Throttleable hybrid engine for planetary soft landing

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Abstract

The SPARTAN research program aims at developing a throttleable propulsion technology, which is mandatorily needed for any planetary soft and precision landing. It relies on the hybrid engine technology, exploiting its capability of being throttled and its proper performance. This research program is complementary to ESA TRP and Piedmont Regional development programs. It implements and strengthens the technological base in view of the future robotics and manned space exploration missions. The outcomes from the SPARTAN development can be reflected also in many Earth/Space civilian and military applications, exploiting both the throttling capability of the propulsion system and the peculiar characteristics of the hybrid engine technology, like: safety, minimum environmental impact (green propellants), lower life cycle costs, responsiveness, competitive performance, increased reliability, soft ignition, and shutdown.

The hybrid propulsion system is formed by two major constituors: the engine itself, housing the fuel, and the oxidizer injection system.

The research focuses on three major objectives, needed to achieve the soft and precision landing capabilities:

- The engine design, specific for throttling functionality
- The oxidizer throttleable device development
- The design of the landing case: test bench and testing procedures

The development will be supported by establishing an advanced coding, enabling the definition of the fuel and the throttling behavior of the hybrid engine. The design will be supported by development tests: cold injection case, dedicated to the throttling device, and hot firing on subscale model, merging the throttling device and a subscale engine.

In parallel it will be developed a landing test and the associated landing model (flying test bed), providing the availability of proven landing model and landing test capabilities. These capabilities will allow demonstrating the soft and precision landing features of a throttleable hybrid propulsion technology.

1. Introduction

The soft landing on extraterrestrial bodies is a key issue in future space exploration and in long-term vision of European and Non-European space programs. Soft landing is required for unmanned and necessarily manned missions, which have to deliver on planet surfaces always more heavy equipments and manned modules that cannot withstand strong impact loads or that needs to maintain the landing place as unaltered as possible. Such approach is applicable in the near future to both a return of the man on the Moon to future Mars exploration missions and this is also envisaged explicitly in European future plans. ESA’s view on The Long-Term International Scenario for Space Exploration [1] clearly states that the period during Phase 1, through 2016 and perhaps through 2020, will demonstrate key capabilities such as planetary descent and landing, surface mobility, in-situ resource utilization (ISRU), and perform valuable in-situ science (see Figure 1).
Other statements from ESA and other world wide space agencies strongly show the necessity for efforts in Space Transportation to define Mars Robotic Exploration [2] and Lunar Cargo Landers [2][3] that would lead to a Mars Sample Return mission, with precursor program able to demonstrate soft and precision landing capabilities.

Soft and precision landing can be performed only with a chemical throttleable engine, capable to vary its thrust to follow the control commands to successfully deploy its payload on an unknown surface with non fully predictable atmospheric or gravitational entry conditions. At worldwide level the state of the art of throttleable engine is represented by liquid thruster, even if solid thruster throttling is possible with the pintle technology, and different R&D programs are ongoing almost all outside Europe. Current research activity is focusing on high-thrust cryogenic liquid bipropellant rocket engines, mainly for Moon descent missions. NASA and P&W ongoing Common Extensible Cryogenic Engine program is focused in demonstrating the technological feasibility of a LH2/LO2 deep throttled motor (throttle ratio 13:1 demonstrated on ground tests) for Lunar descent. The study baseline is a modified RL10 engine. Injector and oxidizer feed lines had been deeply modified to suppress combustion instabilities at low throttle. Northrop Grumman Space is also developing the TR202 engine for Moon descent missions. Stable combustion was demonstrated over 10-1 throttle range with a pintle injector with GH2 and LOX propellant.

At European level the research in this field is strongly less respect to US. Qualified throttleable engines basically do not exist in Europe, being the available items standard liquid thrusters with limited throttling capabilities. In addition, throttleable liquid thrusters have several problems, being generally designed for fixed thrust with small variations about the design point for throttling. Extension of this capability to deep throttling is expensive, time-consuming, and with limited off-design chance due to high system complexity and sensitivity to combustion instabilities/oscillations. Moreover, existing design is difficult to modify addressing mission requirements changes.

