MINIATURISED STEPPER MOTORS FOR SPACE APPLICATIONS

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ABSTRACT

The development of the smallSats industry and the novel variety of on-boards instruments lead more and more to a miniaturisation of the space mechanisms. In addition to the smaller size, the reduction of the cost and the time to the market became primary objectives for recurring components used in space systems. With this variety of new applications, stepper motors are also more widely used as they bring key features such as powered and unpowered holding torque as well as accurate positioning using step count and open-loop control drastically reducing system complexity and costs.

After a thorough review of stepper motors compatible for space applications, an important lack of product availability was found in the small size range, especially on the European market. Therefore, throughout its harmonisation dossier [1], European Space Agency (ESA) would like to increase the family of available stepper motors compatible with space environment.

1. ACTUATOR SELECTION

Almatech and FAULHABER team was selected by ESA to develop a miniaturised stepper motor fully compliant to space environment in the frame of an ARTES Advanced Technology activity. In accordance with the new market needs and the size of the motors actually available for space, a 22 mm diameter two-phase stepper motor (Fig. 1) has been selected for this first activity. In addition, a high precision 22 mm diameter planetary gearhead (Fig. 2) has been included to allow high-resolution pointing actuation. The combination of both components is shown in Fig. 3. The main characteristics of both components are presented in Tab. 1. The actuator has been named S2M2 for *Space Micro Stepper Motor*.

Figure 1. S2M2 Stepper Motor Series AM2224

Figure 2. S2M2 Planetary Gearhead Series 22GPT

Figure 3. S2M2 Actuator (combination of stepper motor and planetary gearhead)

Table 1. Space Micro Stepper Motor (S2M2) Main Characteristics

Feature	Value	Unit
S2M2 Stepper Motor Series AM2224		
Diameter	22	mm
Length	37.5	mm
Nominal holding torque	22	mNm
Mass	43	g
Nominal power	3.0	W
Step angle	15	°
Phase resistance	75	Ω
Residual torque typ.	1.47	mNm
Back-EMF amplitude	32.7	V/k step/s
S2M2 Planetary Gearhead Series 22GPT		
Diameter	22	mm
Length	47.1	mm
Number of gear stages	3	-
Reduction ratio	72:1	-
Backlash, at no-load, typ.	0.8	°
Mass	82	g

2. MODIFICATIONS FOR SPACE

The first step of this activity was to perform a complete review of the materials and processes in order get a broad view of the industrial actuator configuration. Based on the outcomes of this study, the compatibility with space environmental conditions was evaluated and specific components were adapted. The general philosophy followed during the development by Almatech was to come up with a highly reliable and low cost approach that minimises the impact on the actual industrial processes, to provide the Space Community with an unmatched competitive product line. Materials and processes incompatible with space environment were adapted or replaced. The critical sub-components were qualified in representative conditions including the consideration of on-ground storage and in-orbit life requirements. The following actions were taken to achieve the spatialisation objective:

- Integration of a venting path

The volumes to be vented in the motor and in the gearhead are relatively small, but without a defined path, the venting occurs through the ball bearings, which is not desirable. Venting holes have been added on the motor and the gearhead to provide a defined venting path and thus increasing the lifespan of the ball bearings.

- Use of lubricant compatible for vacuum and low temperature

The choice of lubricant for parts in friction in space environment is critical. Within S2M2 actuator, several elements are subjected to friction: the ball bearing in the motor and in the gearhead, as well as the gears in the gearhead. Grease was chosen based on four criteria: affordability, availability, compatible with space environment and on-ground testability. An appropriate candidate was found and implemented into the ball bearings and the gearhead.

- Ball bearings sizing

The ball bearings in the motor and in the gearhead have been studied with the help of ESTL. It has been checked that the assembly was properly sized for the vibrations environment and for the lifetime in accordance with the lubrication’s choice. To achieve that, the ball bearing preload has been modified.

- Replacement of materials and processes incompatible for space environment

The materials and processes of a certain number of parts were not compatible for space applications. The materials and processes of these parts were replaced with material and processes compatible with space environment and implemented into the actuator.

