Engineering Design of a Thruster Pointing Mechanism (TPM-250) for Deep Space and IOS Nanosats

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Abstract

This paper presents preliminary the design of the Thruster Pointing Mechanism (TPM-250) for electric propulsion thrusters for nanosats. The work described in the paper covers the most critical requirements, trade-off and design description, along with plans for the future development. Project will continue until the development and the acceptance of the Thruster Pointing Mechanism Flight Model for the ESA M-Argo mission. A breadboard and an engineering model will be built during 2022, including the control electronics, allowing us to reach TRL 6 towards the end of 2022 or early 2023.

AVS is a worldwide leader in the development of complex instrumentation for Science and Space applications. The background of AVS in vacuum engineering, high-precision mechanisms and mechatronic systems has led us to become one of the only few specialized and EN9100-approved Space mechanisms suppliers in Europe. AVS and its subsidiary URA Thrusters are also one of the most active players in the in-space propulsion field, and will use this specific development as the stepping stone to develop a wide variety of TPM products for a wide set of missions, platforms and application, from nano or micro-satellites, to large GEO spacecraft.

In particular with the M-ARGO's TPM, the system design is challenging due to the typical nanosatellite volume (in this case half 1U), power, and mass constraints. At the same time, the requirement to fit the tubing and harness inside (particularly possible connectors from thrusters) is limiting space inside the allowable volume. Likewise, it is creating additional resistive torque terms, which are quite difficult to assess at initial stage without testing.

Introduction

The aim for the project was to design a pointing mechanism for electric thruster propulsion for nanosat, for the development of a miniature pointing mechanism (TPM250) compatible with standard nanosatellite requirements, to enable deep space missions, inter-planetary exploration or rendezvous with a Near Earth Objects using CubeSat platforms. Due to the limited resources of CubeSats in terms of power, mass and volume, thrust vector control needs to be implemented to enable efficient use of all on-board resources, including the propellant.

AVS plans to develop a product able to compete against current TPM commercial solutions, by offering commercial TPM systems by 2025, not only for CubeSat platforms, but also for larger satellites and complex institutional missions. The project is being funded by European Space Agency General Support Technology Programme.

The paper covers description of the main design drivers, the technical trade-off that resulted from it, the selected solution and final budgets. Plans for further development are presented at the end of the paper.

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Technical Requirements

The main design requirements for the TPM are presented in Table 1.

Table 1. TPM main requirements

ID	Description
Req-1	TPM shall accommodate payload with external dimensions of 80 mm diameter, height 70 mm, CoM (Center of Mass) at 54 mm from IF (Interface) plane and mass of 0.5 kg
Req-2	TPM shall withstand maximum operating thruster temperature of 100°C
Req-3	The TPM shall accommodate the tubing and harness required for the ETPM from the spacecraft.
Req-4	The TPM shall fit into half of 1U Cubesat volume (100x100x50 mm)
Req-5	The TPM-Thruster assembly shall comply with the provided Tuna-can dimensions in launch configuration.
Req-6	The mass of the TPM, including all features (possible HDRM, required harness…) shall be lower than 280 grams, including maturity mass margin factors (20% currently considered).
Req-7	The TPM shall enable a positioning within a resolution of 0.05 degree at each axis
Req-8	The TPM shall provide a range of ±5 degrees around each axis
Req-9	The TPM shall consume no more than 2.4 Watts at its maximum power setting (+20% margin currently considered)
Req-10	The TPM shall withstand, with no degradation of functionality nor performance, a maximum duration of 5 years in orbit, and no less than 3 years.
Req-11	The TPM shall enable 500 full range cycles during in-orbit operation.

Technical Trade-off

State of the art

An analysis on the current State-of-the-art systems related to TPM has been carried out, which includes other possible variations such as Thruster Orientation Mechanisms or Electric Propulsion Pointing Mechanisms. Although most of the systems are adapted to larger thrusters compared to the current one considered, those same ones are used mainly for Electric Propulsion. There are several types of architecture considered for the TPM, the concepts are described further in the paper.

The requirements that have been established by the TPM of this proposal are relatively demanding, mainly regarding the available volume and the limited mass. Based on analysis of various systems of the current State of the Art, with many different configurations that have been designed for specific thruster assemblies with their own requirements, some conclusions can be drawn focusing on the following specific features:

- Joint/motion type. There is a large tendency to use gimbal-based systems. They present the advantage of reduced joints, similarity between structural elements, and a "direct" rotary actuation, without having relative motion transformation.
- Number of actuators: All studied concepts include two actuators. Gimbal systems have theirs assigned directly to each rotation axis, while the linear actuator concept studied provides a hinged platform so one actuator can be removed and control the platform with only two motors.
- Range: The usual required range that the systems need to fulfil is low, ranging between 5 to 7 degrees, similar to the established range of 5-degree half cone to the current TPM proposed.
- Actuator type: The use of stepper motors is predominant within the concept actuation. Stepper motors provide a relatively robust, low-cost solution, and accurate positioning in open-loop control configuration. Their inherent detent torque coupled with a high gear ratio provides the possibility of holding a position while the actuation is unpowered.

