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FROG, a Rocket for GNC demonstrations: Firsts flights attempts of the FROG turbojet version and preparation of the future mono-propellant rocket engine

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Abstract
Reusability in the launcher sector has been studied for quite a long time in Europe, but so far, projects have mostly stayed on the drawing-board. Today, players from the so-called “NewSpace” 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, a feeling that we need to seize the moment and change our ways, to prove that Europe still possesses the ability to surpass itself.

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 (Guidance, Navigation and Control) for landing is deemed to be one of the most challenging ones. This must not be studied only by simulation, but also with tests on demonstrators.

Among these studies, FROG corresponds to the early sandbox approach. It is a small scale and low-cost flying vehicle developed as a testbed platform for guidance, navigation, and control algorithms that will be used by CNES Launcher Directorate and students in order to test various landing algorithms and approaches.

This paper is the continuation of a first one about FROG presented at IAC 2018 conference held in Bremen [14]. In this paper, we will first quickly introduce the project then describe the common platform which has been developed and finally delve into the GNC aspects. Secondly, we will present the first version of FROG based on a small turbojet, the associated development outcome and also the main flights results. Finally, we will also present the ongoing development of the second version of FROG based on small monopropellant rocket engine.

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1. Introduction

1.1 Context

CNES, the French Space Agency, has historically been very active in Europe regarding rocket development. Beginning with Ariane 6 new governance scheme, CNES refocused its efforts on looking further forward and preparing the next generations of European launch vehicles. CNES future launchers programmes were introduced in [1], with a deep look into the Ariane NEXT initiative, which is a system framework to drive the technology effort.

Today, reusability is deemed to be one of the levers allowing to reduce launch costs beyond what will be achieved on Ariane 6. Considering economical models, recovery/reuse is not intended to be systematic for each of the Ariane NEXT launch missions, but efficient first stage Return To Launch Site (RTLS) on some of the less demanding missions (e.g. SSO missions) is envisioned.

Several return modes are still being evaluated (vertical vs. winged horizontal landing for example), although a specific effort is being pursued for vertical landing concepts, with a dedicated roadmap.

1.2 Reusability roadmap

As shown on Figure 1, CNES reusability roadmap [15] 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 and DLR.

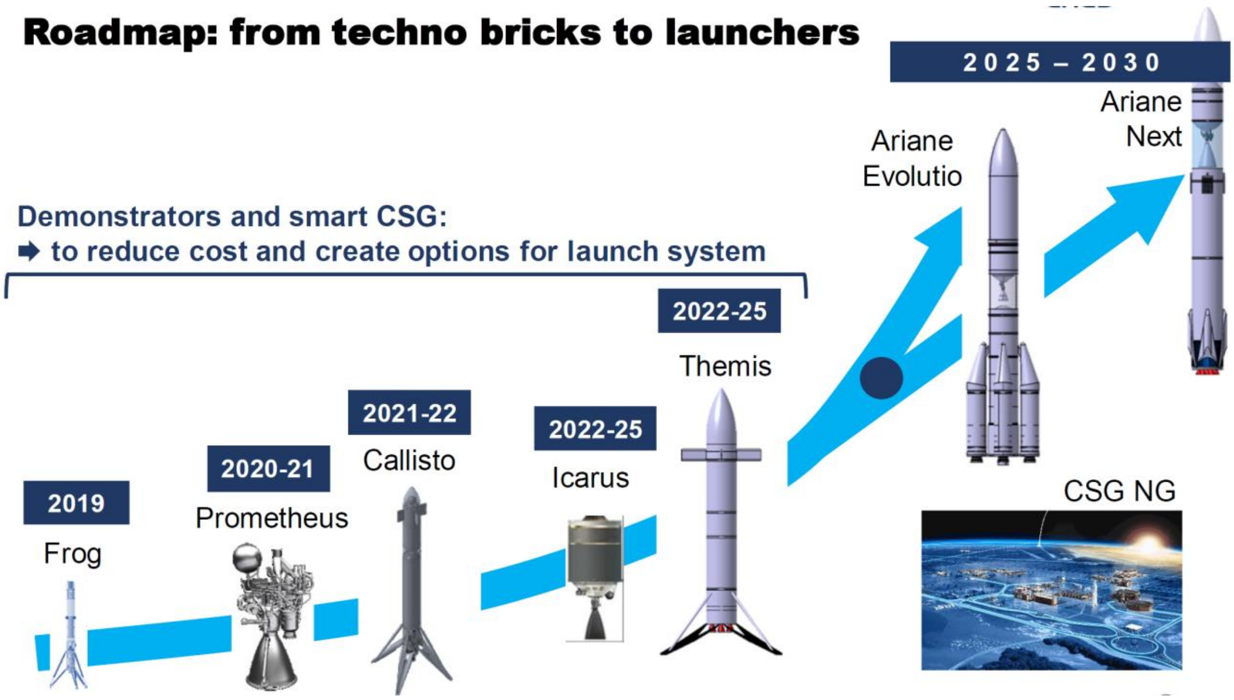

Figure 1: CNES future launcher roadmap, May 2019

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 for landing is 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 is 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 [2]and [3]), supported by industrial partners including ArianeGroup.

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The subsequent stage 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.

2. FROG approach, concepts and logic

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

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

- CNES Launcher Directorate:
  - Project management, system engineering and technical expertise.
- Planète Sciences, a scientific non-profit organisation:
  - Prime contractor, project management, system engineering, avionics, propulsion and structural design. System integration, safety studies and tests.
- 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, and with the help of SENIOR Calorstat :
  - 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.

This organisation involves a team of aerospace students, volunteers, engineers and researchers.

2.2 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".

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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 has to 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 version of FROG (FROG turbojet or FROG-T) in compliance with French regulation about experimental UAV weighing less than 25 kg. This means that FROG-T 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.

Of course, to also comply with this third key factor, FROG design is based on COTS (Commercial off-the-shelf) equipment and especially from proven open source or DIY (Do It Yourself) projects.

2.4 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) 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 w.r.t. 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 (CO2 or N2O),
- Pumped water propulsion,
- Propulsion by catalytic decomposition of pressurized H2O2,
- Hybrid propulsion N2O/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 [4] and was interesting in terms of safety, and the CO2 propulsion was considered for Mars probes in [5] and for the Mars Gas Hopper concept from NASA.

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 H2O2 engine (catalytic decomposition).

In term of roadmap, FROG is seen as a two-step project where FROG-T is the first step as short term development goal. The first tethered flight has been done in May 2019 and the first free flight is foreseen in September 2019. 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 has to be specifically design. Based on FROG-T benefits, the first tethered flight is planed end of 2020.

3. FROG-T platform presentation and test logic

3.1 FROG-T platform presentation

The mechanical structure of FROG-T is based on a flight-proven architecture close to the one used on Planète Sciences experimental rockets. It is composed of several spars on which are added the various elements of the demonstrator

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(engine, tank, avionics, parachute...). This mechanical structure is covered by a thin composite skin allowing easy access to demonstrator equipment.

To cope with landing loads on contact with the ground, a landing legs system with shock absorbers has been designed. The general conception of this demonstrator is shown on Figure 3, without the composite skin.

The FROG-T engine is a small COTS kerosene turbojet engine developed principally for unmanned systems and RC planes, which can be used horizontally or vertically. This engine provides up to 400 N of thrust, and needs around 0.8 kg/s of air and 1.2 l/min of kerosene at maximum thrust.

Control and orientation of the vehicle is based principally on the direction of flow of the exhaust gas through the steerable nozzle system. The nozzle shape and kinematic have been designed to mimic the way a rocket nozzle work. This nozzle can be considered as a tubular deflector. This nozzle is controlled by servomotors.

The avionics is composed of one on-board computer, motor controllers, power control units and actuators (servomotors and electric valves). Several independent RF communication system are used for telemetry/telecommand (TM/TC), remote control, and safety link and are shown on Figure 2. In addition, various on-board sensors are used like several inertial measurement units, magnetometers, RTK GNSS receivers, laser rangefinder (LIDAR), contact sensors, etc.

