Delta IV or Ariane 5, it is foreseen that another product will take a large share of the global market: small satellites in the 50-150 kg range. This growth will be mainly driven by two factors. On the one hand, miniaturisation enables to embed in such platforms functionalities that few years ago were exclusively attainable by larger satellites. Furthermore, the availability of space-grade COTS (Commercial Off-The-Shelf) components makes small satellite more and more affordable. These capabilities extend the applicability of small satellites for a wide range of application, such as communication, Earth observation, remote sensing, scientific experiments and in-orbit technology demonstration. On the other hand, several projects of new constellations comprising few hundred (OneWeb Constellation) to few thousands (Space X Constellation) small satellites have been announced, raising even more the number of projected launches of those small satellites. According to recent surveys, several hundreds of small satellites with a mass lower than 100 kg are expected to be launched in the 2014-2020 timeframe, and the demand will continue to rise thereafter. However, no current launch system can adequately addresses the market of small satellites in this payload mass range. Indeed, the only existing possibility for the access to space of small satellites below 150 kg is to be launched as a secondary passenger (rideshare / piggy-back) on a heavy launcher. This poses severe constraints, since the target orbit and the launch date are fixed by the primary payload. A dedicated launch system without these constraints would further boost the development of small satellite applications, provided it is also affordable and reliable.

ALTAIR's strategic objective [1] is to demonstrate the feasibility of a new, cost-effective and reliable space launch system for the access to Low-Earth Orbit (400-1000 km) of small satellites. The ALTAIR launch system aims to answer to the needs of small satellites users, providing an affordable and adapted access to space service, without the constraints of current rideshare launch options. ALTAIR will boost space applications to the benefit of an increased spectrum of users, from classic satellite operators to academics and research centres. To support this ambitious goal, the ALTAIR system combines an innovative semi-reusable concept and the integration of relevant technologies in all parts of the system. ALTAIR is an innovative air-launch system using a reusable unmanned aircraft carrier optimised specifically for this mission. The expendable rocket launch vehicle, which is released at high altitude, associates green propellant hybrid propulsion, lightweight composite structure, innovative avionics and a versatile upper-stage, providing mission flexibility. Cost-effective ground operations are obtained through innovative ground systems

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architecture. ALTAIR will pave the way for a feasible system ready to address the market needs through an original approach associating a cost-oriented preliminary design of the whole system (carrier vehicle, launch vehicle and ground segment) using advanced Multidisciplinary Design Optimisation (MDO) techniques, and the definition of a credible development roadmap and business model, supported by market analyses.

Figure 1: Artistic view of the ALTAIR Launch Vehicle booster ignition and early flight after carrier releasing

2. Mission & Objective of the space launch vehicle

The objective of the ALTAIR air-launch system is to carry 150 kg of payload(s) to a sun-synchronous orbit (SSO) at 600 km. Reference mission expects the unmanned air carrier to takeoff from the launch base by using a classic runway, bring the rocket vehicle at the right altitude and speed (> 10 km, subsonic velocity), release it and autonomously return to the ground for further reuse. After releasing, the two hybrid-propelled rocket stages of the launch vehicle boost the payload through the atmosphere up to space. ALTAIR versatile orbital module provides final payload injection on the target orbit, carrying out several manoeuvers to ensure single or multiple satellites delivery on expected altitude and inclination (Fig. 2). Finally, the orbital module carries out a decommissioning manoeuver in order to limit space junk proliferation.

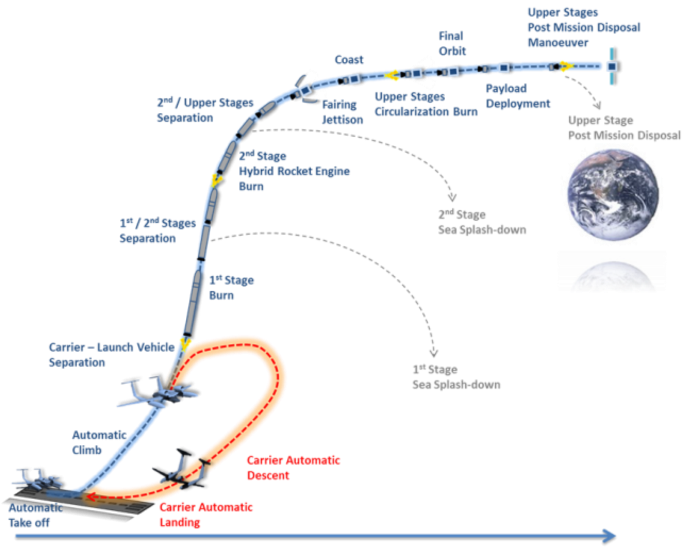

Figure 2: Mission profile

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3. Space launch vehicle design

3.1 Overview and general performances

The design of the space launch vehicle relies on strong interactions between all the partners. The main difficulty for a design starting from scratch is to establish a first design point, as the sensitivity on the various design parameters makes this step difficult. To ensure a good optimization of the vehicle, simplified models have been elaborated and use in an optimization platform to find the best launch vehicle that satisfy design constraints [2]. The use of hybrid propulsion module is very interesting in terms of costs. The design at the middle of the project is presented on Fig.3. This design, which will undergo subsequent refinements, shows the main architecture of the foreseen launch vehicle.
ALTAIR Launch Vehicle (ALV) has two main propulsive stages equipped with hybrid propulsion modules. The modules in the first and second stage are nearly identical. Only the nozzles are different to take advantage of the working altitude. In each stage, there is one main hydrogen peroxide tank at low pressure. The high pressure required in the chamber is attained by an hydrogen peroxide turbopump. The orbital module is encapsulated in the fairing with the payload(s). Similar to the other stages, it relies on hydrogen peroxide monopropellant thrusters to perform the orbital manoeuvers (the various phases of the launch trajectory can be seen in Fig. 4). Aerostructures are made in high performance composite materials. Through these radical contributions, the launch vehicle can be considered truly green, owing to its low environmental footprint.

