Optimised thrust steering of a gridded ion engine

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Abstract: In any spacecraft installation of an ion propulsion system it is likely that there will be a need to alter the position of the thrust vector with respect to the centre of the vehicle in order to minimise attitude and orbital perturbations during operation. Of most importance is the need to correct for the movements of the centre of mass of the spacecraft. These movements are caused by the consumption of propellant, and by the deployment and rotation of solar arrays. The conventional solution is to incorporate gimbal systems (ie thruster orientation mechanisms). Whilst these devices can perform perfectly well, they do represent a considerable mass overhead (typically 9 to 20kg), amplify launch vibrations to the thrusters, occupy a large volume, present a significant cost penalty, and add to the integration schedule for a satellite. Consequently, a method for providing direct vectoring of the ion beam has been developed under an ESA TRP program. This uses a novel technique of screen grid translation with respect to the accel grid, which has the effect of deflecting the ions as they are accelerated through the grid apertures. This paper presents the design evolution and test results for a prototype T5 thruster.

I. Initial prototype

During the course of the ESA TRP program, a prototype T5 vectoring engine was designed, developed, and successfully tested, demonstrating vectoring up to 13° with a resolution of 0.01°, and a response time of less than 6ms. No degradation in specific impulse and engine efficiency were found compared to a standard T5.

The method selected for grid translation incorporates small piezoelectric (PZT) actuators. A stack of approximately 50 in a 14 x 55 x 12mm flextensional shell is capable of providing a stroke of 500 microns, equivalent to 16° of vectoring. Translation is then achieved by applying a potential difference of up to 200V across the piezoelectrics which then contract, causing a corresponding expansion of a flextensional shell in the axis of translation to provide the appropriate grid movement.

Figure 1. Vectoring T5

In the original prototype, two of these devices are located on the polepiece to give two axis steering, as depicted in the thruster subassembly Figure 2.

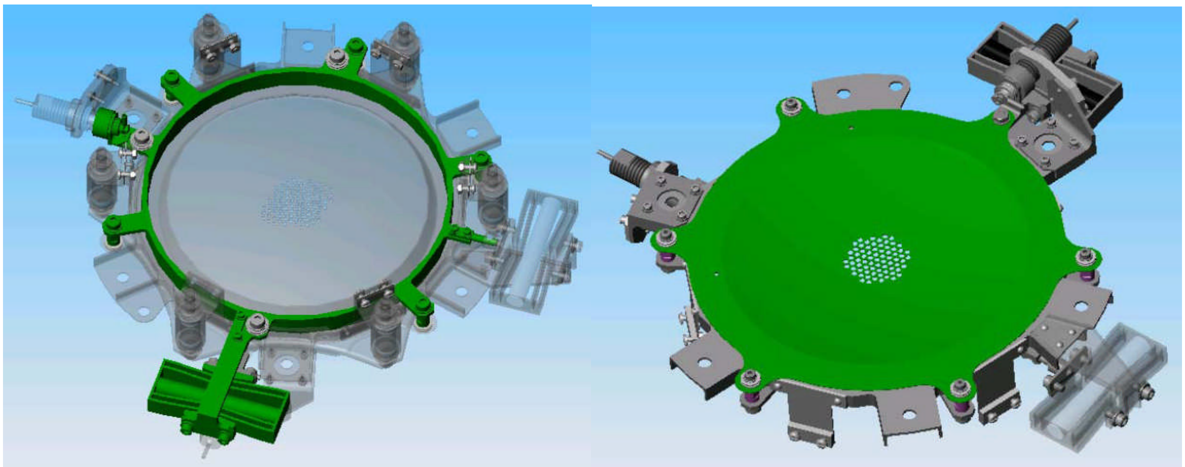


Figure 2. T5 thruster sub assembly with actuators

One of the actuators applies a force directly to the support ring, which is allowed to move in one axis by vertical slots. This movement is translated to the screen grid by perpendicular slots in the screen grid attachments. The second actuator applies a force directly to the screen grid, and consequently movement occurs just for the grid but not the support ring. Closed loop feedback control is then provided by use of miniature capacitive displacement sensors. These devices are beneficial in rapidly compensating for any small effects such as hysteresis or friction which would otherwise lead to a reduction in precision.

In order to accommodate the actuators within a T5 thruster shown in Figure 2, a small amount of redesign of the polepiece, screen grid, earth screen, and cable bracket is necessary.