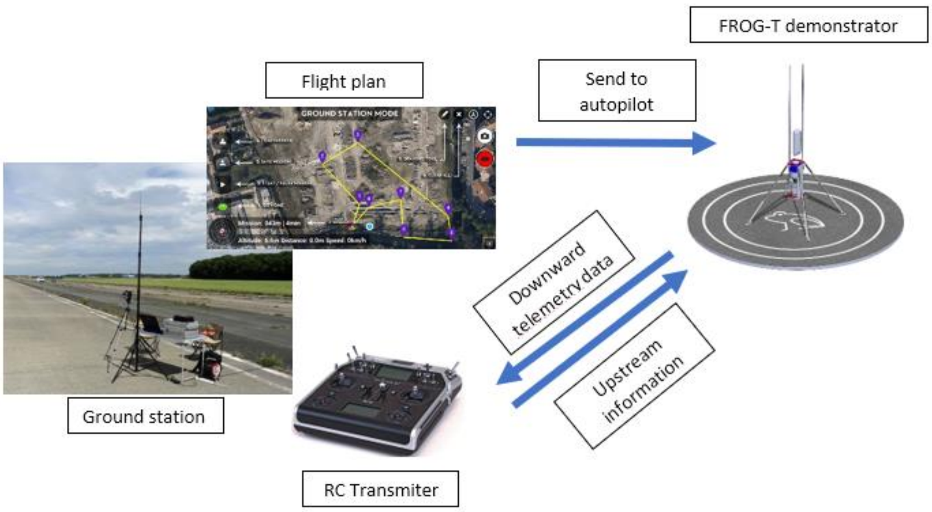

Figure 2 : Ground station and data links

FROG flight operations relies only on on-board algorithm and sensors. The steerable nozzle allows to control the vehicle around pitch and yaw axes. The roll is controlled by the Roll Control System (RCS) which consists of four electric turbines (Electric Ducted Fans).

As a matter of fact, the turbojet engine is known to induce some roll torque which may be difficult to model and control, as has been demonstrated quite dramatically during the AirBooster tethered tests [6] a few years ago. Hence, the RCS on such a platform needs some robust design margins.

To ensure safety and security, FROG has an independent safety chain. This safety chain is remotely operated from the ground segment and is able to turn off the engine and to trigger a pyrotechnic parachute system. The safety chain can also be triggered automatically by the autopilot if safety criteria are reached. In addition, with the assist of the autopilot the vehicle can be remotely piloted by a ground operator if necessary.

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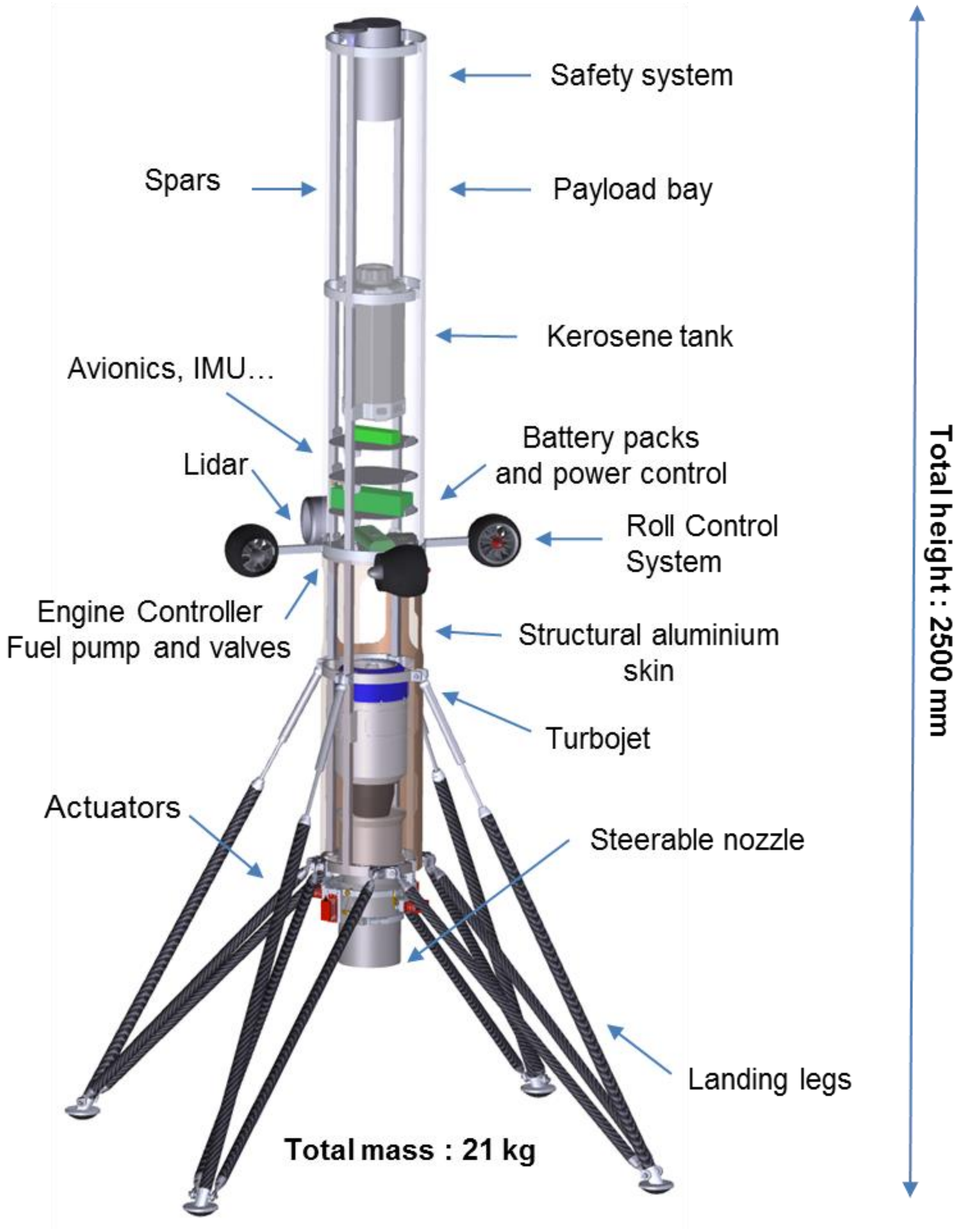

Figure 3: FROG-T architecture

3.2 GNC & Embedded Software

One of the main objective of the FROG demonstrator is to develop a GNC research platform, to investigate the efficiency of different modern algorithms in the landing phase of a reusable space launcher first stage.

In this context, and at the present time, the current work focuses on a simple control law which is able to perform the following mission: take-off, horizontal translation, and landing, to validate the overall system (platform, hardware, avionics, embedded software, GNC), before performing more advanced research in the GNC field. Once this simple control law and mission perfectly qualified trough tethered or free flights, more complex algorithms and missions will be developed and tested in order to meet the needs of other projects or demonstrations.

Up to now, the following tasks have currently been done during the project:

- Forces and moments determination.
- Formulation of the dynamics equations, and determination of the automation model (transfer functions and also state space).
- Development of a control law and firsts guidance algorithms.

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- Implementation of this control law and guidance algorithms in the embedded software of FROG.
- Validation of the embedded software on SITL, HITL and on reduced-scale version of FROG-T named Pi-FROG (see § 3.3).

More detailed descriptions of FROG GNC models are available on [14]

3.3 Test logic

In order to implement our experimental and progressive approach, numerous tests have been conducted in order to qualify the design (hardware and software) and to refine our models and simulators. Several tests benches have been specifically developed for FROG-T and are described in [14]:

- Servomotor test bench.
- RCS electric ducted fan test bench.
- Turbojet thrust and thermal bench.
- Turbojet induced torque bench.
- Turbojet steerable nozzle efficiency test bench.

The Figure 4 illustrates some of these benches in action.

