SMART-1 ELECTRICAL PROPULSION STEERING MECHANISM (EPMEC)

Author:
Mr. Brian Wood

Co-Authors:
Mr. Walter Buff, Mr. Philippe Delouard

Contraves Space AG
Schaffhauserstrasse 580
CH-8052 Zürich-Seebach
Switzerland

Tel: +411-306-2457
brian.wood@unaxis.com

ABSTRACT

The SMART-1 Spacecraft is due to launch in 2002 and is being developed as a test bed for various new technologies that will be needed for interplanetary missions. One of these new technologies is the Electric Propulsion system (EPS) which is to be used as the main source of thrust during the mission. Contraves Space AG were selected for the development of a "low budget" Steering Mechanism (EPMEC) for the EPS and for the associated drive electronics (EPMEL).

The EPS selected for the SMART-1 mission is the PPS 1350 developed by SNECMA Moteurs in France. Since this thruster configuration is almost identical to that used on the STENTOR mission, the use of this thruster unit has placed certain limitations on the design of the EPMEC.

In satisfying the requirements, the design of the EPMEC described in this paper utilised some novel ideas and new technologies in the spacecraft mechanism branch. The EPMEC mechanism has recently successfully completed the qualification test programme for SMART-1 and has been mounted into the spacecraft for system testing. The flight model is currently in manufacture. The results from the Qualification Tests will also be briefly presented in this paper.

1. INTRODUCTION

The SMART-1 Spacecraft is being developed by the Swedish Space Corporation for the European Space Agency (ESA) Horizon 2000+ programme. It is to be used as a demonstration test bed for various new technologies needed for interplanetary missions, one of which is to use an Electric Propulsion System (EPS) as the main thruster power source for the mission. The launch of the Spacecraft is anticipated in 2002.

Contraves Space AG are subsystem responsible for the development of a "low budget" Pointing Mechanism (EPMEC) for the EPS and the Drive Electronics (EPMEL).

In line with the "low budget" approach in the development of the EPMEC; none of the major components have been especially developed for the SMART-1 mission. Instead, other similar missions and applications were reviewed and suitable components selected which could be slightly modified where appropriate.

Additionally, the EPS system that has been selected for the SMART-1 Mission is the PPS-1350 from SNECMA Moteurs. The use of existing technology has placed certain constraints on the design of the EPMEC.

The selection of the PPS-1350 imposed both thermal and mechanical constraints on the design of the EPMEC.

As the PPS-1350 is based on the design of the STENTOR thruster, the thermal design of the mechanism requires the inclusion of a radiator to dissipate 20W from the base of the thruster. Since the maximum temperature at the PPS-1350 interface with the EPMEC is 200°C and as this cannot be allowed to conductively dissipate into the mechanism, the thermal design of the mechanism and the radiator had to be carefully considered.

Since the EPMEC/PPS-1350 assembly is located at the Spacecraft/Launcher interface, the vibration and shock loads that will be experienced can be high. The EPMEC therefore has to be able to damp the loads transmitted from the S/C to the PPS-1350 Thruster.

The PPS-1350 Thruster contains 3 Titanium Xenon Tubes and 6 High/Low Voltage cables which have to pass from the Spacecraft to the PPS-1350 Thruster over the EPMEC. The effect of the stiffness of the cables and tubes on the EPMEC was considered in the detail design of the hold-downs for the cables and tubes. Special
consideration was made for the stiffness and the hysteresis effects on the mechanism position.

**Figure 1**  
**Photograph of EPMEC**

As stated previously, existing technologies have been combined in the EPMEC, which is shown on figure 1. These technologies include an actuation system utilising an improved AR14 Multi-Purpose Actuator from ETEL SA [1], a launch lock system which utilises STARSYS QWKNUT release bolts [2] and a novel mechanical damping system developed by Contraves Space AG.

Figure 2 shows the EPMEC integrated into the STM S/C structure and shows the thermal skirt around the EPMEC, which has the function of minimising the effects of sun radiation on the mechanism.