II. Optimisation

The drawback with a 2 actuator system lies in the thermal expansion behaviour of the assembly. If the grids are initially aligned, then as the thrust level is increased, the screen grid is pulled in the direction of the actuator. This occurs due to the thermal expansion of the polepiece to which the actuator is attached via a bracket. Although attempts were made to match the thermal expansion of the actuator flextensional shell to the grid movement, an offset in the vector without actuation was apparent. This offset varies with thrust and leads to a non symmetrical vectoring range. Consequently a 4 actuator system has been designed and manufactured to maintain symmetrical vectoring at any thrust level, as depicted in Figure 3. The constraints created by the opposite actuator pairs also allows the screen grid to bow away from the accel grid due to thermal expansion, thus minimizing any grid shorting effects.

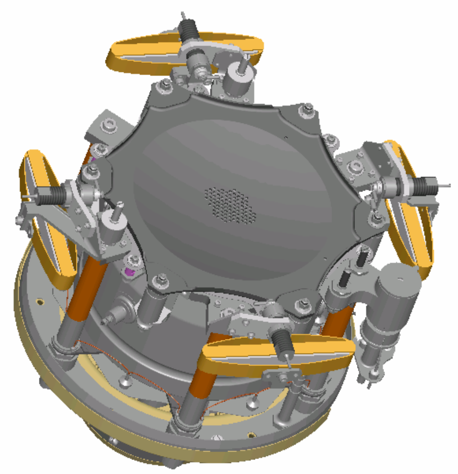


Figure 3. Optimised vectoring T5

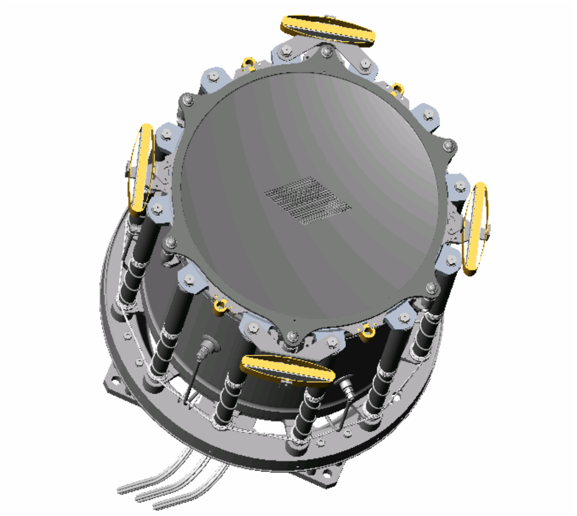


Figure 4. Optimised vectoring T6

In addition, a number of additional alterations have been incorporated. These include modification to the displacement sensor such that it is more precisely collocated with the actuators to detect motion in the axis of translation. The neutralizer has also been relocated to the earth screen to reduce heat transfer to the actuators. Furthermore, the accel grid hole pattern has been optimised to maximize lifetime, by aligning the hole centres with the screen grid. Improvements have also been introduced with the slot arrangement to eliminate frictional effects.

The technique is also scaleable, and the T6 design, suitable for North South stationkeeping or interplanetary missions is shown in Figure 4.

III. Lifetime

The lifetime limitation for gridded ion engines is typically due to erosion of the accel grid arising from charge exchange between the ion beam and the grid material. Careful selection of the grid separation, grid voltages, and thrust levels is applied to avoid direct impingement of the ion beam with the bore edge, which would lead to higher erosion rates and lower lifetime.