To ensure a proper functioning of the actuator, some critical sub-components needed a qualification. They were performed on the following critical elements:

- Laser welding on shaft (motor and gearhead)

The shafts of the motor and the gearhead are closed with a laser welded ring. As the assembly process is critical for the proper functioning of the actuator, a complete qualification has been performed following the rules described in [2].

- Magnets aging

The magnets are essential for the performances and the functioning of the motor. As magnet materials are sensitive to corrosion, it is needed to qualify the corrosion protection coating efficiency.

These two qualification campaigns are discussed in the following section.

3. TESTING & VALIDATION

Several tests and qualifications have been performed at the motor and actuator (motor + gearhead) levels and their results are presented in this paragraph.

3.1. Functional tests

At the motor level, functional tests have been done on terrestrial motors (COTS) and on modified motors for space (BBM). The goal of these tests is to check if the performances of the BBM have been altered because of the implemented modifications. A dedicated test bench composed of a torque transducer and a DC motor has been designed to measure the characteristics of the stepper motors (see Fig. 4).

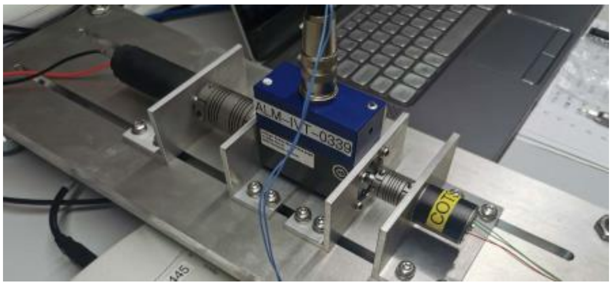

Figure 4. Functional test bench

The measured characteristics and the percentage of difference between the COTS and the BBM values are presented in Tab. 2. The average speed-torque curves are shown in Fig. 5.

Table 2. Difference of value for the functional tests between COTS and BBM

Characteristic	Difference [%]
Coil's Resistance	-2.2
Coil's Inductance	~0.0
Back-EMF amplitude	~0.0
Phase shift between coils	~0.0
Detent torque	+5.9
Holding torque	+0.7

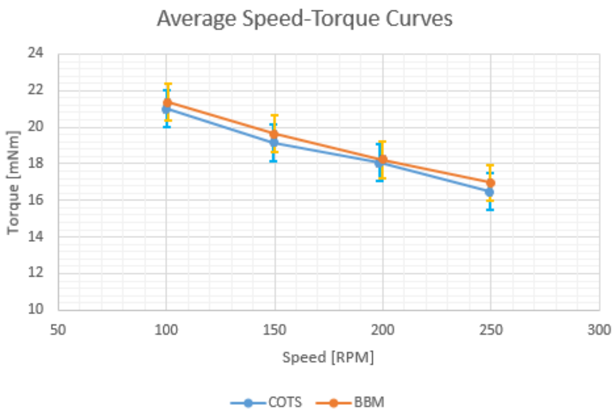

Figure 5. Average speed-torque curves for the COTS and BBM motors

Non-negligible differences have been observed between the COTS and BBM motors for the coil's resistance and the detent torque. For the resistance, the change can be explained by the use of more precious metals for the electrical connections i.e. the cables and the soldering material. Indeed, both of the aforementioned elements have been changed to follow the rules described in [3] and [4], which leads to utilisation of materials with less electrical resistance than the ones used in the terrestrial configuration. For the detent torque, the implementation of a grease compatible for space environment increases slightly the friction torque hence leading to a greater detent torque. Although, these changes of characteristics are not significant. As a conclusion for the functional tests, Tab. 2 and Fig. 5 indicate that the modifications of the stepper motors did not impact their characteristics and performances.

3.2. Outgassing test

A MOC test has been performed at the actuator level (motor + gearhead) to determine outgassing properties of the contaminants present in the part. To do so, the test consisted of a bake-out monitored by QCM and MOC windows at 120 °C. This test was performed at ESTEC facility. Due to the large mass of the sample (125g), it was not feasible to obtain TML, RML from sample mass measurements. QCM data analysis was used for monitoring and determination of the bake-out duration. The FTIR analysis of the MOC windows provided information regarding the outgassed products.

