Perseus Propulsion System development and enabled missions
(oral presentation)

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Abstract

The development of the first propulsion system of the family "Perseus" is under execution within the Iperdrone program framework, funded by the Italian Space Agency, and performed by Tyvak International and Technology for Propulsion and Innovation (T4i). A detailed market analysis was conducted by the two companies, aiming at identifying a CubeSat propulsion system suitable for the execution of proximity operations missions, including Iperdrone Program, and exploitable by the nanosatellite community. In the frame of this work, the two teams focused on the identification of technology gaps and competitive benchmarks. As a result of the market analysis, a specific market need was identified which led to the decision to develop a dedicated propulsion system, aiming at demonstrating the capability of a CubeSat to perform proximity operations for space assets visual inspection and a controlled re-entry in a predefined corridor (Iperdrone.0 key requirements). Optimization approach and strategies driven the design and the development plan. The Perseus development was kicked off by the Italian Space Agency in 2021 and the first prototype was integrated, functionally tested and is currently under a qualification test campaign, with the support of the Iperdrone program prime contractor, the Centro Italiano Ricerche Aerospaziali (CIRA), which is providing the environmental test facilities ("Laboratorio di Qualifica Spaziale"). The foreseen tests include vibration, shock and Thermal Vacuum and related levels are defined to include a wider range of launch vehicles.
The aim of this paper is to go through the details of the context that led to this development – Iperdrone mission needs and market analysis driving requirements – and present to the audience the first qualification campaign results together with the dissemination of the main product performances. In addition, the mission that this technology will enable will be presented. The presentation will be held by Tyvak International and will include contributions from Technology for Propulsion and Innovation (T4i).

Introduction

Propulsion Systems for CubeSats are consistently capturing the scene of commercial space sector, leveraging on the increasing number of nano-satellite missions of the last years. Furthermore, the performances required to space thrusters are always more challenging and the constrains tighter, leading to the necessity of development of new systems exploiting state-of-the-art technologies.

In this framework, Tyvak International and Technology for Propulsion and Innovation (T4i) are developing a family of cold-gas propulsion systems suitable for 6U+ CubeSats proximity operations missions in LEO. The first system "PERSEUS" will fly onboard Iperdrone.0, mission funded by Italian Space Agency (ASI), involving a 6U CubeSat aiming at demonstrating real-flight proximity operations capabilities.

Market Analysis Outputs

Tyvak International executed a market analysis in order to identify a propulsion system characterized by performances suitable for a proximity operations mission. In the frame of the research, Tyvak focused on the identification of the main features, requirements and constrains applicable to CubeSats.

Ad-hoc performances are needed for nanosatellites proximity operations, including the followings:

- Average thrust of tens of mN
- Thrust vectoring capabilities (ideally full 3-axis vectoring)
- Medium total impulse (considering delta-V, 10÷50 m/s for a 6U)
- Low minimum impulse bit (for precise manoeuvering)
- Reduced envelope (ideally 2.5U or less if 6U satellite)
- Safety features for critical applications with relevant and/or manned targets

European market offers several solutions for CubeSats propulsion systems, although was challenging to identify a single product satisfying all the requirements above listed. As main outcome of the market analysis, a technological "gap" of suitable propulsion systems was highlighted (above all in the European market). Indeed, European market for nanosatellite propulsion is mainly characterized by:

- Cold-gas with moderate thrust but very low delta-V
- Electric propulsion systems with very low thrust, very high delta-V and very high power draw

Figure 1 and Figure 2 present snapshots of the market solutions available in US and in Europe, with respect to the main characteristics to be investigated for propulsion system selection (thrust, delta-V, envelope). The grey box highlights the range of performances required to enable and execute the identified CubeSat proximity operations mission profile.

It can be seen that no European solution fits in the highlighted area, confirming the gap in the market for extended proximity operations cold gas.