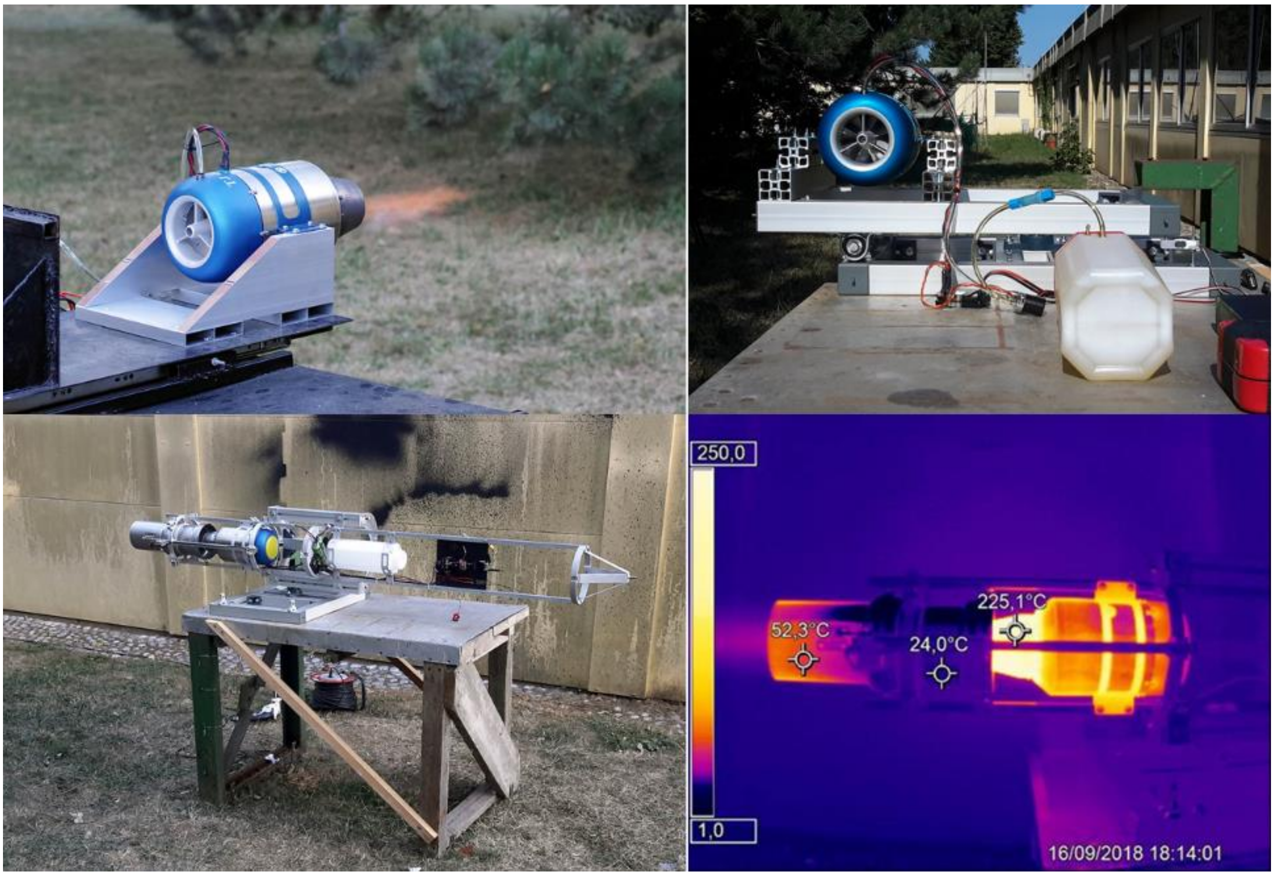

Figure 4: Some FROG-T characterisation benches

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In order 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 which is a reduced-scale version of FROG-T using the same avionics and embedded software. Illustrated in Figure 5, numerous free flights have been conducted on Pi-FROG since autumn 2018.

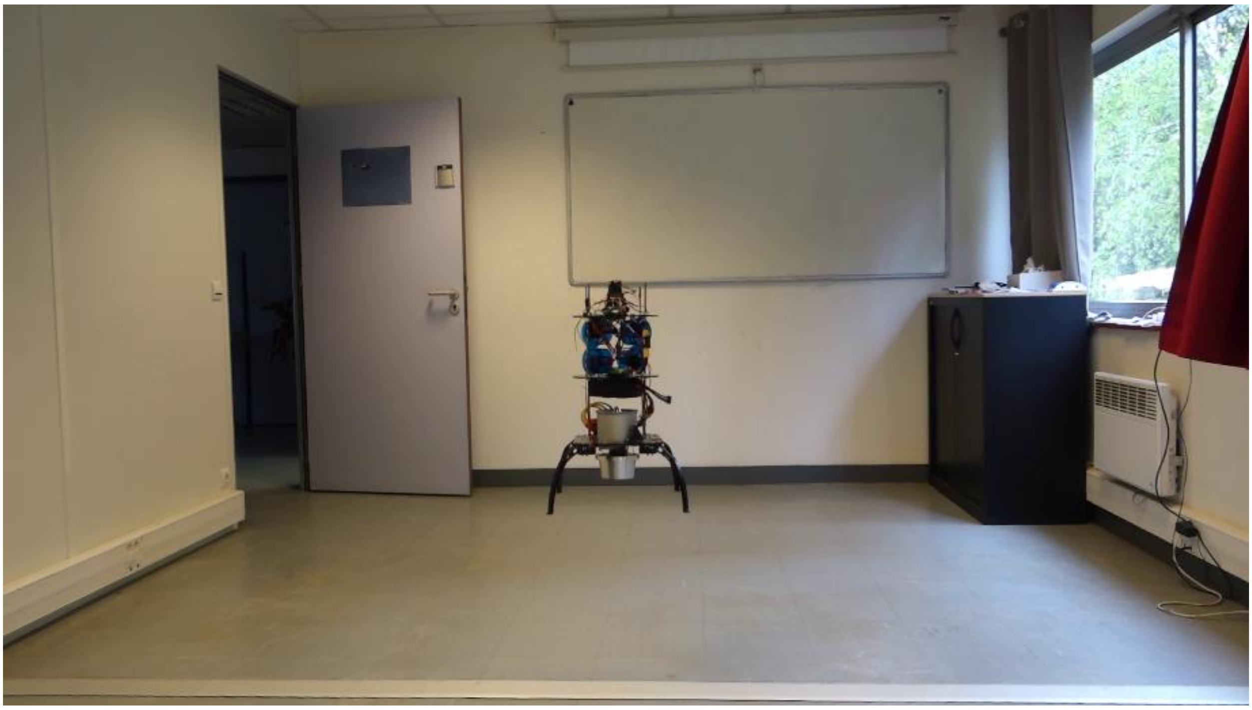

Figure 5 : Pi-FROG, a reduced-scale version of FROG-T, during an indoor free flight

- Tethered FROG-T flights on a 6 m high gantry. Illustrated in Figure 6.

- Tethered FROG-T flights on a 20 m crane. Illustrated in Figure 6. This 20 m test will allow a greater vertical motion than the gantry, which will ease the transition to free flights.

