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Progress in preparation of a small scale and low-cost flying test bed for reusability: FROG-H

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Abstract

In order to test vertical landing related technologies in a small-scale, low-cost, hands-on way, CNES initiated an experimental "flying platform" project. A first prototype, FROG-T, powered by a turbojet engine, successfully flew in 2019. This paper will present the next generation prototype, FROG-H, based on a H2O2 propulsion system under the responsibility of Lukasiewicz Institute of Aviation with the support of ESA. FROG-H vehicle, its mechanical, functional, avionics & software architecture and expected flight domain will be described. A focus will then be made on the propulsion system including engine ground firing test results as well as on the general development status of other sub-systems.

1. Introduction

Reusability of the first stage is one of the key assets for competitive access to space for next generation of European launchers. It allows cheaper and more flexible launch system exploitation models. Reusability implies however many challenges and requires the mastering of several new technologies and flight domains.
CNES roadmap towards reusability, active since 2017, includes several flagship demonstrators like CALLISTO [1] and SKYHOPPER [2], supported by a strong set of Research and Technology activities [2].
Major flagship demonstrators of the roadmap (see figure 1) directly tackle all the complexity of reusable launcher first stages including cryogenic propulsion and are not adapted for quick, low-cost, hands-on experimentation. For this reason, CNES wanted to have a "sandbox" demonstrator in order to enable the testing of vertical landing related technologies, in particular guidance and navigation algorithms in a small-scale, low-cost experimental "flying platform".
The project, dubbed FROG, is executed in partnership with non-profit association Planète Sciences, the small company Polyvionics and the IUT Cachan technology institute (Paris Saclay University), and more recently with Lukasiewicz Institute of Aviation (ILOT) under and ESA contract.

The first prototype, FROG-T, was initiated in 2017 as a learning vehicle for vertical landing technologies. Standing 2.5 meters tall with a diameter of 30 centimetres and weighing 21 kg, FROG-T is powered by a 400 N turbojet engine. The prototype is fully equipped for vertical landing, featuring a steerable nozzle, active attitude control, and four legs designed to absorb landing shocks. FROG-T made its first captive flight with the turbojet at the end of May 2019 [3].

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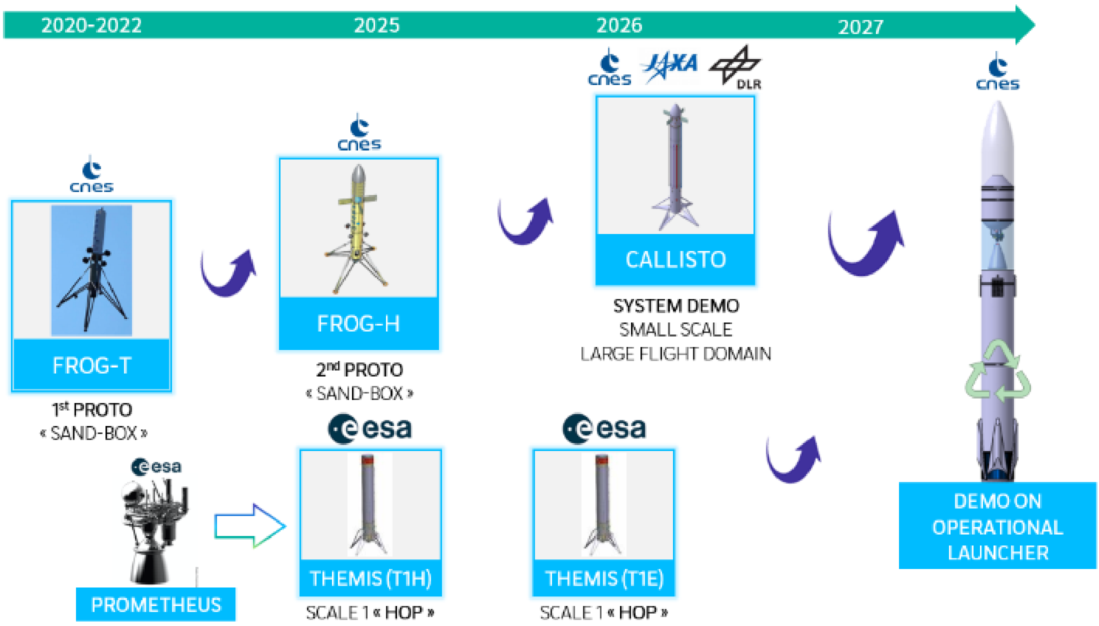

Figure 1 - CNES demonstration roadmap for first stage recovery & reuse

The specific approach of FROG, as well as results from FROG-T flight campaigns, has been described in previous publications [3]. This papers aims at providing an up to date overview of FROG-H design and development status.

2. Project organisation

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

- CNES Space Transportation Directorate:
  - 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:

- 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.