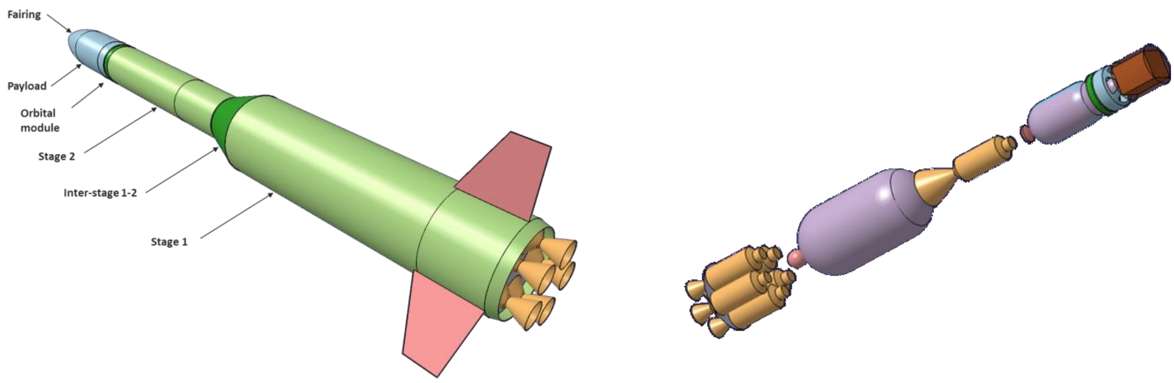

Figure 3: General architecture of the launch vehicle

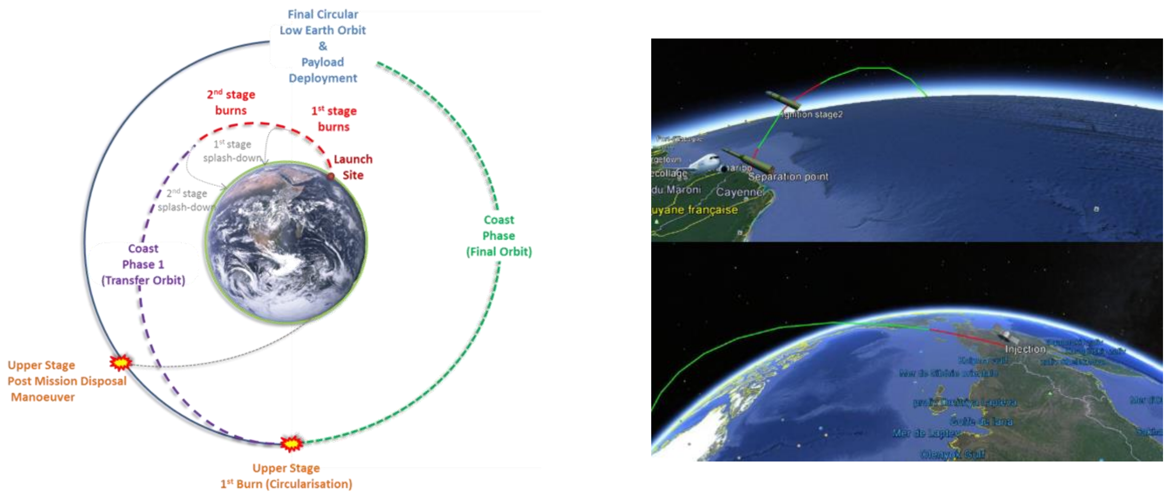

Figure 4: Trajectory of the launch vehicle

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3.2 Hybrid Propulsion Modules

Hybrid propulsion has gained a lot of interest in the last decade as a promising low cost technology for sounding rockets and nano-launcher propulsion. Hybrid propulsion is an appealing technology, which combines the advantages of both liquid and solid motors, such as simplicity, low cost, safety and fast responsiveness. Nammo Raufoss started investigating Hybrid propulsion as early as 2003 and has since increased the TRL level of its own technology through a step-wise approach, from lab scale engines to today's Unitary Motor 1, a 30 kN-class engine (Figure 5) whose properties and performances are an excellent fit for its use in a sounding rocket (see ref [3]).
Among others, the main features of Nammo's hybrid technology are:

- self-ignition increasing engine start reliability and enabling an unlimited restart capability,
- wide range throttling with limited performance losses,
- green lifecycle and exhaust properties,
- solid inert fuel (HTPB) and high-density green storable oxidizer (87.5% Concentration H_2O_2),
- high engine combustion efficiency, performance and stability,
- simplicity of a single circular port and single feedline configuration,
- low development and operational costs.

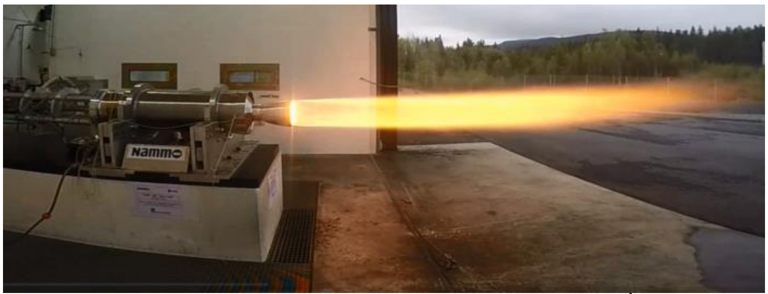

Figure 5: The UM1 during its first firing, on May 19th, 2016

The Unitary Motor 1 is a novel concept of hybrid rocket engine developed by Nammo. It uses high concentration hydrogen peroxide (87.5% H_2O_2, the rest being water) as oxidizer and hydroxyl-terminated polybutadiene (HTPB) rubber as fuel. Its working principle is shown on Figure 6. The incoming liquid oxidizer is first decomposed through a catalyst into hot steam and gaseous oxygen to a temperature of 670°C. It is then injected into the combustion chamber in hot gaseous form, where ignition of the hybrid combustion occurs without any dedicated ignition device due to the high oxidizer heat flux, sufficient to vaporize the solid fuel. Vortex injection contributes in maintaining a high heat flux to the fuel surface and in achieving appropriate mixing of the reactants for a high combustion efficiency. The hot product gases are then expelled through a nozzle, generating the thrust.

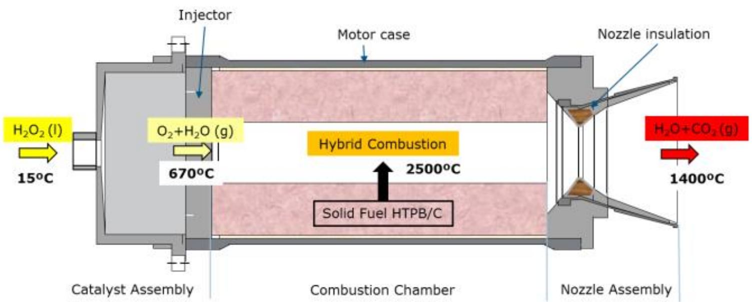

Figure 6: Schematic Showing the Working Principle of the Unitary Motor 1

The hybrid motors considered for the ALTAIR project are based on upgrades of the Unitary Motor 1, with performances tailored to the specificity of the typical ALTAIR mission. An important effort is made on reducing to a minimum the dry mass, while keeping the performance demonstrated so far and the low cost approach. A trade-off had to be made between the need of the mission (total rocket ΔV, maximal acceleration,…), the capabilities of the motors (maximal burntime, motor envelope,…) and the foreseen cost of the overall propulsion system.