The Qualification model for the EPMEC has recently successfully completed the qualification test programme. The results from this test programme will be briefly presented in this paper.

2. **MECHANISM DESIGN**

**Mechanism Function**

The one PPS-1350 Thruster is located on the central axis of the Spacecraft with the thrust vector pointing along the –Z-axis of the spacecraft.

The function of the EPMEC is to enable pointing of the PPS1350 within a half-cone angle of 10° with respect to the S/C Z-axis so that the thrust vector passes through the S/C Centre of Gravity. As the propellant used by the PPS-1350 is Xenon, and since the mass of the Xenon at launch, some 80Kg, contributes about 23% of the spacecraft mass, the centre of mass of the spacecraft will move as the Xenon is used up.

The EPMEC must therefore be able to point the thrust vector away from the CoG of the S/C and to also allow for the axial and lateral variation in the CoG during the flight by moving the thrust vector accordingly.

**Overall design of the EPMEC**

The EPMEC design shown on figure 3 consists of the following elements:

- Two Rotary Actuators
- Launch restraint system
- Shock Attenuation System
- Thermal Radiator and Mechanism Protection
- EP Harness and Xenon Tubing Routing

A further sketch of the mechanism is shown on the figure 4.

**Figure 2**  
**EPMEC integrated in S/C**

**Figure 3**  
**Sketch of the EPMEC Assembly**
The launch lock system for the EPMEC consists of 3 support legs as shown on figure 3 and 4. Each of the legs contains a hinge and spring assembly, a support arm, an end stop and a Qwknut® release mechanism from Starsys Research Corporation, USA. Once the Qwknut is activated, the spring in the hinge assembly rotates the support legs away from the clamp fixation until the endstop is reached as shown on figure 5. The stowed EPMEC shown on figure 3 shows the position of the Qwknut® which is mounted at the top of the Support Leg. The bolt catcher (part of the Qwknut Assembly) is located on the Support Ring and has the function of catching the separation bolt when the Qwknut® is released.

The Qwknut® was selected in the place of a Pyro release device mainly because of its excellent resetting features. The device is designed to carry a nominal 13,350N tension load and release this load when a controlled pulse/current input (which is similar to the standard requirements for pyrotechnic release devices) is provided to actuate a shape memory alloy (SMA) wire. More information on the Qwknut can be obtained in [2]. The critical performance characteristics for the Qwknut® are given on table 1.

Table 1
Performance Characteristics of Qwknut

<table>
<thead>
<tr>
<th>Performance Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release Time</td>
<td>50ms at 3.5Amps (at 25°C)</td>
</tr>
<tr>
<td>Nominal Preload</td>
<td>13,345N /14,234N</td>
</tr>
<tr>
<td>Operating Lifetime</td>
<td>100 cycles</td>
</tr>
<tr>
<td>Maximum Static Load</td>
<td>16,681N</td>
</tr>
<tr>
<td>Mass</td>
<td>0.214Kg</td>
</tr>
<tr>
<td>Operating Circuit Resistance</td>
<td>4.1 to 4.3 Ohms</td>
</tr>
<tr>
<td>Current requirements</td>
<td>3.5 to 5.5 Amps</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-45°C to +65°C</td>
</tr>
<tr>
<td>Non-Operating temperature</td>
<td>-80°C to +85°C</td>
</tr>
</tbody>
</table>

Launch Lock Interface

The three Legs, which support the EPMEC during the launch phase, are attached to the Support Ring using a wedge interface. The legs are attached to the Spacecraft Xenon Tank Support Platform. The spring at the base of each of the Legs is designed such that the force is sufficient to open the wedge fixation. The Support Arm rotates until the end stop is reached. The End Stop consists of an open Honeycomb, which has been designed to dissipate the energy in the legs during the release action. This damper needs to be replaced after each actuation.

