DOI: 10.13009/EUCASS2022-9718

FROG project: small demonstrator for big ambitions in RLV European objectives. Status quo and results

Massimo FERLIN[a], Badr RMILI[a], Sebastien LE MARTELOT[a], Anouk SCHINDLER[a], Olivier BOISNEAU[a],*
Stéphane DUSSY[b],
Stéphane QUERRY[c],
Błażej MARCINIAK[d], Paweł SURMACZ[d], Marek PŁOCHÓW[d], Grzegorz PELA[d], Tadeusz GORNICKI[d],
Gilles POIREY[e], Sylvain BESSON[e]

[a] Centre National d'Etudes Spatiales (CNES), 52 rue Jacques Hillairet – 75012 Paris, France
[b] European Space Agency (ESA), 52 rue Jacques Hillairet – 75012 Paris, France
[c] Polyvionics, 13 rue de Plélo, 75015 Paris, France
[d] Łukasiewicz Research Network– Institute of Aviation, al. Krakowska 110/114, 02-256 Warsaw, Poland
[e] Planète Sciences, 16 place Jacques Brel, 91130 Ris-Orangis, France

** Corresponding Author (massimo.ferlin@cnes.fr)*

Abstract

Reusability in the launcher sector has been studied for quite a long time in Europe and is still on going, for instance, CALLISTO and THEMIS are two of the main European projects. Today, players from the so-called “NewSpace” sector demonstrate rocket boosters’ recovery and reusability on a regular basis. The established rocketry industry is being challenged by new space actors and emerging space nations. In this climate of intensifying competition, there is a growing sense of urgency in Europe, materialized by numerous new companies and projects.

The French Space Agency (CNES) is one of the stakeholders in Europe for future launchers preparation, along with ESA, other national agencies and industry. To catch up as quickly as possible, CNES promotes several initiatives at different scales, whether it be with students, academics, SMEs or big players, aiming at fostering key competencies for reusability in Europe. As a matter of fact, among the required technologies for reusable rockets, GNC and avionics for landing is deemed to be one of the most challenging ones. This shouldn’t be studied only by simulation, but also with tests on demonstrators.

Among these studies, the FROG vehicles family corresponds to the early sandbox approach. They are a small and low-cost flying vehicles developed as a testbed platform for guidance, navigation, control algorithms and avionics used by CNES and students in order to test various landing algorithms and approaches. This platform is developed by a multidisciplinary team from a non-profit organisation (Planète Sciences), and a start-up (Polyvionics) with the funding and the technical support of CNES, in collaboration also with academics (Innov’Lab at the Cachan Institute of Technology) and Arianeworks.

After successful free flight campaigns of previous FROG generations (FROG-T and Pi-FROG/FROG-E), a new generation of vehicle is under development with new partners: the European Space Agency (ESA) and Łukasiewicz Research Network – Institute of Aviation (Poland). This new generation of vehicle named FROG-H, is based on a monopropellant hydrogen peroxide catalyst engine developed by Łukasiewicz - ILOT.

In this paper, we will first quickly present the project status including some results of the free flight campaigns and a FROG-H introduction, including new propulsion system design as well as the project’s roadmap. Then we will delve into the GNC studies and the propulsion system simulation results linked to the monopropellant catalyst HTP engine. Promising hot-fire test results of the new, long-endurance catalyst, developed by Łukasiewicz-ILOT, will be presented. This sub-scale tested catalyst is applicable to the full-scale FROG-H engine.

DOI: 10.13009/EUCASS2022-9718

1. Introduction

1.1 Context & Reusability roadmap

Today, reusability is deemed to be one of the levers allowing to reduce launch costs beyond what will be achieved on expendable launch vehicle. Considering economical models, recovery/reuse is not intended to be systematic for each mission and stages, but efficient first stage Return To Launch Site (RTLS) or sea DownRange Landing (DRL) is envisioned for future launchers.

As shown on Figure 1, CNES reusability roadmap [1] is based on several demonstrators at different scales. All these experimental Vertical Take-off Vertical Landing (VTVL) vehicles are complementary and fit with CNES global strategy and collaborative approach with ESA, DLR and ArianeGroup.

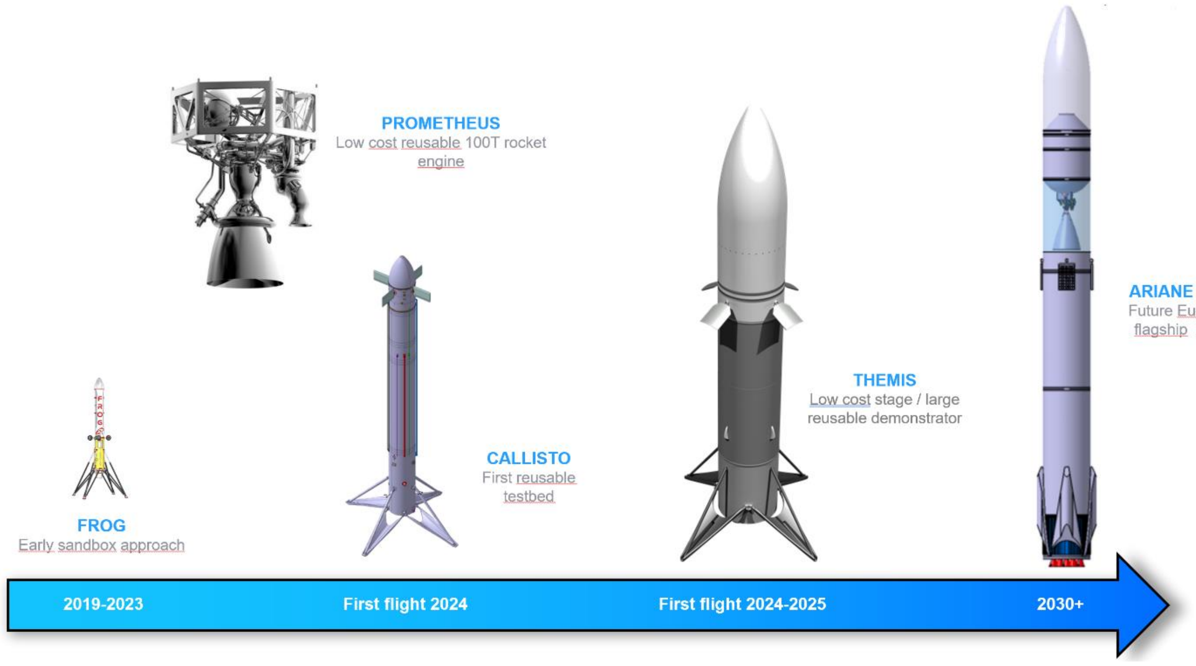

Figure 1: CNES reusability roadmap

In this roadmap, FROG demonstrator corresponds to the early sandbox approach. It enables to demonstrate guidance and control algorithms for vertical landing, quickly, at low cost, low risk and with high agility. As a matter of fact, among the required technologies for reusable rockets, GNC and avionics for landing are deemed to be one of the most challenging ones. This must not be studied only by simulation, but also with tests on demonstrators. FROG is both a technology demonstrator and an agile project demonstrator.

After FROG, CALLISTO and THEMIS are the next step in mastering and demonstrating technologies for recovering and reusing a VTVL first stage. CALLISTO stands for Cooperative Action Leading to Launcher Innovation in Stage Toss-back Operations. It is an inter-agency cooperation with DLR and JAXA (see [3] and [4]), supported by industrial partners including ArianeGroup.

The subsequent step of this workplan – after FROG and CALLISTO – is a program devoted to oxygen/methane stage-level technologies, with a full-scale VTVL demonstrator, codenamed THEMIS, standing for Technologies for a Methane Innovative Stage and using the new PROMETHEUS low-cost engine. THEMIS project is an ArianeWorks, ArianeGroup and CNES initiative supported by ESA.

2. FROG organisation, approach and concepts

First, before diving into the project organisation, approach and concepts, let us start by the meaning of the FROG acronym, FROG is a recursive acronym meaning “FROG, a ROcket for GNC demonstrations”. This acronym inspired

DOI: 10.13009/EUCASS2022-9718

by open-source projects like GNU (GNU is Not Unix) reflects the collaborative and open approach of the FROG project. Indeed, this project has been initiated by CNES Launcher Directorate in 2017 with the will to:

- Benefit from a very small-scale, low cost and easy to use VTVL GNC testbed platform.
- Apply original approaches to demonstrator development (collaborative, “Agile”, experimental, etc.).
- Involve start-ups, academics, students and non-profit organisations.

2.1 Project approach

From the beginning, the idea was to have a collaborative approach with all the CNES partners involved in the project. For the launcher directorate team, the involvement was more than project management, specification and technical expertise but to really take part in design, tests, etc.