Along with the motors, the full fluid system bringing the liquid oxidizer to the motor has to be developed. This system includes the oxidizer tank, the oxidizer pressurization system and the filling elements.

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To complete the propulsion system, avionics and controls are needed to drive the different controlled elements (TVC, flow control valve,…) and to assess the performances of the system.

The current propulsion system architecture selected for ALTAIR is presented in Figure 7. The rocket itself is composed of two main propulsive stages while an orbital module takes care of the orbit insertion. The 1st stage is composed of five motors with a vacuum thrust level of 120 kN each. These motors are pump-fed, meaning that the oxidizer is pressurized by a turbo-pump. The 2nd stage is then composed of a single motor, whose design is exactly the same as the ones of the first stage, with exception of the nozzle exit cone fitted for near vacuum operation. It then delivers a thrust of about 130 kN in vacuum. This motor is as well pump-fed.

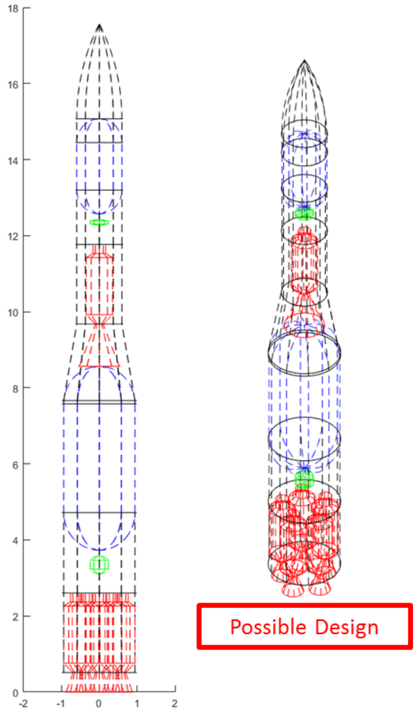

Figure 7: Current design of the propulsion system

The presented architecture is based on modularity, with a single hybrid engine to be developed, and thus reducing drastically the development cost. Besides, this brings a higher production rate of the motor which allows as well to reduce the recurring cost (serial production) while increasing the quality of the manufacture (potential for automatic production). The only element dedicated to each stage is the nozzle exit cone, whose production can be as well quite cheap.

The turbopump is seen as possibly the most costly component of the launcher propulsion system and one that will need dedicated specialists. The solution presented here is therefore only highly preliminary and based on different trade-offs. Firstly, a trade-off between cost and performance is to be made. Indubitably, both the high development and recurring cost of such a turbo-pump would make the developers of a nano-launcher turn toward a cheaper solution, i.e. a pressure-fed system, meaning that the oxidizer tank is directly pressurized to the level needed for the motor to perform. However, while technically feasible, this cheaper solution has a major impact on the dry mass of the stage, as the main element, the oxidizer tank, will need to withstand the high pressure required by the motors, on top of requiring a dedicated pressurization system of a consequent size. A preliminary mass budget analysis for this pressure-fed system shows that it results in a far too heavy system, degrading the attractiveness for such a system. A second trade-off is needed regarding the number of pumps in the launcher. As for the motors, one could think of having a single pump design for each of the six hybrid engines, as for both stages the motors have the same requirement regarding oxidizer mass-flow and pressure rise. This would allow for reducing to a minimum the development cost as only one pump would need to be designed and each motor could as well be tested separately in a representative way. On the other hand, having a single turbo-pump per stage simplifies greatly the architecture and minimizes the risk of failure. The development cost of the turbo-pumps for both stages is anyways reduced compared to typical development for liquid propulsion based launchers, based on the idea that each turbo-pump will have to work with a single fluid (historically two: the liquid fuel and the liquid oxidizer) and using at best commonalities between the two sizes. These aspects need further in depth analysis, which are planned for future steps.

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Regarding safety regulation, dedicated work will have to be achieved, notably with respect to a potential regulation not yet created for those nano-launchers. However Nammo's hybrid technology is seen as a considerably safer option than other propulsion systems, and would thus help reducing the costs on these aspects.
The fuel grain is completely inert and does not require dedicated safety procedure to be handled. It can be stored in a traditional warehouse with limited control needs. Similarly, the assembly procedures, at stage or launcher level, or even while connecting the rocket to the aircraft carrier, do not require additional safety aspects when compared to doing those operations without the motors installed.
The handling of the oxidizer is much simpler than what is typically required by other liquid propellants, either because of their toxicity (hydrazine) or their need for conditioning (LOX); it nevertheless requires that dedicated procedure and the adoption of a simple set of rules concerning materials compatibility, cleanliness and safety are respected but all these aspects have a consolidated heritage and represent today a totally affordable standard. It is important to remark that hydrogen peroxide is a fully storable propellant at ambient conditions, if the mentioned rules of compatibility and cleanliness are respected. In case of spillage, just water is needed to guarantee safety.
Finally, the exhaust of the motor, thanks to the composition of the propellants and the high quality of the combustion process (shown partially in Figure 5, where the transparency of the plume downstream the reactive zone can be appreciated), is mainly composed of water vapour and carbon dioxide. No additives are needed in the fuel or the oxidizer, making the exhaust as green and safe as it could get. These features contribute as well on reducing the costs related to safeguarding the environment and, to a somewhat lower degree for an air-launch system, the launch area.

Hydrogen peroxide can as well be used as monopropellant thruster for attitude control, working on the same principle as hybrids but without the fuel grain afterwards. Commonalities with the main propulsion system would as well help in reducing the complexity of the system and thus the costs. A dedicated attitude control system is not needed for the first stage, as all the motors would be fitted with a movable nozzle: having a cluster of motors allows to control all three axis of the rocket, roll (all the nozzles moving tangentially), pitch and yaw (all the nozzles moving in the same direction). For the second stage, an attitude control system might be needed as roll control is not possible with a single motor. This attitude control system could then be based on H_2O_2 thrusters fed from the main oxidizer tank, simplifying the architecture.
The orbital module (see next chapter) is also based on H_2O_2 thrusters, making the complete launch propulsion working with a single fluid. This as well simplifies the needed ground support equipment and the filling processes, therefore contributing even further on saving costs.