Rotary Actuator Design

The Rotary Actuator used in the design of the SMART-1 EPMEC was developed by ETEL SA, Switzerland for ESTEC. The actuator is one of a family of actuators that were discussed in [1]. The design of the actuator for the EPMEC was made by ETEL. Contraves Space AG have now taken over the right of design and future development of the Actuator Technology, which has many uses in Space Mechanisms and has significant advantages over other similar products. The actuator used for SMART-1 utilises a redundant winding hybrid electrical stepper motor and a stiff speed reducer based on conventional gear technology.
The Actuator consists of the following elements:

- Speed reducer (gearbox)
- Main bearing assembly to provide tilt and translation stiffness at the output level
- Fixed input flange
- Rotating output flange
- Electrical Motor

A mechanical I/F exists on the output flange to provide a connection to the angular positioning sensor. In the case of the EPMEC, a Potentiometer is sufficient for output angular position sensing. The potentiometer (type 25413) manufactured by Betatronix Inc in the USA, has an accuracy of ±0.1° which, coupled the accuracy of the actuator is accurate to within 0.1°, gives an overall actuator accuracy of ±0.2°.

The potentiometer requires a 5V supply from the EPMEL, and returns an analogue signal to the EPMEL where it is converted into a digital signal and sent on to the S/C system control unit.

The motor consists of a frameless stator fixed within the actuator housing. The rotor is mounted directly to the shaft, which maintains the concentricity and stiffness required for the small air gap in the stepper motor.

The bearings are thin-section bearings supplied by ADR, France. The Bearings utilise AISI 440C Stainless Steel and the cage reinforced Phenolic resin impregnated with Fomblin Z25 oil.

The Gearbox design is very simple and utilises only a few parts. The differential epicyclic drive uses two sets of single internal wheels mating with a two stage pinion gear. The gears used are conventional spur gears with concentric input and output shafts. The gears are lubricated with Braycote 601EF.

The typical performance characteristics for the Actuator are presented on table 2.

In order to provide two-axis steering for the EP Thruster, two actuators are employed. The output shafts of the actuators are connected with a bracket that is extremely flexible to minimise the transfer of launch loads over the actuators (the mechanism is over constrained for launch). To avoid large deformations during ground testing, the mechanism should be off-loaded to avoid these large deformations of the EP Thruster support plate with respect to the rest of the mechanism.

### Table 2  
**Actuator Performance Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Step angle</td>
<td>0.0021°</td>
</tr>
<tr>
<td>Differential Epicyclic Drive ratio</td>
<td>-486.67 : 1</td>
</tr>
<tr>
<td>Drive motor</td>
<td>1° Permanent Magnet Type</td>
</tr>
<tr>
<td>Step Rate</td>
<td>0.3°/s</td>
</tr>
<tr>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>(Peak &amp; Continuous), (RedundantWinding)</td>
<td>+20°C &lt; 7.5 Watts</td>
</tr>
<tr>
<td></td>
<td>+80°C &lt; 8.6 Watts</td>
</tr>
<tr>
<td></td>
<td>-45°C &lt; 6.5 Watts</td>
</tr>
<tr>
<td>Output Torque /powered</td>
<td>&gt;7.0 Nm</td>
</tr>
<tr>
<td>Holding Torque /unpowered</td>
<td>&gt;6.5 Nm</td>
</tr>
<tr>
<td>Stiffness/Torsional</td>
<td>9,400 Nm/rad +/-10%</td>
</tr>
<tr>
<td>Stiffness/Axial: Outwards</td>
<td>140 E6 N/m +/-10%</td>
</tr>
<tr>
<td></td>
<td>260 E6 N/m +/-10%</td>
</tr>
<tr>
<td>Stiffness/Bending</td>
<td>95,000 Nm/rad +/- 6.3%</td>
</tr>
<tr>
<td>Shaft Static Load capability</td>
<td>Axial 3,930 N</td>
</tr>
<tr>
<td></td>
<td>Transverse 2,000N</td>
</tr>
<tr>
<td>Total Assembly weight (excl. Position Sensor)</td>
<td>1.9 kg</td>
</tr>
<tr>
<td>Accuracy Positioning</td>
<td>+/-0.04°</td>
</tr>
<tr>
<td>Repeatability</td>
<td>+/-0.0041°</td>
</tr>
<tr>
<td>Backlash</td>
<td>&lt;0.1°</td>
</tr>
<tr>
<td>Wobble over 360</td>
<td>&lt;0.012°</td>
</tr>
</tbody>
</table>