A first key factor in the FROG approach was to find the right balance between classical space engineering development methods and iterative and incremental development methods (like Agile). This right balance and the collaborative approach have helped us to reduce the documentation to an ideal amount. For example, the need of detailed technical or interface specification has been greatly decreased.

A second key factor is the experimental approach used to quicken the development and the team expertise. The idea is to reduce all the complex and time-consuming theoretical design demonstrations and to quickly assess design performance through early iterative hardware and/or software tests. The tests results are used to quickly confirm the design worthiness and to consolidate models and simulators. Of course, to apply this approach we have to accept failures: “Failure is ~~not~~ an option” and “Fail fast, fail often”.

A third important key factor to apply the above approach is to be able to fly easily, often and at a low cost. In order to do this, an acceptable compromise must be found between FROG scale and representativeness to a full-scale vehicle. Also, FROG flight operations and maintenance shall be simple, safe and low cost.

In order to comply with these requirements, we have deliberately chosen to design the first versions of FROG (Pi-FROG/FROG-E and FROG-T) in compliance with French regulation about experimental UAV weighing less than 25 kg. This means that the first versions of FROG shall weigh less than 25 kg, shall include a remotely piloted mode, shall always stay in VLOS (Visual Line Of Sight), shall include an independent FTS (Flight Termination System) and shall fly in a “No-Fly Zone” in accordance with French Civil Aviation Authority.

2.3 FROG concepts and roadmap

At the beginning of the project, FROG was just an idea without any detailed definition, but we wanted a low-cost (using mainly COTS), light (less than 25kg for the first versions) and flexible platform allowing to demonstrate vertical landing with an initial vertical speed of at least 15m/s, and a speed at touchdown between 0 and 2m/s, with thrust vector control. We deliberately left open many options during a first phase of “creativity”, but each of the considered options had to be subject of a feasibility analysis with regard to missions, cost and safety.

Therefore, during these first few months quite a wide range of concept have been proposed and analysed, among which:

- Compressed air/cold gas propulsion,
- Pressurized water propulsion,
- Auto-pressurized liquid propulsion (CO_2 or N_2O),
- Pumped water propulsion,
- Propulsion by catalytic decomposition of pressurized H_2O_2,
- Hybrid propulsion N_2O/PBHT,
- Turbojet engine.

Some concepts have been quickly rejected after the first feasibility analysis. Other ones were looked at more thoroughly. For example, the waterjet propulsion (pumped water concept) has been well studied in [5] and was interesting in terms of safety, and the CO_2 propulsion was considered for Mars probes in [6] and for the Mars Gas Hopper concept from NASA.

DOI: 10.13009/EUCASS2022-9718

Finally, two concepts have been selected for detailed design, both versions with a common platform but different timeframes:

- FROG-T with a Turbojet engine, for short-term experimentations,
- FROG-H with a H_2O_2 engine (catalytic decomposition).

In addition, Pi-FROG or FROG-E with "electric turbine" (EDF : Electric Ducted Fan) has been developed for early debugging purpose.

In term of roadmap, FROG is seen as a two-step project where FROG-T is the first step as short term development goal. FROG-T development has started in January 2018 and the first tethered flight has been done in May 2019. The first free flight has been performed in September 2020. Indeed, as the turbojet is a COTS equipment, FROG-T allows to quickly gain maturity and to qualify as much as possible the components foreseen for FROG-H. Therefore, FROG-T and FROG-H share a common baseline for GNC, avionics, sensors, some actuators, mechanical structure, landing feet, ground station and flights operations.

FROG-H is the second step as mid-term development goal where the engine must be specifically designed. In comparison with FROG-T, the goal with FROG-H is to gain more representativeness with respect to a VTVL first stage. **In order to develop a real rocket engine, two key partners have joined the project in 2019 : the European Space Agency (ESA) and the Łukasiewicz Research Network – Institute of Aviation (Poland).** Only the exothermic decomposition trigged by the contact of the HTP with a catalyst bed will be used to deliver a higher thrust than the turbojet engine used in FROG-T. In addition, this HTP engine will allow a much faster response time and no more turbojet induced torque. These characteristics will make it more representative with respect to a launcher.

FROG-H main milestones are the following:

- Beg. of 2020: Project kick-off
- End of 2022: Propulsion System and Mobile Propellant Loading System (MPLS) qualification
- Beg. of 2023: FROG-H static firing and tethered flight campaigns.
- Mid 2023: FROG-H first free flight campaign.

2.4 Project organisation

In terms of partnership, the FROG-T project relies on a multidisciplinary organisation with shared roles:

- CNES Launcher Directorate and ArianeWorks:
    - Project management, system engineering and technical expertise.
- Planète Sciences, a scientific non-profit organisation:
    - Prime contractor, project management, system engineering, avionics, propulsion expertise and structural design. System integration, safety studies, tests, flight operations.
- Polyvionics, a start-up specialised in GNC, avionics and UAV:
    - System engineering, avionics, embedded software, GNC, SITL/HITL design and validation.
- Cachan Institute of Technology in association with its incubator Innov'Lab:
    - Structural and mechanism design plus manufacturing.
- Drones-Center, a SME specialised in experimental UAV flight operations:
    - System engineering, flight operations and certified experimental UAV pilot in accordance with French regulation.
- Sonatronic, a SME specialised in electronics and avionics:
    - Avionics design and integration.

The above FROG-T organisation involves a team of aerospace students, volunteers, engineers, and researchers.

For FROG-H, the organisation is based on FROG-T team and organisation with the addition of two key partners:

DOI: 10.13009/EUCASS2022-9718

- ESA through Future Launchers Preparatory Programme (FLPP):
    - Project management, system engineering and technical expertise.
- Łukasiewicz Research Network – Institute of Aviation:
    - Propulsion system and Mobile Propellant Loading System (MPLS): Prime contractor, project management, system engineering, components design, manufacturing, integration, safety studies, tests and qualification.

3. FROG-T platform, test logic and flight results

3.1 FROG-T platform

In depth FROG-T platform presentation, test logic and flight results are presented in [7], [8] and [9]. As a reminder, the platform architecture is summarised in the following figure:

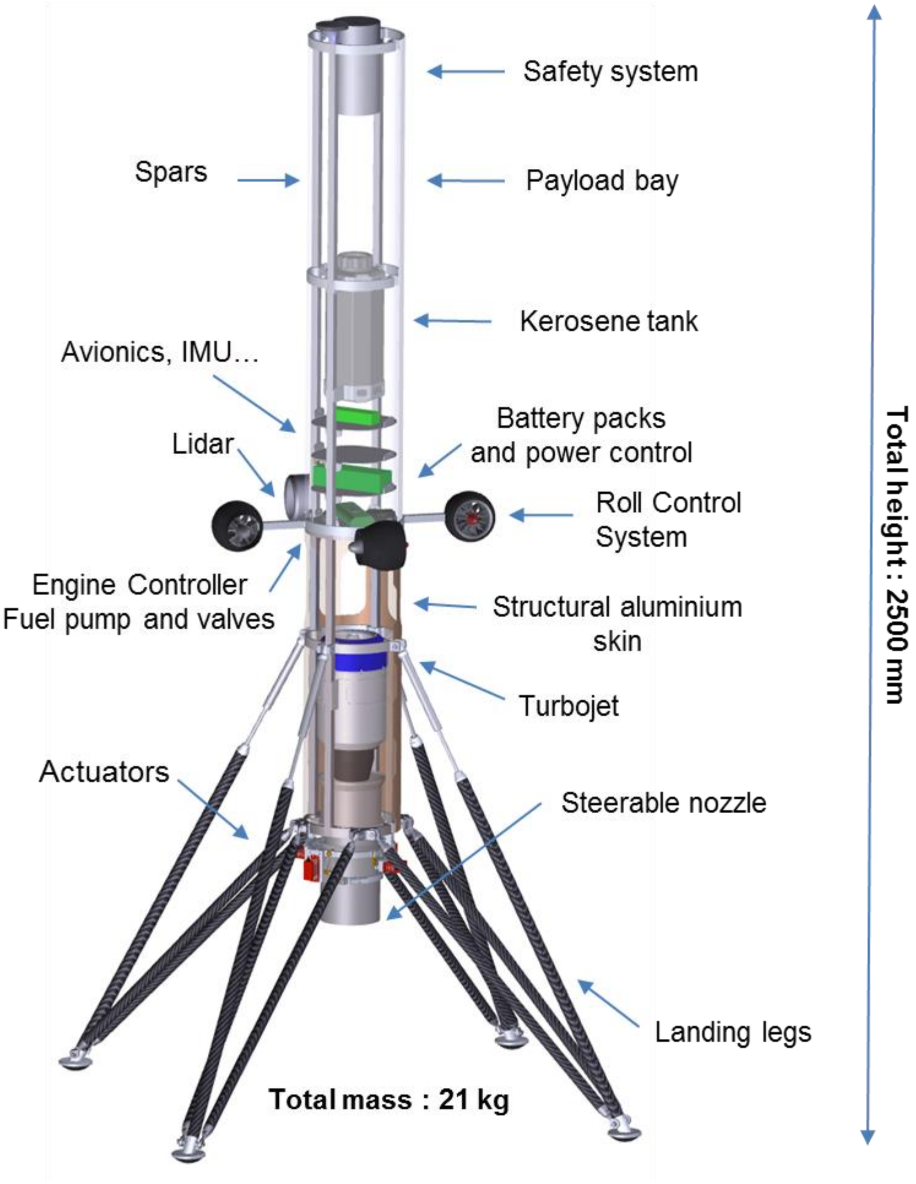

Figure 2 : FROG-T platform architecture

3.2 FROG-T test logic

In order to implement our experimental and progressive approach, numerous tests have been conducted to qualify the design (hardware and software) and to refine our models and simulators. Several test benches have been specifically developed for FROG-T and are described in [8] and [9].