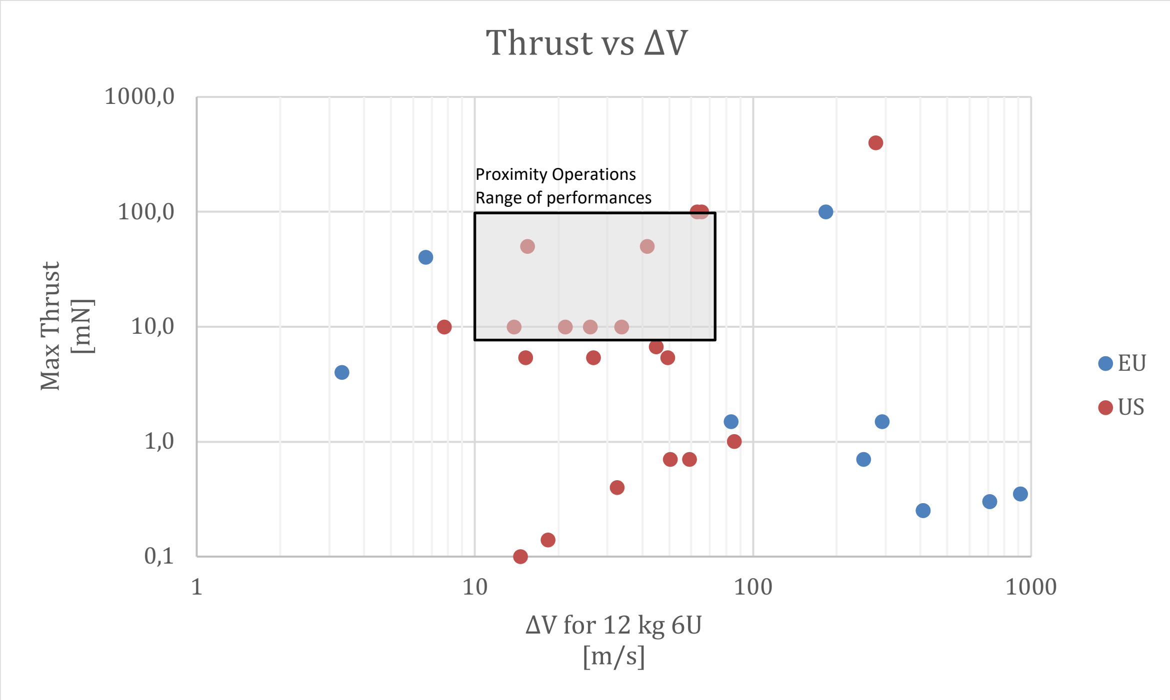

Figure 1 Thrust vs Delta-V market offer

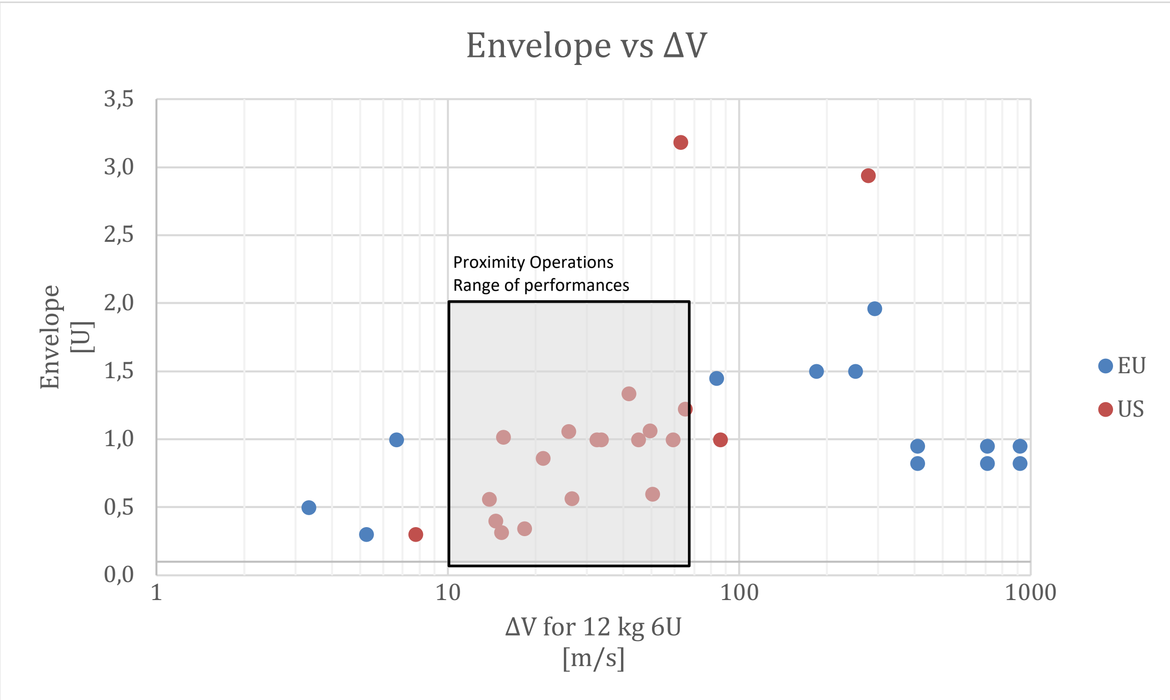

Figure 2 Envelope vs Delta-V market offer

Eventually, the results of the research led to the need of executing a conceptual analysis of enabling technologies to be expressly developed. Tyvak International identified as industrial partner Technology for Innovation (T4I), supporting a conceptual design phase, aiming at identifying the possible configuration of a cold-gas propulsion system family enabling proximity operations missions.