DOI: 10.13009/EUCASS2025-441

3. Vehicle design & development status

3.1 Vehicle main design features

FROG-H is the second vehicle of FROG demonstration project. The main evolution in comparison with FROG-T is the use of a rocket engine instead of a turbojet, in order to increase the representativeness for the guidance and control toward a reusable space rocket. The torque reaction effect due to rotating part of the engine is suppressed with FROG-H, and flight quality representativeness will be increased for all flight phases and landing.

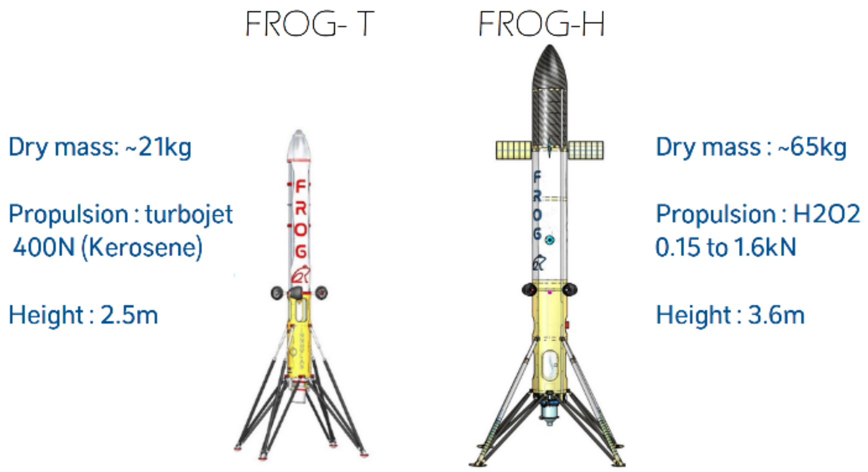

Figure 2: comparison of FROG-T and FROG-H

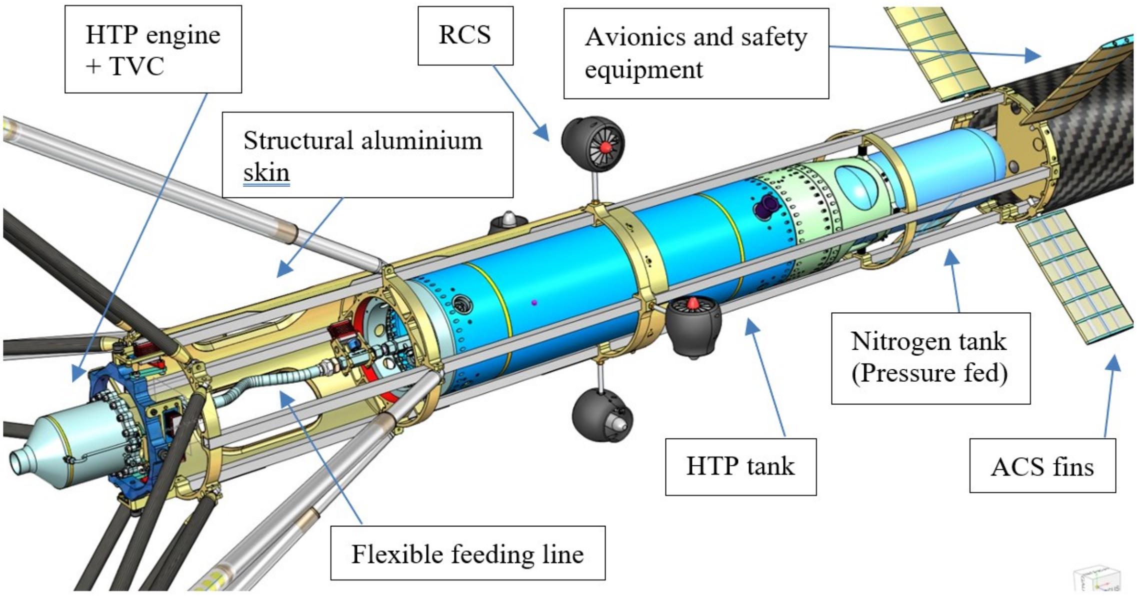

Figure 3: FROG-H architecture overview

FROG-H Propulsion System was designed on the basis of the ILR-33 Amber rocket hybrid engine and feeding system **Erreur ! Source du renvoi introuvable.**. 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.

The Propulsion System uses a compact, pressure-fed monopropellant arrangement built around 87.5 % High-Test Peroxide (HTP), but capable also to work with 98% concentration.

The hardware is arranged in three self-contained assemblies to simplify manufacture, integration, and maintenance.

DOI: 10.13009/EUCASS2025-441

1. High-Pressure Nitrogen Module (HPNM)

A composite over-wrapped vessel carries 2.25 kg of gaseous N_2. The gas leaves the bottle at 200 bar(a) and is stepped down to the required feed level to pressurise the peroxide tank. The resulting blow-down profile keeps tank pressure above engine inlet demand for the full duty cycle while avoiding unnecessary structural mass.