To develop and qualify GNC, embedded software and avionics, several means have been developed for step-by-step validation:

- SITL (Software In The Loop) partially based on FROG-T embedded software.
- HITL (Hardware In The Loop) based on FROG-T avionics and embedded software.
- Pi-FROG and FROG-E which are a reduced-scale versions of FROG-T using the same avionics and embedded software. Illustrated in Figure 3**Erreur ! Source du renvoi introuvable.**, numerous free flights have been conducted on Pi-FROG since autumn 2018.
- A 6 m high gantry used for tethered flights. Illustrated in Figure 3.

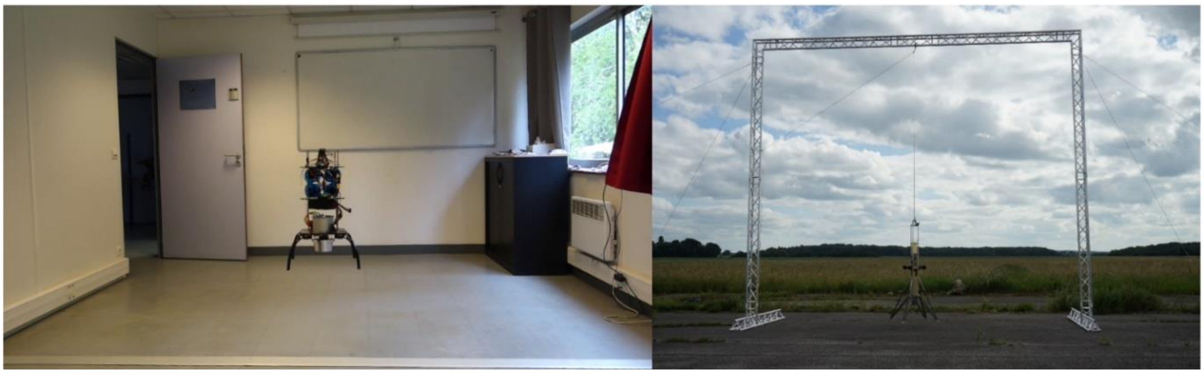

Figure 3: (left) Pi-FROG a reduced-scale versions of FROG-T – (right) 6 m high gantry used for FROG-T tethered flights

These means and the step-by-step approach allow us to apply an experimental and short iteration approach with reduced risks (Figure 4 below). The same approach will be used for FROG-H.

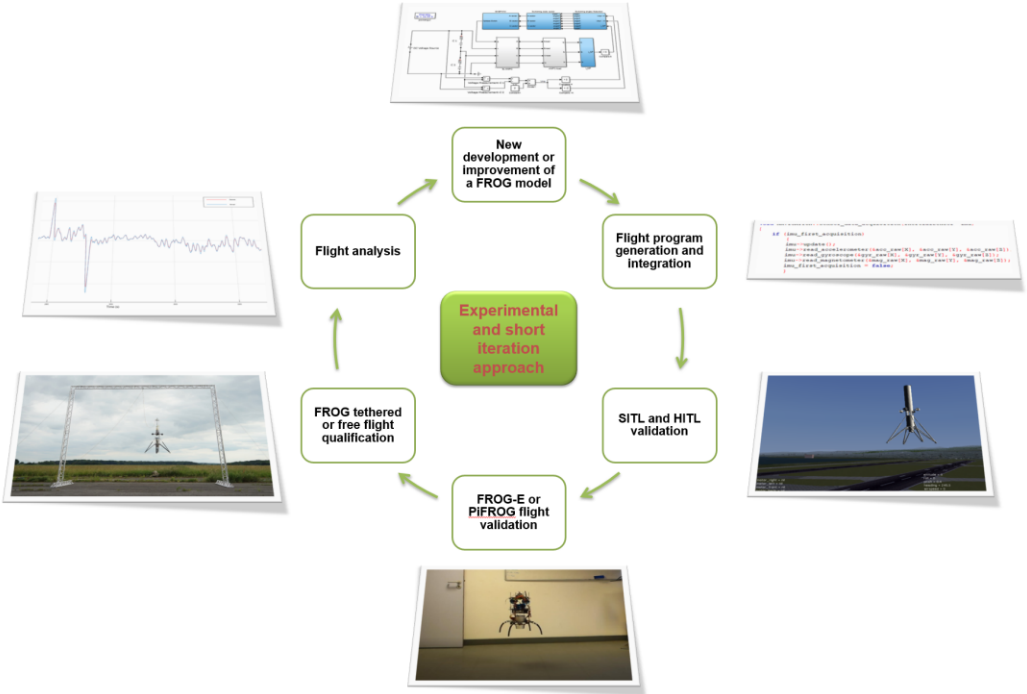

Figure 4 : FROG experimental and short iteration approach

DOI: 10.13009/EUCASS2022-9718

3.3 FROG-T flight results

Between May 2019 and September 2020, 40 tethered flights and 5 free flights have been performed. Some flights analysis have been published in [8] and [9]. To sum-up, the lessons learned are very rich and cover all technical and operational domains. Even with the step-by-step approach including SITL/HITL and/or Pi-FROG flights, there are always unexpected events or unknown details coming from the field with real hardware, real physics, and operational constraints. Most of these events and details do not lead to major failures or damage on FROG but unfortunately some does. Some of them are illustrated in Figure 5 below. Even for major damages, the FROG team has been able each time to identify and to correct in few days the anomaly including the repairs.

Figure 5: Various RUD (Rapid Unscheduled Disassembly) of FROG-T during tethered flights

But for sure, all these unexpected events or unknown details coming from the field provide unvaluable knowledge and knowhow that are less or even not accessible with simulation only approach.

Figure 6 : FROG-T free flight in a former military air base at Brétigny-sur-Orge (France)

DOI: 10.13009/EUCASS2022-9718

4. FROG-H project status and main characteristics

At the time of the writing of this paper (June 2022) the CDR (Critical Design Review) of the propulsion system and the MPLS are ongoing. The CDR for the complete system will follow by end of August 2022. The FROG-H approach and main milestones are described in **chapter 2.3**.

At this stage of the project, simulations or prototypes of some key components or subsystem have been already tested. For instance, to mention a few:

- Extensive and numerous simulations at system level, GNC level, propulsion system level or at subsystem/components level have been conducted.
- A sub-scale catalyst bed has been manufactured and characterised during hot-fire tests
- Dedicated motorized valves prototypes have been manufactured/assembled and the development of a valve characterisation test bench is undergoing.
- Full scale engine gimbal with associated TVC (Thrust Vector Control) and representative loads has been manufactured/assembled and is currently under test.
- Full scale landing legs prototypes have been manufactured/assembled and are under tests with representative loads.

In term of design, the structural mechanic architecture is in practice the same as FROG-T but with different dimensions and some specific adaptations. FROG-H has a total height of 3.5 m and a diameter of 30 cm, with a total wet mass around 100 kg. It is equipped with a catalysed and non-pyrotechnical H_2O_2 propulsion system developed by Łukasiewicz Research Network – Institute of Aviation. The propulsion shall be bi-compatible with 87.5% and 98% HTP concentration and provides a variable thrust going from 150 to 1600 N. The goal is to carry out typical missions of 40 seconds of flight, at speeds greater than 20 m/s, and to perform precision landings, "hard landing" or even "suicide burn". FROG-H is reusable, low cost and shall simplify operations and safety procedures in order to allow up to 5 flights per day. Figure 7 and Figure 8 below provide some illustration of FROG-H.