Following the aforementioned needs of the European space community, the design of a fully throttleable engine for soft planetary landing is the objective of the SPARTAN project, which for this activity is supported by European FP7 program. The engine will provide smooth and wide throttle range coupled with high-thrust and will be based on the hybrid rocket motors technology. Differently than liquid engines, hybrid rockets are intrinsically simpler, safer, with a wide throttling capability and have the possibility to use green propellants, which concur to lower the development cost along with the other aforementioned qualities. Their main drawback is modeling issues on the combustion process, which will be considered during the research on codes and motor fuels.
2. SPARTAN approach on throttling validation

The aim of the SPARTAN program is to develop a new throttling technology which will be applied to a newly designed throttleable engine for the soft and precision landing on a planetary surface. This goal will be the result of an intense research program that will involves 8 partners from 6 different countries from both universities and industries.

The approach followed by the SPARTAN project is to not only design a new motor, but also to test it with full soft landing test with a new low-cost highly realistic test bed. To perform the test a lander will be developed, in order to provide the necessary elements to carry out successfully a soft landing on the Earth. The test, optimized for the Earth environmental conditions, is linked to Mars planet requirements and robotic missions. The test plan and development will interact with the lander design requirements, leading the lander configuration and engine nominal performances. During the test, the Lander will be lifted to 100m and dropped by a helicopter. Once the Lander will be lifted up to the proper height, it will be released for a free fall of about 50 m to achieve 30 m/s of vertical velocity before activating the propulsion system to its nominal operations.

The test objectives are:

- To damp the vertical velocity verifying the engine throttling capabilities;
- To maintain the vehicle stability during the velocity damping phase.

It is notably that this approach is strongly challenging but can provide an insight in the technology that is difficult to achieve in other ways. New propulsion systems concept has been tested till now in Europe exclusively with static ground tests, with the exception of small motors for sounding rockets or interceptors missiles, fired in safe and low populated zones like Norway (i.e. Nammo hybrid sounding rocket). Space motors are difficult to test, mainly regarding their dynamic capabilities and safety issues related to the nature of the propellant, and no drop test has been performed in Europe to explicitly test a working mock up of a chemically propelled lander. The gap with US testing method is evident, many drop tests have been performed and also tests with ascending and descending lunar landers mock-ups. It is possible to cite the Northrop Grumman Lunar Lander X PRIZE Challenge: “a $2,000,000 incentive prize program designed to build an industry of American companies capable of routinely and safely flying vertical take-off and landing rocket vehicles useful both for lunar exploration and other applications”. The private companies that are competing for the prize must perform a dynamic test that requires the proposed landers to actually take off, sustain, move laterally and land.
The test approach foreseen in the SPARTAN program is totally new for Europe, in the frame of the soft landing capability verification, with an active and throttling propulsion system. A dynamic test able to verify the performance of the developed technology on ground allows performing a dynamic end-to-end test in a representative scenario, providing a new methodology and architecture for testing of landing technology and payloads. Therefore this project is providing for a real step forward with respect to the state of the art in Europe.

2.1 The Lander

The capability of a mechanical structure to land safely on a planet surface is mandatory for each manned and unmanned mission. Other than the parachute and the thrusters, which scope is to reduce the initial entry velocity to few meters per second, the lander structure and most of all the lander legs, have to dissipate the residual energy reducing at the same time the impact shock to preserve the integrity of the payload. Also the soft landing test approach, the conclusive validation of the developed throttleable engine, requires the design of the lander. This will be sized to allocate the engines and all the relevant equipment, and to withstand the impact loads and the environmental issues that will be identified in the drop test location, such as wind, temperature and soil composition to avoid dust raising. The Landing Model Structure will be developed by using qualified material and processes: light weight high strength carbon fiber structures will be maximized.

