DEVELOPMENT OF THRUSTER POINTING MECHANISMS FOR CUBESAT & SMALL SATELLITE APPLICATIONS

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ABSTRACT

In recent years the reduction of size of satellites has led to Chemical (CP) and Electric Propulsion (EP) systems being developed specifically for Cubesats and Small satellite applications, mostly in the form of modular compact solutions compatible with standard Cubesat interfaces.

The need for higher impulsive manoeuvres and/or longer firing durations together with the limited capacity of the Cubesat systems to absorb and compensate residual torques has revealed the need of implementing gimballed thruster solutions. Based on this LMO has developed a series of CP & EP Thruster Pointing Mechanisms (TPMs) for CubeSat and Small satellite applications with leading Chemical and Electric Thruster suppliers for CubeSats.

This paper presents the family of TPMs developed by LMO for CP & EP applications. The complexities in the design, build and testing of TPMs for small satellite applications are described. A review of the driving requirements and how to tackle the complexity of scaling down technologies is also provided.

TPM DEVELOPMENT FOR A 2U CHEMICAL PROPULSION SYSTEM

A Thruster Pointing Mechanism (TPM) has been developed to control the orientation of a 1N thruster for a 2U chemical propulsion system being developed by LMO for the “2U High Test Peroxide (HTP) propulsion system” project in the framework of an ESA de-risk program. The design of this TPM is optimized for a 12U platform. The key design drivers have been derived from the higher-level requirement specification of the 2U propulsion system, which is heavily based on the Open Cosmos (OC) 12U platform. The propulsion subsystem uses Nammo’s MHTP-1N thruster, which is the HTP variant of the flight qualified hydrazine thruster LEROS-MHT-1N thruster. The main mechanical interfaces of the TPM have been designed around this thruster, although the design remains flexible for implementing other thruster models. Although the selection of materials is based on HTP, the philosophy of the design remains the same for hydrazine. At system level this thruster is operated at the lower range of the operational pressures (~5 bar) to produce a thrust of ~350 mN with a measured Isp of 172 seconds [1]. This thrust is relatively large for a 12U platform where the biggest reaction wheels typically have a torque capacity in the order of 2 mNm and a momentum storage capacity of about 30 mNs. This requires the thrust vector to have an offset of no more than ~3 mm with respect to the platform CoG to provide a 50% margin in the RW torque capacity and limits the maximum duration of the firing to ~ 25 seconds. It is to be noted that this large thrust has been selected precisely to achieve faster transfers on a Cubesat mission. The big perturbations that the thrust can generate on the Cubesat added to the uncertainties associated with the Cubesat CoG location make the use of the TPM a necessity. In addition to this, the CoG migration due to the propellant depletion throughout the mission is not negligible and needs to be compensated for. LMO has built a model to analyse this migration based on all possible locations of the CoG at beginning of life (BOL) and the average displacement, considering a 20 kg platform and a 2U propulsion system based on HTP is in the order of ~7 mm which, based on the discussion above, requires to be compensated.

A detailed analysis was done early in the programme to ensure that, given the configuration of the propulsion system in the OC platform, the TPM would allow the thrust vector to be pointed to all possible locations of the platform CoG inside the volume of uncertainty defined by the platform specification. This ensures maximum flexibility to cope with different starting configurations in multiple platforms, using essentially the same design. The results from this analysis drove the optimum location of the gimbal in the platform, the offset initial angle of the thruster and the angle range requirement.

As part of the ESA programme, the technical specification for the TPM was generated. The key driver requirements for this unit (designated as TPM-CP-1N) can summarised as follows:

- Envelope: < 1U
- Rotation axis: 2 axes independent control
- angle range: 10° half cone
- angular resolution: 0.05°
- pointing accuracy: 0.3° (1-sigma, including thermal effects)
- max velocity: 1.5°/s (delta-V application)

- max cycles: 2000
- Operational temperature: – 20°C to +80°C
- Mass: 0.300 kg maximum

The resulting TPM design is shown in Fig.1. It consists of a 2-degrees-of-freedom (2-DoF) mechanism that allows rotation around two axis that are contained in the same plane. The assembly is comprised of three main parts: (1) an outer body or TPM bracket that links the gimbal to the satellite platform and therefore remains fixed relative to the satellite, (2) a ring moved by Actuator 1 (henceforth named simply M1 Ring), and (3) an inner Ring connected to M1 Ring, moved by Actuator 2, and to which the Thruster is attached (henceforth named simply M2 Ring). The overall envelop is 81 mm x 81 mm x 56 mm.