**EPMEC Support Structure**

The Support Structure, shown on figure 6, for the EPMEC consists of two platforms that are connected together using the Shock Damper System. The support structure also contains the Thermal Control Subsystem for the EPMEC, which includes a Thermal Radiator, a Reflector and thermal stand-offs, used to isolate the various elements. The Elevation Actuator is attached to the underside of the Actuator Support Platform, the damping element is mounted to the upper side of the ring and forms the interface with the Thruster Support Platform which is supported on a series of thermal stand-offs to isolate the mechanism.
The PPS-1350 EP Thruster contains several ceramic components that are very sensitive to the shocks arising during the Ariane V launch phase and spacecraft separation. In order to minimise the induced shocks to satisfactory levels, the shock damper system used for the EPMEC (shown on figure 7) has been especially constructed by Contraves Space AG for SMART-1 using techniques developed in house.

Initially commercially available wire wool dampers were considered. However, due to the effective mass penalty associated with the use of this type of damper, it was decided that an alternative approach using a damping ring made from Silicone Rubber would be used. The load capacity of the individual wire wool dampers is low and for this reason c.a. 15 dampers would be required to provide sufficient damping; this led to an increase in mass of c.a. 1.4 kg. Contraves Space AG had already used a similar damper element on the MOMO Instrument with surprisingly good results.

A development model of the EPMEC was assembled so that vibration testing and shock test could be performed (this consisted of the Shock Ring hard mounted to a plate and a dummy thruster mass of some 4.3Kg) to check the suitability of the design. The results from the shock tests are shown on Figure 8a and 8b where it can be seen that the damping effect is c.a. 10:1 at the worst instance. In some instances values of 100:1 were obtained. The damping ring easily meets the requirements for high frequency damping.

The design requirements on the system with respect to the damping and frequency were felt to be contradictory; a highly damped system (low-stiffness) has inherently a lower eigen-frequency and visa versa, a system with low damping i.e. higher stiffness, has higher eigen-frequencies. Since the EP Thruster is susceptible to shock vibration a compromise between the two requirements had to be achieved in the EPMEC design. It was decided to provide a good damping coefficient but this lead to a low eigen-frequency for the system, which from tests on the DM showed that a first eigen-frequency in the region of 40Hz could be expected on the EPMEC. The DM tests also demonstrated that an amplification factor of 9 could be expected for the vibration loads on the thruster at this frequency. This effect had to be considered in the stress analysis of the mechanism, especially, as from table 4, it can be seen that the mechanism will be subjected to the full high level sine vibration at this frequency. With the amplification factors witnessed on the DM, this will lead to extremely high loads on the Thruster if the input loads are too high. Fortunately, on SMART-1, the actual load at this frequency is less than 1g which gives less than 8g on the thruster which is well within its specification limit of 20g.

Thermal Control Subsystem

From experience gained during the STENTOR programme, it has been seen that the EP Thruster (when operating) is extremely hot (c.a. 200°C). Since the heat flux can only be dissipated in conduction to the rest of the EPMEC and in radiation, the I/F temperature between the Thruster and the EPMEC can also be expected to reach c.a. 200°C.

Since the maximum operational temperature of the EPMEC disregarding the temperature of the Launch Lock System that is released before EP Thruster activation, is 125°C, a staged thermal insulation approach is required.

One of the main thermal control elements included in the EPMEC is the Radiator that is used to radiate the heat at the EP Thruster interface to space and hence cool the thruster to within the acceptable limits. The radiator was designed such that the white painted radiative area was sufficient to take 20W from the Thruster.