The hybrid propulsion system will be further developed in a greater level of detail in the coming phases of the ALTAIR project. Notably, dedicated work will be done in order to define in detail the interfaces between the propulsive elements and the other subsystem of the launcher. A baseline has been already conceived, from which those details can be extracted in a collaborative work with the other partners of the project.

3.3 Orbital module

ALTAIR Orbital Module (OM) will provide final target orbit injection of the 150 kg payload(s), by ensuring multiple manoeuver capability as well as decommissioning. Multidisciplinary Design Optimization (MDO) and collaborative engineering techniques (Figure 8) have been applied from the very beginning of ALTAIR OM design.

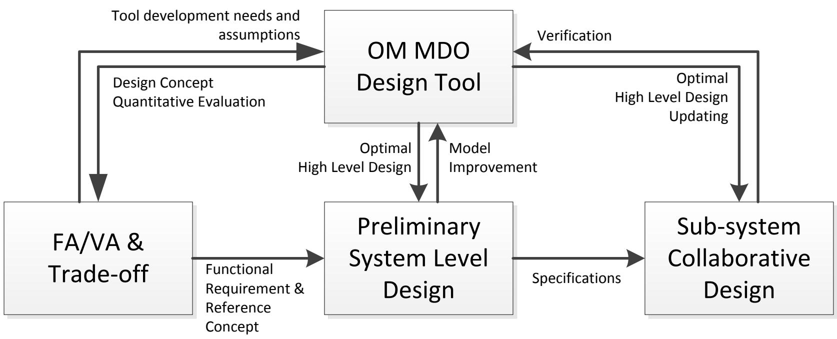

Figure 8: ALTAIR OM Design Strategy

So far, a preliminary concept of the ALTAIR Orbital Module has been produced as a result of the initial functional and value analysis and the trade-off. This design has been obtained by using a dedicated MDO in order to provide at least the following manoeuvring and control functions:

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- Orbit circularisation from a transfer orbit provided by the ALTAIR Launch Vehicle boosters
    - –50 km × 600 km, i = 98.7° to SSO 00 km
- Attitude and orbit control capability
    - Rough 3 axis attitude control capability
    - Partial error injection correction capability
    - Collision Avoidance Manoeuver (CAM)
- End of Life disposal manoeuver to ensure a 25 years natural re-entry
    - 500 km x 600 km

Resulting ALTAIR OM preliminary design consists in a 200 kg class spacecraft able to interface with Fairing, Payload Module (PLM) and Launch Vehicle 2nd Stage (Figure 9).

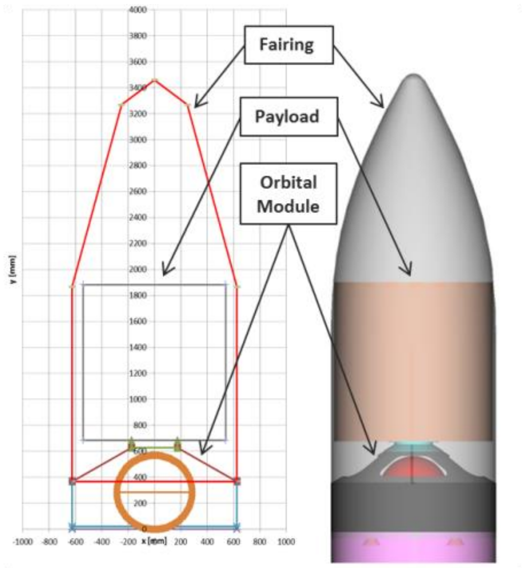

Figure 9: Current status of ALTAIR ORBITER Configuration.

The core of the vehicle is a green H_2O_2 monopropellant propulsion and attitude control system accommodated in a lightweight structure. The 800 N re-startable hydrogen peroxide propulsion system is able to provide a total ΔV of about 500 m/s. This will ensure mission extended performances to ensure flexibility through multiple boosts capabilities for both orbital rising to altitude up to 800 km as well as attitude control and end of life disposal.
OM primary structure is mainly based on composite technologies to reduce mass and ensure mechanical strength and stability. It consists in two main sections: a conical Payload Adapter and a cylindrical Central Structure. Main interfaces with fairing and booster sections are aluminium alloy monolithic rings. OM/PLM interface is designed to be compatible with the PAS 381S (15") Separation System, a COTS pyro-free low shock satellite separation mechanism developed by RUAG [4]. In order to reduce global height of the launch vehicle, part of the OM is inside the fairing and only the Central Structure will be exposed to external environment.
A thermally conductive aluminium alloy sandwich Base Panel closes the OM bottom part. It provides accommodation support for propulsion and attitude control system equipment as well as for avionics.
Actually, most of the electronic components of the launch vehicle will be centralised in the OM avionics suite. So far, a preliminary accommodation concept consists in four boxes to group on board computer and controllers, TC/TM and internal communication electronics, navigation equipment, including GNSS cards and inertial navigation units, as well as batteries. An umbilical connector hub is expected to ensure electrical interfaces with both launch vehicle boosters (during flight) and ground segment equipment (during ground operations). A second connector hub will provide OM/PLM electrical interface. Finally, TC/TM and GNSS antennas will be mounted on the cylindrical structure to provide ground segment communication capabilities during flight.

The reference concept selected does not expect a controlled re-entry. This means the overall design will be carried out by applying Design-for-Demise techniques to ensure a safe uncontrolled re-entry with a casualty risk (risk of damaging for people on ground due to a partial disintegration of the spacecraft during its atmospheric re-entry) less than 10^{-4}. For example, employment of titanium alloy will be limited in order to reduce risks, while the tank is developed using demisable aluminium alloy.

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Current high level technical specifications for the reference OM are listed in Table 4 while its overall architecture is shown in Figure 10.

Table 1: Orbital Module Mass Budget and Overall Dimensions (Maximum allowed value)

Mass	Orbital Module Dry Mass	kg	107
	Propellant Mass	kg	90
	Total Orbital Module Mass	kg	197

Dimensions	Height	m	0.68
	Diameter	m	1.25

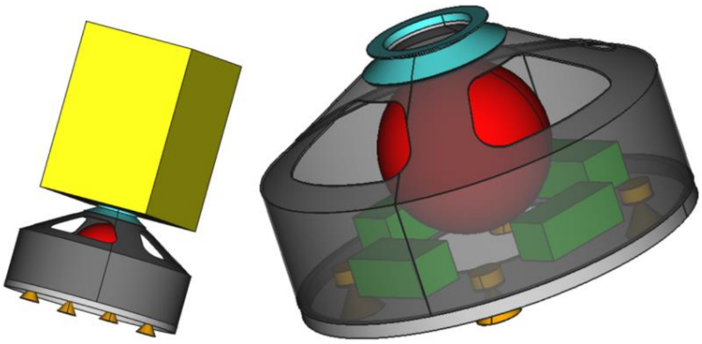

Figure 10: Preliminary ALTAIR Orbital Module CAD views with (left) and without payload (right).