2. High-Test Peroxide Module (HTPM)

The dedicated HTP tank accommodates 36 kg of 87.5 % peroxide. Starting at 34 bar(a), it feeds the engine throughout the burn, its pressure decaying predictably as propellant is expelled and the ullage grows. Tank, piping, and valve materials are peroxide-compatible alloys chosen for low catalytic activity.

3. Engine Module (ENGM)

A catalyst bed initiates exothermic peroxide decomposition, producing the high-temperature steam/oxygen mixture that generates thrust in the nozzle. A proportional ball valve at the inlet modulates mass-flow, enabling a wide thrust envelope from 160 N up to 1.6 kN. At the nominal 1 kN setting the engine delivers a total impulse of 40.6 kN·s.

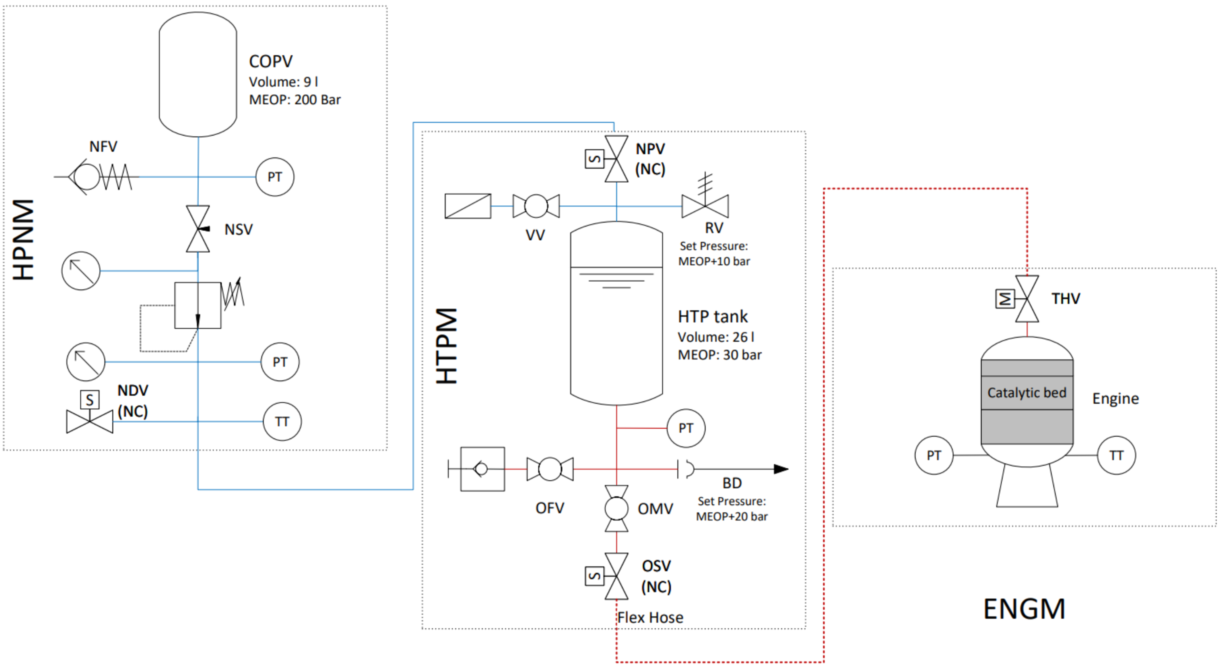

Figure 4: Propulsion System P&ID

The Design and Propulsion System envelope is presented in Figure , where the ENGM is on the left-hand side, and the HPNM is on the right-hand side. Note that the TVC and the throttling valve actuating system are not included in the figure.

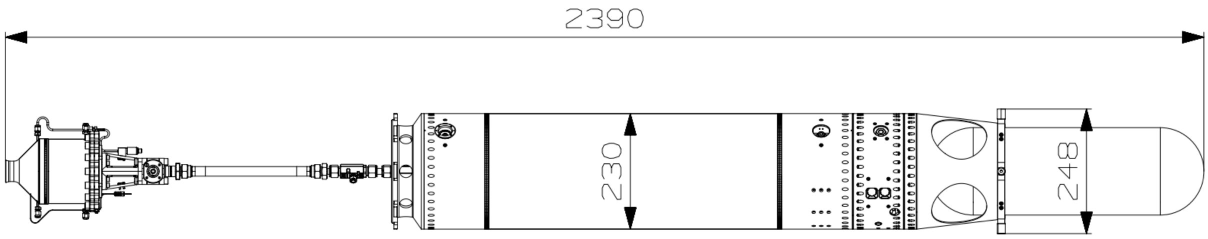

Figure 5: Propulsion System Design

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

No	Parameter	Value	Unit
1	Maximum thrust	1 600	N
2	Minimum thrust	150	N

DOI: 10.13009/EUCASS2025-441

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	-

Table 1 : Propulsion System Specification and Performance Parameters

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) is mounted to the platform via gimbal, which provides the Thrust Vector.