The centre area of the radiator and the underneath surfaces were covered with MLI.

In addition to the radiator, the EPMEC is protected from high temperature conduction by mounting the Thruster Support Plate to the Damping Ring using thermal standoffs to limit the conductive thermal flux reaching the lower part of the EPMEC. In addition it should also be noted that the damping ring itself is a thermal isolator and provides additional protection.

To minimise the radiation from the lower surface of the EP Thruster to the EPMEC Actuators, a gold plated...
reflector shown on figure 6 is used to protect the EPMEC. This is also supported from the Thruster Support Plate using thermal stand-offs.

In addition to the measures already described, elements with an external view to space will be treated with a black coating to provide protection from sun radiation that occurs when the mechanism is tilted inside the spacecraft central cone.

With these measures in place, the nominal operating temperature range of the EPMEC is between –20° and +55°C. A sketch of the Thermal Control Subsystem design is shown on figure 9.

Cable and Xenon Tube Layout

Since the actuator is unpowered for much of the EP Thruster operational periods, the stiffness of the cables and the Xenon tubes must not unduly influence the positional stability of the Thruster. After the testing of the actuator it was clear that the backdrive torque of the actuator was significantly high enough to resist any effect that could be induced by the stiffness of the cables and tubes. During the design phase, however, this was not known and a limit was set for the back drive torque which in turn provided a value for the resistance (spring) torque from the cable routing and tubes. The EPMEC cable routing consists of two separate paths. The first is for the EPMEC control where 7 cables are required to provide motor power, potentiometer sensing and Qwknut activation. These cables are routed to the Connector Bracket mounted on the Spacecraft. The second is for the EP Thruster Harness that contains 7 high voltage and heater cables that have to traverse the moveable part of the mechanism. The connectors for the EP Thruster harness are mounted inside the spacecraft. In addition to the cables, three titanium tubes also traverse the moveable part of the mechanism.

Cable Layout

The main problem with the harness routing design was that the EPMEC moves within a half-cone of 10° with respect to the thrust axis. Since the EPMEC is switched off between repositioning manoeuvres, the residual
torque in the cable must not influence the positional stability of the thruster.
Analysis was performed to define the harness routing configuration with the least influence. With a ±10° angular rotation of the EPMEC, the induced residual torque in the selected configuration was c.a. 900Nmm.

Xenon Tube Layout

Since the Xenon tube supplies the EP Thruster with gas under pressure (albeit low pressure) the design of the tube routing must consider fatigue and fracture as a mode of failure. Special consideration has to be made for the movement of the EPMEC (10° half-cone) and the launch environment.
After several iterations, the final design was defined where the stress in the tubes did not exceed the allowable limit which considered both the fatigue and fracture effects. A three-helical arrangement was selected which offered the advantages of high flexibility, low induced residual torque and also leads to stresses that satisfy the fatigue and fracture stress limits. In addition, to reduce localised high stresses at the tube clamp fixations, the tubes are clamped within Viton rubber supports.
The residual stiffness with the selected layout was a factor of 1/10 less than the stiffness of the harness.

3. QUALIFICATION TESTING

The EPMEC was subjected to a full Qualification Test programme that included a Vibration Test, a Thermal Balance Test to correlate the thermal model, a TV cycling test and finally a Life Test for the mechanism and the Tubes and Harness.
The configuration of the EPMEC for the test programme is shown on figure 1. Although the mechanism is complete, the EP Thruster subsystem, the thruster, the harness, tubes and Hot Connection Box are all simulated by mass dummies.

Vibration Test

The EPMEC was subjected to a full vibration test programme including High Level Sine and Random Testing.
Additionally the EPMEC was subjected to a low-level sine sweep to identify the modes of vibration of the mechanism.
The results from the test were correlated against the FEM analysis and the model updated to reflect the eigen-frequencies identified during testing.
Table 3 shows the correlated eigen-frequencies which assume the spacecraft interface and not a hard-mounted interface.
As shown on figures 10 to 13, it can be seen that the 4 eigenmodes under 100Hz are heavily influenced by the Shock Damper.