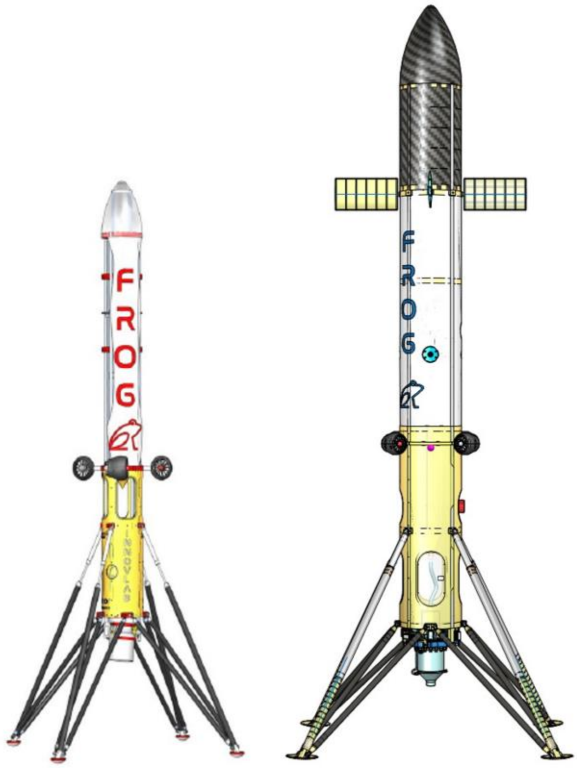

Figure 7: Side by side scale comparison of FROG-T (left) and FROG-H (right)

DOI: 10.13009/EUCASS2022-9718

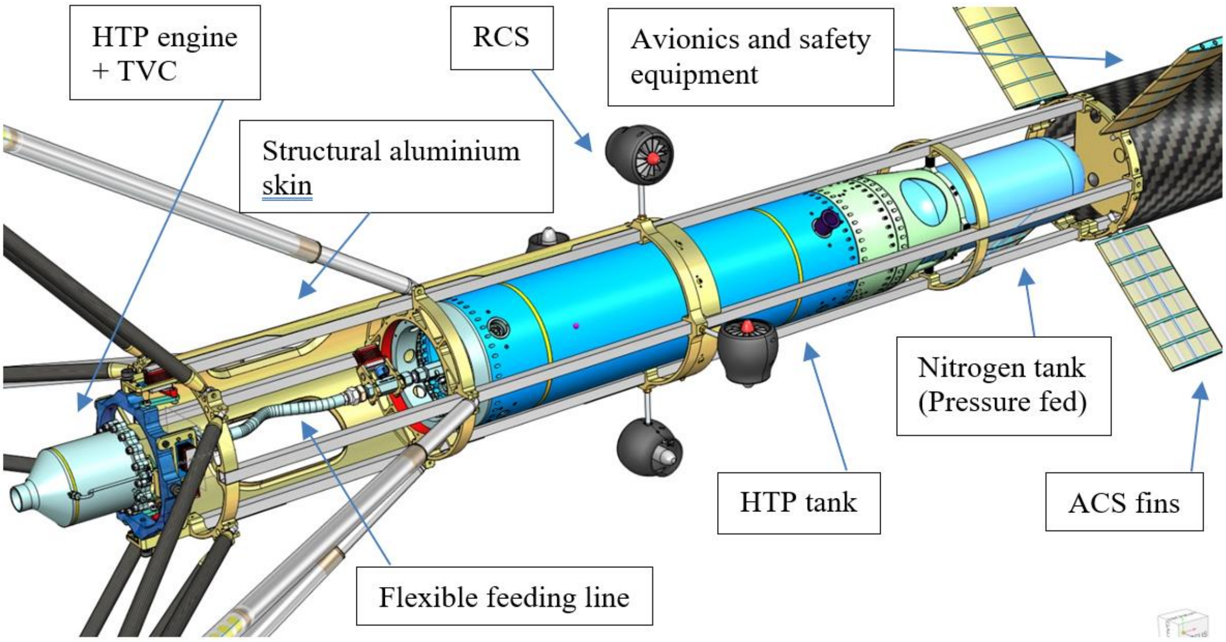

Figure 8 : FROG-H architecture overview

In the next chapters, we will delve into the following subjects:

- Mission, vehicle, and propulsion system simulations loops used at system level for designing FROG-H,
- Approach and modelling used FROG-H GNC,
- FROG-H propulsion system description, engine design and preliminary test.

4. Mission, vehicle, and propulsion system simulations loops used at system level for designing FROG-H

FROG-H propulsion system consists in three main parts:

- The pressurisation gas module (G area in Figure 9),
- The HTP (High-test hydrogen peroxide) module (H),
- The Engine module, containing the decomposition chamber (D) and the thrust chamber (E).

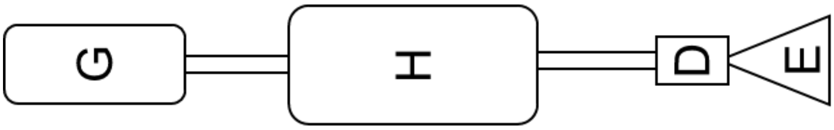

Figure 9: FROG-H propulsion system simplified synoptic

The pressurisation gas module (G module) contains the nitrogen (GN_2) high-pressure vessel (> 150 bar) as well as pressure regulator and safety components. Its main goal is to supply GN_2 to the HTP module in order to keep the H_2O_2 tank pressurised to the nominal pressure required to obtain the thrust in the engine.

The next module is the HTP module (H module). This module is mainly composed of the liquid H_2O_2 tank with connection to GN_2 module and engine module. It also contains filling, venting and safety components. The function of this module is to supply liquid pressurised H_2O_2 to the engine module.

The last module of Frog-H propulsion system is the engine module. It is composed of the H_2O_2 catalytic decomposition chamber (D) and the thrust chamber (E). The main goals are generating thrust, handling throttling with a dedicated valve and providing thrust vector control through a gimbal and actuators.

DOI: 10.13009/EUCASS2022-9718

4.1 Modelling and simulation

Numerical simulations of the propulsion systems have been made in order to design its main parts to satisfy the targeted missions and provide propulsion analysis and curves for guidance, navigation and control (GNC) needs.

The modelling has been done using a transient in-house code coupling 2D flight dynamics (trajectory, aerodynamic stability) and engine dynamics (tanks pressurization, valve control thanks to a perfect pilot, H_2O_2 decomposition efficiency, thrust transient). Coupling flight and engine dynamics is especially important to anticipate GNC needs and to obtain an accurate design of tanks, valves and decomposition chamber.

Flight dynamics module is based on numerical resolution of forces and torque applied in a plane to a vehicle described by a mass, a cross section and a length.

$$\begin{aligned} \sum F_x &= m\frac{d^2x}{dt^2} \\ \sum F_y &= m\frac{d^2y}{dt^2} \\ \sum M_z &= I\frac{d^2\alpha}{dt^2} \end{aligned} \qquad (1)$$

With:

- m: the vehicle mass, in kg
- I: the vehicle inertia, in kg·m²
- α: the vehicle angle of incidence

This system of equation allows us to determine the exact corrections of GNC to reach a targeted altitude or to control the vehicle attitude that are directly converted in throttling valve law. Then, the pressurization tank and the pressure regulator are modelled (targeted pressure, flow cross section). Eventually, the H_2O_2 decomposition rate is modelled in three steps:

1. Determination of theoretical efficiency of decomposition from thermochemical equilibrium code (RPA) depending on H_2O_2 concentration
2. Corrected efficiency considering the H_2O_2 mass flow rate and catalytic bed temperature (correction based on Łukasiewicz-ILOT preliminary experimental tests or literature)
3. Decomposition delay (~ 0.25 s) between injection and high temperature gas generation (correction based on preliminary experimental tests or literature)

In all simulations, a lateral wind of 10 m/s is considered, giving a strong attitude correction and majoring the HTP consumption.

At each time step, thrust, velocity, altitude, incidence, throttling valve command, liquid H_2O_2 mass, inertia, tank and chamber pressure, are all resolved.

HTP concentration (mixture of liquid H_2O and H_2O_2) is a major concern for safety and performance aspects of FROG-H. Indeed, high HTP concentration (98% or 87,5 %) requires specific safety procedures to avoid any hazard.

4.2 System iterations

Firsts system iterations between Łukasiewicz-ILOT, CNES and Planète Sciences gave us an estimation of propulsive mass (tanks, valves, plumbing, fluids, electronics, structures etc.) of around 100 kg, that is a strong mass inflation from FROG-T. As a direct consequence, the thrust class engine had to be significantly increased to around 2000 N.

A short mission of around 10 seconds is simulated and presented in the Figure 10 below. A five seconds of catalytic bed heating before flight is considered. The inert mass of the propulsive system is 52.5 kg, including tanks and combustion chamber. HTP pressurization is done by a 9-litre tank of N_2 at 100 bar (5 kg mass). The mass flow rate is allowed thanks to a motorised throttling valve (2.5 kg estimated mass). The total mass at lift-off is 83.5 kg and includes

12.5 kg of H_2O_2. A safety margin of 10 % of HTP is taken into account at the end of mission. System efficiency (I_{SP}) is in good agreement with experimental data available at the time of this simulation.