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.

Figure 6: Engine Design

3.2 Propulsion system recent progress

Following the 2024 component-level trials, the Łukasiewicz - ILOT team completed a full-system qualification campaign that integrated the engine, feed lines, and pressurisation hardware in a flight-like vertical configuration. Thrust was commanded in open loop by applying a sequence of pre-programmed set-points to the proportional ball valve.

- Reference thrust profiles. The test series reproduced the mission-defining load cases. Figure 7 overlays the measured response on the commanded law and confirms that the actuator can track transient demands without noticeable lag or overshoot.
- Thermal envelope verification. Separate runs were performed with the HTP tank conditioned to both the lower and upper limits of the specified operating window. Active cooling (4.3 deg C) or heating (40 deg C) continued until the bulk fluid reached thermal equilibrium, after which the nominal firing sequence was executed. Figure 8 compares the resulting thrust histories and demonstrates consistent performance across the temperature extremes.

DOI: 10.13009/EUCASS2025-441

- Model correlation. Time-domain data from the campaign were used to tune and validate the propulsion-system mathematical model that underpins closed-loop attitude-control simulations. Agreement between simulation and experiment is now within the margins required by the guidance-and-control team.
- Catalyst-bed durability. Cumulative firing time indicates that the current catalyst charge maintains full efficiency up to roughly 300 kg of processed HTP, after which a gradual decline in decomposition effectiveness becomes detectable.
- Flight-set acceptance. One reference mission was performed on the first flight-qualified engine hardware. All subsystem and end-to-end tests met their acceptance criteria, and the propulsion packages have been released to the integration team in France.

The results close the remaining verification items at system level and clear the way for combined-vehicle testing later in the programme.