<table>
<thead>
<tr>
<th>Eigenmode No.</th>
<th>Frequency</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.0 Hz</td>
<td>Rocking on Damper Ring</td>
</tr>
<tr>
<td>2</td>
<td>36.6 Hz</td>
<td>Rocking on Damper Ring</td>
</tr>
<tr>
<td>3</td>
<td>68.4 Hz</td>
<td>Vertical Deformation of Damper Ring</td>
</tr>
<tr>
<td>4</td>
<td>79.9 Hz</td>
<td>Rocking of EPMEC</td>
</tr>
</tbody>
</table>

High Level Sine Test

The EPMEC was subjected to the High Level Sine Vibration levels shown on table 4.
The maximum amplification factor measured on the mechanism during the test was 10.3 at a frequency of 68Hz. This peak acceleration was measured on top of the thruster and occurs at the 3rd eigen-frequency of the mechanism.
The amplification factors for the remaining structural items are not significant during the high-level sine test.

Random Vibration Test

The EPMEC was successfully subjected to a random vibration test with inputs as shown on table 5.
During the Random Vibration test it was not the Thruster that exhibited the highest loads as this was effectively damped at higher frequencies but the actuators together with the attached potentiometers which were the most effected.
Due to the responses at the actuators, the input in the Z-axis was slightly notched at high frequencies to reduce the loads on the Potentiometers.

Figure 10
Eigenmode Nr. 1
Thermal Vacuum Test

The EPMEC was subjected to the Thermal Vacuum Test as defined on the figure 14. At the start of the test, the mechanism was subjected to a simplified Thermal Balance test to correlate the Thermal mathematical model. As a consequence of the results obtained from the thermal balance test, minor changes were made to the thermal resistance of the stand-offs described earlier.

Table 4

High Level Sine Vibration Inputs

<table>
<thead>
<tr>
<th>Axis</th>
<th>Frequency</th>
<th>Acceleration Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>X &amp; Y</td>
<td>20 – 100 Hz</td>
<td>5g</td>
</tr>
<tr>
<td>Z</td>
<td>20 – 60 Hz</td>
<td>10g</td>
</tr>
<tr>
<td></td>
<td>60 – 80 Hz</td>
<td>slope to 5g</td>
</tr>
<tr>
<td></td>
<td>80 – 100 Hz</td>
<td>5g</td>
</tr>
</tbody>
</table>

Table 5

Random Vibration Inputs

<table>
<thead>
<tr>
<th>Axis</th>
<th>Frequency</th>
<th>PSD</th>
<th>Grms</th>
</tr>
</thead>
<tbody>
<tr>
<td>X &amp; Y</td>
<td>10 – 100 Hz</td>
<td>+3dB/oct</td>
<td>8.95</td>
</tr>
<tr>
<td></td>
<td>100 – 300 Hz</td>
<td>0.14 g²/Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 – 2000 Hz</td>
<td>-5dB/oct</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>10 – 100 Hz</td>
<td>+3dB/oct</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>100 – 300 Hz</td>
<td>0.14 g²/Hz slope to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 – 650 Hz</td>
<td>0.038 g²/Hz slope to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>650 – 660 Hz</td>
<td>0.010 g²/Hz</td>
<td></td>
</tr>
</tbody>
</table>

The results from the thermal balance test show that the thermal design of the mechanism responds as intended and that with a 195°C I/F temperature on the Thruster, the radiator cone has a temperature of c.a. 100°C. The rest of the mechanism is well isolated from the upper structure and exhibits a maximum temperature of less than 60°C. During the TV test, functional tests were performed on the mechanism. The results from these measurements are discussed later in this paper.