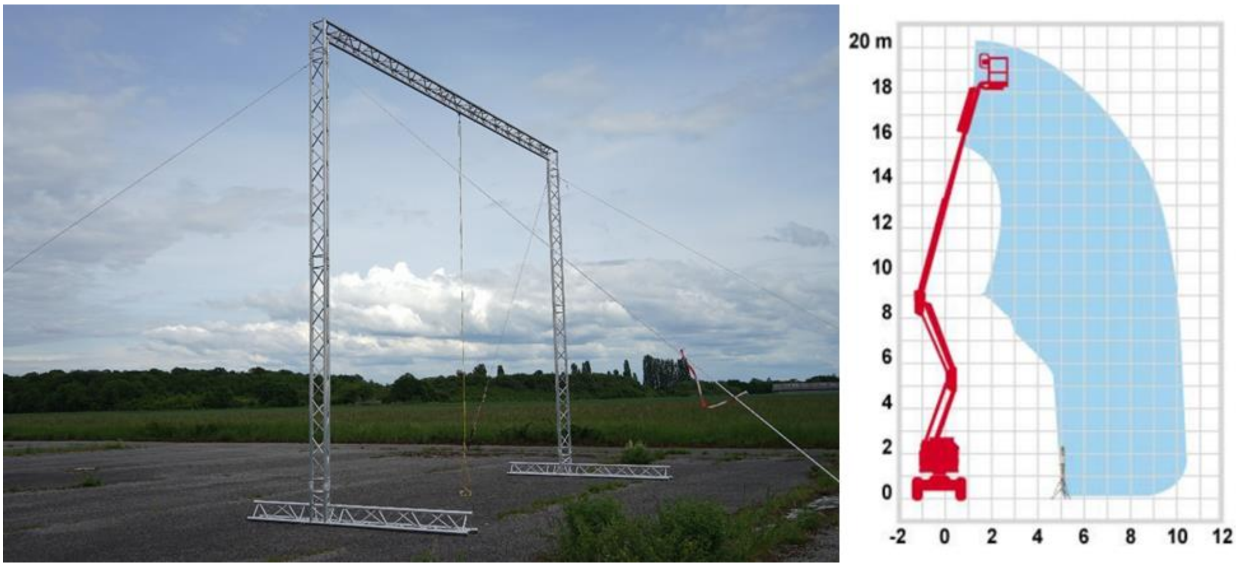

Figure 6 : 6 m fix gantry and 20 m crane for tethered flights

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4. FROG-T firsts flights attempts

Several tethered flights of FROG-T have been conducted from end of May 2019. These flights are the firsts attempts where only navigation and attitude control functions have been activated and successfully tested. As for Pi-FROG, guidance functions will be activated progressively once control functions will be fully optimised. On these first flights and on the following flights results, the vehicle guidance has been done manually by remote control. The Figure 7 shows FROG-T before seventh successful tethered flight.

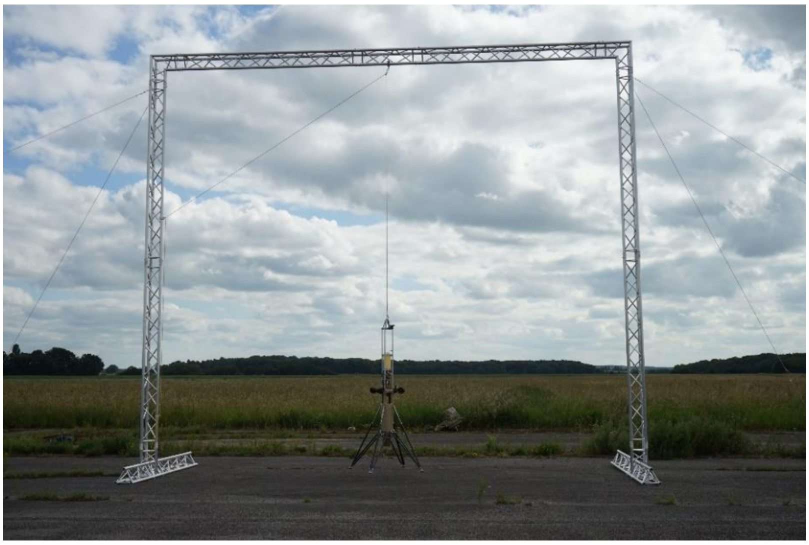

Figure 7: FROG-T tethered to the 6 m fix gantry just before engine ignition

4.1 Attitude tracking

The **guidance accuracy directly depends on the attitude tracking task** therefore it requires an important attention and post analysis. Indeed, as previously mentioned, the guidance computes the attitude angles which have to be tracked to fit perfectly with the planned trajectory. In this context, the control needs to perform his task with the best possible accuracy, and a suitable response time.

The **pitch angle** tracking has been performed **with an error mostly under 0.3 degree** (in the steady states, this error is even smaller), which is an accuracy better than the current FROG requirements (see Figure 8).

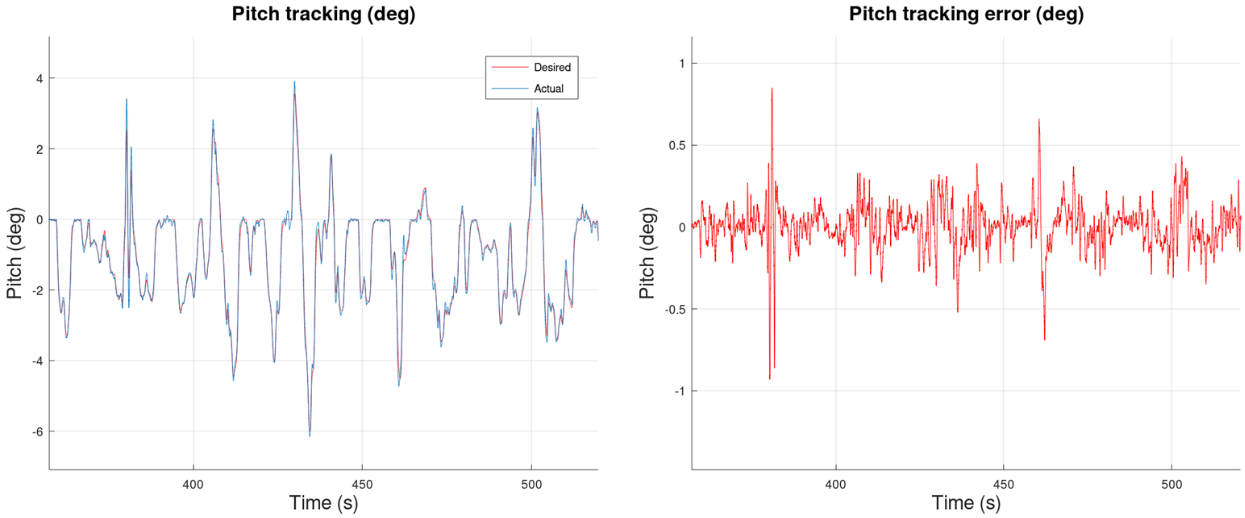

Figure 8: Pitch tracking (both actual and desired curves are superimposed) and pitch tracking error

The **yaw angle** tracking has also been performed **with an error mostly under 0.3 degree**, which is also better than requirement. However, as it can be seen in the figure below, a very small stable oscillation is present in the steady states (see Figure 9).

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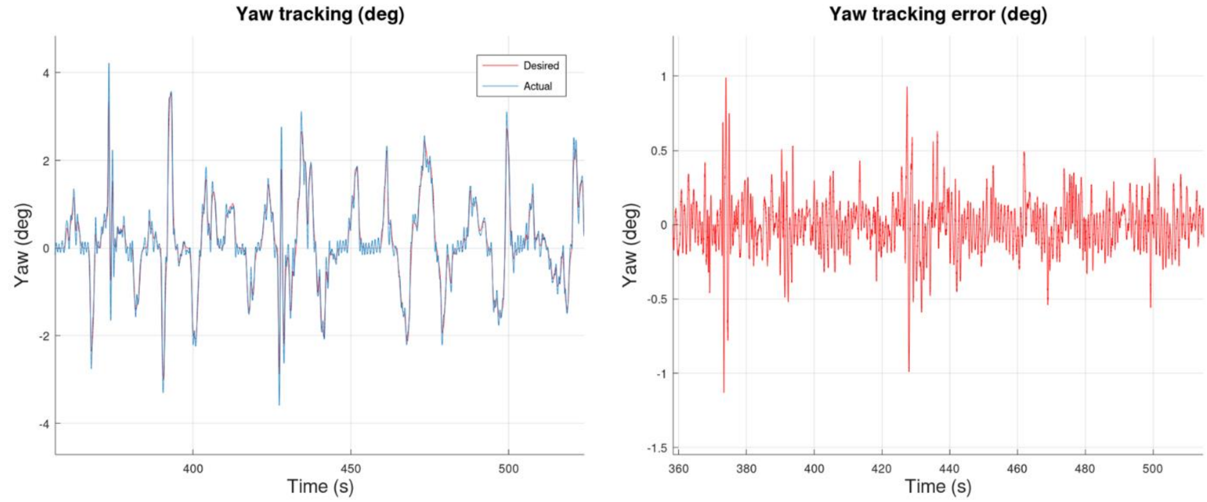

Figure 9 : Yaw tracking (both actual and desired curves are superimposed) and yaw tracking error

This small **steady state oscillation**, even if it is not critical, has an **amplitude of 0.3 degree**. Its origin is explained in the yaw rate tracking part, which is the root of the control loop. It can be concluded that the FROG-T platform yaw dynamics is not exactly the same than the pitch dynamics, since the same control coefficients are applied for both axes.