The propulsion subsystem so far designed by Bertin Technologies is based on the blow down H_2O_2 monopropellant propulsion technology currently being developed by Nammo Raufoss AS. With respect to that technology, some modifications are expected in order to meet ALTAIR OM requirement, mainly in terms of tank propellant storage capability.

Current propulsion sub-system design consists in four 200 N Hot Gas Thrusters and a demisable aluminium Tank able to store up to 90 kg of hydrogen peroxide (Figure 11). In order to provide a coarse 3-axis control capability (yaw, pitch and roll), the thruster will be mounted with a double opposite inclination with respect to the vertical axis of 5°.

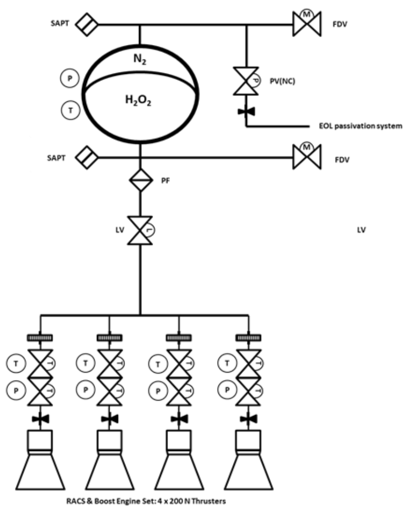

Figure 11: Preliminary ALTAIR Orbital Module Propulsion architecture and description

More information on the orbital module are available on [5].

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3.4 Avionics

The avionics subsystem concerns all the electrical and electronic equipment including software (SW) interfacing the actuators and sensors. The functional analysis of the avionics leads to the identification of the following main functions:

- Ensure the flight safety of the mission during:
  - Captive flight
  - Release manoeuvre
  - Thrusted flight
- Manage the flight regarding GNC and mission timeline
- Manage communications:
  - Internal communications between launcher subsystems
  - External communications between launcher interfaces (PL, ground systems and carrier)
- Configuration and validation of the avionics with respect to a given mission, avionics missionization
- Components house-keeping, regarding equipment supervision (power management, thermal control, buses,…)

The integrated and modular avionics aim to maximize the launcher functional autonomy by reducing ground infrastructures and operations, as well as SW missionization to increase mission adaptability. The objectives for the avionics subsystem are the same as for the whole launch service:

- The reduction of mass and volume in order to increase capacities in the framework of nano-micro satellites
- Increase responsiveness to adapt to high-frequency rate launch service
- Improve overall RAMS in the ground and flight seeking the reduction of operations and autonomous avionics for long missions

The major axis of improvement and innovation proposed aiming those objectives are the following:

▪ <u>Reduce Weight and volume</u>

  - Unify communications, via a full-duplex communications bus covering the telemetry (sensors and supervision data interfaces) and control (actuators interfaces) functions
  - Reduce harness complexity and mass, using remote IO (input/output) components for each stage interfacing avionics equipment and avionics interfaces at each stage, enabling the inter-stage communications via a unique centralized point
  - Optimize battery use
  - Distribute and relocate as maximum as possible equipment to lower stages in order to reduce equivalent mass: the mass is proportional to the flight-time of the equipment, so the lower the mass is placed, the sooner it is released, and consequently less impact on mission efficiency

▪ <u>Increase Responsiveness</u>

  Define mission-configurable avionics SW, which is validated against a well-defined operational frame, allowing loading mission configuration for each campaign. As a result, the SW validation is optimized so reducing mission analysis and preparation time, always the configuration respects the operational frame. We obtain improvement in:

  - Increase SW missionization
  - Allow to use COTS and more flexible HW configuration and testing
  - Reducing ground segment facilities and mission submission operations

▪ <u>Improve RAMS</u>

  - HW/SW Architecture Modularity:

  An avionics architecture modular design guarantees validation, traceability and interchangeability between components, equipment, specifications and functions. A modular software system is composed of encapsulated parts, called modules, each with a specific function. In this type of system, any module can be switched by another module with the same interfaces without affecting the rest of the system. If a module is modified/updated, the whole system regains its validated status by only validating the new version of the module. The modules have access to common services and interfaces independently. Modules have their own dedicated memory and time partitions to ensure module independency. From a HW point of view, modularity

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allows the use of COTS making the avionics non-dependent of ad-hoc equipment, so obtaining a more maintainable and upgradable system, increasing total obsolescence.

- Increase SW functions:

  The overall system RAMS is increased by balancing ground segment functions to launcher SW functions, mainly on Safety and GNC subsystems, taking advantage of airborne reference scenario:

  - In-flight initialization: avionics initialization and release consent sequence in nominal and non-nominal scenarios
  - in–flight Launcher autonomous safety and integrated vehicle health monitoring (IVHM)
  - In-flight navigation performance assessment

The main axes of actuation described above are assessed through unified modelling language tools (UML/SysML), which provide:

- Metamodeling capabilities to define abstract components:
  - Ports
  - Classes
  - Components
  - Interfaces
  - Data, messages and information flows
- Traceability, exhaustive through all phases of systems engineering:
  - Specifications
  - Functions
  - Architecture components
  - IV&V elements

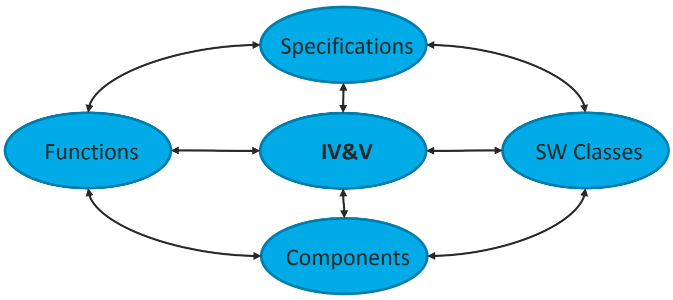

Figure 12: Systems engineering elements traceability

The tool traces the impact of an evolution in the design or a change in one specification through model components, improving maintainability, validation process and availability of the system. Moreover, the tool allows to extract and present the model information into documentation adapted to providers and subcontractors.