- Thruster tubing/harness: Leaving a central gap on the TPM and connecting the thruster from the platform through the thruster mechanical interface is a common feature in some concepts. A helical configuration for the tubing reduces its resistive torque when the thruster is rotated.

In this paper, following the state of the art analysis and other mechanism analysis, two subsystems have been the main focus of further study: the actuation, that translates into the type of motor considered, and then the mechanism concept, which drives the structure, transmission system and thruster interfaces, among other critical sides of the TPM.

<u>Actuation type selection</u>
Following the state-of-the-art analysis, stepper motors are the preferred choice for most of the concepts analyzed so far. In determined applications within some of them, piezoelectric motors and Brushed DC motors are mentioned as well. These actuators (and similar ones) are analyzed for its possible use in the TPM.

Piezoelectric motors have been undergoing an increasing demand in more uses. Their accuracy and operation method makes them robust and adaptable to many applications. As of characteristics of interest for this application besides their accuracy, they provide high detent torque at small sizes, moving only when powered. However, they present some disadvantages. They usually require relatively high voltages to enforce their motion, sometimes translating in high power. Their electronics are usually custom made for the specific actuator and application, incurring higher costs, and are not supported with the large heritage of stepper motor electronic components.

Brushed and Brushless DC motors could be considered as well. Brushed ones present a simple, low-cost choice, with many different products available. However, their use is limited due to the constant wearing, their efficiency is low, and they present poor thermal characteristic in vacuum, among other disadvantages. Brushless DC motors are an improved version of the brushed ones, providing high torque at high speeds, doubling the output compared to them. They are vacuum compatible and have an improved heat dissipation. However, their cost, mainly related to the required electronics, is higher and of more complexity. They usually require closed-loop position control and positioning sensors, and their unpowered torque is lower than the stepper's.

For the application at hand, then, where a simple system with high positioning accuracy, low speeds and high holding and detent torque is required for long periods, the stepper motor is the baseline selected, although other options could be considered in the future.

<u>Mechanism Trade analysis</u>
The initial mechanism trade analysis provides a final selection among different traded general concepts, developed and filtered using the previous analysis performed as baseline. "General concepts" is referred to the mechanism and motion type, without having specific components related to each concept. Some assumptions are therefore placed before preparing the Figures of Merit and providing the concepts with scores based on them. Following the State-of-the-Art Analysis in TPMs, the same actuation based in stepper motors will be baselined for each option.

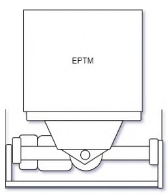
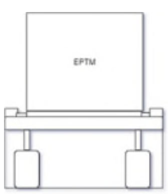
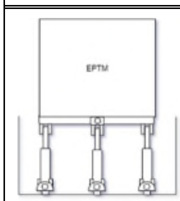
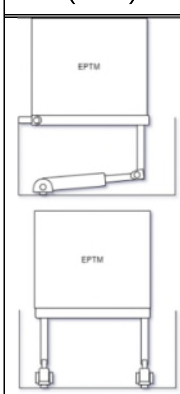
- For concepts using direct rotary motion, a gearbox is assigned. The ratio considered will be 100.
- The baselined leadscrew is a Stainless Steel 5-mm diameter and 0.5-mm pitch one, assumed from an analysis on lead/ball screws that suppliers like Reliance can provide.
- Being almost negligible in mass and volume, all joints are considered with the same mass and volume, although the required DOFs for each of them will be included in the trade. A stainless steel, 5mm rod-end characteristics are baselined
- The "thruster platform", or the thruster support, is the same for all concepts
- The structural material used for all concepts is Aluminum 7075-T6.

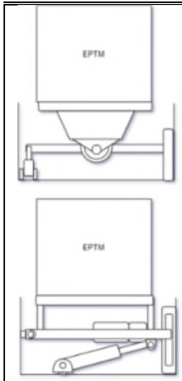
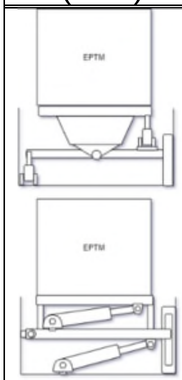
The trade-off was intended to provide orientation on which concept to select. Moreover, rather than choosing a specific one, the result was meant to limit many choices to just some of them and give insights on which kind of mechanisms could be better suited for the TPM.

Concepts: Description

The considered concepts are shown and described in Table 2. Each concept has a depiction through a simple, conceptual drawing to understand the mechanism's function. The specific position of the actuators, shape and volume of the joints and other features are not representative.