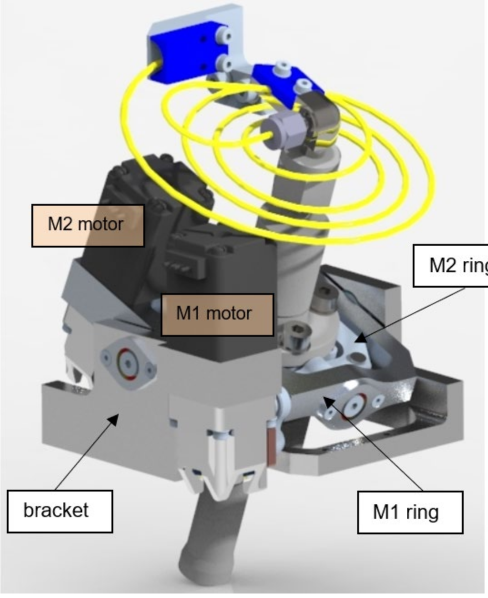

Figure 1. TPM-CP-1N design

It is to be noted that the TPM concept includes the feed lines to the thruster, which now require to be flexible enough to cope with the movement of the thruster which involves a combination of rotation + translation. The torques produced by the flexible pipe are design drivers for sizing the actuators, which also impacts on the power consumption. A lesson learnt from this programme is that the flexible pipe design has to be done iteratively with the design of the mechanism from early days. LMO has produced multiple flexible pipe designs of various materials and varied geometries. The example shown in Fig.1 is a 1/16'' metallic pipe with the maximum number of coils used. Each geometry selection requires a bespoke connection design to ensure that the fitting connection to the thruster does not absorb any stress that could lead to leakage during the mission lifetime. The pipe design has a complex geometry that exploits mainly the torsional stiffness of the pipe while ensuring that the pressure drop through the pipe does not impose stringent requirements on the pressurant budget of the system (pressure regulated system).

The TPM envelope was one of the most stringent requirements imposed by the available volume around the thruster. It heavily depends on the overall propulsion system configuration. In the case of the LMO system, the lateral dimensions were more stringent than the total height requirement. This made the trade-off between linear and rotary actuators a straightforward decision and the linear actuators result in the selection of the latter, due to the challenge of finding rotary actuators which could be accommodated within the envelope and produce the required torques without the aid of a gearbox. Within the family of linear actuators available in the market a trade-off was done between solenoid, voice coils and stepper motors. The result was the selection of stepper motors due to their force capacity, their ability to hold the position when unpowered and the possibility of operating them in open loop, provided a good motorization margin is achieved. In this design a motorization margin of 50% was selected.

The selection of linear actuators comes with its own challenge: the conversion of linear actuation to rotary movement in the assembly requires designing links that require stringent tolerances, including proper guidance to ensure the motors do not absorb undesirable forces that can greatly degrade their lifetime. In this design the guide and linkage design included the selection of tribologically suitable materials that can operate without lubricant for the required number of cycles. It is to be noted that for the particular case of Delta-V operation the number of cycles is not too demanding and provides margin if a reduction of the motorization margin is required. The wearing of the materials has to be accounted for in a tolerance mathematical model that assesses the impact of the key mechanical tolerances in the overall pointing accuracy. At the moment of writing, the lifetime test of the assembly is due to happen in a month, where the suitability of the selected materials will be validated.

TPM-CP-1N Analysis

A random vibration analysis was performed in Ansys Workbench to determine the design robustness (Fig.2)

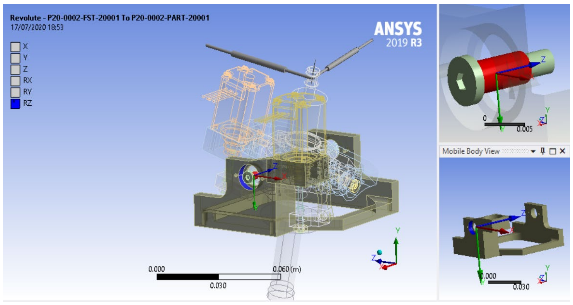

Figure 2. TPM EM Analysis in Ansys

To simulate the effect of the pig tail acting on the valve, 3 spring elements were applied in the 3 main directions. These are derived from the worst-case result of the expected pig tail stiffness analysis. The stiffness of each spring element is simply calculated by dividing the reaction force in each direction by the respective displacement. Assuming the pig tail always remains in the elastic domain its behaviour should be linear with displacement.
This analysis showed that the current gimbal EM design can sustain the necessary load levels during launch.