The preliminary architecture is based in the following additional design hypothesis:

- The batteries are taken into account as part of the avionics. However, the electro-mechanical actuators power sources are considered part of the actuation control system, so an external avionics interface
- Safety subsystem components are considered redundant (batteries, equipment, buses and communications)
- Safety subsystem relies on devoted navigation instruments
- No RACS system (Roll-Attitude control system
- The harness, connectors and wiring are estimated based on launcher geometry and ECSS standards
- External communications considered are:
  - telemetry and GNSS on Orbital Module
  - Radar and neutralisation tele-command equipment are relocated on lower stages since their contribution to mission ends before OM mission flight.
- Launcher equipment are accessed via Carrier Gateway Interface
- Equipment are distributed to lower stages as possible
- Main avionics functions are embedded on Orbital Module

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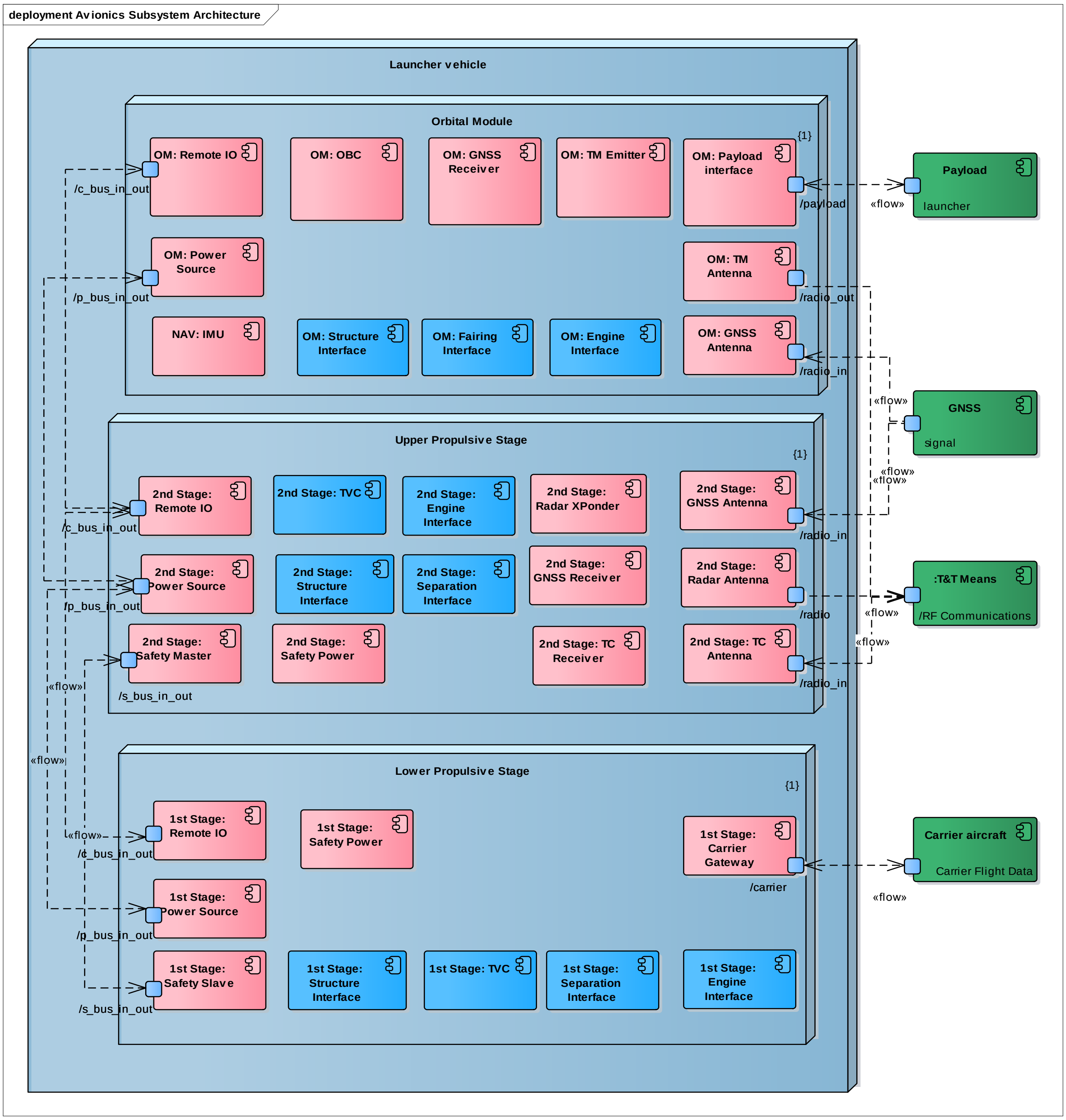
The avionics external interfaces and internal interfaces within other launcher subsystems are shown in the figure below along with the avionics components architecture PBS:



The green components are the external interfaces to the launcher system. The blue components represent those avionics components that interface other launcher subsystems.

In further design loops the interval of avionics estimated mass shall be refined depending on:

- More detailed interfaces with other subsystems, allowing to better estimate the harness and the controllers
- Final launcher geometry shall allow to better estimate internal communications harness and wiring
- Analysis of data budget and power consumption shall allow to size communications equipment and power sources above all.

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3.5 Structures

To identify the optimal design for the ALTAIR launcher structure, models with increasing levels of details have been utilized since the early design phases. Specifically, the load identification is performed by relying on a simplified aeroelastic representation of the coupled launcher-carrier model, resulting in the distribution of global shear, bending and axial loads at various lengthwise positions along the system. The structure, in turn, is divided in lengthwise segments (e.g.: intertank sections, interstage fairings, engine and fairings, nosecone...), each of which is characterized by specific structural entities and is designed to be manufactured with one construction technique. As the interface between adjacent segments is rigid, owing both to the required staging, and to assembly and transportation needs, the ideal construction typology and sizing for each segment can be identified independently from the others, enabling to attain a global optimum by combining a number of optimal sub-designs. Finally, once the design typology for each segment is identified, the interfaces between these parts can be designed. In particular, staging needs require the design of separation systems, aiming to achieve their full functionality while avoiding the use of large pyrotechnic elements, for logistics and structural (shock) reasons. The following paragraphs describe in greater detail these phases, aiming to offer a detailed overview of the followed approach and achieved results.