Table 2. Description of the concepts considered for the Trade-off

CONCEPT	DESCRIPTION
 (GRM)	**Gimbal Ring miniaturized concept** • Based on the Gimbal Ring concept. • Gimbal joint type mechanism. • Thruster platform is not connected with the primary structure. • 2 actuators. • Direct rotation actuation. • The first actuator rotates the gimbal ring with reference to the lower bracket, while the second actuators rotate the upper bracket with reference to the gimbal ring.
 (VAG)	**Vertical Actuation Gimbal concept** • Concentric Gimbal joint type mechanism. • Thruster platform and middle platform are connected to primary structure through two joints. • 2 actuators. • Linear motion actuation. • Two concentric plates, with their hinges perpendicular to each other, are pushed by 1 actuator each to provide the required rotation.
 (GS3)	**Gough-Stewart 3 actuator platform** • Based on the Gough-Stewart platform. • Thruster platform is not connected to the primary structure. • 3 actuators. • Linear motion actuation. • The orientation is given by adjusting the lengths of the 3 actuators, allowed with the 3 DOF joints that unite the structure with the thruster platform.
 (HAL)	**Horizontal Actuation Lid concept** • Based on the Austrian Aerospace TPM concept. • Thruster platform is connected to a primary structure through one hinge. • 2 actuators. • Parallel linear motion actuation. • The horizontal linear actuators, already inclined in resting position and with the required joints to allow their movement, pull and push the vertical arms connected to the thruster platform. Independently actuated, they can provide 2 axis rotation

 (LRS)	**Linear-Rotary in Series concept** • Combination of base concepts. • 2 platforms. One hinged to the structure, while the thruster platform is connected to the first one. • 2 actuators. • Linear motion followed by rotary motion • Linear motion actuation for 1 axis, while a direct rotation is applied for the other, similar to the GRM concept. The linear actuator provides a rotation with reference to the hinge, supported by a prismatic joint on the other side to keep alignment, while the second rotation is performed by a motor.
 (LLS)	**Linear-Linear in Series concept** • Similar to the HAL concept but with actuators in series. • 2 platforms. One hinged to the structure, while the thruster platform is connected to the first one. • 2 actuators. • Linear motion followed by linear motion • Linear actuation for both axes. The first actuator provides a rotation with refence to the hinge, supported by a prismatic point on the other side to keep the alignment, while the second linear actuator creates the rotation of the thruster platform

<u>Figures of Merit: Rationale</u>

The Figure of Merits (FoM) finally selected for the concept trade-off have been selected following the requirements and critical characteristics that would define the further design of TPM.

- PTA (Pointing Accuracy) Proportionality: Inverse, Accounts for the accuracy that the system can achieve;
- MVL (Mass & Volume) Proportionality: Inverse, Accounts for the expected total mass/volume of the mechanism, which are related for the trade-off;
- HER (Heritage) Proportionality: Direct, Accounts for the heritage that the mechanism type has had, be it in space or in other known applications;
- NAC (Number of actuators) Proportionality: Inverse, Accounts for the number of actuators that the system requires, Number of actuators can also be used as a representative of power consumption and complexity, amount of TPM harness. The scoring is straightforward;
- NJN (Number of Joints) Proportionality: Inverse, Accounts for the number of joints of the mechanism, considering also their DoF;
- LLD (LLD requirement) Proportionality: Direct, Accounts for the possible requirement of a Launch Locking Device or a HDRM to support the TPM during launch;

<u>Weight factors</u>

Once the FoM are defined, their prioritization, and therefore the applied weight to each of it, has been made by a priority matrix, where each Figure has been compared to the others, establishing a ranking. The results on the weights are shown on the visual pie chart, Figure 1.

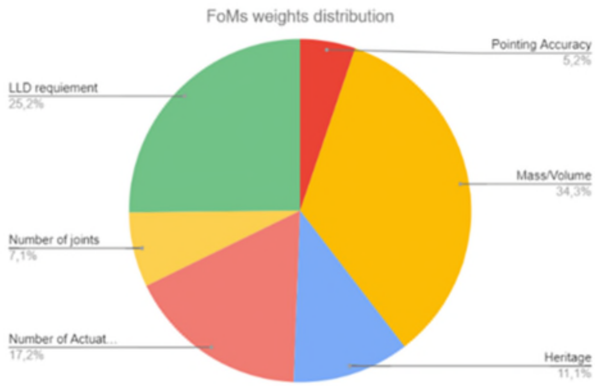


Figure 1. FoM weight distribution pie chart

As critical requirements for a mission like M-Argo where the considered spacecraft is a Cubesat, limiting the mass and the volume is critical for every system included within it. MVL therefore would obtain the highest weight with 0.343. The addition of an LLD would imply an increase in complexity, mass and volume that is rather reduced or avoided, and therefore it ranks second with a 0.252, followed by the number of actuators. Although, as mentioned before, heritage is crucial when systems for the space industry are developed, the requirements of the M-Argo mission, where the TPM will be used as TVC and its integration requires the downsizing of many components, provide an opportunity for innovative solutions that are not specifically required to mimic the current system, but either include reliable components and materials for their application in space. Following the number of joints in second to last position, Position Accuracy is the FoM with the lowest weight, with 0.052.