Table 1 summarizes the technology assessment executed by Tyvak and the proposed solution compared with European state-of-the-art propulsion systems available at the moment.

Table 1 Tyvak proposed design vs state-of-the-art

	Tyvak proposed Prox-Ops CGPS (Perseus)	Best Performing EU Cold Gas	Best Performing EU Electrical Thruster
Safety	**2+ Fault Tolerance Cold Gas (R134a) No hot exhaust No plasma**	2+ Fault Tolerance Cold Gas (Butane) No hot exhaust No plasma	Fault Tolerance n/a Hall Effect Thruster (Xenon) Plasma exhaust
Max Thrust	**25 ÷ 100 mN**	4 ÷ 40 mN	1.5 mN
Minimum Impulse Bit	**< 5 mNs**	0.1 mNs	unknown
Total Impulse	**480 Ns**	80 Ns	1000 Ns
Thrust Vectoring	**Full 3-axis thrust vectoring Full 3-axis attitude control**	No thrust vectoring 2-axis attitude control (pitch, yaw)	No thrust vectoring No attitude control
Envelope	**< 200 x 100 x 125 (2.5 U)**	200 x 100 x 50 (1.0 U)	100 x 100 x 200 (2.0 U)
Mass	**< 4 kg wet**	0.9 kg wet	2.0 kg wet
Power	**< 2 W keep-alive 30 W peak power**	< 2 W keep-alive 18 W peak power	< 2 W keep-alive 50 W peak power

PERSEUS System Architecture

PERSEUS propulsion system, as previously stated, is a cold-gas thruster able to provide 6 degrees-of-freedom to the spacecraft. Most of the Perseus propulsion system components are part of the fluidic system, which can be described as follows:

1. **Tank**. Passive pressurized vessel of the selected propellant.
2. **High-pressure stage**. It is composed of all the fluidic elements that come before the pressure regulator, mainly: two solenoid valves, and the evaporator (a phase separator system).
3. **Passive two-stages pressure regulator**. This is a COTS item that has flight heritage (it has been already employed on board the ISS). It is used to stabilize the low-pressure stage.
4. **Low-pressure stage**. It is composed of all the fluidic elements that follow the pressure regulator, mainly: eight solenoid valves (closed as per default) that independently control the related eight nozzles.
5. **Fill & drain**. A subsystem devoted to the filling of the propellant in the tank and its draining after its use in laboratory.

The functional principle behind PERSEUS propulsion system is hereafter explained. The R134a, a bi-phasic propellant that has high safety characteristics, is stocked in the tank. When the system needs to produce a thrust by means of its 8 independently controlled nozzles, the evaporator system is powered on in order to reach the operative temperature, which is set between two thresholds through a bang-bang control. The heating up of the evaporator should take only a few seconds, thus allowing for a very low time-to-fire (in the order of < 10 s). When the pre-heating phase is completed, the valves upstream the nozzles are opened and the propellant is then able to flow through the fluidic line. The fluid flows through the evaporator where it is vaporized, whatever the mass quality at its inlet is. It then flows in a passive pressure regulator which lowers and stabilizes the fluid pressure at a pre-selected level. Eventually, the propellant goes through the nozzles, where the constant pressure is used to produce a constant mass flow through the choked throat area and, thus, a constant thrust.

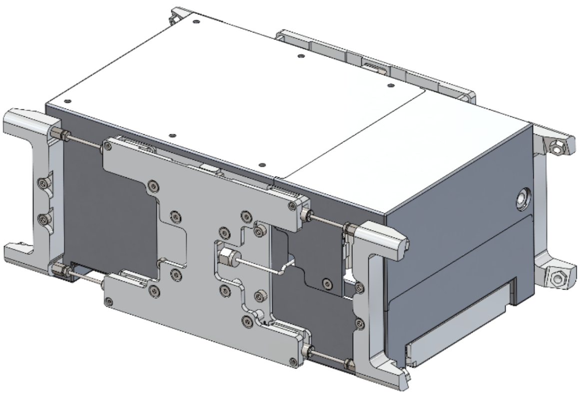

Figure 3 PERSEUS Overview

The Propulsion Control Unit (PCU) of the thruster consists in a single electronic board, mounting a microprocessor that has consistent flight heritage thanks to its presence in multiple flown missions. The PCU is situated on top of the tank and is mated with it through screws, furthermore it is shielded by an aluminium lid that has no structural purpose and prevents the board from being damaged by accidental interference with other elements of the spacecraft. The firmware flashed on the microcontroller performs all the task enabling thruster nominal operations, including fast FDIRs such as pressures and temperatures monitoring. Telemetry and commands are respectively sent and received through a specific connector, which also serves as power interface with the spacecraft. Control is based on a semi-closed loop in synergy with the GNC controller on the flight computer: external commands coming from the spacecraft and feedback sent back from the thruster, in order to update in real-time the status of the manoeuvre.