For the presented mission, a maximum mass flow rate of 1.6 kg/s is calculated for a maximum of thrust of 1700 N. 10 kg of HTP is consumed and the targeted altitude is correctly maintained. The 9-liter pressurisation tank seems to support longer missions up to 30 seconds of hovering without any change in overall system performance, as presented in Figure 11.

In this case, the vehicle total mass at lift-off is 96 kg and 32 kg of HTP is consumed. Of course, a bigger HTP tank capacity of 25 litres is then needed.

By simulation, it is demonstrated that various kinds of landing can be addressed with FROG-H. The hard landing is achieved by a longer free fall and a shorter landing burn. For our demonstrator, no significant consumption improvement is observed by this means.

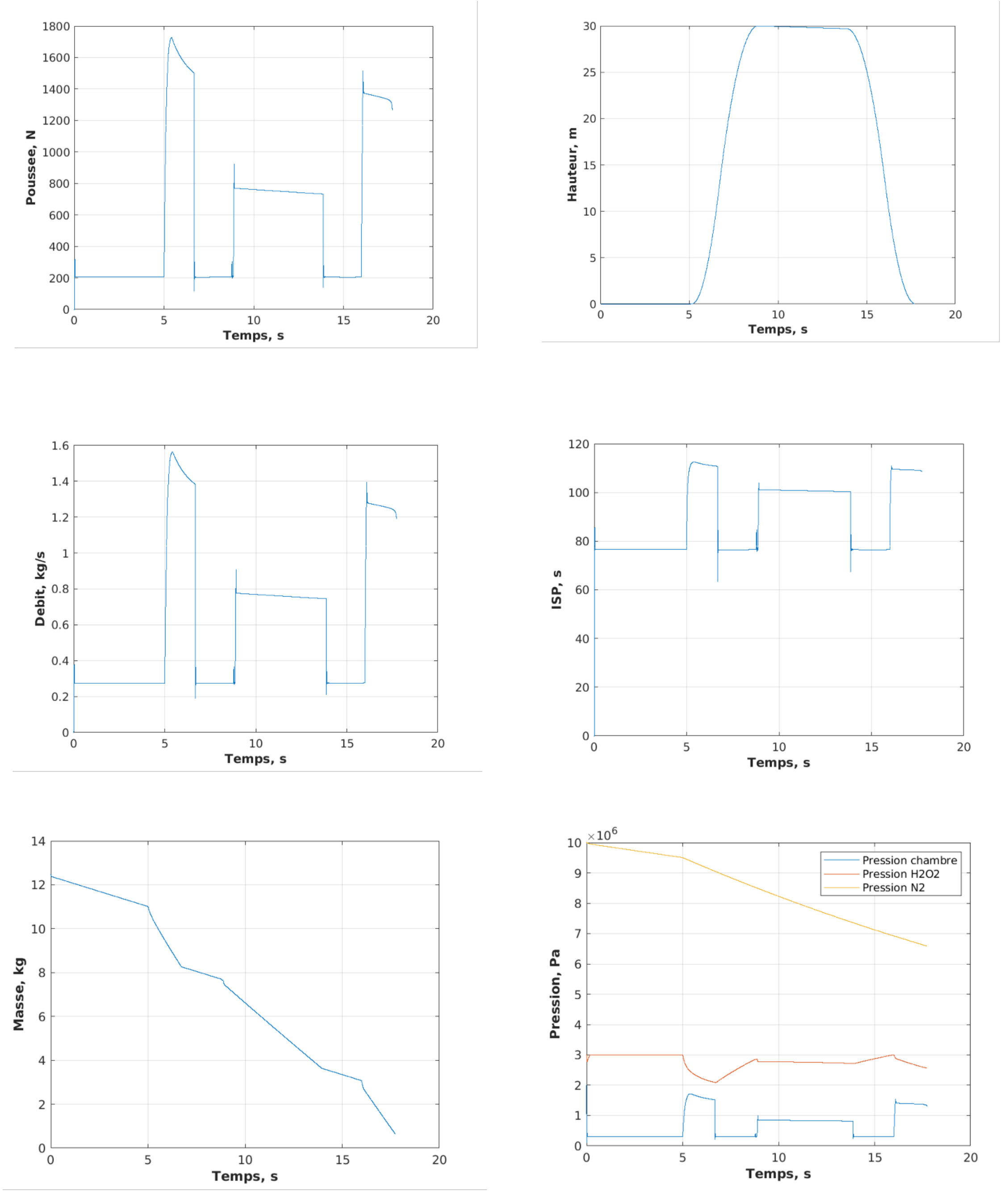

Figure 10: FROG-H “short mission” performance analysis

DOI: 10.13009/EUCASS2022-9718

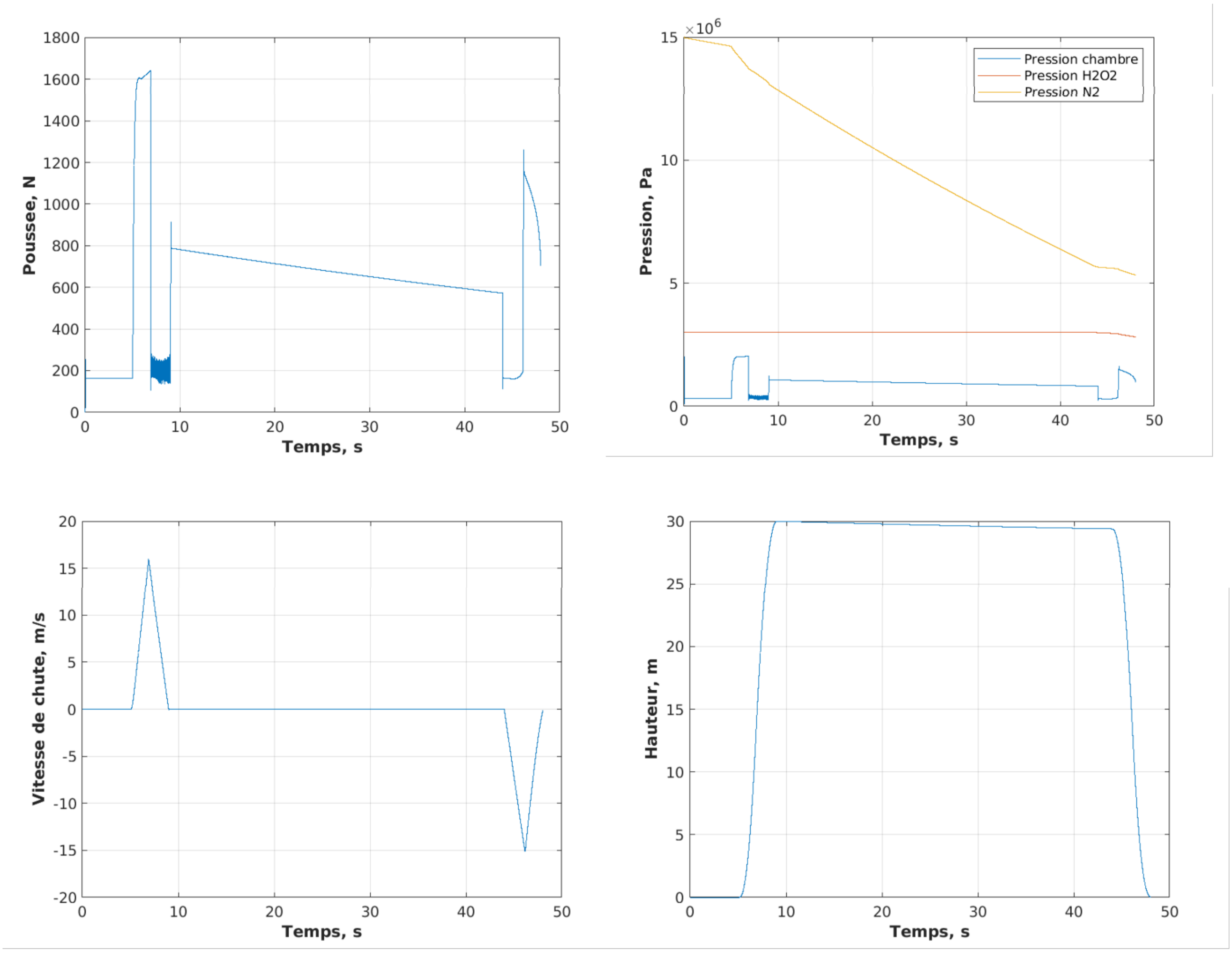

Figure 11: FROG-H "long mission" performance analysis

4.4 HTP thruster controllability

For now, the remaining work at system and GNC level is to evaluate the controllability of such an engine. The same kind of dynamic simulation and tests than those for FROG-T will be realised to access the propulsion system frequency content. But it can be already anticipated that the characteristic time will be lower than FROG-T because there isn't the inertia of the turbojet rotor. Concerning the thrust throttling, a small nonlinearity could be observed between command and thrust depending on the thrust level because efficiency (HTP decomposition, pressure drop in the catalytic bed) is not the same outside the functioning point. New experimental data have been provided by Łukasiewicz-ILOT colleagues at the time of writing and will help for consolidating/improving the models.