<u>Concept Scoring and selection</u>

Considering each concept with the aforementioned figures of merits, the results obtained are represented on Figure 2. The trade-off results show a rather clear tendency toward the gimbal ring (GRM) and the vertical actuation, concentric gimbal joint (VAG) concepts. The GS3 is heavily punished due to its extra actuator and “free” thruster platform mainly, although it does not perform badly in the Mass/Volume FoM. LRS and LLS obtain very similar scores, since their noticeable differences are more related to the FoM that are lower ranked. Finally, the HAL obtains high scores in the MVL, first on the ranking, but performs rather poorly in the rest of them.

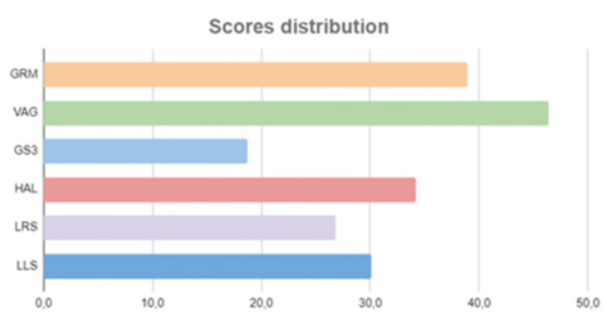


Figure 2. Bar chart with final score visualization

Further design has followed the result of the trade-off and focused primarily on the Vertical Actuation Gimbal concept. Besides the result, the VAG provides a potentially lightweight, simple system with low number of joints, and with the consideration of having the concentric platforms attached to the primary structure by more than one hinge, a robust and compact TPM can be developed.

Design Description

Overview

The preliminary design proposed by AVS UK is shown in Figure 3 along with the designation of the main components.

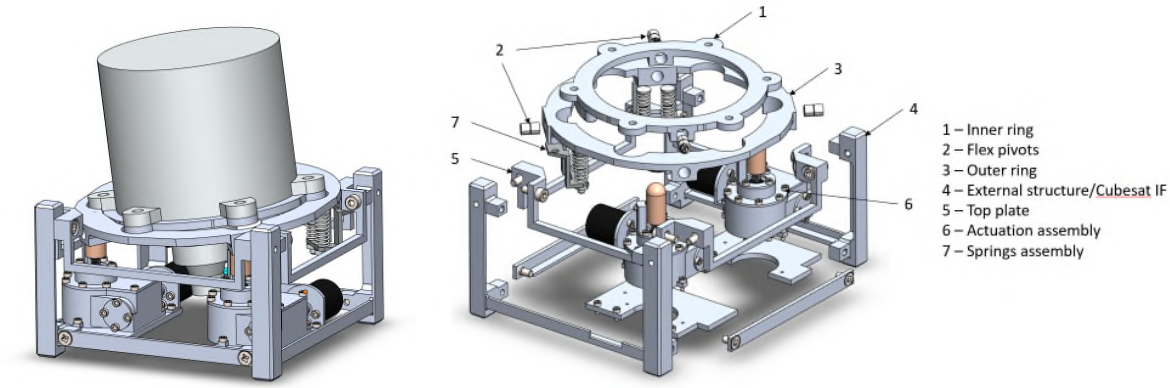


Figure 3. TPM assembly with Thruster (left)/ Exploded view of TPM with component list

Functional description

The TPM connects the thruster to the spacecraft structure, with the main function of orientation control. It provides a ±5-degree cone, with its rotation axis lateral to the flight direction. A two independent axis configuration has been implemented, where each actuation subassembly provides a rotation around one of the axes. While the actuation is fixed to the TPM structure, both axes include two supporting points via two opposed flex pivots. To take advantage of the space available in the corners of the assigned volume, the axes are in an “X” configuration with respect to a typical 12U Cubesat body’s dimensions, as shown in Figure 4.

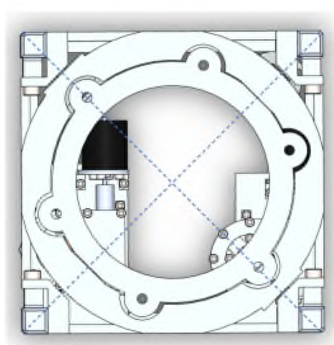


Figure 4. Top view with marked rotation axes

The system is controlled in an open-loop mode, and relies on high accuracy sensors to provide a homing function for the actuators. It also includes the required electric and fluidic interfaces for the thruster coming from the spacecraft. The actuation (per axis) is formed by a motor-transmission assembly and a pair of redundant springs placed opposite to each other, in a perpendicular direction to the rotation axis. The primary actuation has a nut with a push contact with the moving ring and rotates the platform counteracting the spring force. An initial preload of the springs allows for the rotation in the opposite direction, so when the nut is retracted, the spring pushes back, keeping constant contact with it and overcoming the resistive torques of the system. Both active actuation assemblies are in a fixed position, but the pair of springs corresponding to the thruster ring are connected to the outer ring to ensure a perpendicular contact with the first one. The actuation of the inner ring, although fixed to the structure, is positioned so the nut and the ring make contact in the line formed by the rotation axis of the outer ring. This way, although there is some relative rotation of the outer ring, the rounded tip of the nut presents no opposition to this rotation and can push the inner one vertically.