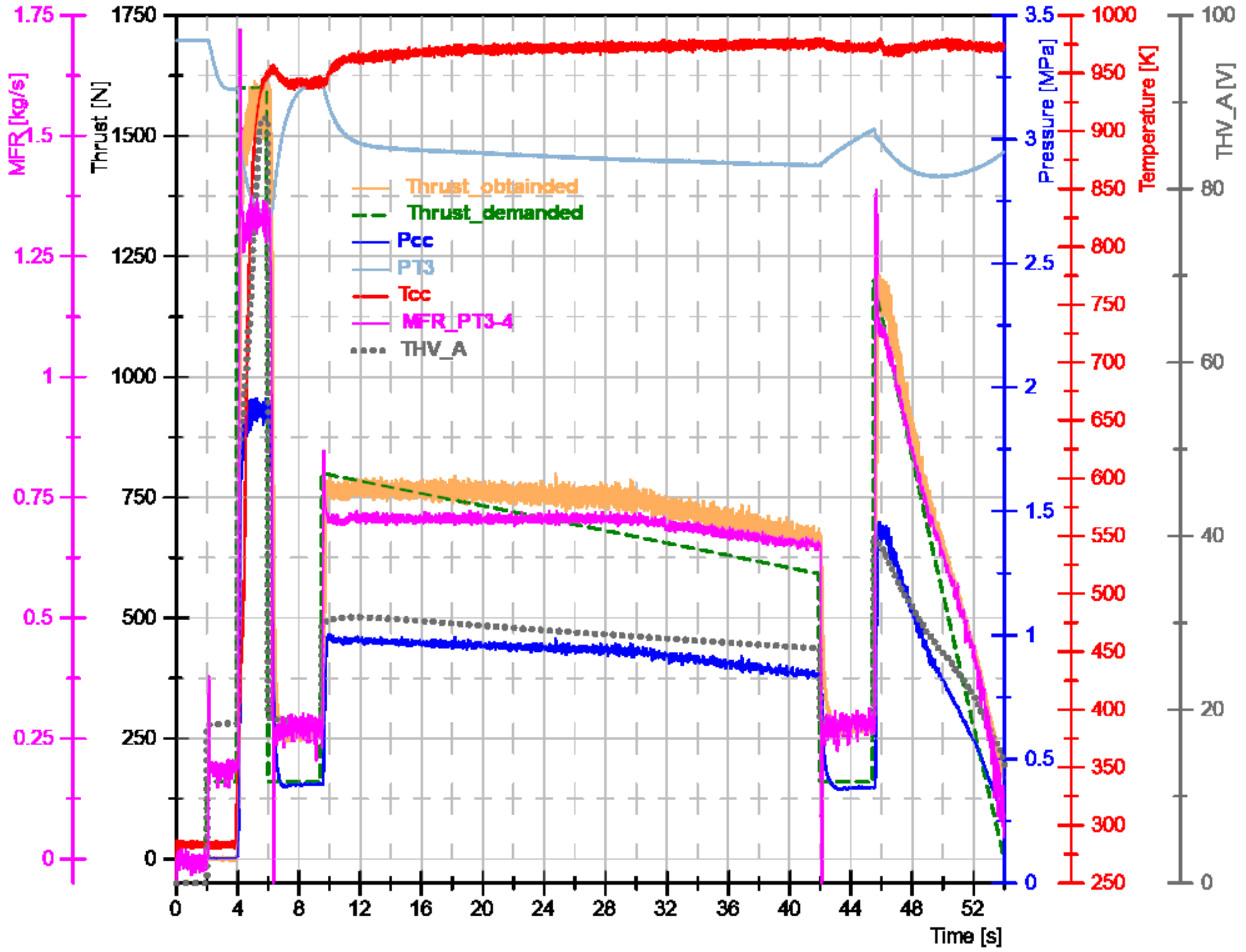

Figure 7 - one of the reference mission profiles during the Qualification Test Campaign.

DOI: 10.13009/EUCASS2025-441

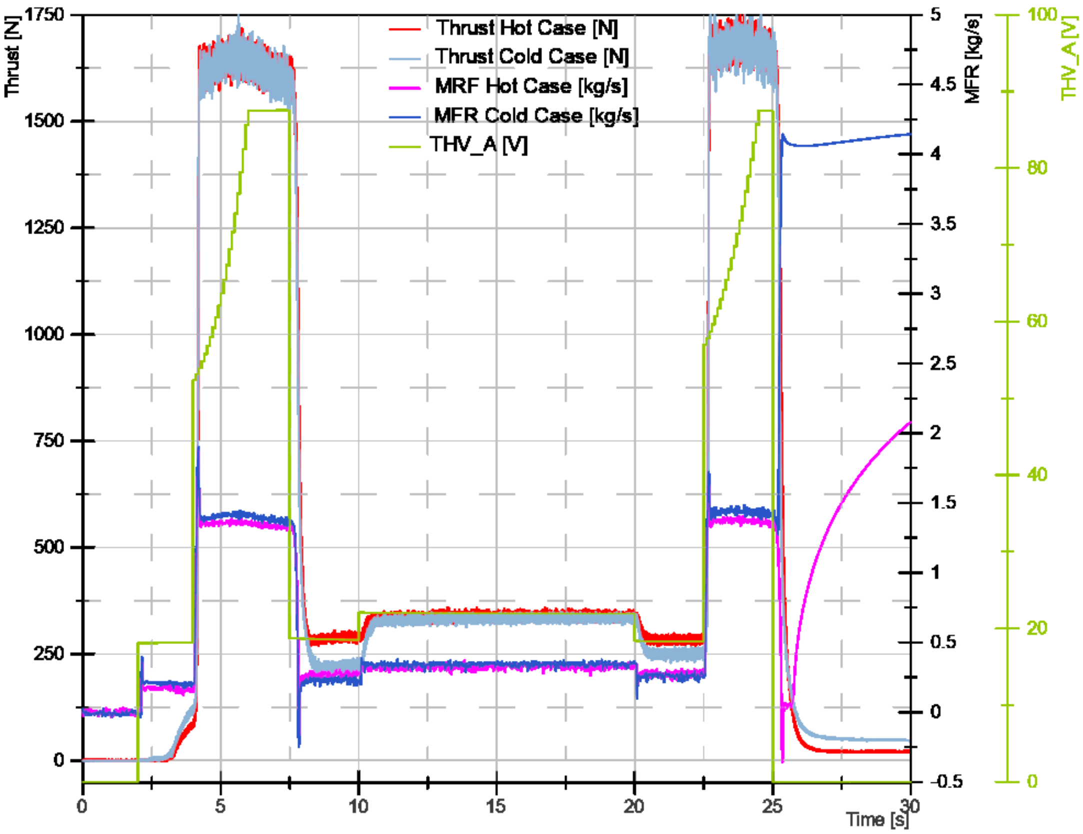

Figure 8 – two tests of the reference mission, with hot and cold HTP.

3.3 Development Status and model logic

One propulsion model is dedicated to qualification test and one model for flight.
The engine and propulsion system have just achieved the qualification and acceptance tests at Łukasiewicz-ILOT. The flight model chamber has been fire tested within the rest of the propulsion parts dedicated to the qualification tests. The other parts of the flight model are not fire tested but functional and tightness tests have been performed.
Flight model of the whole propulsion system has just been delivered for mechanical and electrical assembly of the rest of the vehicle at the Cachan Technological University (France).
Cachan University and Sonatronic have provided and tuned the regulation valve controller and actuator used during the propulsion tests. The rest of the vehicle avionics is jointly developed by all the French partners.
The mobile propellant loading system composed of hydrogen peroxide tank and water tanks with ground - vehicle connections and command control system is already manufactured and still need to be tested for acceptance at Łukasiewicz-ILOT by end of July 2025. It is based also on ILR-33 Amber rocket propellant loading system heritage.