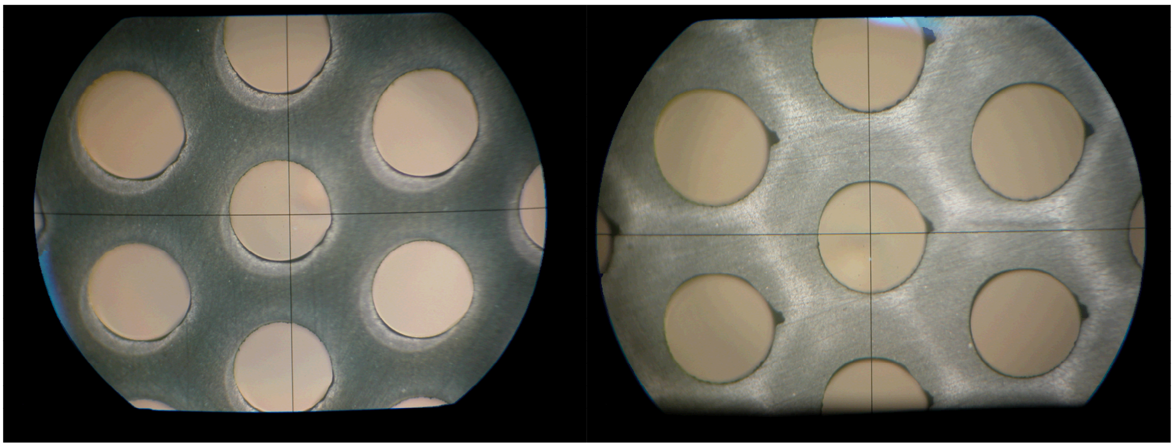


Figure 5. Downstream and upstream faces of accel grid

For a vectoring engine, it is clear that there is a greater possibility of direct impingement on one edge of the bore due to the intentional misalignment of the screen and accel grid holes. This is evident from Figure 5a, which shows the downstream face of the accel grid after testing for a period of more than 100 hours over a range of angles up to 16º. However, in the event of direct impingement the erosion rates quickly reduce once the region of impact has eroded. Examination of the upstream face of the accel grid shows the traditional hexagonal pattern offset with respect to the grid holes.

Table 1. Sapphire modeling inputs

Plasma potential (V)	1176
Electron density (m^{-3})	4.98 x 10^{+17} @ centre
Electron temperature (eV)	3
Utilisation (%)	61 - 80
Sigmund exponent	1.7
Surface energy	0.0121
Maximum angular enhancement	100
Yield coefficient	1.81
Threshold energy	22.8
Yield exponent	9.5

To simulate the erosion effects over the full lifetime we use the Sapphire particle in cell code, which has been matched to test data throughout the T5 and T6 developments. In particular, the electron density can be matched to the beam and grid currents. The principal input data for plasma conditions and carbon accel grid material erosion at 18mN are presented in table 1. Electron and plasma densities are typically greatest at the middle of the discharge chamber, reducing by an order of magnitude towards the edge.

Of course, each mission presents a different thrust and vectoring scenario, so a variety of simulation cases have been considered. A good example is the angular demand for the thruster orientation mechanism (TOM) for Smart-1 shown in Figure 6.

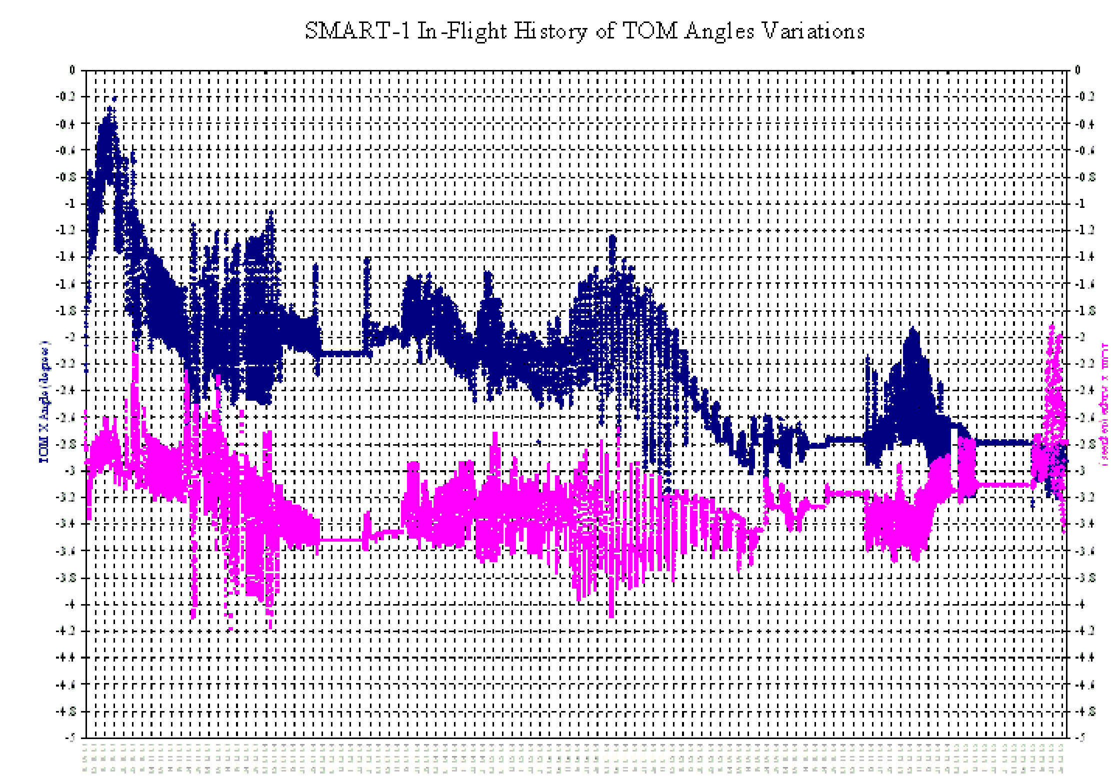
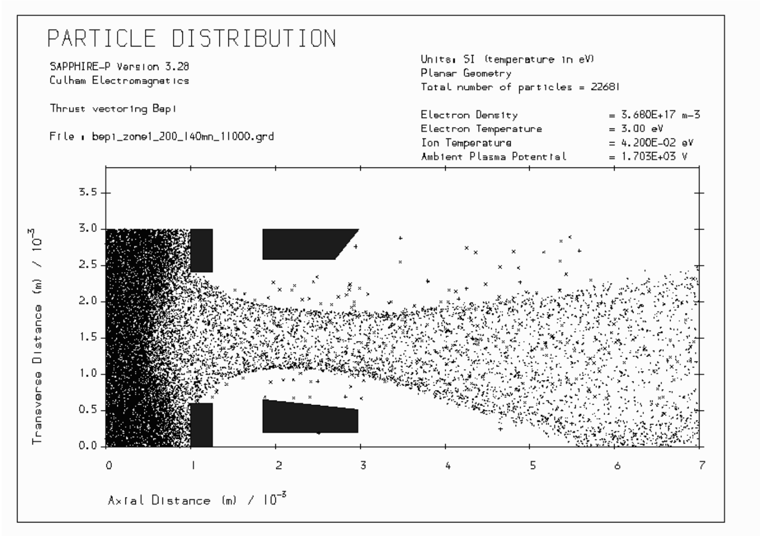