TPM-CP-1N Build and Testing

The lessons learnt from the gimbal development model built under previous programmes (see [2]) were implemented in the design of the TPM Engineering Model which was built and tested under the ESA de-risk programme. The control electronics to command the TPM was supplied by LMO.

The linear actuators were initially tested under compression and tension loads representative of the expected loads at assembly level by means of a dedicated test setup (Fig.3) that allows to combine different sets of springs to achieve a range of forces. The setup allows for operation in both directions while measuring the real displacement of the actuators and compare it with the commanded actuation. This allowed to characterise the motors and understand how the velocity and load affects the accuracy (essentially loss of steps in a random fashion), bi-directional repeatability (this is dependent on the velocity), hysteresis effects, etc. Based on these results the optimum operation mode was selected and the errors were analysed and input into the assembly error budget.

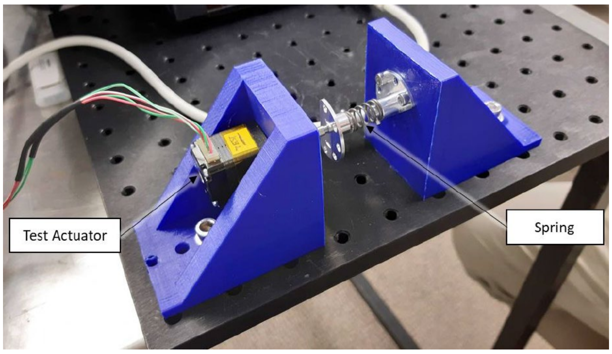

Figure 3. Linear actuators characterisation

The TPM assembly was tested by installing a laser pointer in a position coincident with the thrust vector, such that the laser direction represents the thrust (Fig.4). The TPM performance can then be measured by measuring the displacements of the laser spot in a target plane placed perpendicular to the laser nominal position and converting the displacement in the target reference frame to angular displacements.

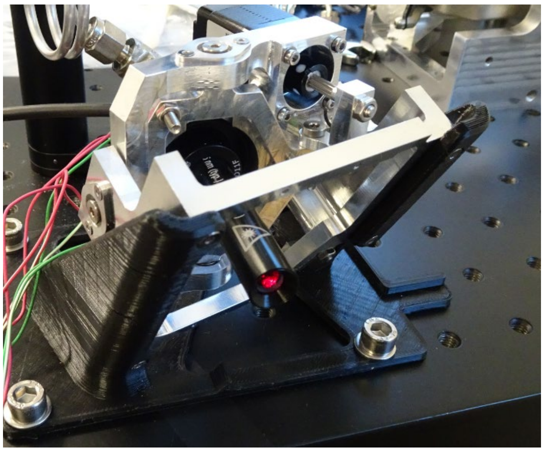

Figure 4. Laser assembly on TPM EM during a test run

The TPM EM was tested for resolution, accuracy (cumulative and bi-directional), travel range and velocity profile. Tests were carried out in ambient conditions only and multiple flexible pipe configurations were tested. It was found that the influence of the material and geometry of these flexible pipes was far larger than initially expected. One of the key challenges is not only the design of the geometry, but also the installation of the flexible pipe with clamps that guarantee that the pipe behaves in the direction it was designed for, without local plastic deformations and without stressing the connections to the thruster and valves. This required multiple design iterations including modification of the motor links. After many trials LMO has downselected the geometries and materials that work best. Among them is a flexible PFA hose with bespoke end connection, and several geometries in aluminium pipe of 2 different sizes, as a result of the trade-off between motorization margin and pressure drop through the pipe. The best achieved assembly accuracy was 0.099° and 0.178° (1-sigma) for motors M1 and M2 respectively. At the moment of writing this paper, a new design iteration has been made in order to improve the robustness of the links and is due to be tested in the next month. The best flexible pipe solutions found will be validated through a lifetime test and will be later qualified as part of a follow-on program to take the TPM-CP-1N to qualification level in 2022 making it ready for flight.

TPM DEVELOPMENT FOR A CUBESAT EP ENGINE

LMO is supplying a miniaturized system for the thrust vectoring of Exotrail's ExoMGTM – micro thruster as part of a concurrent engineering development programme.