DOI: 10.13009/EUCASS2022-9718

5. Approach and modelling used FROG-H GNC

5.1 Modelling of the Platform

To develop a control law, the first and most important step is to determine a mathematical model of the platform, by calculating the forces and moments of the demonstrator during a flight. These equations will also be used by the embedded software to compute the nozzle orientation, as function of the required rotational accelerations. This is a static model (steady state) which does not contain the actuators behaviour.

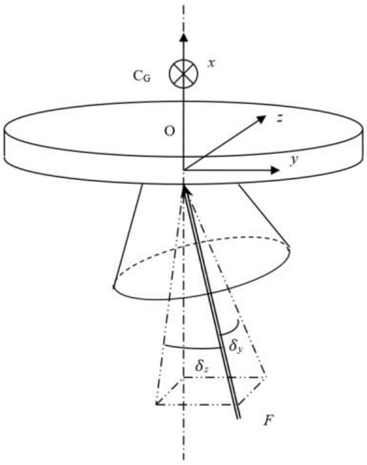

Figure 12: TVC schematics

The coordinates of the **propulsion force**, in the body frame (by supposing that nozzle deflection angles are small during the mission, which permits the linearization of the trigonometric functions), are the following ones:

$$\begin{cases} F_x = \|F\| \dfrac{1}{\sqrt{1+tan^2\,\delta_y + tan^2\,\delta_z}} \\ F_y = \|F\| \dfrac{tan\,\delta_z}{\sqrt{1+tan^2\,\delta_y + tan^2\,\delta_z}} \\ F_z = -\|F\| \dfrac{tan\,\delta_y}{\sqrt{1+tan^2\,\delta_y + tan^2\,\delta_z}} \end{cases} \Rightarrow \begin{cases} F_x = \|F\| \\ F_y = \|F\|\delta_z \\ F_z = -\|F\|\delta_y \end{cases} \tag{2}$$

With δ_y and δ_z the angles of the deflector (in the body frame), and F the engine thrust.

The roll/pitch/yaw accelerations $(\dot{p}, \dot{q}, \dot{r})$ can also be calculated as function as the RCS thrusts (F_{T1}, F_{T2}, F_{T3}, F_{T4}), their distance the center of the platform (l), the position of the center of gravity (x_G), the nozzle deflections (δ_y, δ_z) and the inertia of FROG (I_y, I_z).

$$\begin{cases} \dot{p} = \dfrac{l(F_{T1} + F_{T3} - F_{T2} - F_{T4})}{I_x} \\ \dot{q} = -\dfrac{x_G\|F\|\delta_y}{I_y} \\ \dot{r} = -\dfrac{x_G\|F\|\delta_z}{I_z} \end{cases} \tag{3}$$

5.2 Navigation

Navigation requires a large number of **navigation sensors embedded** in the FROG platforms to calculate its dynamic state; including an inertial measurement system consisting of gyroscopes measuring the platform's rotational speeds and accelerometers measuring its accelerations.

DOI: 10.13009/EUCASS2022-9718

The inertial unit allows for what is known as inertial navigation, which consists of updating the orientation of FROG via the gyros, and then the speed and position via the accelerometers, which are essential for mission control, as we have seen.

The platform is also equipped with other sensors that not only prevent the inertial navigation from drifting, but also provide additional information, as shown in the following figure:

- The magnetometer uses the earth's magnetic field to determine the platform's magnetic heading,
- The use of satellite tracking such as Galileo or GPS (aided by precision beacons) provides an absolute raw position and velocity (the use of RTK beacons can be done depending on the accuracy required),
- Pressure sensors and laser rangefinder provide altitudes (barometric and ground).

The inertial unit allows for what is known as inertial navigation, which consists of updating the orientation of FROG via the gyros, and then the speed and position via the accelerometers, which are essential for mission control, as we have seen.

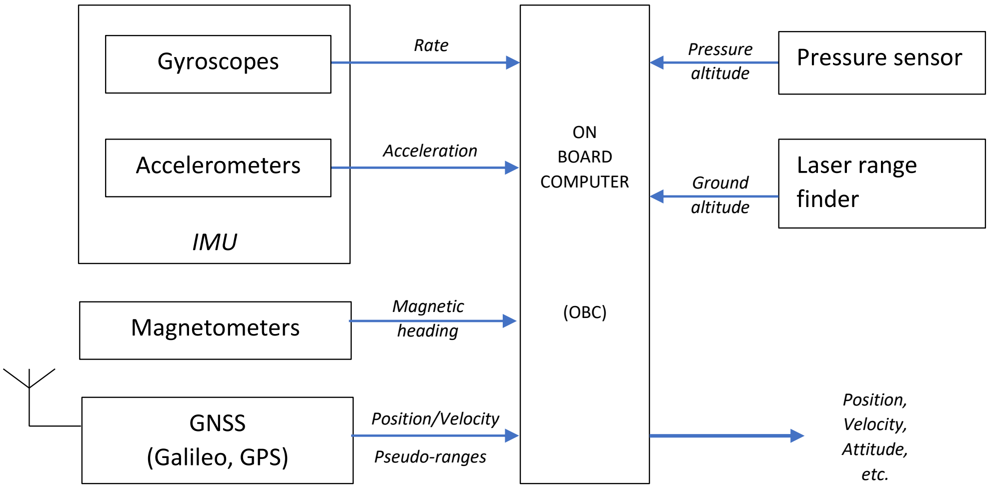

Figure 13 : FROG navigation architecture

All this information is then subject to a so-called data fusion, through a non-linear state observer (extended Kalman filter), which allows:

- Predict the current dynamic state of the platform (Position, Velocity and Attitude) via the inertial unit at a significant frequency,
- To recalibrate this information, thanks to the other navigation sensors, at a slightly lower rate (when the information is available),
- To estimate (and thus compensate for) sensor errors, as well as errors in the estimation of the current state,

5.3 Control

Controlling a platform like FROG requires some care, as it is naturally unstable. Indeed, it can be compared to an inverted pendulum or an upside-down broom that you are trying to balance with an outstretched hand.

The FROG platforms are usually controlled by two subsystems: the orientation of the main engine nozzle for pitch/yaw angles and four electric turbines as Roll Control System (RCS).

However, the development of the FROG-H pitch/yaw **control laws** integrates **critical elements** to be taken into account for the stability of the platform during flight: the **TVC**.

Indeed, in order to create the required moments for the control of the platform and contrary to what was the case with FROG-T, it is no longer a question of deflecting a part of the flow of a fixed engine via a deflector, but of moving the whole engine, with response times compatible with the necessary dynamics of the entire system: the steering dynamics depend directly on the response time of the TVC, i.e. the time it takes for the engine block to reach a required steering speed.

The motor (with a mass of about 10 kg) represents an important inertia, and as a result, the time **the TVC will take to reach its steering set point will depend directly on the power of the actuators** (as well as their maximum rotation speed): parameters that must be **selected with the greatest care**, via a study of the complete control loop. It is important to note that the **speed of rotation indicated in the actuator manual** has no influence on the response time: it only allows to check that the actuator never enters speed saturation during the control.

The strategy adopted to carry out the synthesis of the correctors in piloting as well as to carry out the selection of the actuators has been the following: development of the TVC model, including the actuators; development of the complete model of the pitch/yaw control loop; attitude tracking of a real FROG-T flight, in the most complicated weather conditions (based on real data recorded in flight); **study of the necessary actuator torques** to achieve setpoint monitoring with different response times (compatible with the constraints and objectives set); **selection of actuators** in consequences.

The following schematic representation of the TVC as integrated in FROG-H allows a basic modelling of its dynamics to be carried out in order to size the actuator.

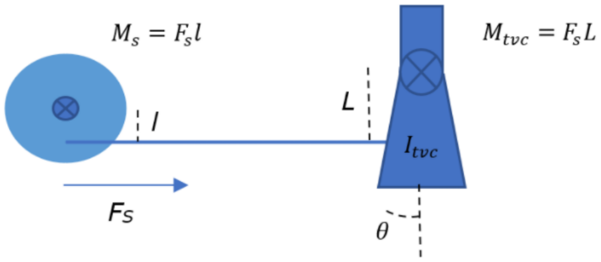

Figure 14 : Simplified TVC model

Applying the fundamental principle of dynamics, the relationship is obtained:

$$\ddot{\theta}_{tvc} = \frac{L}{l}\frac{M_s}{I_{tvc}} \tag{4}$$

with $\ddot{\theta}_{tvc}$: the TVC angle acceleration, l: the actuator moment arm, L: the engine moment arm, M_s: the actuator torque, I_{tvc}: the engine inertia (at the attachment point).