The **roll angle** tracking has been correctly performed, **with an error under 2 degrees** most of the time (see Figure 10). As for the yaw axis, some non-critical oscillations have been observed in the steady states. It is considered as non-critical issue and can be easily corrected. This has been the first flight with the theoretical model of the roll dynamics, which is slightly different than the actual model.

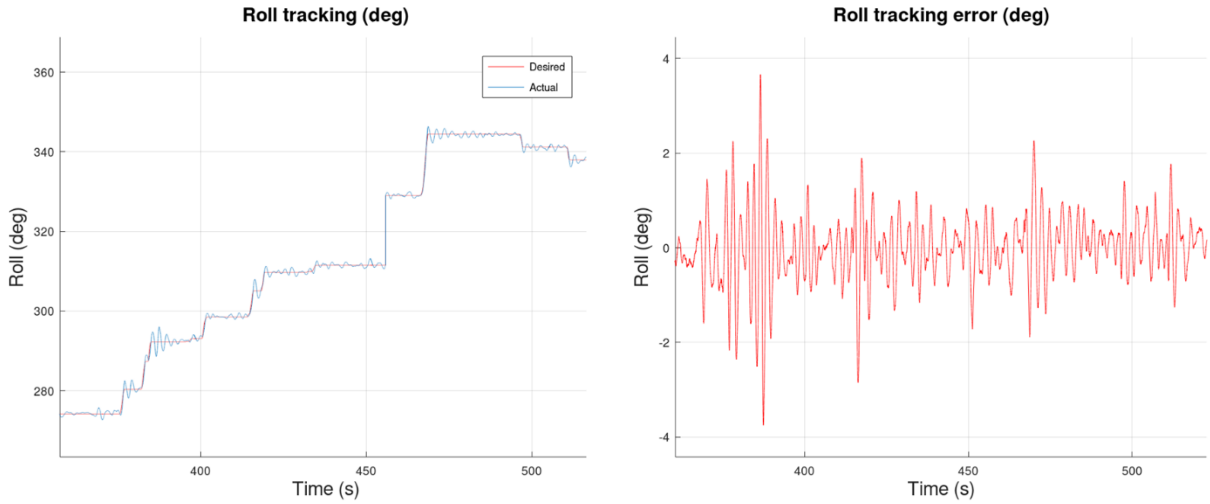

Figure 10 : Roll tracking (both actual and desired curves are superimposed) and roll tracking error

4.2 Spectral analysis

It is important to conduct a spectral analysis, after the first real flight campaign, in order to have a precise idea of the **noise profile**.
According to the gyrometers PSD in Figure 11 , several observations can be done:

- The highest power is concentrated under 10 Hz, which is quite logical, since the control have been tuned with a 10 Hz bandwidth.
- A 12-13 Hz vibration mode appears in the Roll axis.
- Pitch and Yaw axes have a vibration power which increases after 20 Hz.

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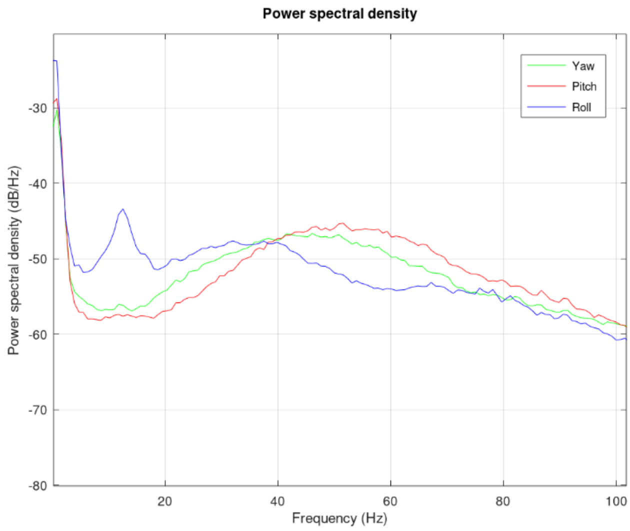

Figure 11 : Gyrometers power spectral density

These observations show that the navigation sensor measurements have **to be filtered at 20 Hz** for the **pitch and yaw** axes, and at **10 Hz**, for the **roll axis**. The filters had been tuned at 20 Hz for the first flight campaign (which is not the best value for the roll axis).

4.3 Attitude rate tracking

This attitude rate tracking is one of the more important control parameter (with the vertical guidance) of the complete system. Indeed, it has direct influence on the attitude tracking accuracy, and on the platform stability.

The pitch rate tracking is performed **with an error mostly under 3 deg/s**, which is a satisfactory accuracy (see Figure 12). Its **response time is between 0.10 and 0.15 s**, which fits with the requirements of the control loop design.

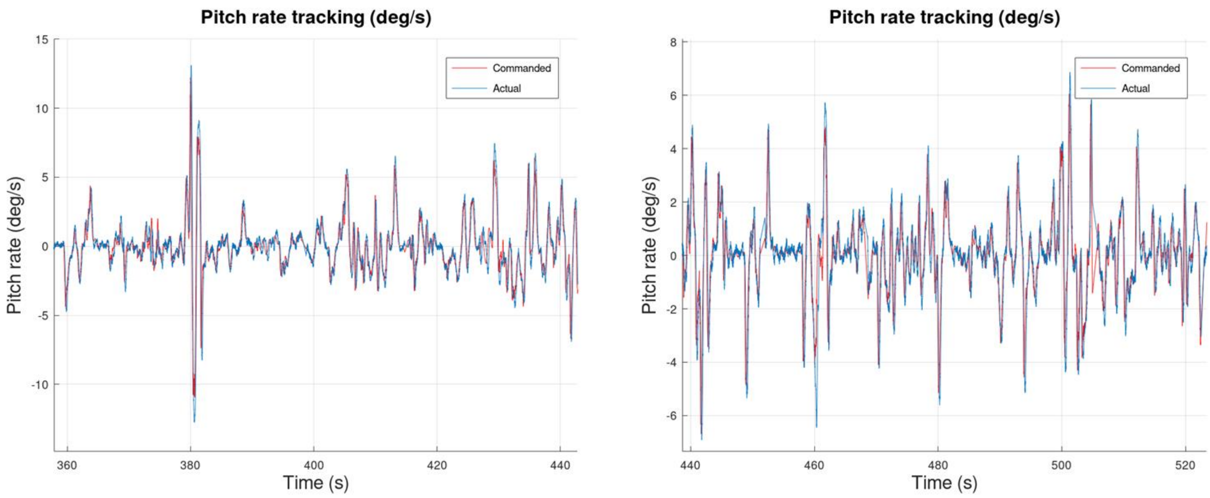

Figure 12 : Pitch rate tracking

The yaw rate tracking is also performed **with an error mostly under 3 deg/s**, which is an acceptable accuracy (see Figure 13). However, its **response time is around 0.20 s**, which does not fit perfectly with the requirements of the control loop design which were at 0.15 s. This difference, which explains the small oscillation observed in the yaw attitude tracking curves, comes from the fact that the theoretical model is not the same than the actual model, and has to be identified for a proper control tuning.