Other than the structure the design of the lander includes the Thrust Control Algorithm and GNC and the Storage system. The Thrust Control Algorithm baseline concept is to have a classical outer loop in which estimation of kinematics state of the vehicle (position, velocity, attitude) is performed by the Navigation function based on the available sensor data, a simple guidance logic generates a descent profile (no obstacle avoidance capability is foreseen at this stage), while the control block will issue the command vector in terms of desired thrust level for the four hybrid engines. In addition to this, the actual thrust level of individual engines will be evaluated by load cells in order to establish an inner control loop on the thrusters output.

![Figure 3 SPARTAN Landing Model Structure and Landing legs](image)

The Storage System is made of one oxidiser tank and one pressurant vessel. The oxidizer tank will be maintained at the constant pressure by the pressurant (GHe) contained in a dedicated pressure vessel. In order to avoid gas and liquid mixing, the oxidizer tank will have an elastic bladder, compatible with the chosen oxidizer (H2O2).

2.2 Drop Test requirements

The mission main objective is that the demonstrator shall be able to perform a “soft landing”, which means that the lander shall be able to achieve a desired impact velocity ad a desired altitude in order to be able to absorb the residual energy thanks to the landing legs. The most important requirement is obviously the touchdown velocity, which impacts the structure of the demonstrator.
A short survey shows that while Deep space 2 was supposed to touchdown at 2.4 m/s (mission failed), Phoenix landed at 1.6 m/s, and Mars sample return is supposed to land at 2 m/s. A good compromise is hence represented by the last option, which means that the required landing velocity is assumed to be 2 m/s.

In order to avoid hazards to objects and persons with the motors firing at ground level the lander shall not be posed in the condition of losing stability during the impact, meaning to avoid stresses to the hinges so to compromise the integrity of one or more legs. Hence two requirements are derived: that the stability of the lander shall be maximized even in case of the loss of a leg and that the desired lateral velocity shall be assumed null to avoid stresses that can damage one or more legs. From the first requirement a four legs configuration is mandatory, being a good compromise between stability and mass penalty.

Summarizing the final requirements are:
- Four legs configuration
- Vertical impact velocity: 2 m/s
- Lateral impact velocity: about 0 m/s

These requirements shall be fulfilled by the chosen configuration and by the foreseen thrust profile. The thrust profiles are the desired thrust throttling law that should be followed during the soft landing test starting from the engines ignitions. They are calculated in order to fulfil the mission timeline and the requirement above on final vertical velocity, with the objective to simulate a thrust profile able to show the engine throttling capabilities. Obviously from a GNC and Navigation point of view those possible thrust profiles have to face the external environmental conditions that would provide variation in attitude and lateral velocity. The objective of the Navigation algorithm is to follow as close as possible the chosen thrust profile minimizing and compensating external factors. Figure 4 shows a possible thrust profile for two possible lander configuration of different weight.

![Thrust profile option for a 253 kg lander (left) and a 370 kg lander (right)](image)

3. SPARTAN Throttling technology development

As introduced above, hybrid propulsion has been selected by the SPARTAN project being the best candidate for space exploration applications that requires throttling capabilities because of: (i) its higher ISP compared to both monopropellant and solid motors; (ii) its intrinsic simplicity, only one feeding line for the fluid oxidizer is required compared to bipropellant liquid motors; (iii) the thrust chamber is easy and cheap to be build and catastrophic failure
related to throttling operation is very unlikely (differently from solid and liquid engines), and last but not least; (iv) the inert characteristic of the propellants used. In addition often these non toxic propellants can be considered “green”, representing a good step forward from the planetary protection point of view. Throttling is achieved just varying the oxidizer mass flow rate, and that has already been demonstrated. However, full system controllability, required for soft-landing applications, requires a good knowledge of combustion process especially during unsteady operations.