The design builds on elements and lessons learnt from the ESA de-risk programme described in previous sections. The key driver requirements for this unit (designated as TPM-EP-EX) can summarised as follows:

- Envelope: < 1 U
- Rotation axis: 2 axes independent control
- angle range: 15° half cone
- pointing accuracy: better than 0.25° (1-sigma, including thermal effects)
- max cycles: 3000
- Operational temperature: – 30°C to +60°C
- Mass: 0.500 kg maximum

The resulting TPM design is shown in Fig.4. Similar to the concept described in previous sections, it consists of a 2-degrees-of-freedom (2-DoF) mechanism that allows rotation around two perpendicular axes that are contained in the same plane. The assembly is comprised of three main parts: (1) the TPM bracket that links the mechanism to the satellite platform and therefore remains fixed relative to the satellite, (2) The TPM inner ring that rotates with respect to the TPM bracket around a single axis (X-axis) by means of bearings, and (3) a thruster I/F plate, where the ExoMGTM thruster is installed, which is at the same time linked to the TPM inner ring by means of bearings and rotates with respect to it around an axis perpendicular to the other one.

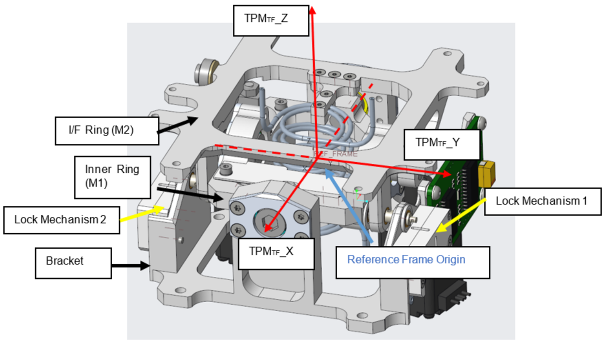

Figure 4. TPM-EP-X Design

This design concept has an envelope of 96 mm x 96 mm x 85 mm (including the accommodation of the flexible pipe that feed the propellant to the ending) and can perform rotations of ± 15 degrees around both axes independently.

Two locking mechanisms (each one with internal redundancy) have been incorporated in this design. These consist in a simple design of pins that hold the thruster I/F plate and inner ring in place under the loads experienced during launch. It is based on an electrical cutter that is activated only once in-orbit, with a power consumption (each) that can vary between 3.5 W and 7 W depending on how fast the actuation is needed. This is a one-off actuation.

The actuators are linear actuators that use stepper motors and a gearbox to convert step angle into translation (travel/step). They are attached to the mechanism by means of links that convert their linear travel into rotation. All bearings and the motors use a lubricant compatible with operation in vacuum.

TPM-EP-EX Analysis

Several analyses have been carried out to design the TPM-EP-EX engineering model. One of the main drivers to sizing the motors is the elastic behaviour of the flexible pipes. For EP engines the baseline solution is to use stainless steel pipes to avoid the risk of humidity presence in the lines. Sizes like 1/16’’ SS pipe are a reasonable solution considering pressure drop for the given flowrates are not very critical (in comparison with liquid propellant systems). In order to assess wall thickness, pigtail geometry (essentially the helicoid parameters), etc. the Ansys workbench has been used (Fig.5). This analysis aims to translate the deformation of the pigtails into the torques that the motors are required to generate. One of the challenges in this design is the constraint volume available to accommodate the pigtails.

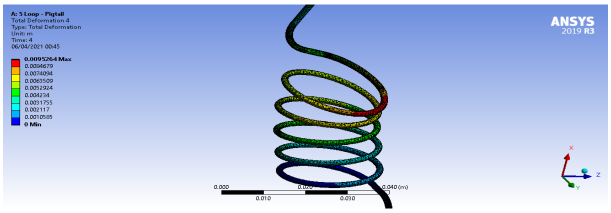

Figure 5. Derivation of pigtail torque vs displacement

Motorization margins have been analysed considering the effect of the tubing, the engine harness, friction of the bushings and friction of ball bearings using well understood models, on top of which the typical ECSS margins have applied to demonstrate an acceptable motorization margin (a ratio of 2.65 and 5.86 for motors 1 and 2 respectively).

To assess the structural integrity of the TPM a dedicated structural analysis was done (Fig.6). This included modal analysis, random vibration, and quasi-static acceleration.