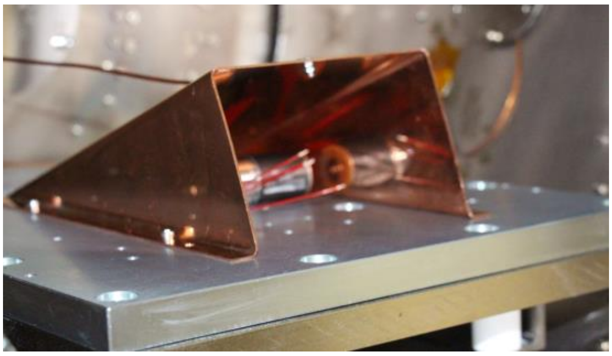

Figure 6. Test setup view (hot plate, actuator sample and baffle), courtesy of ESA-ESTEC

From the QCM data, the deviation from linearity (<1%) was achieved after about 74h at an isothermal temperature of 120°C. The MOC analysis has confirmed the presence of hydrocarbon compounds in the CVCM estimated at 0.2% of the total mass. A bake-out of the actuator is thus needed to guarantee a CVCM value below 0.1%.

3.3. Laser qualification

Two critical assembly locations with laser welding operation have been fully qualified according to [2]. The first location is between the motor's shaft and its retaining ring (Fig. 7) the second one is between the gearhead's output shaft and its retaining ring (Fig. 8). For each location, the test sequence presented in Tab. 3 has been followed.

Table 3. Test sequence for laser welding qualification defined in [2]

Type of test	Sample number							
	1	2	3	4	5	6	7	8
Non-destructive test								
Visual inspection	x	x	x	x	x	x	x	x
Penetrant inspection	x	x	x	x	x	x	x	x
Radiographic testing	x	x	x	x	x	x	x	x
Destructive test								
Metallography and hardness	x	x				x		x
Tensile tests			x	x	x			

Figure 7. Laser welding spot on motor's shaft

Figure 8: Laser welding spot on gearhead's output shaft

For the gearhead's location, the qualification was totally successful. On very rare occasion, micro-cracks with a length between 10µm and 20µm have been observed on the motor's shaft weld. These cracks are not critical and have no impact on the tensile strength of the weld. Indeed, the results of the tensile tests show no reduction of tensile strength. Considering that micro-cracks are only present on some few samples, it has been deduced that the used set of parameters for the laser is near the optimal configuration. Nevertheless, a correcting action is implemented: the amount of power given to the laser will be reduced to decrease the thermal gradient and hence avoid the formation of micro-cracks.

The quality of the laser welding is judged very satisfactory as all the qualification tests were passed successfully.

3.4. Magnet aging

The magnets and their whole encapsulation casing have been subjected to humidity exposure and then thermal cycling. With these tests conditions, an accelerated lifetime of the component including storage (humidity exposure) and use in space (thermal cycling) can be considered. The objective is to verify the corrosion resistance of the magnets encapsulated in their casing. Two groups of components have been exposed to the conditions presented in Tab. 4. The test has been performed in ESTEC facility.

Table 4. Test sequence for magnet aging

Test condition	Group A	Group B
Humidity exposure		
Temperature [°C]	85	40
Relative humidity [%]	85	95
Duration [hours]	108	240
Thermal cycling		
Temperature range [°C]	±100	
First 10 cycles	Under vacuum	
90 remaining cycles	Under ambient pressure	

Four samples of group A and four samples of group B were tested with twenty-four magnets encapsulated in each sample. The vast majority of the magnets showed perfect corrosion resistance, as no corrosion strain could be seen (see Fig. 9). Some of the magnets showed small spots of corrosion on their top surface. The quantity and dimensions of these spots are larger for the group A, as the conditions are harsher. Examples of surface corrosion spots are shown in Fig. 10 and in Fig. 11 for the groups A and B respectively. In Fig. 12, light intergranular attack can be observed, but it is limited to the surface of the magnet. The samples exposed to thermal cycling did not exhibit any further degradation from the corrosion.