An overview of the benefits of hybrid technology respect to other propulsion concept is clearly visible in Table 1. The table summarizes pro and cons of rocket motor technologies, with focus on throttling and soft-landing capabilities.

### Table 1 Competing technologies

<table>
<thead>
<tr>
<th>Rocket motor type</th>
<th>Thrust</th>
<th>ISP (s)</th>
<th>Throttling ratio</th>
<th>Propellants</th>
<th>Advantages</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>monopropellant rocket engine</td>
<td>low</td>
<td>low</td>
<td>10:1</td>
<td>mostly toxic (hydrazine)</td>
<td>compact and high responsivity to throttle</td>
<td>low ISP, limited maximum thrust, hazardous propellant</td>
</tr>
<tr>
<td>low-thrust bipropellant rocket engine</td>
<td>low</td>
<td>medium</td>
<td>10:1</td>
<td>toxic and hypergolic</td>
<td>compact and high responsivity to throttle</td>
<td>hypergolic propellant, complex throttle control</td>
</tr>
<tr>
<td>high-thrust bipropellant rocket engines</td>
<td>high</td>
<td>high</td>
<td>10:1</td>
<td>high-energetic, usually cryogenic</td>
<td>high ISP, high thrust, wide throttling capability</td>
<td>cryogenic propellants, complex system, expensive design and testing</td>
</tr>
<tr>
<td>solid rocket motor</td>
<td>high</td>
<td>medium</td>
<td>10:6</td>
<td>pre-mixed, susceptible to fracture</td>
<td>compact, storable, medium ISP</td>
<td>limited throttling capability, hazardous premixed propellant</td>
</tr>
<tr>
<td>hybrid rocket motor</td>
<td>medium</td>
<td>medium</td>
<td>10:1</td>
<td>green</td>
<td>simple, wide throttling capability, medium ISP, green propellant</td>
<td>modelling issues on combustion process, low TRL of high-regressing fuels</td>
</tr>
</tbody>
</table>

Hybrid rocket motors appear so to be the perfect candidate for missions where deep throttling coupled with medium thrust and good ISP are required. Moreover, hybrids offer substantial advantages to development costs due to their simplicity, safety and green propellants. Research is required on codes and fuels to improve knowledge on the fundamental physical aspects required to successfully qualify hybrid rocket motors for soft-landing and other mission with throttling requirements.

Current TRL of hybrid throttleable motors, for in space application, is still low, between 3 and 4. With the proposed research it would be possible to raise the overall TRL of the technology to 6, demonstrating it in a relevant environment. To reach this it is required the development of a complete and integrated Lander system, not just a propulsion system, to execute a complicated task. The concept will be developed in detail and the throttling device is harmonized with the hybrid propulsion technology to obtain a reliable technology demonstrator.

The benefits from the SPARTAN program are not limited to the field of the space propulsion, with the improvement of the hybrid engine technology and the widening of its application, but also extended to the expertise which will be matured in the field of the controlled landing test, which can be exploited for further development steps to validate further landing features.
3.1 Development logic

In SPARTAN program the development of the throttling concept, as in case of the other R&D activities of the project, is not a self standing activity but is intimately connected with the different parts of the program. The study logic concerning this part of the work is represented in Figure 5.

The **Throttling Technology Development** block is the project pivoting task: it establishes both the throttling requirements and its concept, which drive the technology development. This result will be achieved by leading an intensive concurrent design session, harmonising the mission requirements (project reference), the testing requirements (soft landing on Earth), and each subsystem performance characteristics.

The **Hybrid Engine Throttling Capability Development** block leads to the development of the throttling technology, through the advanced coding, the CFD analyses and the development testing (cold and hot on the subscale model). These main tasks are supported by design activities (the **Propulsion System Design and development** block) relevant to the throttling device and the engine itself. A proper concept selection for the throttling device and the engine preliminary design, coming from the **Propulsion System Design and development** block supports the start up of the coding activities and will give input to the final design activities of both the throttling device and the engine components (injectors and combustion chamber). Development tests will be used to validate the code.