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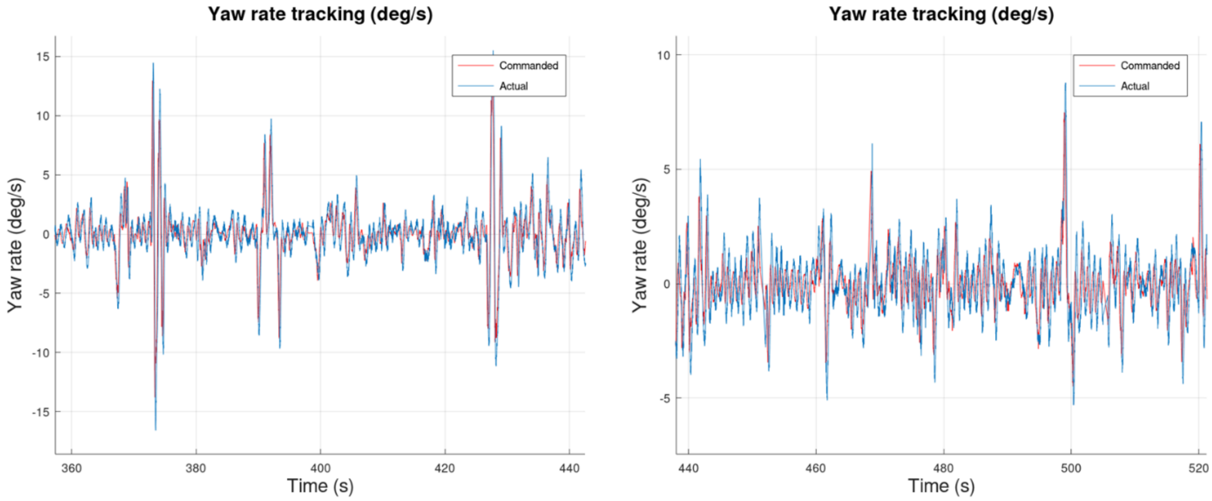

Figure 13 : Yaw rate tracking

The roll rate tracking has a **higher response time of 0.5 s**, which also does not fit perfectly with the requirements of the control loop design which were 0.3 s (see Figure 14).

It also can be seen fast oscillations in the roll rate tracking, which comes from the fact that the roll sensors filter had been tuned at 20 Hz, instead of 10 Hz which is the best value.

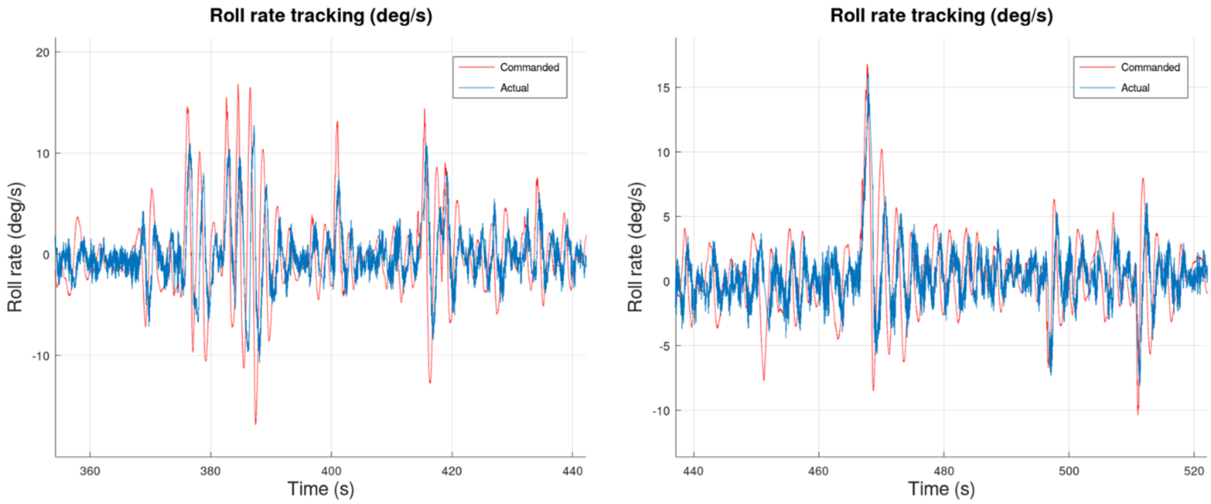

Figure 14: Roll rate tracking

These variations also come from the main engine RPM variation, which involve a roll moment. At the present time, this roll moment is not taken into account in the GNC algorithms, and is considered as an external perturbation.

4.4 FROG-T model Identification

The **flight data** which have been generated by these firsts tethered flights campaigns contains a lot of information, and **has permitted to perform a model identification**, for each attitude axis. When the model does not fit properly with the reality, identification has to be performed to compute more accurately the platform parameters, and to perform new GNC tuning (and maybe design).

Indeed, as previously mentioned, a simple model (required to design the firstly implemented control law) does not take into account the gyroscopic effects and is defined by the following equations:

$$\begin{cases} \dot{q} = -\dfrac{r.x_G.F_T}{I_y}\beta_y = -C_q\beta_y \\ \dot{r} = -\dfrac{r.x_G.F_T}{I_z}\beta_z = -C_r\beta_y \end{cases}$$

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According to the Yaw and Pitch axes models, the theoretical model seems to describe in a good way the dynamics of the system. However, it is possible to see some differences which come from:

- Gyroscopic effects (not taken into consideration at the present time);
- Hanging system which has, in some moments, affected the roll moment;
- Several others elements which also have their importance: sensors inaccuracy, nozzle (deflector) rotation angle accuracy, gusts of wind, etc.

The previous equations defined the relation between turbojet engine **nozzle (deflector) deviation angle** and **attitude acceleration**, with x_G centre of gravity (*x-axis*), F_T the thrust, I_Y et I_Z the inertia, (β_x, β_y) the nozzle (deflector) deviation angles according to the x-axis *x* and *y*-axis, and *r* the nozzle (deflector) deviation angles efficiency (0-1).
The identification has given the following results:

- Concerning the **roll axis**, the identified C_p parameter has been shown to be 0.60 smaller than the theoretical model, which explains the oscillations and bigger response time.

A nozzle (deflector) offset has also been observed, during the identification:

- 0.8 degree for the pitch axis.
- 1.5 degree for the yaw axis.

4.5 Real time computed attitude rate PID terms

The PID terms give interesting information of the control. The most important one is the fact that the Integrative term is never saturated. This point is important, because it shows that the attitude rate tracking is performed in a proper way, that the model of the platform is quite accurate, and finally, that the external perturbations are not that important.

It is important to notice that the pitch/yaw rate PID terms show no integration saturation, which is the indication of a healthy behaviour of the platform: an action of a maximum of 4 degrees on the deflector (normalized value of 0.3) had been given to the Integrative term, and it has never been used.

The roll rate PID terms show an important oscillation of the derivative terms, because of the non-suitable 20 Hz filter (which has to be corrected to 10).

4.6 Nozzle angle during the flight

The nozzle (named nozzle in order to stay in the "rocket approach but it is a tubular deflector) is quite active during the flight, because the FROG-T demonstrator is very instable, and its centre of gravity is quite low (as all the reusable stage when they are almost empty).

A usual angle between -2 and 2 degrees can be observed, which is a good performance, since the maximum deflector angle of the platform is 13 degrees and so offers a potential additional reactivity for external perturbations.

4.7 Short term GNC actions for improving FROG-T behaviour for preparing the free flight

In terms of short term GNC actions toward the first free flight foreseen in September 2019, of course, the feedback from the firsts successful flights (see Figure 15) shall be taken into account. Also, in accordance with the experimental and progressive approach, the guidance functions and the flight domain shall be activated and opened progressively.
Short term GNC actions:

- Refined model identification and optimised attitude control.
- Modification of the roll filter: 10 Hz instead of 20 Hz.
- Turbojet nozzle software calibration.
- Progressive activation of automated guidance functions before free flights and landing manoeuvres.