- **Loads identification**

Due to the air-launched nature of the ALTAIR system, great emphasis has to be given to the interaction between the behavior of the carrier airplane and that of the launcher, on top of the conventional powered flight phase.
To identify the design loads for the sizing of the launch vehicle structures, an aeroelastic model of the coupled launcher-carrier system was developed, permitting to assess behavior of the plane in steady and unsteady flight conditions (manoeuvers, gusts). This model is based on a simplified beam-based idealization of the entire carrier/launcher system. The various structural parts of the launcher and carrier are modeled through beam elements with cross-sectional properties and mass distributions representative of the actual characteristics of each component and of its associated subsystems (Figure 13).

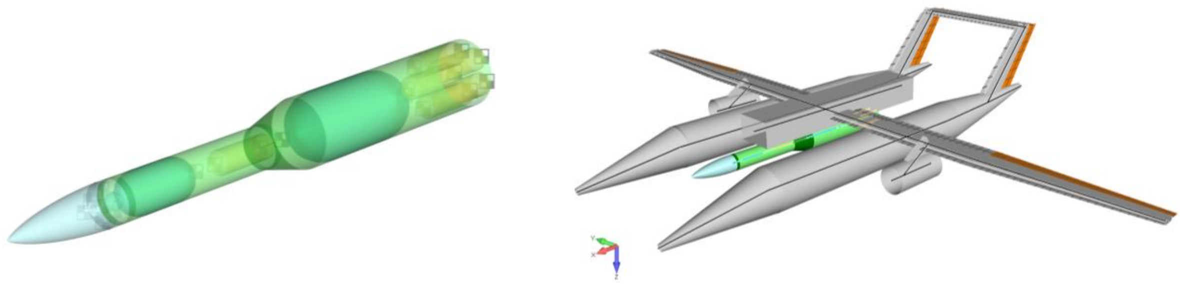

Figure 13: Beam-based launcher model with representative mechanical and inertial properties (left) and aeroelastic model of the launcher-carrier system (right) for global loads assessments

Numerous flight conditions are considered, both representing the captive phase (combinations of carrier fuel loads, flight velocities, attitudes and manoeuvres, in both steady and unsteady atmosphere) and the powered phase (combinations of propellant and oxidiser loads, different manoeuvring inputs, different number of stages). This method enables to obtain the distribution of dimensioning shear forces, torsion and bending moments along the structure of the launcher and of the aircraft (Figure 14).

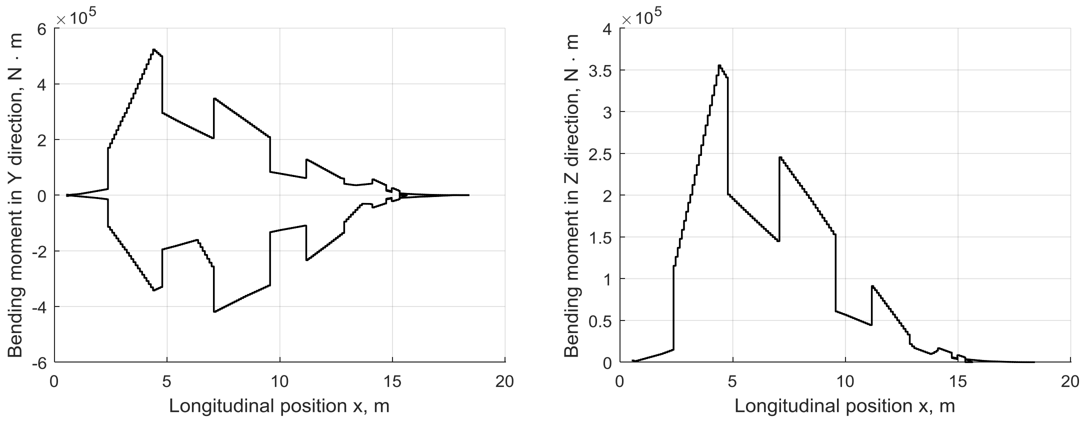

Figure 14: Bending moments envelope for the critical launch events

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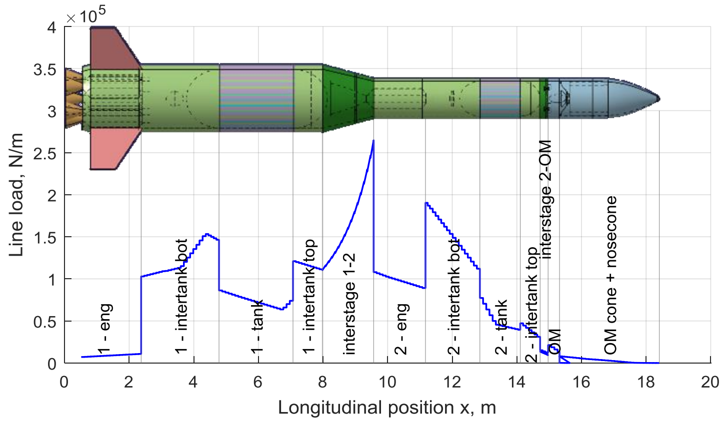

Figure 15: Equivalent sizing line loads for the various stages of the launcher

- **Structural design**

Given different requirements on load-carrying capability in the different sections of the launch vehicle, the airframe of the ALTAIR launcher is subdivided into components surrounding the load-carrying engine modules, intertank structures transferring the loads between the engine modules and the tanks, tank skirts, as well as interstages. In order to accommodate the diameter change imposed by the propulsive system, a conical interstage is used between the first and second stage. The launch vehicle is attached to the carrier aircraft during the captive flight phase by means of two attachment points, which are placed within the intertank sections in order to minimize the resulting loads on the airframe while avoiding interference with components of the propulsive. The launch vehicle will furthermore feature a multi-purpose thrust structure enabling structural integrity of the clustered engine modules in the first stage, introduction of the propulsive forces into the launcher airframe, as well as attachment of the external fins. As the payload capability of the ALTAIR launcher is mainly influenced by its aerodynamic drag, the launch vehicle will be designed with an aerodynamically optimized fairing featuring a low-drag von-Karman shaped nosecone. The various airframe components of the ALTAIR launcher are sized individually in order to optimally adapt to the loads distribution over the launch vehicle. Figure 15 shows the loads envelope for the ALTAIR launch vehicle, resulting from the distribution of axial and shear force, as well as bending and torsional moments. The loads analyses based on the coupled launcher-carrier model have revealed that both static maneuvers (3g pull-up of the fully fuelled launcher attached to the carrier) and dynamic conditions (vertical gust with a 30ft and 150ft gradient, respectively at sea level and cruise altitude, with respectively empty and full oxidizer tanks) lead to sizing loads for the vast majority of the airframe components. In addition, the TVC capabilities offered by the first stage propulsion generate bending moments in addition to the longitudinal forces, which – combined – become sizing for the remaining parts of the structure.