Turning-key Technologies

CubeSats propulsion systems must comply with challenging constrains, leading often to the involvement of state-of-the-art technologies that permits the satisfaction of the requirements. One of the most challenging constrains is the envelope, since CubeSats are dense systems and every item needs to be miniaturized as much as possible.

To exploit the available envelope at its best, it was decided to take full advantage of Additive Manufacturing (AM) technologies. This permitted to design several structural parts from scratch with a tailor-made form and size, including the tank that alone occupies circa the 75% of the available volume. Other parts developed using a combination of AM and classical techniques are manifolds, clamps, inserts and the fill and drain tool, which design has been miniaturized to permit filling of the thruster in several configurations. It is crucial indeed to permit the filling operations when the thruster is assembled into the spacecraft, being it both inside and outside of the deployer, in order to assure a flexible approach to launch integration activities.

Generally, in typical propulsion systems for spacecraft the propellant is in liquid phase, so it is important to avoid gas ingestion and to guarantee a liquid flow to the tank outlet. The PERSEUS propulsion system, instead, takes advantage of the bi-phasic condition of the propellant and it is mandatory that only gaseous fractions reach the nozzles inlet, because liquid ingestion would determine specific impulse loss. For this reason, the presence of a phase separation device is mandatory, and a trade-off between active and passive components has been executed.

Evaporators were identified as the best technological solution for the following reasons:

1) relative easiness of miniaturization process;
2) presence of extremely precise empirical methods to estimate the behaviour of evaporating R134a fluids by means of numerical simulations.

The main drawback of such technology is that it requires a certain amount of electrical power, proportional to the maximum thrust.

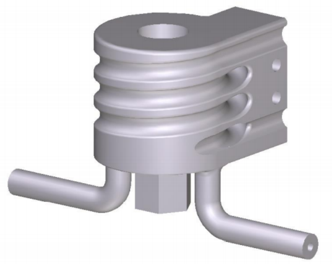

Figure 4 Evaporator conceptual design

Key Features and Performances

Main system parameters, characteristics and performances are hereafter presented:

Table 2 PERSEUS Key Features

Key Feature	Value	Notes
Type	6 DoF cold-gas thruster	
Maximum pressure	< 50 bar	
Total Impulse	~450 Ns	
Envelope	246x148.5x95 mm	
Mass	<4 kg	Wet
Power consumption	<30 W	When firing
Temperature range	-10 ÷ 50 °C operative -20 ÷ 60 °C survival	
Thrust	9/9/27 mN along X/Y/Z axis	
Torque	0.4/1.6/0.4 mN*m about X/Y/Z axis	

Development Plan

PERSEUS development followed a full double prototype approach, preceded by an early breadboarding phase conceived to validate each subsystem stand-alone. In particular, during breadboarding phase the following components have been procured and tested:

- Specifically designed
  - Tank
  - Nozzles
  - Evaporator
- COTS
  - Solenoid valves
  - Pressure regulator
  - Sensors

After breadboarding, the first prototype has been integrated and underwent the Environmental Test Campaign at the premises of CIRA (Centro Italiano Ricerche Aerospaziali) specifically the Laboratorio di Qualifica Spaziale (LQS). The tests have been performed with qualification loads and durations, and consisted in:

- quasi-static load
- sine burst
- random vibrations
- pyro-shock
- TVAC

The second prototype is currently under development and the qualification completion and production of the flight model is foreseen in 2022.

Iperdrone Mission Overview

IPERDRONE Program will consist of a series of missions characterized by incremental objectives, aiming at qualifying a new type of mission and the related enabling technologies: the program targets the realization of an autonomous space drone, to be in future accommodated in launch vehicles and to be released for executing different types of missions, supporting the eventual manned crew; space payload re-entry is included, aiming at providing the scientific community with scientific experiments' results to be validated on ground.

The first mission of Iperdrone program, named Iperdrone.0, will heavily leverage of PERSEUS technology, being the main scope of the mission the simulation of proximity operations and inspection activities around a Virtual Target (VT), with a final rendez-vous demonstration.