A complete **modelling of the FROG-H pitch/yaw control loop** (equipped with the TVC model) has been developed, and it has been shown that the desired **response time of** the FROG-H platform for speed control must be **determined with great care**. A **response time that is too short** will lead to frequent or even permanent saturation of the actuators because of the torque they must provide. A response time that is **too long** will have **consequences on the horizontal guidance**, and therefore on the error in position.

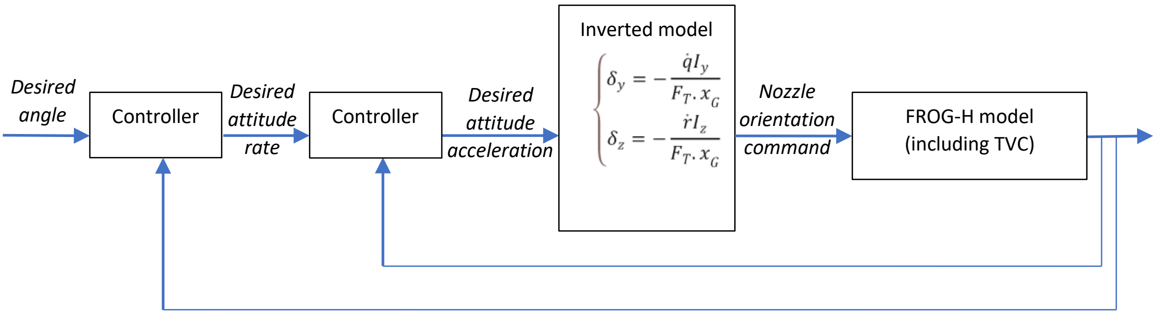

Figure 15: modelling of the FROG-H pitch/yaw control loop

5.4 Guidance

DOI: 10.13009/EUCASS2022-9718

The mission handling philosophy of landing such a platform is new, since unlike conventional guidance (or tracking error may be allowed if it is not too large), there is an obligation of maximum performance in terms of accuracy, given that there is contact with the ground at the end of the flight (even if a strategy is usually to land slightly above it, before the engine shuts down). Since the reference trajectory is known, one of the best laws possible to achieve such a mission is an **optimized algorithm which uses the platform model** in real time to compute the command (this work focuses on the vertical guidance of FROG-H).

To study the performance and robustness of the guidance algorithm, the **first step has been to generate a set of reference trajectories** (which will serve as a benchmark for the evaluation of the control) with the following characteristics: 6 different initial altitudes; no initial vertical speed; hovering thrust when releasing; constrained command during the mission.

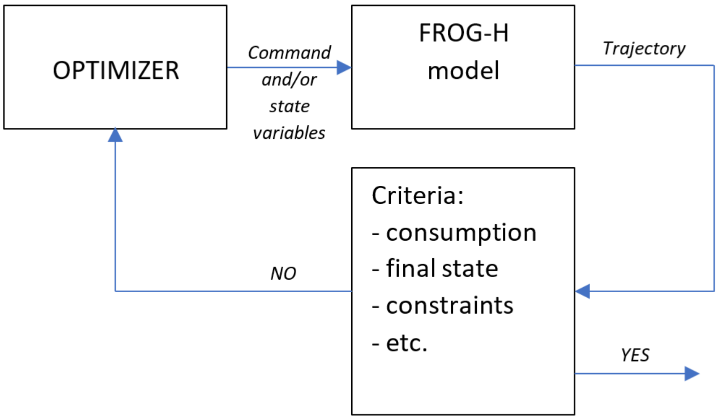

Figure 16 : Optimizer used to generate the set of FROG trajectories

As shown in the previous figure, an optimizer has been used to generate the set of trajectories. It has been linked to a FROG-H model (which contains the engine model) to create references which satisfy several constraints, as consumption, initial and final state, etc.

To assess the robustness of the guidance algorithm, **estimation errors** between the simulator parameters and the guidance algorithm parameters **have been introduced**: 20% of additional mass; 20% of lower thrust, and 65% of lower engine dynamics.

It can be seen, in the following figures, that the control performs a proper robust tracking.

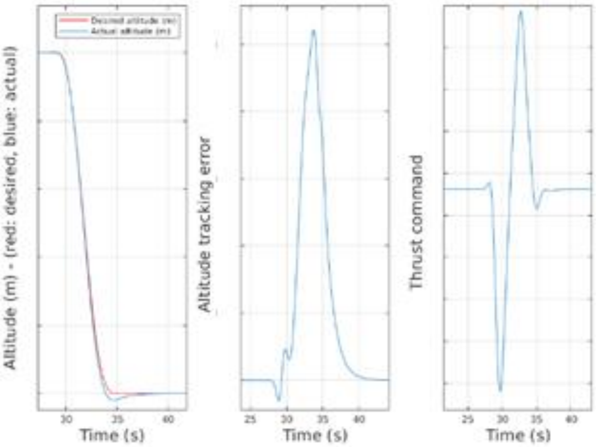

Figure 17: illustration of control robustness

DOI: 10.13009/EUCASS2022-9718

6. FROG-H propulsion system description, engine design and preliminary test.

6.1 Propulsion system description

FROG-H Porpulsion System was designed on the basis of the ILR-33 Amber rocket hybrid engine and feeding system [10]. Both solutions utilize hydrogen peroxide, HTP-class , as propellant with the key difference being that the first one operates in so called monopropellant mode, providing lower thrust levels. Use of flight proven design, allowed for much faster development process and more reliable design. Key challenge in the design for this unit is the high-rate throttle ability, which will allow to vary the thrust level from 150 N up to 1.6 kN.

Propulsion System was divided in 3 main sections (see Figure 18). First one, High Pressure Nitrogen Module (HPNM), is responsible for providing the required pressure for the HTP to be supplied into the engine. Second one, High Test Peroxide Module (HTPM), enables the onboard storage of the propellant. Last one, Engine Module (ENGM), contains the catalytic bed, which decomposes the peroxide and provides the thrust.

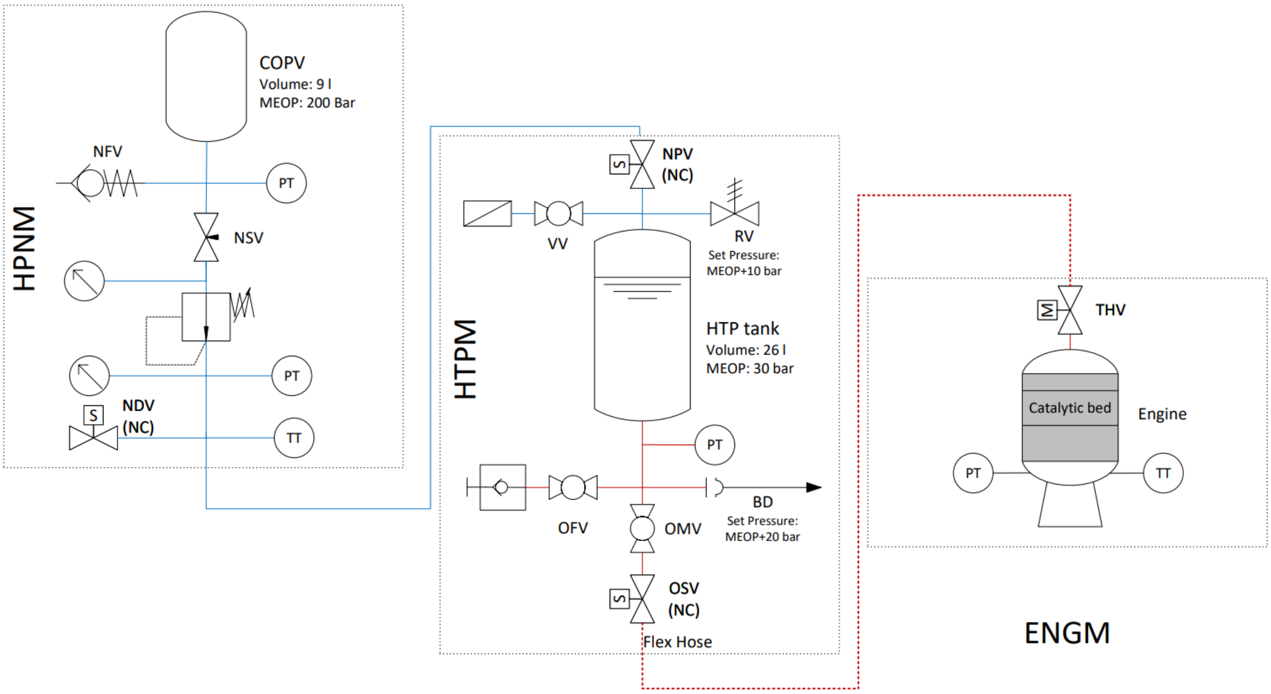

Figure 18: Propulsion System P&ID

The Design and Propulsion System envelope is presented in Figure 19, where the ENGM is on the lefthand side, and the HPNM is on the righthand side. Note that the TVC and the throttle valve are not included in the figure.