The validated code, and the sub-scale experimental set-up, will be used to design the throttling devices and the engine and to optimize them, than a full scale model is built and tested. This will be the object of activity clustered under the **Propulsion System Design and development** block.

3.2 Throttling Technology for hybrid propulsion

The development of the hybrid engine will rely both to the experience of the partner of the project in this technology and to the development of new methodologies for studying the critical issue of such thrusters mentioned above. In particular in order to understand the behavior of the fluids inside the engine a 3D code will be developed. This code will be a new model to simulate the hybrid rocket motor, from upstream injector to the nozzle.

The 3D unsteady CFD code will be capable of simulating detailed physics of the hybrid combustion phenomena in case of general hybrid rocket. In this case the greater goal will be to simulate the regression rate local variations and combustion efficiency.

As mentioned before the code is validated through both a cold test, dedicated to the throttling device only, and a hot test on a sub scale model, to validate the full chain of devices. The code will run in parallel on super computer.
This model will be divided into three main parts:

1. Simulation of the internal flow of the injector;
2. Atomization/ break-up of the two-phase fluid exiting the injector due to its interaction with air, together with the combustion simulation. Combustion shall cover internal flow dynamic, species diffusion, reactions kinetics and heat transfer to the fuel surface in the combustion chamber;

![OpenFoam model subdivision](image)

Figure 6: OpenFoam model subdivision

The subdivisions in the above picture:

1. The first block refers to the injection system;
2. Block number two refers to the combustion code;
3. Block number three refers to the nozzle exhaust.

These blocks are to identify the specific areas in which the rocket physics is simulated, whereas it is important to highlight that the reservoir and feed-lines will not be modelled or simulated.

The physics behind the throttling technology is strictly related with the hybrid propulsion working model. In chemical rockets thrust is proportional to exhaust/burned propellant flowing out of the nozzle. At steady-state, in hybrid motors, this is the sum of injected oxidizer mass and regressed fuel mass. The latter, due to the inherent burning process of hybrid rocket motors, is proportional to oxidizer mass flow. Thus throttling is simply achieved varying the oxidizer mass flow rate.

![Schematic of the Oxidizer feed system](image)

Figure 7 Schematic of the Oxidizer feed system
Let’s consider in an example of schematic hybrid motor oxidizer feed system, which in this case is focused on the SPARTAN vehicle due to the presence of four thrusters. Downstream the FCV there is the injector, one for each motor. The baseline is a constant area injector, as simple as a plate with many orifices. The scope is to increase the oxidizer velocity thus promoting its atomization before reacting inside the combustion chamber with the gasified fuel. Good atomization of the liquid oxidizer is achieved with a reasonable pressure drop across the injector. If the pressure difference is reduced below a threshold limit, oxidizer droplets become too coarse, neglecting efficient and stable combustion. Nevertheless the oxidizer mass flow reduction by means of a FCV has the drawback of reducing pressure drop at low throttle.

The pressure drop across the injector is function of oxidizer mass flow rate, and approximately is expressed as:

\[ \Delta P_{\text{inj}} = \left( \frac{\dot{m}_{\text{ox}}}{A_{\text{in}} \cdot Cd} \right) \frac{1}{2 \cdot \rho} \]

Given the oxidizer mass flow rate and fixed injector area, the pressure drop is minimum at minimum \( \dot{m}_{\text{ox}} \). Thus atomization is worst at low throttle. The oxidizer mass flow rate \( \dot{m}_{\text{ox}} \) is fixed by the FCV:

\[ \dot{m}_{\text{ox}} = A_{\text{FCV}} \cdot Cd \cdot \sqrt{2 \cdot \rho \cdot \Delta P_{\text{FCV}}} \]

At maximum flow rate \( \Delta P_{\text{FCV}} \) is at minimum, at minimum oxidizer flow rate, \( \Delta P_{\text{FCV}} \) is at maximum (see Figure 8). The combustion chamber pressure \( P_{\text{CC}} \) is approximately proportional to the motor thrust.