The system includes end-stops to limit the movement of the rings, as an added value to the functional end-stops provided by the maximum compression of the spring and the maximum retraction travel of the nut.

Structure

The main structural element is the 100 mm x 100 mm outer square-shaped plate. In its center, two round, concentric elements are the two rotation rings actuated for the thruster rotation. The square plate has four perpendicular side parts connected to it, delimiting the volume, and will be the elements attaching the whole TPM to the platform. Actuation assemblies are attached to the opposite sides of the frame.

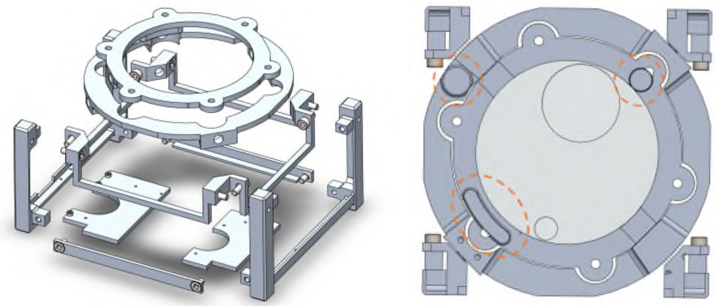


Figure 5. Bottom exploded view of TPM structural components (left)/ Bottom view with marked actuation contact features

The inner ring provides the mechanical interfaces for the thruster. In the outer side of the ring two flattened surfaces with a through hole each are included for the flex pivots that connect it to the outer ring. In the lower side, two specific extrusions are added, one to contact the actuation nut, and the other to contact the springs. Both surfaces will be hardened to avoid any possible deformations or undesired attachments due to temperature and stress (Figure 5).

The outer ring is similar to the inner one. Two through-holes are included to accommodate the flex pivots that connect it to the square plate, and two added extrusions with a hardened surface for its respective actuation nut and spring. The material baselined for the structural parts is Aluminum 7075-T6.

Active actuation

The actuation is an assembly made of a stepper motor and a transmission system, that includes a 2-stage transformation using worm gears and a lead screw. The baselined motor is a Faulhaber AM1524, a 2-phase stepper motor with 24 steps. This Faulhaber model provides motors suited for high levels of vacuum. Selected model of the motor will be suitable considering TRL 6 needs to be met. Based on the heritage of this motor series it is considered that the same line will likely be suitable for higher TRL levels, after some additional tests which we will conduct on the motor i.e., radiation resitance.

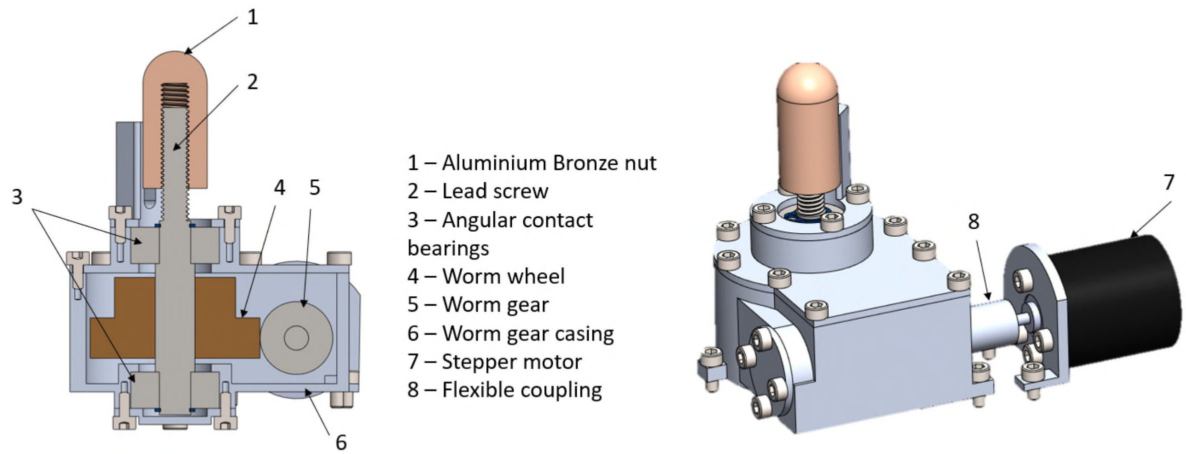


Figure 6. Cut view of active actuation assembly with main parts list

The 2-stage transmission system will be developed using a COTS miniaturized worm gear set provided by Reliance Precision. Current worm gear ratio is 1:40, increasing torque downstream of the system. The worm wheel is attached to the non-threaded part of the lead screw. The lead screw is supported by two angular contact bearing at two different points, providing a good support for the axial and radial forces. The rotation of the lead screw creates a linear displacement of the nut, which is hollowed and threaded inside, so it provides the 8 mm of stroke required to enforce the 5-degree rotation of the rings. The nut is guided using a pin running in the slot, which disables its rotation.