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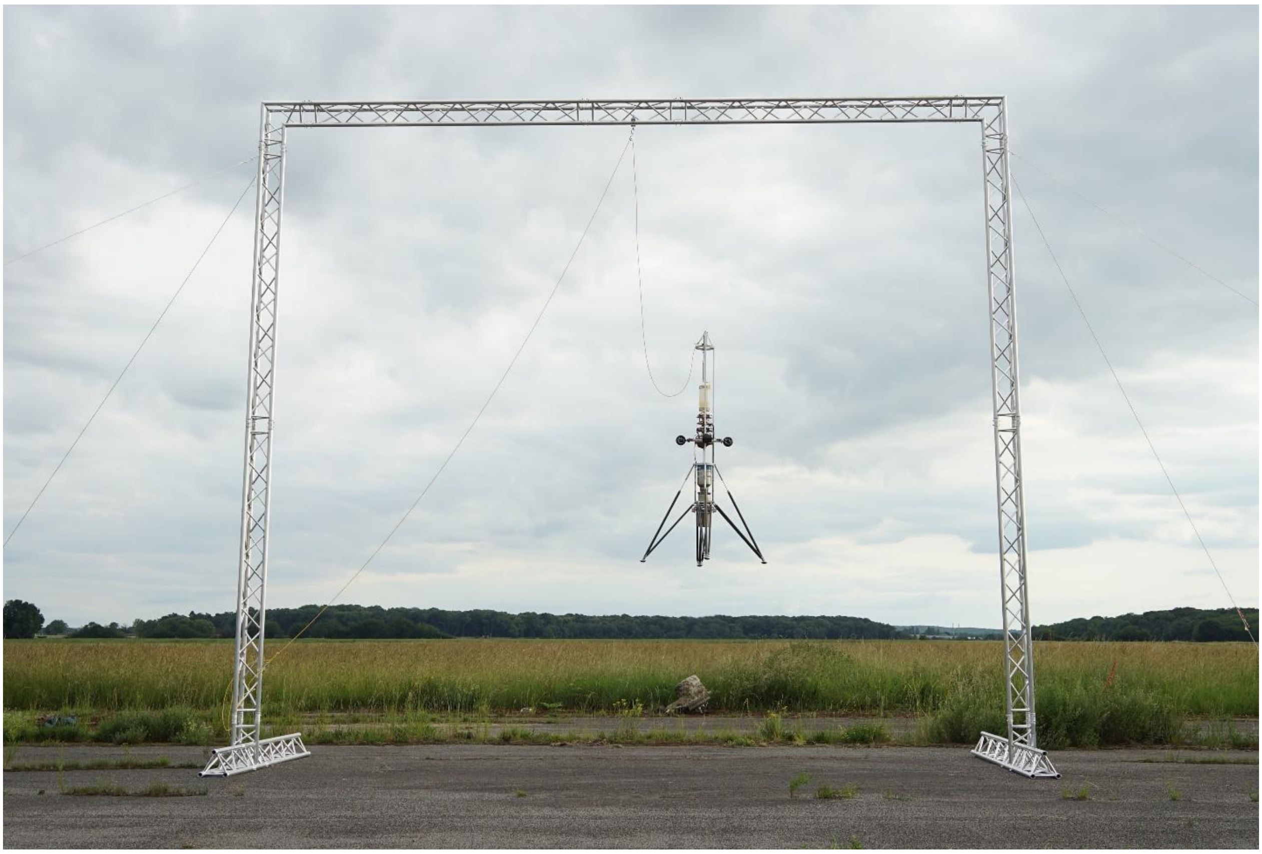

Figure 15: FROG-T during a tethered flight

5 FROG-H: mono-propellant rocket engine

5.1 Overview

In order to improve the experimental approach of the demonstrator, the next version of FROG is currently in preliminary design phase. This second release, known as FROG-H, will use a so-called “green propellant”: High Test Peroxide (HTP). HTP shall be used as the sole propellant of the demonstrator in the upcoming concept. 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 enabling a quicker and more accurate GNC. This characteristic will make it more representative with respect to a launcher.

5.2 Principle of the FROG-H motor

FROG-H shall be kept as simple as possible, and will work in the following way:

1. HTP is pressurised by a high pressure Nitrogen tank. This pressurised HTP is injected in the decomposition chamber and regulated by a proportional valve. In this decomposition chamber, the HTP goes through a pack of silver screens (the catalyst bed) that will activate the decomposition. Heated water steam and oxygen downstream are released. Both of them will form a high-pressure gas mixture which will be expanded by the nozzle to deliver the thrust.

2. Thrust vectoring (pitch and yaw axis) is achieved by gimballing the engine, thanks to a gimbal system controlled by servomotors.

3. The opening and closing of a ball valve activated by a servomotor allows to adjust the flow of HTP fed into the chamber, and thus allows to control the thrust.

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4. Temperature and pressure sensors in addition to various feeding/purging valves allow the complete control of the operation of FROG-H motor.

The conceptual process is illustrated in Figure 16 below.

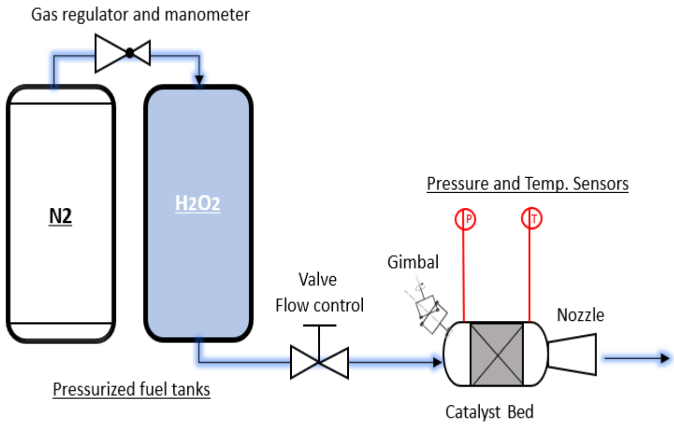

Figure 16 : Conceptual view of the FROG-H motor

5.3 Performance analysis

Catalyst decomposition kinetic and turbojet engine transient induce some delay between needed and efficient thrust. Propulsion dynamics have been studied to determine the required GNC to achieve the mission trajectory. As intended, the FROG-T engine tests have provided us a first insight into turbojet engine performance. A transient of around 1 second is observed with the turbojet engine. According to previous works [10], with FROG-H the transient should be shorter, therefore controllability should be better.

HTP concentration (mixture of liquid H_2O and H_2O_2) is a major concern for safety and performance aspects of FROG-H. A low HTP concentration reduces the released energy and increases the energy needed to activate the decomposition shortly. But a high HTP concentration requires specific safety procedures to avoid any people injury.

Calculations are conduced to illustrate the capability of H_2O_2 thruster to satisfy a typical VTVL mission with hovering. Two concentrations of 87.5% and 98% are considered. Thermochemical efficiency is used [11][12] but reduced to take account of thermal transient and pressure drop towards the catalyst bed.

Figure 17 below illustrates the computed efficiency of HTP thrusters depending on HTP concentration and mass flow rate. Those realistic assumptions are necessary to evaluate thruster capability to satisfy the VTVL mission and to help us to design it properly in terms of mass, thrust, structural load, inertia and GNC parameters.

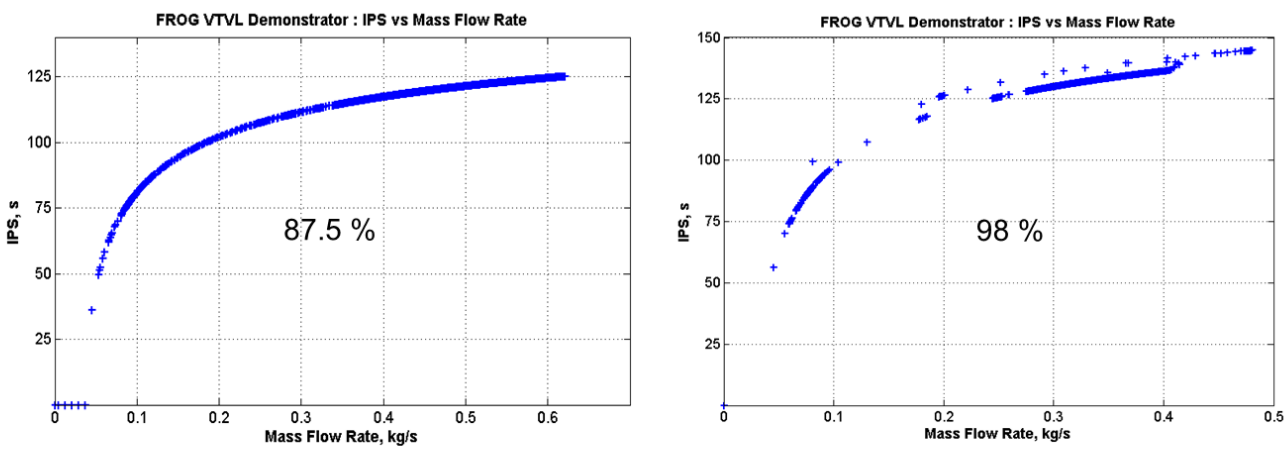

Figure 17: Computed efficiency of 87.5% and 98% HTP thrusters at different flight operation point

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For both of them, FROG-H should be able to deliver a higher thrust of around 1000 N. And to avoid any problem of start / stop transient and to ensure attitude control, a minimal thrust of 200 N is maintained during all mission.