Figure 9: Mobile Propellant Loading System

DOI: 10.13009/EUCASS2025-441

Based on Łukasiewicz-ILOT extensive propulsion system test data and first engine models, the thrust model identification is ongoing by Polyvionics in order to fine tuning the regulation valve command to the expected thrust level.
The characterization of the landing system is also ongoing with dedicated instrumented free fall drop tests in different conditions, at the assembly facility. These tests are conducted by CNES and Cachan University.
The operations manuals finalization and safety training are expected this summer 2025 before performing rehearsals for the first static fire test of the complete vehicle. These activities will be followed by tethered tests flights and then and finally the free flight tests.

Figure 10: FROG-T free flight at Brétigny-sur-Orge (France)

Figure 11: main structures status in July 2024. On the right FROG-T and on the left FROG-H

DOI: 10.13009/EUCASS2025-441

4. Dedicated tests and software simulators

4.1 Landing tests

Some landing tests have been performed at the Cachan Institute of Technology of the landing system alone. These tests are useful not only for FROG-H tests but also for tuning the CNES landing simulators for other reusable rocket projects and testing instrumentation.

It consists on free falling and landing tests from different altitudes and angular positions, with the help of a pneumatic release system. Some masses are added on top in order to represent other parts of the vehicle. Sensors and acquisitions system are coming from CNES laboratory. Special care has been taken for sensor attachment for avoiding perturbation. Fast acquisition cameras have also been used during the drop tests.

The tests results measure the dynamic response for vertical and lateral shocks, with different material of contacts with the ground. The efficiency is assessed for different damping and it allows to obtain finally the correct tuning for FROG-H landing system.

Figure 12: Landing legs tests: damping system identification

4.2 Thrust Vector Control test

In comparison with FROG-T vehicle controlled by engine exhaust deflection, FROG-H is equipped with dedicated Thrust Vector Control actuating directly the engine chamber. The actuator has been selected based on dynamic system study involving the actuator, the controller, the engine support inertia, and the command and control algorithm.

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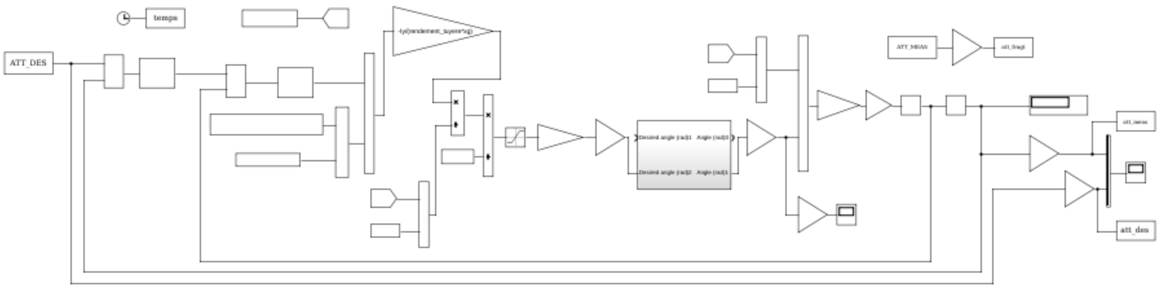

Figure 13: Thrust Vector Control block diagram

The simulator results provide the necessary speed and torque for controlling the vehicle under the worst case of wind in flight. Additional effort due to engine misalignment has been considered.

A dedicated TVC test bench has been used in various validation campaign in order to assess the real performance of the of the actuator and associated software. Final fine tuning test campaigns are foreseen this summer.

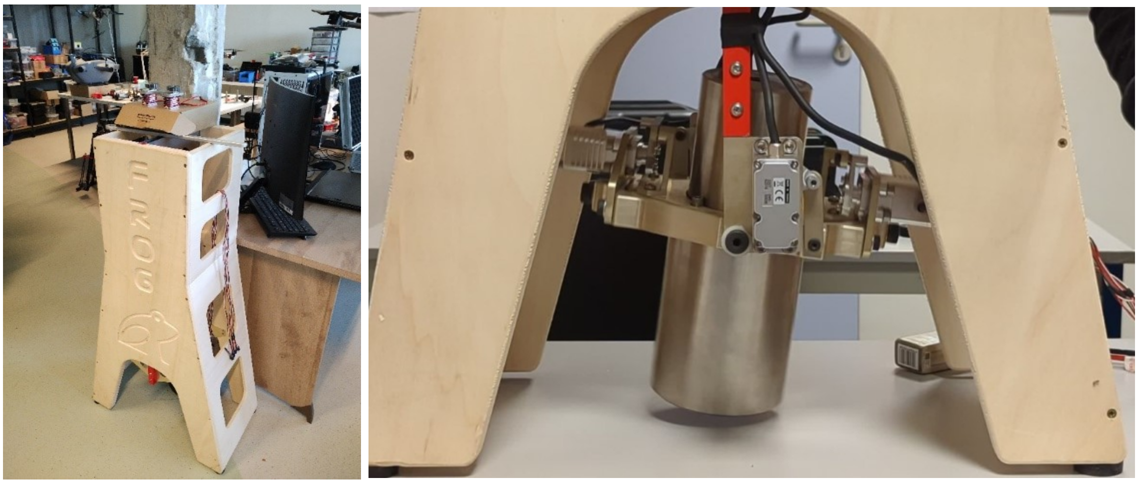

Figure 14: TVC test bench designed by Cachan University and operated by Drones-Center