The baseline lead screw has a diameter of 3.6 mm and a fine pitch of 0.3 mm, which enables high resolution in the system rotation and enhances the required back-driving torque (already provided in worm gear), providing the system with a robust positioning when the system is unpowered. The current material for the nut is Aluminium Bronze. Its tip is rounded to provide a single-point contact, and in the case of the thruster ring, adapts to an initial perpendicular rotation the outer one may have before actuating it. Material considered for the gears set are Aluminium Bronze for the worm wheel and SS 304 for the worm.

The resolution reached for the solution utilizing motor with 24 steps, worm gear with ratio of 1:40 and lead screw with 0.3 mm lead is in the range of 0.00002° - complying with Req-7. Enough margin is considered for gear and lead screw backlash effect, although the constant load in the nut will greatly reduce the effect in the lead screw by a pre-loading provided mainly by the spring.

Passive actuation - Springs

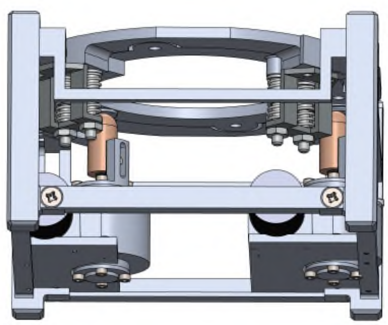


Figure 7. Side view. Spring assemblies on top right and left

At the opposite side of the active actuation contact point with the rings, the redundant springs provide the required force to keep the contact between the active actuation nut and the rings. Each spring is sized so that, when the nut is retracted and the system is rotated towards the active actuators, therefore reaching the minimum deflection, the force provided is enough to counteract all resistive torque trying to compress it. A determined pre-load is applied to enforce this condition.

While a pair of springs is attached to the square plate and therefore is static, the pair corresponding to the inner rings is held to the outer ring, always keeping a perpendicular position and not counteracting its rotation. The baseline attachment is a simple bracket that connects the plates and has a horizontal surface for the springs to contact on. The springs' inner space is filled with a shoulder screw to ensure spring assembly is robust and the outer and inner rings compress the spring through a contact with the screw. A nut is placed in its bottom after a through hole to keep the springs in place and, if needed, can be used to limit the decompression of the spring to a desired value.

Position sensors

Although absolute angular position can be extracted from the step counting, to enable the recalibration of the system, redundant homing position sensors are implemented. The BAUMER MY-COM F75/405600 is the baselined sensor. With a repeatability of less than 0.001 mm and no mechanical pre-run, it provides a high accuracy positioning. The switch is vacuum rated, and for future applications, RUAG has a similar end-switch qualified for space (RUAG Space MSwitch), reducing risk and development time of the system.

Preliminary position of the sensors is considered next to the actuation, with a similar shaped extrusion to contact them. They are precisely positioned so the end-stops can avoid overstressing them, but just enough to measure the position accordingly.

Materials

Aluminum alloy 7075-T6 is the baselined for the structure of the TPM. Used in applications that require high strength and temperature, including extrusions for aerospace, fittings and major structural components. It provides fatigue performance and fracture toughness at the low density of Aluminum.

In the transmission system the baselined material for the nut body is Aluminum Bronze. A proposed alloy is 2.0966. Although the nut/pusher is expected to always stay in contact with the pushed rings, due to their relative motion, to ensure a minimum of 500 HV is achieved, the tip would be substituted with a higher hardness material, and the rings surface will undergo a surface treatment to harden it. The baselined material for the worm gear wheel is Aluminum Bronze as well, and for the worm it is SS 304. End stop material used will be a dissimilar to the structure with suitable hardness for contact with the rings.

Tribology

To ensure low wear and friction over the required temperature range and lifetime of the components and interfaces, proper lubrication must be applied in relative motion areas.

The gimbal joints have to perform an oscillating motion, which is detrimental in conventional bearings, with an angular stroke between +5° and -5°. For a relatively small range, flex pivots offer many advantages: they do not need lubrication, are compact and their performance is not affected by the oscillating motion, and their working temperature range is wide, without significant performance variations. However, unlike conventional bearings, they provide a resistive torque that depends on the applied rotation. For the specific rotation range expected, though, the contribution is not of primary effect within the full resistive torque.

The passive actuation is also free of such issues, essentially having a similar working principle to the flex pivots, translated into linear motion instead of a rotary one. This is not the case for the active actuation, though. The motor and transmission system’s angular range is higher. Considering the number of cycles with the applied ECSS corrective factors that the actuation needs to perform, the motor itself performs over 200,000 cycles. The mating surfaces of the worm gear will be lubricated by Braycote 601 grease. Worm gear set will be working in elasto-hydrodynamic lubrication regime, which is considered to have infite life providing enough film thickness on mating surfaces, which for our geometry had deemed to be possible (despite high number of cycles, contact loads are very low).

Harness and tubing routing

With the current configuration of the TPM proposed, there is central space available to include the propellant lines the ETPM will require.