Below 40% of nominal thrust flows atomization becomes too inefficient for motors with fixed injectors. To achieve 10:1 thrust modulation, upgrades to this baseline configuration are needed. The objective is thus to limit the reduction of pressure drop across the injector \( \Delta P_{\text{in}} \) when thrust is reduced, preserving atomization quality. To achieve this task several concepts can be applied. They have been developed in the past 60 years in the framework of LRM (liquid rocket motor) throttleability studies. Main concepts applicable to liquid oxidizer injection are:

1. **High pressure-drop**: minimum pressure drop across the injector is fixed at the lowest oxidizer mass flow rate; however this solution requires increasing the pressure drop at high thrust. This does not neglect good atomization, but requires loading higher than required pressurant, increasing motor mass. This method is usually feasible for throttling between 100% and 60%;

2. **Dual-manifold injectors**: oxidizer mass flow rate is provided to the injector by two separate feed-lines. This reduces the pressure drop at low thrust but requires to double valves;
3. **Gas injection**: gas is mixed into the oxidizer flow before injection, reducing the mixture density. The decrease in density is proportional to the increase of pressure drop and good atomization is provided even at reduces mass flows. This concept requires adding a gas tank and related feed lines;

4. **Moveable injector components**: the injector area is changed during throttling, i.e. using a pintle. If area is reduced pressure drop increases at low oxidizer mass flow, preserving good atomization. This concept adds substantial complexity to the hybrid rocket motor;

The main issues to be addressed in investigating the throttle capability for the development of a performing variable mass flow injector/system are:

- Optimized injector atomization, flow stability and jet shape with variable mass flow/throttle ratio;
- Minimal time-lag to throttle command;
- Throttle device simplicity, robustness and reliability.

Summarizing, the throttleable device is the sum of two systems: the flow regulation device is required to modulate the oxidizer mass flow rate, the injection system to atomize the oxidizer and possibly, to guarantee a good performance and stability of the system over the throttling range. A good injection system shall be able to adapt to the oxidizer mass flow rate and always provide good oxidizer atomization and high feed-system stiffness (insensitivity to couple with or trigger combustion instabilities). CFD analyses are planned to investigate these issues.

### 4. SPARTAN Test plan

The full scale soft landing drop test is the final point of a development process which foresees a series of intermediate tests for both the development of the throttleable thruster and for the validation of its throttling capabilities. Before reaching the confidence to actually load the lander on the helicopter a series of Full Scale Hot test with dedicated test bed will be performed. These tests will stress the newly designed engines in restricted and safe conditions, allowing the validation of the throttling ranges without the worries of environmental condition and Guidance algorithms application.

Prior to this step a sequence of extremely important cold and hot firing test will be performed on parts of the throttling device and on fully representative models of the final engine.

#### 4.1 Full Scale Hot test

Nammo is responsible for carrying out the full scale test program of the SPARTAN propulsion system before commencing the flight test program. All testing will be carried out on Nammo’s own test centre, which contains all necessary state-of-the-art hardware like: environmental test facilities, 6-DOF (Degree Of Freedom) force cells, high speed video cameras, calibrated multi channel high-frequency band recording equipment, skilled personnel and more. Nammo also have seven years of experience in testing hybrid rocket motors with thrust levels up to 30kN.

Two main Full Scale Hot test will be performed:

- **A static test**, devoted to measure SPARTAN vehicle actual thrust and lateral forces. See Figure 9.
- **A dynamic test**, represented by a **low altitude drop test** (to mitigate the risks for the final full height drop test from helicopter), in which the SPARTAN vehicle is lifted with a crane or an appositely designed structure and is dropped locking one or two degrees of freedom.