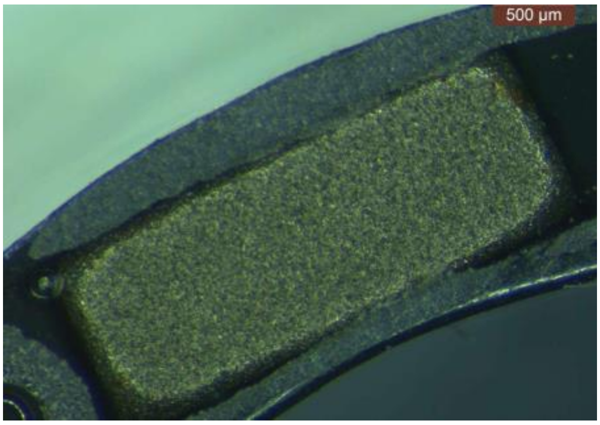

Figure 9. Uncorroded surface after humidity exposure, Sample from group B, courtesy of ESA-ESTEC

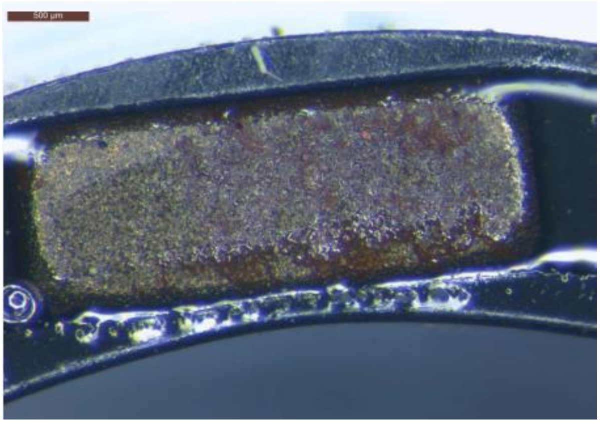

Figure 10. Surface corrosion after humidity exposure, Sample from group A, courtesy of ESA-ESTEC

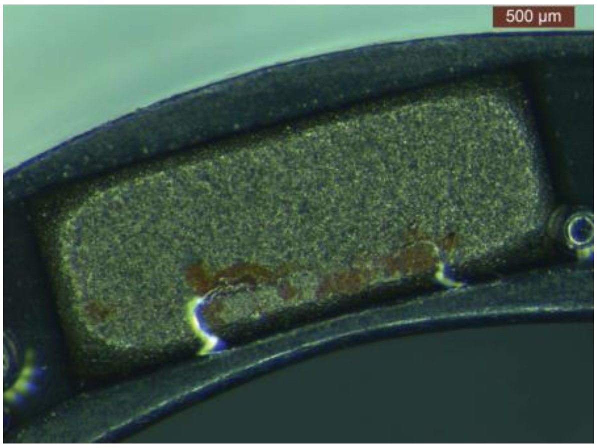

Figure 11. Surface corrosion after humidity exposure, Sample from group B, courtesy of ESA-ESTEC

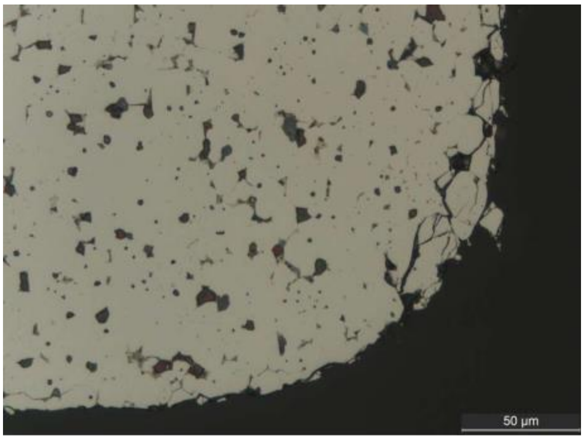

Figure 12. Micro-section of corroded sample, courtesy of ESA-ESTEC

The quantity of corrosion is limited on the surfaces of the exposed samples. Moreover, no sign of corrosion has been observed on the samples where the magnets were properly encapsulated by the potting.