4.3 Engine Control Algorithm and flight software development

The propulsion system and engine have been extensively fire tested to several profiles of feed system conditions and regulation valve opening and dynamics. Numerous data allowed to make a link between the expected thrust level and valve command.
The thrust model identification is ongoing by Polyvionics in order to fine-tune the regulation valve command to the expected thrust level. This model will be integrated in the Guidance and control algorithm to tune the coefficients and perform the robustness analyses. Good progress has been made recently thanks to ILOT and CNES support and experience on rocket engine and simulators.

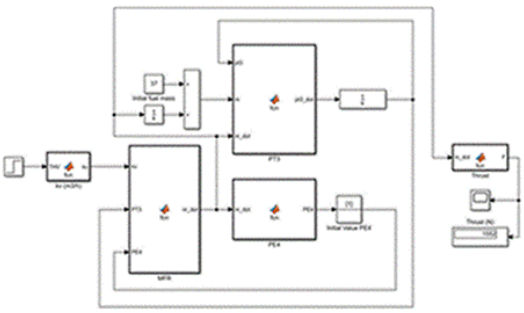

Figure 15: Thrust Control block diagram

DOI: 10.13009/EUCASS2025-441

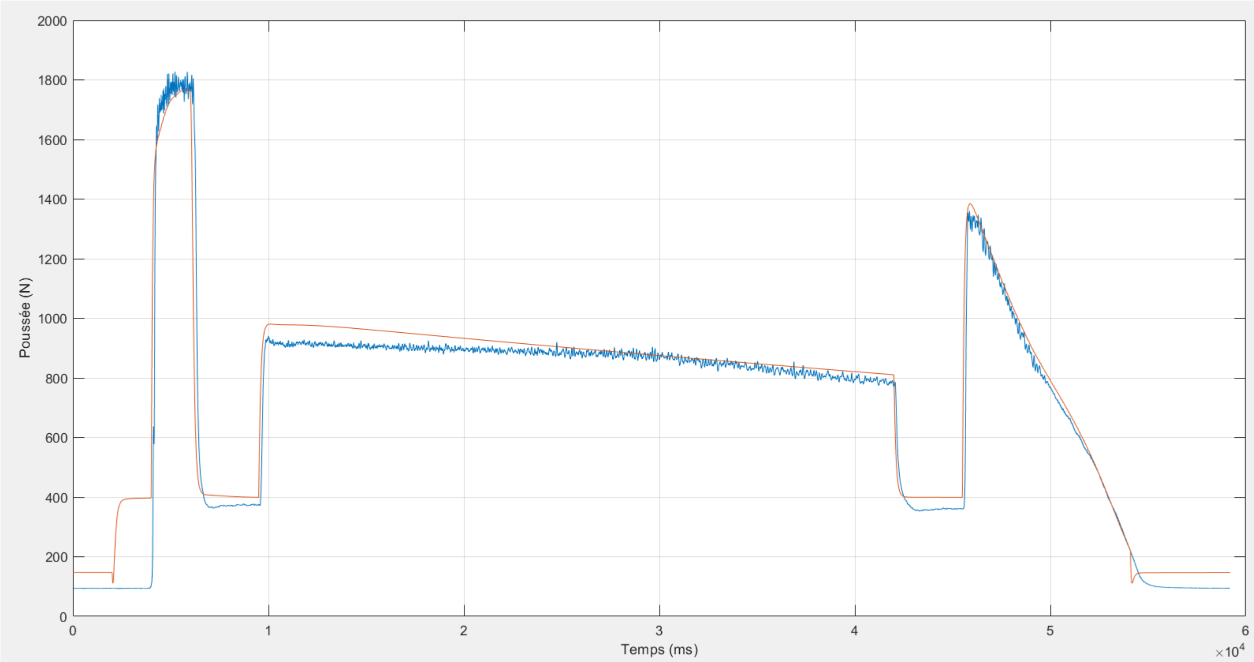

Figure 16: engine simulator correlation with in red the simulator in blue the test results.

Then engine simulator will be added to the ones for thrust vector control for yaw and pitch and RCS (Roll Control System) for roll. Once the flight control is OK, the response time of the system will be assessed, torque and force transmitted to the internal parts of the vehicle will be assessed to verify that the structural parts can sustain the loads and that the flight trajectory is under control.
A short cycle iterative validation logic has been adopted in FROG project from the very beginning, in order to speed up GNC, avionics and flight software development. This approach is illustrated in the following figure.