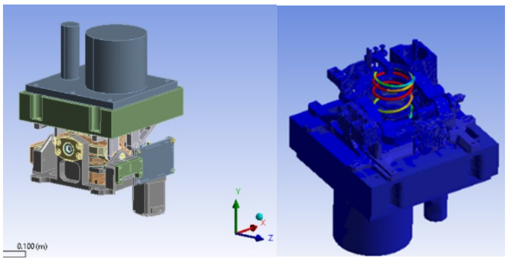

Figure 6. TPM-EP-EX structural analysis (Ansys)

The structural analysis was key to detect areas that needed improvement and it resulted in changes of materials for some components, modification of shape in one of the TPM rings, and a change in the configuration of the interface between the engine and the TPM. The final output showed that the TPM meets the structural requirements and, since it was done using a model of

engine heavier than the actual engine it provided an additional margin.
Finally, a thermal assessment was provided demonstrated suitability of the design and provided inputs to the thermal control system in case it becomes a necessity as the program progresses.

TPM-EP-EX Status

At the moment of writing this paper the TPM-EP-EX is being manufactured and the next stage will consist in the assembly and acceptance testing of the unit. It is expected that the test programme to be carried out at Exotrail's facilities will take the technology to a maturity level of TRL 5 in Q4 2021/Q1 2022.

TPM DEVELOPMENT FOR A HYDRAZINE 22N THRUSTER

LMO was awarded a grant by STFC Harwell and Sci-Tech Daresbury Campus Cross-Cluster Proof of Concept Grant to develop innovative gimbal technologies for On-Orbit satellite servicing. The objective of this programme is to develop a Proof-of-Concept (PoC) TPM for a 22 N monopropellant thruster that operates with hydrazine, by scaling up the previous LMO concepts to accommodate thruster ranges of up to 22 N therefore covering a wide spectrum of chemical thrusters used for most missions, initially for small spacecraft including in-orbit servicing missions (e.g. Clearspace, MEV) and space exploration missions. The goal was to design, manufacture, assemble and test a prototype gimbal for a 22 N-size engine validating the design approach by test.

In order to ensure a technical solution that is applicable to the market, LMO partnered with Nammo who supplied representative hardware, together with technical inputs to the TPM requirements definition. Nammo supplied a thruster (Fig.7) that runs on hydrogen peroxide at 98% concentration (also known as HTP). This thruster has already successfully undergone hot fire testing, meaning that real experimental data is available to support the design activity. This thruster is representative in size to a 22 N thruster.

Figure 7. Nammo engine used for the TPM design.

The most challenging aspect of this TPM was the design of fluidic connection, i.e. the lines and joints to feed the liquid propellant into the thruster. The implementation of metallic pipework formed into a pigtail shape to achieve the required flexibility to work at different angles (like the ones used in the smaller LMO developments) has its drawbacks: pigtails result in larger volume envelopes and impose restrictions due to the need of accommodating the lines in the design. They also result in high resistive torques which impose more requirements on the motors, resulting in larger motors and higher power consumption and thermal considerations. An added complexity is the design of the pigtail to perform satisfactorily under random vibration loads, given that it is basically a resonator. All these factors increase considerably as the pipework diameter increases. For bigger thrusters (e.g. 22 N) this solution is no longer optimum from many points of view, and the hydraulic solution needs to be re thought.

LMO has taken the approach of designing a novel fuel rotary joint that can be embedded in the gimbal mechanism itself, using internal channels inside the gimbal structure to feed propellant into the thruster. The TPM therefore becomes part of the system pipework and all aspects related to pressurised systems, water-hammer, pressure drop and chemical compatibility become an intrinsic part of the TPM design. This means that the simplicity of design on the outside translates into more complex design in the "inside" and the TPM can be optimized to operate with different engines. An advantage is that this design is relatively easy to expand to bipropellant engines.

This solution results in virtually zero resistive torques (other than those arising from the friction of the mechanism and seals which are uniform and independent of the rotation angle as opposed to pigtails), an estimated 10% reduction in weight, 40% reduction in volume, and estimated 60% reduction in power consumption due to the reduced torque. Such solution also becomes easier to integrate into existing platforms, given that the fluidic connection is greatly simplified and can be made bespoke for different applications.

From LMO discussions with key players in the in-orbit servicing market, the following key functional requirements were derived for this unit (designated as TPM-CP-22):

- Propellant: Hydrazine (monopropellant)
- Steering Range: ± 10 degrees
- Pointing Accuracy: 0.5 degrees
- Mass: < 1 kg

These functional requirements were later implemented in the gimbal technical requirement specifications used for the detailed design. The resulting design is shown in Fig.8. It is in essence similar to the previous ones described above, with the main difference being that no flexible line is present.