Figure 6. Smart-1 TOM angles



It is not practical to model short duration fluctuations in the vectoring angle, so instead a simplified vector profile is created. For example, the effect of solar array rotation on the centre of mass is not modeled specifically, as it appears as a sinusoidal variation with a time period which is too small compared with the overall lifetime. Instead it is accounted for as a fixed offset in the overall vector demand to simulate a worst case situation.

For the T6, Figure 7 shows the end of life grid material for a thrust level of 145mN and a total impulse of 5.7MNs.

Figure 7. End of life bore erosion for T6

The vectoring angle is modeled as 4° at beginning of life due to a thrust vector offset with respect to the centre of mass, and rising to 6° at end of life due to fuel depletion. Erosion rates have been recalculated initially after the first 10 hours when rates are known to diminish rapidly, and then subsequently after 4000, and 8000 hours. This can be observed by monitoring the grid currents as shown in Figure 8.

For a flight system the first 20 hours of operation would effectively be covered by a burn in period during ground testing. In this respect, the in orbit conditions will be more constant.

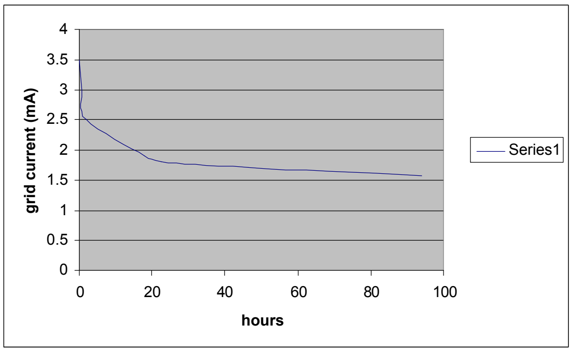


Figure 8. Grid current as a function of time for a thrust level of 15mN and vectoring of 7.5°

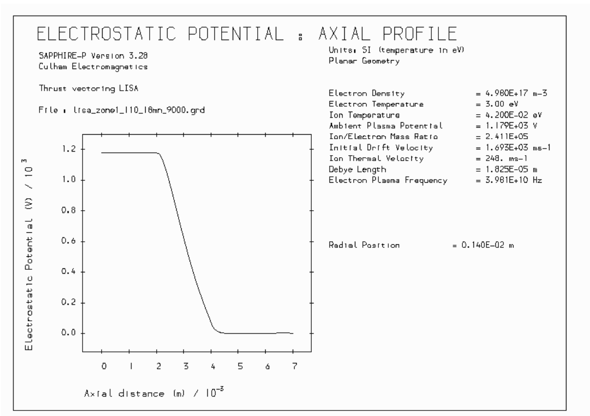


Figure 9. Potential well for end of life gridset

The simulations indicate that there is adequate grid material remaining, and there is no evidence of significant electron backstreaming which would indicate that the engine could no longer function correctly. This can be identified from the predicted potential well voltage along the centre of an aperture through the grids. Electron backstreaming would be evident if the potential does not fall below 0V.