The quantity of corrosion is non-significant in comparison of the magnets' volume and no penetration of corrosion has been observed inside the magnets' volume. Therefore, the corrosion on these samples are judged acceptable.

Nevertheless, a corrective action is put in place to further reduce the amount of corrosion by an enhanced close inspection of the encapsulation material that will be added prior to assembly of the magnets in the motor.

3.5. Lifetime test

A lifetime test has been performed at the actuator level with a continuous motion at constant speed. The objective is to evaluate its long-time behaviour, especially for the friction based components such as the ball bearings and the gears. A gearhead in back-drive is used as a brake. The test setups in ambient and in vacuum conditions are presented in Fig. 13 and in Fig. 14 respectively.

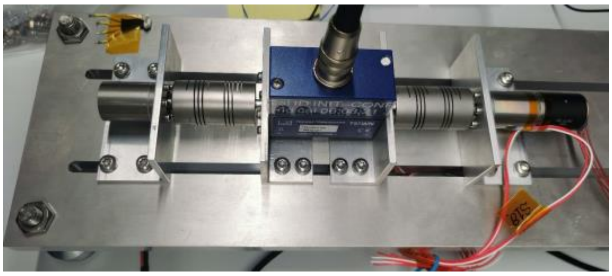

Figure 13. Lifetime setup for ambient condition

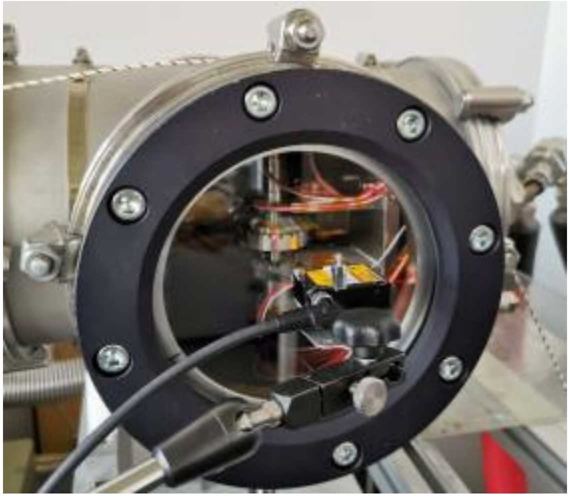

Figure 14. Lifetime setup for vacuum condition

The test is divided in three parts:

- Initial cycles under vacuum and thermal cycling
- Intermediate cycles under ambient conditions
- Final cycles under vacuum and thermal cycling

As the actuator was still functional at nominal performances after these three phases, a fourth phase in ambient conditions has been added to further test the actuator. The results of the lifetime test are presented in Tab. 5.

Table 5. Lifetime test results summary per phase

Test condition / result	Value	Unit
Initial cycles under vacuum		
Number of thermal cycles	8	-
Interface cold temperature	-50	°C
Interface hot temperature	+80	°C
Duration	145	Hours
Cycles at motor level	$12.5 \cdot 10^6$	-
Cycles at gearhead output	$0.173 \cdot 10^6$	-
Intermediate cycles under ambient conditions		
Duration	1164	Hours
Cycles at motor level	$100 \cdot 10^6$	-
Cycles at gearhead output	$1.39 \cdot 10^6$	-
Final cycles under vacuum		
Number of thermal cycles	8	-
Interface cold temperature	-50	°C
Interface hot temperature	+80	°C
Duration	166	Hours
Cycles at motor level	$14.5 \cdot 10^6$	-
Cycles at gearhead output	$0.202 \cdot 10^6$	-
Final cycles under ambient conditions		
Duration	317	Hours
Cycles at motor level	$27.4 \cdot 10^6$	-
Cycles at gearhead output	$0.38 \cdot 10^6$	-

After the final cycles under vacuum, a 3D tomography has been performed to check the integrity of the actuator with a resolution 0.2mm. An example of an image extracted from the 3D tomography is presented in Fig. 15. No damages have been seen on the tomography images. This was confirmed as the actuator was still running at its nominal performances before the measurement.