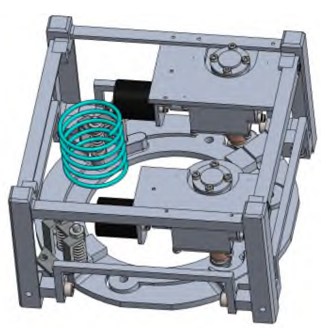


Figure 8. Bottom view with propellant line coil model

Required tubing consists of a 1/16-inch (1.6-mm) Stainless Steel tube. Due to the required rotation, placing the tube in a straight configuration from the spacecraft to the thruster would translate in high bending stresses, being a danger for the tube itself, as well as the added resistive torque that would affect the required motor torque. The necessary flexibility can be obtained by increasing the length of the tube and manufacturing it in a helical shape, simulating a typical compression spring. Such a design can manage axial and lateral deflections, and the sizing can be made manipulating two parameters: the external diameter of the coil, and the number of coils set.

Control

Four modes have been identified for the TPM at the current stage, that will be used to estimate total power consumption.

- Off mode: All electrical systems are shut down on the TPM, and there is no power consumption coming from Stepper motors or homing sensors.
- Stand-by mode: Stepper are powered but no rotation is applied, maintaining the TPM position with the holding torque. This is a bridge mode, where the system is awaiting instructions. Sensors are not powered.
- Configure mode: Considering the mechanical precision end-switches baselined as homing sensors, they are temporarily powered, and motors are powered so the system rotates towards the end-switch, for re-calibration of the positioning accuracy.
- Aligment mode: Nominal movement of the TPM in open loop with step counting. Homing sensors are unpowered since homing is not required, and the motors are powered to orientate the ETPM towards the specified direction.

Motorization

A preliminary sizing of the required motor torque has been performed. Besides the already calculated resistive torques affecting the system, the resistive torques due to the payload and rings' inertias, the reaction force of the springs in maximum deflection and the losses associated with the drivetrain need to be sized.

Spring sizing

Being part of the actuation, the motorization uncertainty factors apply to the spring. All involved resistive torque related to the springs are gathered in the Table 3. The minimum required torque is calculated following the ECSS equation.

Table 3. Preliminary torque budget

Source	Type of contribution	ECSS Factored contribution (Nmm)
Flex pivots	Spring	7.73
Harness	Harness/others	35.04
Tubing	Harness/others	12.59
Orbital Dynamics	Inertia	0.042
Minimum torque (ECSS factor & MF))		55.4
Spring distance (mm)		37
Minimum force (N)		**1.49**

Since two flex pivots are applied for each rotation axis, the resistive torque is doubled. Following the left side of Figure 9, for clarification, the minimum force of the spring is the required force any of them has to provide in a position when the motor is fully retracted. The spring will then be at minimum compression, but still with enough preload to sustain all resistive torque trying to oppose it. The spring distance considered is based on the worst case scenario, which corresponds to the ETPM ring.

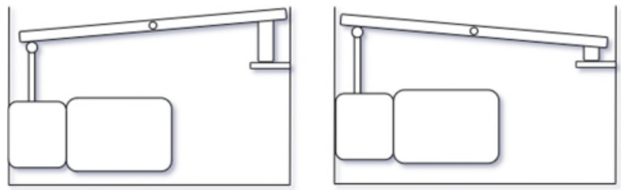


Figure 9. Schematics of two opposite positions.
Left: Spring minimally compressed. Right: Spring fully compressed

Assuming an initial deflection of 6 mm in that position, the required spring stiffness is 0.3 N/mm. This stiffness is used to calculate the maximum force exerted by the spring when the rings are rotated to the opposite side, as shown in the right side of the figure. The actuation needed to be able to provide enough force to compress the spring in order to reach that position, and since another spring has been included as redundancy, the resistive torque provided is doubled.

The maximum force opposing is calculated with the maximum deflection sustained by the spring, which is the addition of the vertical movement to the initial pre-load deflection.

$$F_{spring} = k_{spring} \cdot \left(6 + 2 \cdot d_{spring} \cdot \sin(5)\right) = 6.2\ [N]$$

where k_{spring} is the spring constant and d_{spring} the distance from the center of rotation to the spring. The value will be multiplied by 2 for its addition to the motor resistive torques.

<u>Motor sizing</u>

The value above is added to the list of resistive torques, and the induced acceleration is calculated. Since there is no requirement in speed, an initial value of 0.05 °/s at thruster level has been considered. Considering the lead screw pitch and the bevel gear ratio, the thruster rotation translates into a motor angular rate of 18.5 rpm. An assumed low angular acceleration of 0.5 rad/s^2 has been baselined for the motor. The properties of the Faulhaber AM1524 are shown in Table 4.

Table 4. Faulhaber AM1524 properties

Property	Value
Holding torque	6 N-mm
Detent torque	0.51 N-mm
Rotor inertia	0.045 kg-mm^2
Voltage	1.95 V

The efficiencies of the lead screw and worm gears have been established at a 21% and 28% value, respectively. Table 5 shows the new breakdown of resistive torques, and the minimum torque required for the worst-case scenario. Due to the 2-stage transmission system, the effects of the resistive torques are vastly reduced at motor level, compared to the spring motorization ones. However, their effect is noticeable when the calculation of the transmission losses is performed.