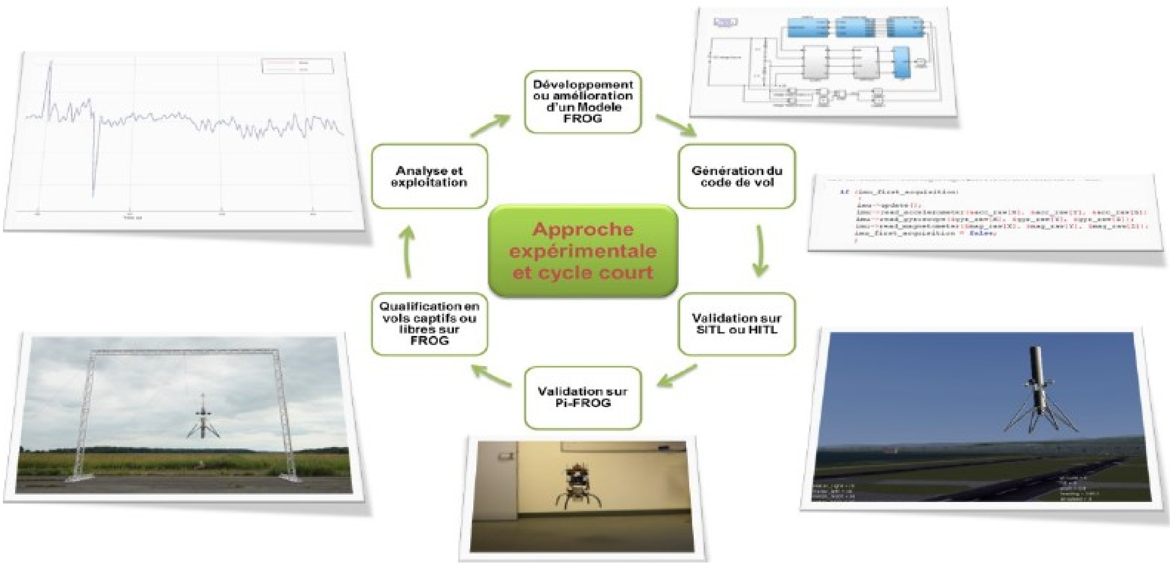

Figure 17: Short cycle experimental logic

DOI: 10.13009/EUCASS2025-441

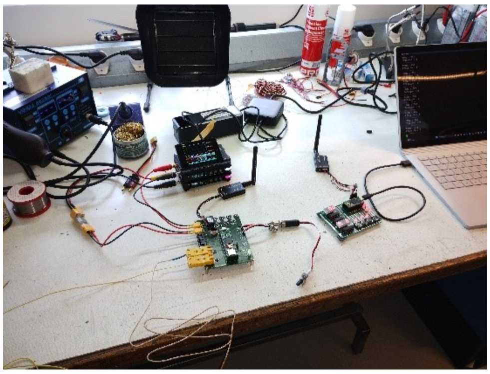

Figure 18: An example of one of the platforms used to simulate avionics

5. Next Steps

The next steps of the project are the following:

- Propulsion system:
  - Ongoing fine analysis of propulsion system and engine test results
- Mobile Propellant Loading System (MPLS):
  - Final acceptance test
  - Delivery of the MPLS to the flight test range
- Vehicle integration:
  - Fuselage and propulsion system assembly
  - Algorithm and flight software fine tuning, TVC/RCS final integration test, system simulator validation
  - Final avionics validation on the vehicle
  - Overall final integration tests
- Ongoing preparation of vehicle firing test, tethered and free flight:
  - Manual and operation procedures finalisation
  - Safety system review and flight worthiness reviews
  - Operational repetitions (partially done @ILOT and @flight test range):
    - Propellant loading to the MPLS and purge
    - Propellant loading to the vehicle and purge
    - Tethered and free flight operation
    - Post flight recovery
    - Degraded scenario tests
- Static firing test foreseen by end of summer 2025, followed by tethered flight and finally free flights.

6. Conclusion

In this paper we presented the FROG-H project and its positioning in the CNES reusability roadmap. We also presented the status and next steps. The experimental and iterative approach of the project relies on a collaborative organisation composed of space agencies (CNES and ESA), 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.

The lessons learned from flight proven FROG-T (turbojet version) have been used for FROG-H (HTP rocket engine version).

Landing system have been tested for different landing conditions and contact material. Propulsion System have been fire tested at qualification levels and flight models have been successfully tested. The engine simulator has made a good progress in term of correlation with the engine firing tests and will be used for guidance and control algorithm. During the vehicle assembly, the avionics will be validated with final thrust vector control tuning.

The next FROG-H main milestones are the following:

- July 2025: Mobile Propellant Loading System acceptance tests
- by end of summer 2025: vehicle static firing static tests

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