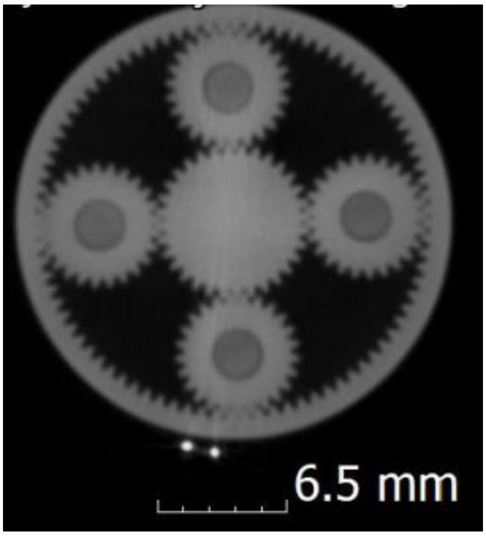

Figure 15. Tomography image of one gearhead's stage

The test has been stopped due to a drop of the actuator's efficiency. The final number of cycles done during the lifetime test are given in Tab. 6.

Table 6. Lifetime test results summary

Test result	Value	Unit
Total duration	1792	Hours
Cycles at motor level	$154 \cdot 10^6$	-
Cycles at gearhead output	$2.14 \cdot 10^6$	-

This test has demonstrated the capacity of the motor to perform large amount of cycles (more than $1.5 \cdot 10^8$ cycles). As the drop of efficiency is probably due to the gearhead, a greater number of cycles can be expected for the motor itself. The amount of cycles at the gearhead output is evaluated as very satisfactory considering the size of the gears and the type of lubricant (grease).

4. ONGOING DEVELOPMENTS

The actuator has been integrated in a 2-axes antenna pointing mechanism application. The specifications have been defined in collaboration with Thales Alenia Space. A reduced configuration of the mechanism with the azimuth axis only is currently being manufactured and the following test campaign is foreseen on it:

- Functional test under ambient conditions
- Pointing accuracy test under ambient conditions
- Functional test under vacuum and thermal cycling
- Vibration tests

The objective of this phase is to implement the actuator in a mechanism for space application and test it under representative environmental conditions. Once this campaign will be completed, the actuator should be fully qualified for space environment including vibrations.

5. POTENTIAL APPLICATIONS

Two different applications using the developed motor are presented in this paragraph. They are briefly described and the advantages of using stepper motors are discussed.

5.1. Antenna Pointing Mechanism (APM)

During the course of the project, specifications for a use case have been defined in collaboration with Thales Alenia Space. The objective was to find an appropriate application for a stepper motor, which can be scaled to a standard mechanism in a constellation for instance. The choice has converged to an APM.

In the second phase of the project, the APM presented in Fig. 16 was designed. The mechanism is characterised by the following features:

- Based for LEO application (communication between satellite and point on the ground)
- 2-axes pointing with 2 stages in series
- 360° rotation on azimuth axis
- ±55° rotation on elevation axis
- Anti-backlash solutions on the whole gear train
- Launch Lock Device on each axis using Nimesis TRIGGY® HDRM
- Full step control
- Resolution achieved by step count (<0.03°)
- Stable static positioning with the detent torque
- Volume: 230mm diameter and 170mm height