For the calculation of the detent torque (Table 6), the same resistive torques as in the table above will be applied to the system. For the worst case scenario possible, no holding contributors have been applied during the detent torque calculations. Since the M-Argo mission is not crewed and AVS UK has some experience in measuring uncertainty factors, high back-driving efficiencies have been considered for a 0.3-mm lead screw. These measured factors have been considered for the sizing of the resistive torques for the required detent torque estimation.

Table 5. Active actuation pull-in motorization margin

Source	Type of contribution	ECSS Factored torque contribution (Nmm)
Commanded acceleration inertia	Inertial resist torque	$5.56 \cdot 10^{-5}$
Flex pivots	Spring	$2.99 \cdot 10^{-4}$
Harness	Harness/others	$3.39 \cdot 10^{-3}$
Tubing	Harness/others	$1.22 \cdot 10^{-3}$
Orbital Dynamics	Inertia	$1.59 \cdot 10^{-6}$
Motorization springs	Spring	$1.18 \cdot 10^{-2}$
Leadscrew efficiency as losses	Friction	0.175
Worm gears efficiency as losses	Friction	1.47
Total resistive torque (ECSS factor and MF) (Nmm)		3.32
Total commanded torque (ECSS factors) (Nmm)		$5.56 \cdot 10^{-5}$
Minimum torque (pull-in) (MF included) (Nmm)		**3.32**
Motorization margin factor		2.06

Table 6. Active actuation detent torque motorization margin

Source	Type of contribution	Factored torque contribution (Nmm)
Flex pivots	Spring	$2.99 \cdot 10^{-4}$
Harness	Harness/others	$3.39 \cdot 10^{-3}$
Tubing	Harness/others	$1.22 \cdot 10^{-3}$
Orbital Dynamics	Inertia	$1.59 \cdot 10^{-6}$
motorization springs	Spring	$1.18 \cdot 10^{-2}$
Leadscrew efficiency as losses	Friction	$3.32 \cdot 10^{-2}$
Bevel gears efficiency as losses	Friction	$2.13 \cdot 10^{-2}$
Motor detent torque	Magnetic effects	$3.4 \cdot 10^{-4}$
Total acting torque (Nmm)		$1.37 \cdot 10^{-2}$
Total resistive torque (Nmm)		$3.94 \cdot 10^{-1}$
Motorization factor (MF)		2
Minimum detent torque (MF included) (Nmm)		**0.0004**
Ratio T_{mot_det} / T_{min_det}		13.4

Budgets

Current mass budget is given in Table 7.

Table 7. Preliminary mass budget

Part code	**Part description**	**Mass**
		g
1	Main top plate	18
2	Outer ring plate	26
3	Inner ring plate & ETPM interface	21
4	Cantilever flex pivots	8
5	Actuator holding bottom plate	17
6	Side plates	21
7	Actuation assemblies	156
8	Spring assemblies	8
9	Positioning sensors	24
10	Harness	12
Total		**311**

The initial power budget is presented in Table 8.

Table 8. Preliminary power budget

Mode	Off	Stand-by	Nominal
Component	**(W)**	**(W)**	**(W)**
Stepper motor 1	0	0	1.04
Stepper motor 2	0	0	1.04
End switches	0	0	0
Thermocouples	0	~ 0	~ 0
Total	0	0	2.1

Summary and Future plans

The work described in this paper is only the preliminary design of the current TPM, but this activity will continue until the development and the acceptance of the Thruster Pointing Mechanism Flight Model for the ESA M-Argo mission. A breadboard and an engineering model will be built during 2022, including the control electronics, allowing us to reach TRL 6 towards the end of 2022 or early 2023.

AVS is a worldwide leader in the development of complex instrumentation for Science and Space applications. The background of AVS in vacuum engineering, high-precision mechanisms and mechatronic systems has led us to become one of the only few specialized and EN9100-approved Space mechanisms suppliers in Europe.

AVS and its subsidiary URA Thrusters are also one of the most active players in the in-space propulsion field, and will use this specific development as the stepping stone to develop a wide variety of TPM products for a wide set of missions, platforms and application, from nano or micro-satellites, to large GEO spacecraft. As part of this endeavor, AVS UK is already working in the development of a fully industrialised, low-cost and compact TPM for the next generation of High Throughput Satellites (HTS) to be used with standard mid and high-power (3-10 kW) Electric Propulsion systems.

In particular with the M-ARGO’ TPM, the system design is challenging due to the typical nanosatellite volume, power, and mass constrains. Furthermore, in this 12U M-ARGO CubeSat application, the propulsion system, including the TPM needs to be installed in half of the spacecraft unit, and therefore this TPM could be easily scalable down to a 6U CubeSat. At the same time, the requirement to fit the tubing and harness inside (particularly possible connectors from thrusters) is limiting space inside the allowable volume. Likewise, it is creating additional resistive torque terms, which are quite difficult to assess at initial stage without testing.

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