Life Test

A Life Test of 4000 operational cycles was performed directly after the TV test was completed. The life test was slightly accelerated by running the mechanism at 0.5°/sec instead of 0.3°/sec. In [3] accelerated life tests are questioned when the lubrication is either oil or grease. In this instance, due to the low speed of the actuator, it was not considered that this would adversely effect the results obtained.
The life test consisted of 1000 cycles of $4 \times \pm 9.5^\circ$ traverses of the half cone. Each traverse being $45^\circ$ displaced from the previous to ensure that both actuators have to be used to obtain the required position. The life test cycle is shown on figure 15. During the life test, the actual position, commanded position and the power consumption were recorded. The plots shown on figures 16 to 19 show the performance characteristics of the EPMEC over the duration of the Life Test. The shape of each of the curves is determined by plotting the maximum, minimum and average values that were evaluated after every 400 cycles. The Positional Errors for the EPMEC are shown on figures 16 and 17. The power consumption measurements over the whole thermal vacuum test and life test are shown on figures 18 and 19.

Observations during Testing

During the test programme it was noted that the internal structural design of the Potentiometer was not suitable for the particular application on the SMART-1 EPMEC. Revisions to the design were discussed with the supplier and the modifications implemented on the Flight Models. It must be said that the electrical design of the Potentiometers is extremely resiliant to the Thermal Vacuum and Mechanical Vibration induced effects. Additionally, whilst the Qwknuts provide an extremely good solution to High Load Release devices, a certain degree of understanding of the design is necessary to be able to correctly handle the devices. Incorrect use, or mishandling of the devices can lead to unexpected problems occurring which can have serious consequences on the hardware. These handling problems have been discussed with the supplier and minor changes are now being implemented in the design.

Pointing Error

The average error shown on figure 17, indicates that the elevation potentiometer zero position has an offset of c.a $0.3^\circ$. The azimuth zero position has a small offset of c.a. $0.04^\circ$. In both the axes, the potentiometers were not adjusted accurately which has lead to the offsets witnessed in the measurements.

The measured positional accuracy for the actuators is c.a $\pm 0.3^\circ$. Due to the build up of errors on the system, the expected RMS error was $0.25^\circ$. Taking into consideration the measurement error in the Control Electronics which is $0.08^\circ$ (8 bit measurement), the predicted error of the actuator and the actual error for each actuator correlate very well.

Power Consumption

As expected, the power consumption for the EMPEC increases as the background temperature for the increases; this is due to increased losses in the motor and a decrease in the delivered motor torque at the higher temperatures. It was promising to discover that the Power Consumption at Cold is also lower than expected. As discussed in [4], it was thought that as the mechanism is lubricated with both oil and grease, the resistance torque of the mechanism would increase significantly due to viscosity effects which would have the effect of increasing the power consumption as more current would be needed to drive the system. The lower power consumption is explained by the fact that the motor losses decrease and the delivered motor torque increases as the motor gets colder. These two effects have more than compensated for the increase in torque due to the viscosity effects.

With a dry lubricated system, the power consumption drop would have been more significant (similar to the difference between the $80^\circ$C and $20^\circ$C values). In fact the increase in power consumption is equivalent to half the expected drop due to the change in the electrical resistance of the motor.
4. SUMMARY

Although during the qualification phase, one or two minor problems were discovered, it can be stated that the design of the EPMEC satisfies the requirements as a steering mechanism for the EP Thruster.

The selection of the Qwknut® was considered to be a wise decision as the mechanism was operated many times during the qualification testing. The cost of replacing the squibs of other non-pyro devices or the replacement of the complete separation mechanism would have added considerably to the cost.

Although the potentiometer structural design needs to be reviewed, the device is suited to this application. Discussions with the supplier have to take place to improve the mechanical design for future applications.

As the EPMEC is now qualified, and any modifications for future missions such as pointing range, mission duration etc, can be accommodated by introducing minor modifications in the design, it is intended to offer the mechanism as the steering mechanism for new generation spacecraft with Electric Propulsion.

5. ACKNOWLEDGEMENTS

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