Figure 18 below illustrates the fuel consumption considering both 87.5% and 98% concentrations for different structural mass (all the system except fuel). It confirms that 1000 N HTP thruster class is able to satisfy the mission up to 75 kg of structural mass. Fuel consumption (for thrust and control) represents 10% to 15% of the total mass.

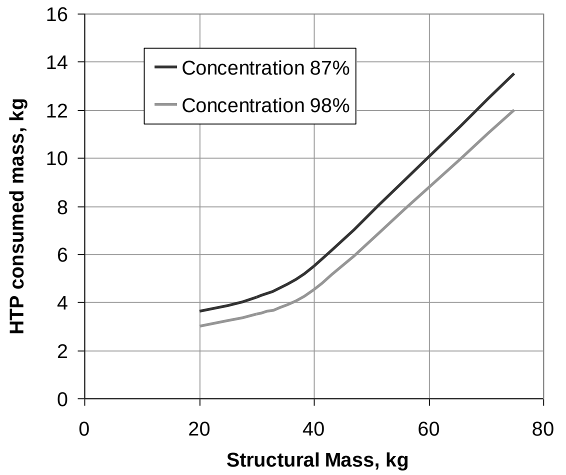

Figure 18: Computed HTP consumption for 87.5% and 98% thrusters and for different flying mass assumptions

Some graphics are also presented below to illustrate simulated transients of H_2O_2 thruster and turbojet engines during a typical VTVL mission with hovering. Simulations of both jet engine and HTP thruster solutions (see Figure 19) show how catalyst decomposition kinetics and motor transient modify the trajectory and the GNC requirements. This will have to be taken into account to make the mission feasible.

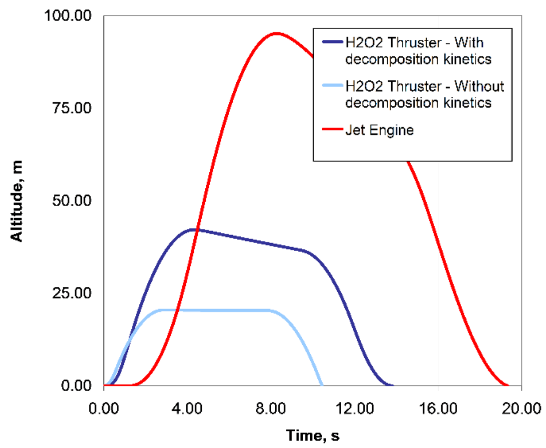

Figure 19 : Computed altitude profiles - Comparisons between jet engine and HTP thruster with infinite or finite decomposition rate

Moreover, simulations highlight how turbojet engine is difficult to control because of its long characteristic transient time of ~1s. To successfully land (with a constraint on the initial vertical speed), the turbojet engine should begin to thrust at an altitude 2 or 3 times higher than H_2O_2 thruster, as can be seen on Figure 19.

Simulations also give a real insight of the GNC and motor requirements to satisfy the mission. On Figure 20 is plotted the altitude and the command of thrust with time. To manage acceleration, hovering, deceleration and attitude control, the HTP thrusters will work in a large interval of thrust and sometimes with very short impulsions of around 0,1 second. Experiments will now help to design the best catalyst bed to do so.

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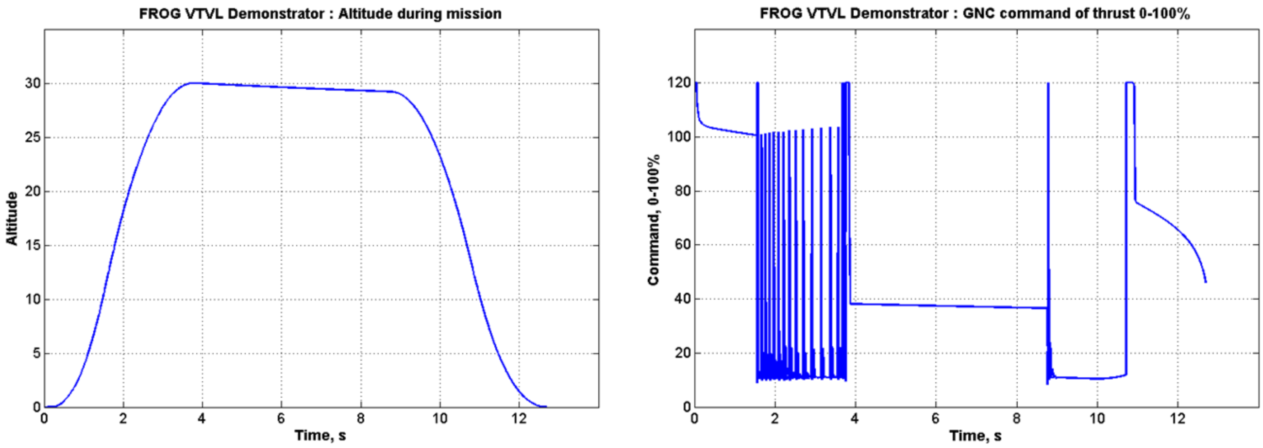

Figure 20 : Computed GNC command of thrust during typical VTVL mission with hovering

For now, the remaining design work is to evaluate experimentally the decomposition rate in the catalyst bed. Some experimental data demonstrate that the effectiveness of the decomposition is depending on the temperature in the catalyst bed [10][13]. A thermal FEM model is currently in development in order to simulate the evolution of the temperature in the bed, which will allow to achieve a better estimation of the decomposition rate throughout FROG's entire mission.

To conclude this chapter, in comparison to the turbojet engine, the HTP rocket motor is heavier, it requires more operations and more propellant and it demands definitely more safety procedures. But this kind of engine is one of the simplest throttleable rocket engine and brings a real representativeness for FROG missions. It allows a faster response time, and does not induce gyroscopic effect nor additional roll torque.

5. Conclusion

In this paper we introduced the FROG project and its positioning in the CNES launcher roadmap [15]. We also presented the experimental and progressive approach of the project. This approach relies on a collaborative organisation composed of CNES Launcher Directorate, a non-profit organisation (Planète Sciences), a start-up (Polyvionics), academics (IUT de Cachan/Innov'Lab), students and several SME (Drones-Center, Sonatronic, etc..).

So far, FROG-T (turbojet version) has successfully done its firsts tethered flights. The flights results show that no major anomalies have been detected. No reserves have been identified and we are able to nominally run through our schedule toward a first free flight in September 2019 and a complete qualification of a landing mission !

FROG-T development also confirmed that FROG-H (mono-propellant rocket engine version) can be based on FROG-T GNC, avionics, embedded software, actuators, landing legs, structure (partially), ground station, etc… In addition, FROG-H vehicle studies and, especially, the propulsion system and associated CONOPS have reached a PDR maturity level. A development plan has been consolidated in which the first FROG-H tethered flight is planned for end of 2020.

In parallel to FROG developments, the practical applications of the vehicle and its flights for contributing to other projects or bigger demonstrators are in preparation. ArianeWorks (the launcher incubator and acceleration platform initiated by CNES and by ArianeGroup), with the support of ESA, is one of the privileged way for practical applications.

Last but not least, the consolidation of FROG-H development plan has been made possible thanks to the huge support of a new partners willing to join the project. The new partnership is about to be finalised and once made official an article will be published. The FROG team is very excited by this new perspective and still focused and mobilised on the ongoing developments !

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