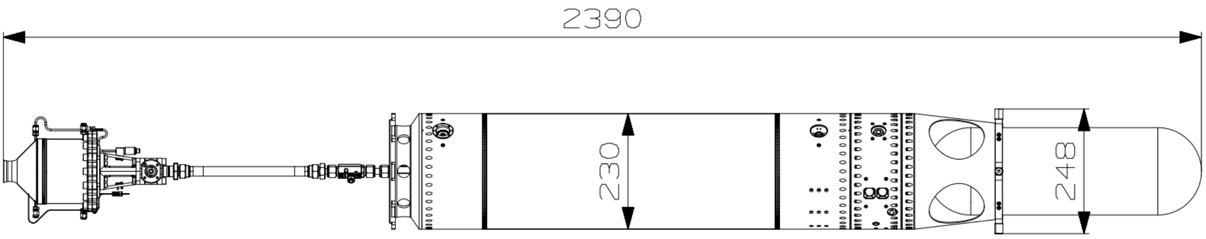

Figure 19: Propulsion System Design

DOI: 10.13009/EUCASS2022-9718

Basic Propulsion System specifications and performance parameters are presented in the following Table.

Table 1 : Propulsion System Specification and Performance Parameters

No	Parameter	Value	Unit
1	Maximum thrust	1 600	N
2	Minimum thrust	150	N
3	Length	2390	mm
4	Maximum diameter	230	mm
5	Propellant type	87.5/98% HTP	-
6	Propellant volume	26	L
7	Operation type	regulated pressure-fed	-
8	Pressure medium	N_2	-

The engine selection for FROG-H platform is driven by: simplicity, safety, non-toxicity, performance, reusability and throttle ability. Therefore, hydrogen peroxide monopropellant was preferred, as a good compromise connecting all those features. The thrust range is achievable with a fixed catalyst bed-based thrust chamber and the adjustable propellant flow control valve. The engine (see Figure 20) is mounted to the platform via gimbal, which provides the Thrust Vector Control.

The engine is compatible with both 98% and 87.5% HTP ensuring diversification in the propellant supply. Assuming equal peroxide decomposition efficiencies, thrust versus chamber pressure characteristics are comparable for both HTP concentrations.

The heart of the engine consists of the in-house developed semi-monolithic catalyst bed. It contains cylindrical “slices” of metal-foam-supported modified silver. Modification, applied to the silver active phase, ensures long lifetime with minimum impact on the catalyst activity. Łukasiewicz – ILOT conducted the endurance testing of the scaled version (26 g) of this catalyst with 98% hydrogen peroxide. The modified-silver catalyst survived over 111 kg of the HTP total throughput in 26 variable-duration hot-fire tests (from 5 to 600 s, exemplary test shown in Figure 21). The factor of 4.2 kg of the propellant per 1 g of the catalyst was reached, with total run time of 1 hour.

Figure 20 : Engine Design

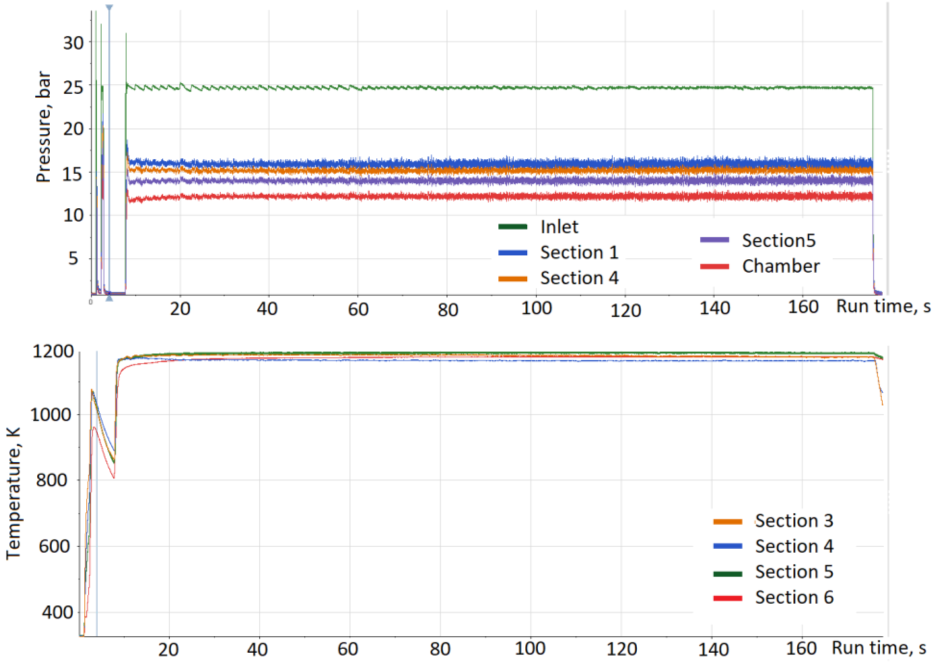

Figure 21: Pressure and temperature profiles in the scaled-down thruster during steady-state operation

7. Conclusion

In this paper we introduced the FROG project and its positioning in the CNES and ESA launcher roadmap. We also presented the experimental and progressive approach of the project. This approach relies on a collaborative organisation composed of space agencies (CNES and ESA), ArianeWorks, research institutes and academics (Łukasiewicz Research Network – Institute of Aviation and Cachan Institute of Technology), a non-profit organisation (Planète Sciences), start-ups and SME (Polyvionics, Drones-Center and Sonatronic) and students!

Between May 2019 and September 2020, FROG-T (turbojet version) has successfully performed over 40 tethered flights and 5 free flight campaigns. The lessons learned are very rich and cover all technical and operational domains. These flights have provided unvaluable knowledge and knowhow that are not accessible with simulation only approach.

In parallel FROG-H (HTP engine version) development is ongoing, at the time of the writing of this paper (June 2022) the CDR of the Propulsion System and the Mobile Propellant Loading System (MPLS) are underway. The CDR for the complete system will follow by end of August 2022. The next FROG-H main milestones are the following:

- End of 2022: Propulsion System and Mobile Propellant Loading System (MPLS) qualification
- Beg. of 2023: FROG-H static firing and tethered flight campaigns.
- Mid 2023: FROG-H first free flight campaign.

Acknowledgements

The authors would like to sincerely thank for their enthusiasm and engagement all the partners, colleagues, volunteers and students who did contribute to the FROG project!!

DOI: 10.13009/EUCASS2022-9718

References

[1] Jean-Marc Astorg, CNES future launcher roadmap, La Sapienza, 7 May 2019

[2] Jérôme Vila et al. (CNES), Weighting options for the next generation of Ariane launchers, IAC-17-D2.4.2, 68thInternational Astronautical Congress, Adelaide, Australia, 2017, 25-29September.

[3] Dr. Paolo Baiocco et al. (CNES), Reusable Rocket Stage Experimental Vehicle and Demonstration, IAC-16-D2.6.6, 67thInternational Astronautical Congress, Guadalajara, Mexico, 2016.

[4] Pascal Tatiossian et al. (CNES), Reusable first stage rocket demonstrator, 7th European Conference for Aeronautics and Space Sciences (EUCASS), 2017.

[5] ParvizGhadimi et al., Performance Assessment of the Waterjet Propulsion System through a Combined Analytical and Numerical Approach, International Journal of Physics, 2013, Vol.1, No.2.

[6] Christopher Perry, Robert Ash, Indigenous Carbon Dioxide as a Propellant for Mars Surface Probes, 2014.

[7] David Monchaux et al., FROG, a Rocket for GNC demonstrations IAC-18-D2.5.3x43308, 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018

[8] Badr RMILI and al., FROG, a Rocket for GNC demonstrations: Firsts flights attempts of the FROG turbojet version and preparation of the future mono-propellant rocket engine, 8th European Conference for Aeronautics and Space Sciences (EUCASS), 2019

[9] Stephane QUERRY and Badr RMILI, FROG : démonstrateur miniature pour la réutilisation des lanceurs, 3AF conference, March 16, 2021

[10] B. Marciniak, A. Okninski, B. Bartkowiak, M. Pakosz, K. Sobczak, W. Florczuk, D. Kaniewski, J. Matyszewski, P. Nowakowski, D. Cieslinski, G. Rarata, P. Surmacz, D. Kublik, D. Rysak, J. Smetek and Piot, "Development of the ILR-33 “Amber” sounding rocket for microgravity experimentation," Aerospace Science and Technology, vol. 73, pp. 19-31, 2018. doi: 10.1016/j.ast.2017.11.034