To reduce the dry structural mass of the ALTAIR launch vehicle, its primary load-carrying structures as well as structural components of the propulsive system are designed using advanced composite materials in combination with lightweight construction technologies. The candidate construction types considered for the external airframe structures include composite monocoque, foam- and honeycomb-core sandwich, as well as anisogrid construction with an aerodynamic skin. Preliminary optimizations for minimum structural mass of compression- and bending-loaded cylindrical and conical composite shells of these construction types have shown that – for the sectional loading range encountered during the ALTAIR mission, and under consideration of constraints imposed by the manufacturing processes – the highest structural performance can be achieved with composite-faced honeycomb core sandwich structures, as well as anisogrid structures consisting of a dense system of intersecting CFRP ribs in the helical and circumferential directions. While, for the structural dimensions of the ALTAIR launcher and the particular carbon/epoxy material considered, the best structural efficiency for load levels below approximately 2.5 – 3 N/m can be achieved with an anisogrid construction type, sandwich construction featuring CFRP facesheets and an aluminium honeycomb core allows for higher structural performance at higher load levels. Hence, for the sectional limit loads encountered by the ALTAIR launcher (Figure 15), anisogrid construction with a Kagome grid pattern and an aerodynamic skin overlapped is considered the most efficient construction type for the airframe structures.

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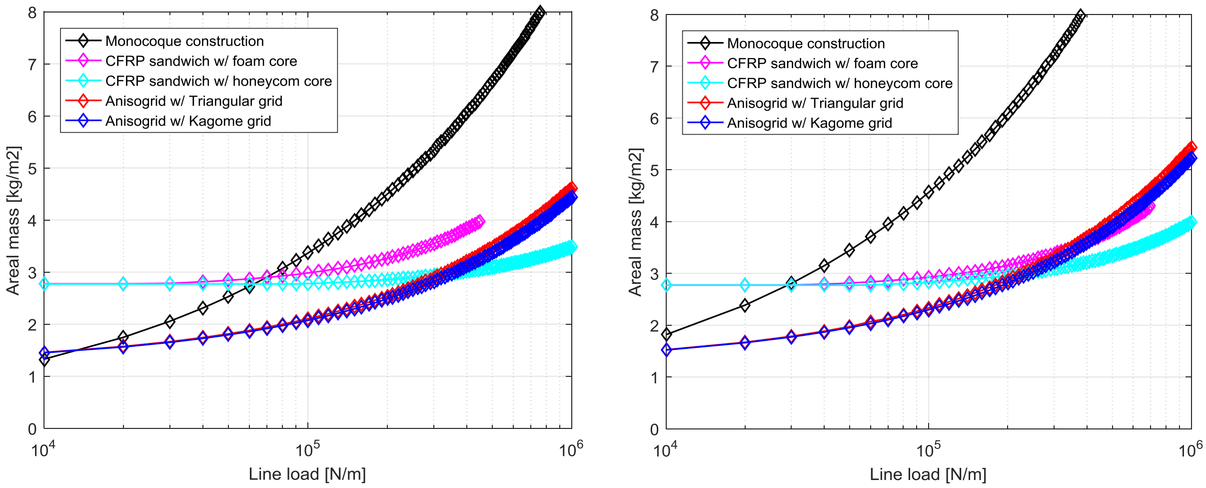

Figure 16: Minimum areal mass vs. Line load for compression-loaded cylindrical shells of different composite construction types under consideration of manufacturing constraints; 1.25 m cylinder diameter (left); 2.1 m cylinder diameter (right)

- **Tank design**

To reduce the dry mass of the propulsive system as well as the stage length, the oxidizer tanks – initially designed in monolithic aluminium construction with spherical end closures – are redesigned in composite construction made by a filament winding process. Preliminary tank sizing studies based on analytical models and FEA have revealed the potential for significant weight reduction compared to a classical aluminum design, as well as the possibility to reduce the length of the launch vehicle by approximately 0.5m through the use of a more space-efficient isotensoid end dome geometry. Comparative analyses aimed at identifying the preferred global tank architecture have furthermore shown that designing the composite tanks as load-carrying structures (i.e. to carry the external compression- and bending loads in addition to the internal pressure), yields a similar overall stage mass as sizing the tanks for the internal pressure and employing an additional load-carrying airframe for integration of the tanks. Considering the decreased tank diameter required for the latter design concept and the associated increase in stage length, designing the oxidizer tanks as load-carrying structures of the launch vehicle is favourable from the viewpoint of structural efficiency.

- **Separation systems**

The separation systems of the ALTAIR launch vehicle are designed to operate without requiring pyrotechnic devices in order to reduce both mechanical shocks as well as costs associated with logistic burdens such as special handling, transportation, and installation procedures. Separation systems typically comprise a hold and release mechanism which provides structural integrity and load path continuity until separation, an actuation system which initiates the structural disconnection between the stages, and a separation-impulse system to provide the necessary relative velocity between the separated stages. Analytical modelling of the most commonly used subsystem technologies, combined with preliminary numerical optimizations aimed at identifying the most efficient pyro-free subsystem technologies for the two stage separation interfaces of the launch vehicle have shown that a V-section clamp band mechanism, consisting of form-fitting interface rings with inclined flanges held together by a tensioning band with V-shaped wedges, is the preferred hold and release mechanism design for the two stage separation systems. The optimizations have furthermore shown that hydraulic cylinders are the most efficient solution to provide the separation impulse on the heavier first stage, while springs provide sufficient energy density to allow a collision-free separation of the second stage. In order to actuate the stage separation on command, commercially available split-spool devices with a burn wire actuation are designated. Following the preliminary design of the 1st and 2nd stage separation system in terms of the optimized design and performance parameters characterizing the respective subsystems, a more detailed design and sizing of the separation systems was carried out using FEA. To provide separation of the payload, a commercially available pyro-free system will be used, which satisfies the nominal payload interface constraints.

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5. Future Works

This paper presents the mid-term status of the design ALTAIR Launch Vehicle. The project is still ongoing and will end in late 2018. During the upcoming months, the design of the launch vehicle will be refined and completed, particularly on sub-systems level.

ALTAIR deals not only with launch vehicle design but has also dedicated works related to the carrier design and the operations [1]. Even if this paper is more focused on the launch vehicle design, strong interactions and optimization are realized at system level to ensure adequacy between performance and costs with other partners

Figure 17: Visualisation of the mid-term status of ALTAIR Launch Vehicle

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