In the full scale restricted movement drop test (Figure 10 left) the lander is forced to move vertically, hence without requiring stability control. In the quasi non-restricted movement drop-test (Figure 10 right) the lander is dropped from low altitude hold by a wire rope for safety purposes and is allowed to start the thrusters and land softly: in case of failure the wire rope will retain the vehicle to crash on ground.
4.2 Cold and Hot test on single engines or technologies

Prior to the Lander Full Scale Hot tests, during the development phase different models will be manufactured to verify the validity of the throttling technology or of entire thrusters concepts. In fact the development of the rocket motor will be conducted at various stages:
1. HW Design phase (HW = Heavy Wall test item)
2. HW test phase
3. FW Design phase (FW = Flight Weight test item)
4. FW test phase

The HW engine will have the same internal geometry and size as the proposed FW configuration; however its surrounding structure will be oversized. Its construction will also be modular, meaning that it can be re-configured, assembled and re-assembled in a fast and efficient way. In addition, the HW design will be prepared to house several sensors for measuring the performance of the rocket motor. HW and FW models and the propellant they contain, will undergo a series of static Cold and Hot test:

**Fuel Characterization:** a complete characterization of the fuel will be given in terms of ballistic and mechanical behavior and theoretical specific impulse under design conditions and throttling operations. Flame visualizations with a high speed and high resolution camera will be performed getting detailed information on the quality of the combustion process. Thanks to a specific implementation of a radial burner, the behavior or formulations under quasi steady combustion will be evaluated. As a complimentary test, mechanical features will be evaluated through uniaxial tensile tests performed at one strain rate and ambient temperature. Also dynamic mechanical analysis will be performed. Elastic, visco-elastic and break-up properties will be reported.
**Subscale Cold test:** the test is devoted to verify the throttling technology. The setup will consist of a pump to pressurize the liquid simulant and pump it through the throttle. A closed loop setup is employed so that tests can be performed at specified conditions for prolonged periods of time. The throttle is controlled by a PC with data acquisition hardware and control logic. Measured quantities include the mass flow through the throttle and the pressure before and after the throttle. Therefore the performance of the throttle and the oxidizer feed system, quantified by mass flow as a function of pressure drop, can be completely characterized.

![Figure 11 Cold Test Setup schematic](image)

**Full Scale Hot test:** these tests will be conducted to validate the throttleable hybrid motor advanced code, a tool which will be developed and used to design the hybrid motor, and to assess the motor performance at steady-state and during modulation, before progressing to full-scale testing. The lab model hot fire set-up is made-up of pressurant and oxidizer tanks, oxidizer feed-line, flow control device, injector and combustion chamber. The diagnostic includes measure of thrust, pressure, temperature, oxidizer and fuel flows. Majority of diagnostic will be used both on codes validation and motor performance assessment.

The diagnostic system for assessing the performance of the throttleable motor will be designed and developed to be used on motor cold and hot-fire testing. The objective of the diagnostics is to assess and quantify the response of the motor to thrust modulation as function of throttling.

System performance of the throttleable device will be quantified as:

- Thrust response characterization (i.e. time, overshoot) during throttling;
- Performance and combustion stability of the motor at different throttling settings and during continuous throttle.

Variation of functioning parameters of the hybrid motor (i.e. oxidizer and fuel mass flow rates, combustion chamber pressure, combustion efficiency etc.) will be measured and correlated with the throttling command and resulting thrust modulation. A schematic of the diagnostic system, to be applied to the motor set-up for hot fire and cold flow tests, is also shown in Figure 12.
5. Conclusions

The SPARTAN project, which aims are to develop a new throttling concept applied to an appositely designed hybrid engine in order to be capable of performing a wide thrust range in a dynamic thrust variation regime, and to develop a soft landing test to demonstrate the technology peculiarities, is presented with the detailed description of the main present and future activities.

6. Acknowledgement

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