As the bore in the accel grid enlarges with increased erosion, the effective vectoring range is predicted to reduce by approximately 5 - 10% over the lifetime, depending on the vectoring range and thrust level selected. This effect can be accommodated by ensuring good margin in the actuator stroke capability, ie by oversizing at beginning of life by 20%.

Actuator fatigue has also been addressed. A cyclic demand can be considered by reference to a North South stationkeeping manoeuvre, which can typically consist of a ±2° operation followed by 48 smaller oscillations of 0.12° over a period of 1 hour once every 12 hours. With this in mind, the gridset has been subjected to 200,000 back and forth movements of ±40µm (equivalent to >1°) at a temperature of 200°C, and a frequency of 1Hz. This demonstrated good fatigue resistance with only a 1% reduction in translation evident.

IV. Thermal

The design incorporates a high emissivity coating (Aquadag paint) applied to the earth screen and earth screen top to dissipate heat. The actuators have been tested effectively in an oven up to 280°C without significant loss of stroke (see Figure 10).

Engine test data for the T5 indicated a maximum actuator temperature of 143°C for a thrust level of 15mN. Further simulations for a T5 model matched to test data indicate a worst case temperature of 185°C for a thrust level of 20mN. Simulations for the T6 suggest that the actuators will not exceed temperature limits for thrust levels of 145mN, commensurate with requirements for communications spacecraft such as alphabus.

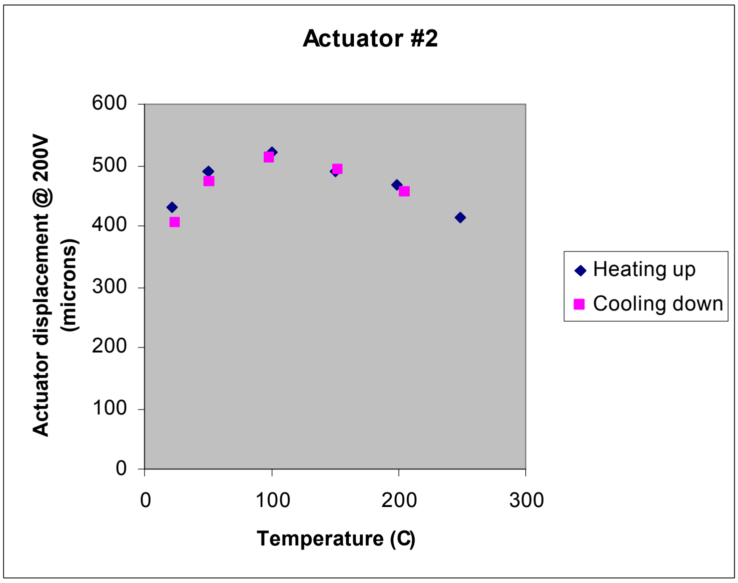


Figure 10. Actuator performance as a function of temperature

V. End of life test

A demonstration of the optimized vectoring T5 with an accel grid drilled to be representative of end of life conditions is scheduled to occur before the end of 2007 in QinetiQ's LEEP3 facility.

The accel grid holes are first drilled as for beginning of life. In this condition, the holes are cylindrical. To replicate the end of life conditions the grid is redrilled with enlarged conical tools to simulate the overall erosion characteristics. In this respect the minimum diameter of the hole increases from 1.50mm to between 1.57 and 1.64mm depending on the radial location. The drilling operation also occurs with a 200µm translation and a 7° inclination with respect to the bore centerline. In addition, the actuators will also be stressed by performing 200,000 actuations of ±40 microns at 200°C

Figure 11. LEEP3

During this test campaign it is planned to re-check the resolution, frictional/hysteresis effects, and grid currents at different vectoring angles up to 10° and thrust levels up to 20mN. Hot and cold starts will also be performed. The tests will incorporate a beam probe with 11 Faraday cups for beam divergence and vector angle determination, and a Langmuir probe for characterization of plasma conditions across the discharge chamber immediately behind the gridset.

VI. Conclusions

The delta mass for the vectoring engine is just 740g with a delta power demand of 1.2W.The technique has been shown to be suitable for missions to Near Earth Objects (eg Don Quixote), the moon, and Mars, and in addition North South Station Keeping manoeuvres could be performed for communications satellites. For T5 sized thrusters, the vectoring technology can be applied to future drag compensation missions.