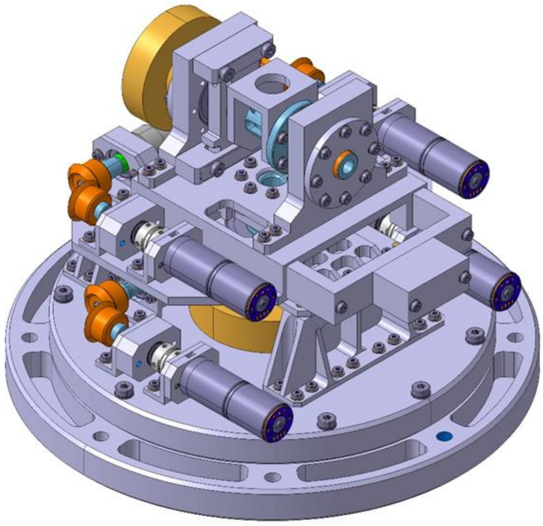

Figure 16. APM design

5.2. Thruster Pointing Mechanism (TPM)

Another application has been studied outside of this current project. A 2-axes pointing mechanism for small electrical thruster has been developed (Fig. 17). In this case, a gearhead is not used, but a ball screw is implemented instead. Whereas the previous application takes advantages of the high reduction ratio to provide precise angular positioning, this mechanism relies on the fine pitch of the ball screw to orient the thruster with its linear motion.

The mechanism is characterised by the following features:

- 2-axes pointing with 2 stages in parallel
- ±5° rotation around each axis
- Integrated launch lock (non-resettable)
- Full step control
- Resolution achieved by step count (0.05°)
- Stable static positioning with the detent torque
- Position reference with end switches
- Low mass (300g)
- Compact design (100x100x50 mm)

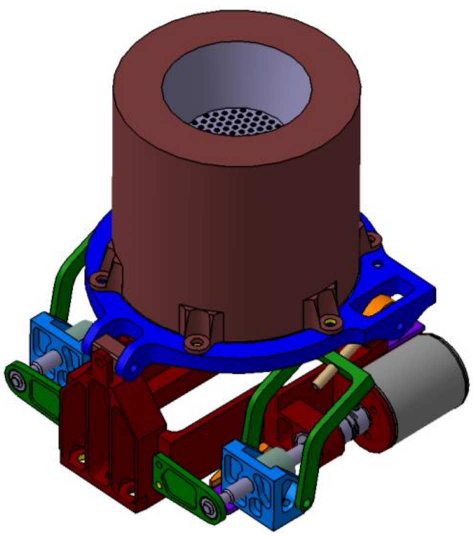

Figure 17. TPM design

5.3. Stepper motor use in high precision mechanism

Numerous advantages are related to the use of stepper motors in high precision mechanism for space. First, the step count can be used as a positioning strategy. With a proper sizing of the mechanism and an open loop control in full step, the approach proves to be reliable and robust. Moreover, it avoids the implementation of complex and expensive positioning sensors.

In addition, the mechanism is maintained in a stable position with its detent torque (no current is applied), which makes it resistant to the external perturbations such as the harness resistive torque. If the passive strategy is not sufficient, the holding torque can be activated by powering the coils simultaneously. This can be useful in some particular case such as the launching phase.

The reliability of this motor's type is high as they do not need external position sensors nor brushes. The repeatability of the motion is guaranteed by the actuator and not by the electronics.

One drawback needs to be taken into account in the frame of high dynamics application. Indeed, the maximal speed and acceleration can be limiting factors for the sizing of the motorization margins.

In summary, stepper motors turn out to be excellent candidate for high precision positioning applications with its robust and reliable working principle. Associated with an open loop control, the solution becomes simple and cost effective at the system level.

6. FUTURE COMMERCIALISATION OF THE ACTUATOR

The collaboration between FAULHABER and Almatech will continue after this project with the commercialisation of the developed actuator as standard components. A general datasheet with the properties of the actuator and its new features for space can be ordered to Almatech. Several options are available such as different reduction ratio to fulfil at best the needs of future customers searching stepper motors for space applications.

7. SUMMARY & CONCLUSION

The first phase of the project with the implementation of the modifications and the qualification has been completed successfully. Some small adjustments will be applied on the processes linked to the laser welding and the magnets encapsulation to correct the defects observed during the qualification phase.

The test campaign at mechanism level is currently in progress with encouraging preliminary results. Further developments in the frame of space high precision mechanisms look promising with the use of the S2M2 actuator.

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REFERENCES

1. Electrical motors and actuators harmonisation dossier, ESA/IPC/THAG(2015)10, 21.03.2016

2. Welding of metallic materials for flight hardware, ECSS-Q-ST-70-39C

3. Manual soldering of high-reliability electrical connections, ECSS-Q-ST-70-08C

4. Wires and cables, ESCC 3901/001