This prototype TPM makes use of metal 3D printing technology for the internal channels. The selection of linear actuators is once more driven by the need of leaving the main joins available for the fluidic rotary joints. Motor encoders have been implemented in this prototype just for characterization purposes, but this technology is not yet directly transferable to a space application. Other methods of feedback control are being researched in parallel by LMO given that the size of this TPM enables the implementation of market available solutions.

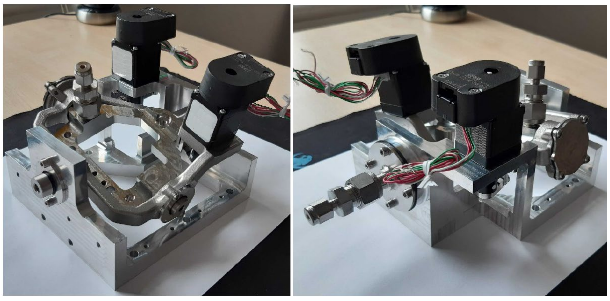

Figure 8. TPM-CP-22 assembly

The TPM was manufactured, build and assembled successfully and preliminary functional tests using gas only have shown it behaves as expected. The thruster was mounted on it to verify the interfaces and clearances are as per design (Fig.9). Not shown in Fig.9, the connection from the thruster to the TPM will be a rigid pipe connection.

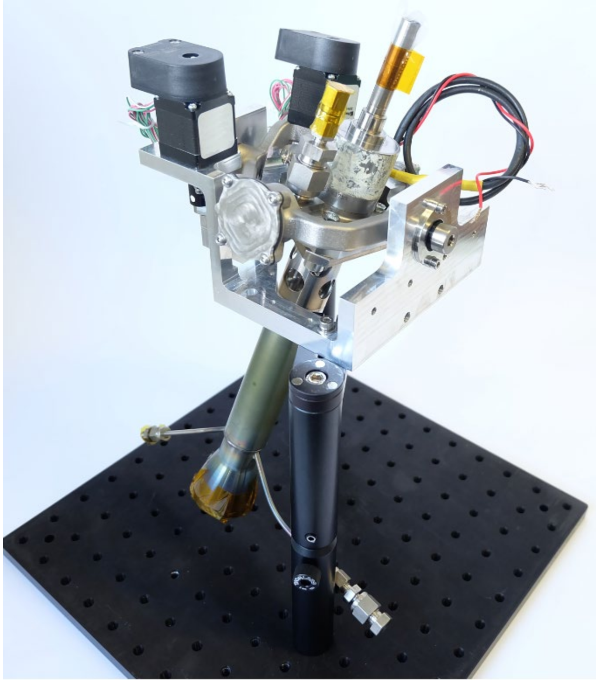

Figure 9. TPM-CP-22 with thruster mounted.

A test campaign using water (simulant) is due in the following months to characterise the hydraulic parameters (pressure drop vs angles, etc.) and also the accuracy and general behaviour of the mechanism. It is expected that this TPM will reach TRL4 in Sep 2021.

CONCLUSIONS

LMO has developed a family a Thruster Pointing Mechanism for a variety of applications and ranges: chemical propulsion engines ranging from 1N – 5N, and 5N – 22 N, as well as electric propulsion engines. The process of development has been done together with the identification of the needs for these TPM solutions from the market, allowing LMO to capture the key driver requirements from key players (including the technical supervision from ESA) at an early phase of the development to ensure a solution compatible with future market needs. For the small engines (both CP and EP) the miniaturisation of the mechanism and the simplicity of the design make the TPM solutions compatible with most Cubesat requirements. For larger engines, the compact designed achieved by the novel design of the fluidic path makes up a modular solution.

The solutions described here are building blocks that setup a technology that can be expanded and progressed further as the requirements become more mature and the industry implements them. LMO's vision for the future is to offer a fully reconfigurable propulsion system (based on chemical propulsion) with steering angles far exceeding those available currently. This will allow not only for more flexibility, and more sophisticated optimization techniques for orbital manoeuvres, but also to reduce the total number of thrusters needed for complex missions.

LMO would like to thank ESA, the UKSA, STFC, Nammo, Exotrail and Protolaunch for their support and guidance during these developments.

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