The schematics in Figure 5 reports mission ConOps.

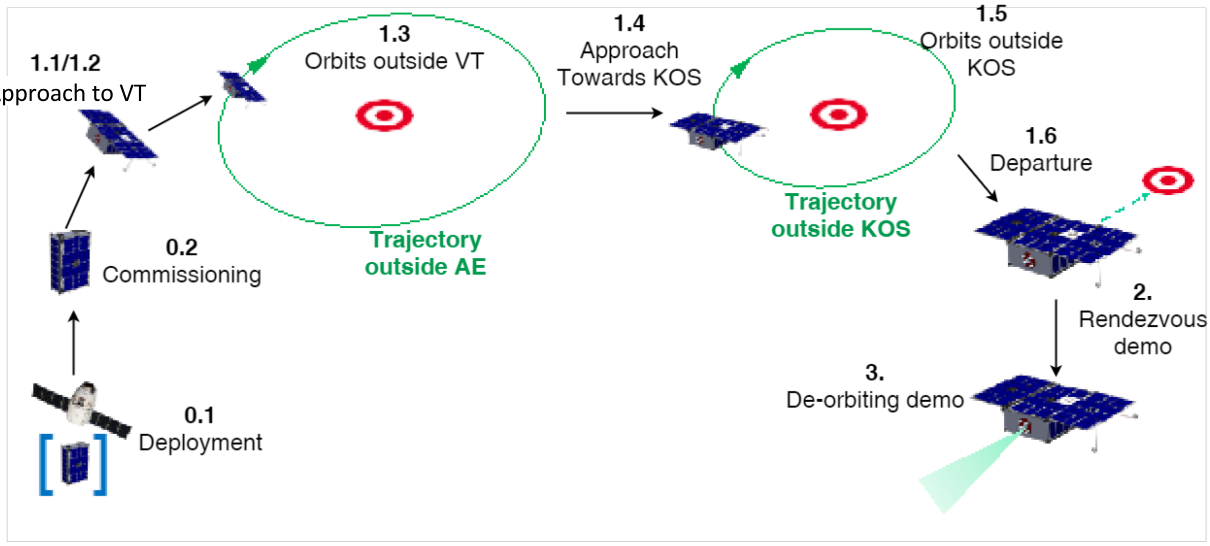

Figure 5 Iperdrone.0 ConOps[1]

In Table 3 the phases enabled by the Cold-Gas technology of PERSEUS have been furthermore detailed and presented, underlying the sub-phases where the thruster has an active role.

Table 3 Iperdrone.0 phases and sub-phases

Phase	Sub-phases description
1 Virtual Target Inspection	**Approach and phasing with the Virtual Target** 1.1 Far field phasing 1.2 Near field phasing 1.3 Passive orbits outside of AE (Approach Ellipsoid) **Close inspection** 1.4 Final approach 1.5 Passive orbits outside of KOS (Keep Out Sphere) **Departure** 1.6 Departure from VT
2 Rendezvous Demonstration	2.1 Precise orbit determination, target designation and preparation for rendezvous 2.2 Alignment 2.3 Long final approach 2.4 Short final approach 2.5 Telemetry downlink
3 De-orbiting	3.1 Precise orbit determination and designation of descent corridor from ground 3.2 De-orbit burn along predetermined descent corridor, until propellant exhaustion 3.3 Downlink of relevant mission telemetry to ground 3.4 Platform passivation completion and re-entry

Iperdrone.0 mission will be launched in the upcoming months, targeting end of Q4 2022 (pending launcher activities).

[1] AE: Approach Ellipsoid
KOS: Keep Out Sphere

Future Developments

The family of Cold-Gas propulsion systems PERSEUS might be suitable for a wide range of missions and spacecraft configurations, since requirements and functionalities needed can vary consistently in between different mission / system concepts. In this framework, Tyvak International, with the collaboration of T4i, is developing another thruster of the cold-gas propulsion family, leveraging on experience and lessons learnt during work done on PERSEUS.

Specifically, a focus has been posed on deep-space suitable propulsion systems, compliant with more challenging lifetime and leakage requirements. This development is currently ongojng and is based on the Hera Milani mission requirements.

Conclusions

The development of the Perseus cold-gas propulsion systems family will allow filling the technological gaps identified by the market analysis for the execution of a specific range of proximity operations missions. Leveraging on the synergies applied in the development approach of the different products of the PERSEUS systems family, and the flexibility of the conceived configurations, this new technology as a whole will enable a wide range of proximity operations missions in Low Earth Orbit and Deep Space environment.

Acknowledgement

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