Micro Electric Propulsion Technology for Small Satellites: Design, Testing and In-Orbit Operations

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Abstract

Electric propulsion (EP) systems can provide an increased specific impulse over typical chemical systems and resistojets. This allows for a higher total delta V for a mission or significant mass savings. The use of EP systems for small satellites has so far been prohibited by the high cost of the systems and the high power needs to run them within the physical constraints of small satellites. The Surrey Space Centre of the University of Surrey, together with its industrial partners is working on the development of low cost, highly innovative micro-EP systems for small satellites which can currently support and enhance current space missions as well as to enable new mission concepts for the near term. In this paper, current work on a micro-PPT, the novel "Quad Confinement Thruster" (QCT) and the Helicon double layer thruster (HDLT).

INTRODUCTION

The Surrey Space Centre is a world leader in small satellite research and development. High performance propulsion systems for sub 250 kg platforms is a key development aspect which will pave the way for the next generation of mission profiles. The use of electric propulsion on board small satellites can allow mass savings through increased specific impulse technologies, which could be translated to a lower launch mass and cost savings, or a correspondingly extended mission lifetime. A range of technologies are in development at the SSC, spanning the TRL scale. The micro-PPT experiment on the STRaND-1 Cubesat satellite launched on the 25th February 2013 which employs a novel design which does not require TEFLON. Experimental results and the expected orbit performance of the PPT is discussed in this paper. The Quad Confinement Thruster (QCT) which is a family of low cost cusp field confinement thrusters with a unique electromagnetic topology which allows thrust vector control. The range of QCT models are presented in here, namely the 40W/1mN, 200W/3mN, 1500W/50mN thrusters designed for various small satellite sizes and missions. Experimental thrust balance results detail the disruptive impact the QCT can have for near term small satellite missions. The Helicon Double Layer Thruster (HDLT), a collaborative research project between the University of Surrey, Astrium and the Australian National University is presented and the principles of operation are described.

THE QUAD CONFINEMENT THRUSTER FAMILY

The Quad Confinement Thruster (QCT) is a new variety of electric propulsion that was conceived in 2009 within the Surrey Space Centre (SSC). The unique feature of the QCT is the capability to actively vector the direction of thrust over a wide range without the use of moving parts. The operating principle is similar to a Hall Effect Thruster: an electric field is sustained within the plasma by imposing a magnetic barrier between a positively charged anode and a neutralizing hollow cathode. The thrust is derived from the momentum of ions accelerated through the electric field, which leave the thruster as a high velocity beam of ions.

The topology of the magnetic field, as illustrated
in Fig. ??, is a quadrupole with the field lines focussed by soft iron cores into four cusps located at the midpoints of the channel walls. Power can be regulated independently to four quadrants in order to steer the direction of ion acceleration.

The family of QCTs under development at SSC is shown in Fig. ?? The naming convention for these thrusters corresponds to their nominal operating power: 40W, 200W, and 1500W respectively.

**QCT-200**

The QCT-200 is the original variant of the technology, and has the most design and experimental heritage. A joint programme is currently underway between SSC, Surrey Satellite Technologies Ltd. (SSTL), and Astrium to develop a flight version of the 200W design.

This device demonstrates reasonable low power performance in terms of specific impulse. Results from recent thrust balance characterization testing of the QCT-200 are shown in figure 3. A specific impulse of 859s was achieved at a power of 200W and a propellant flow rate of 2sccm. The thrust vectoring capabilities of the device were investigated using a 3-axis translating stage to characterize the properties of the plasma downstream of the channel exit. The survey volume for this analysis is illustrated in figure 4. The results for symmetric versus steered magnetic field conditions is provided in figure 4, which shows a vertical slice of the electron density taken at the centre of the survey volume.

**QCT-1500**

The mass savings which may be leveraged through use of high exhaust velocity electric propulsion systems is most lucrative in the context of a commercial satellite system. The current state of the art in telecoms electric propulsion systems provide performances of around 1600 s specific impulse at between 40-80 mN of thrust force. In order to be considered feasible for use, the thermal efficiency of the thruster is typically above ~ 30% with many technologies at around ~ 50%. The QCT has produced promising initial performances in laboratory tests of a 200 W class thruster. The efficiency of the thruster at 200 W input power (~ %5) is low by the standards of high power telecoms propulsion systems, however the measured trend of efficiency versus imposed magnetic field shows that significant gains in efficiency could be made at higher imposed fields. Together with the observed increase in specific impulse and efficiency with increased anode power, the QCT may be suitable for application on board a telecoms platforms after some design modifications. The ability of the QCT to electromagnetically control the thrust vector direction may allow systems engineers to abandon costly mechanical gimbel systems, thus reducing system cost and complexity. This would be of greatest benefit to commercial systems, allowing a higher profit margin and reduced system risk. Following the success of the original Quad Confinement Thruster (QCT) projects, a similar device has

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**Figure 1**: Magnetic field topology for the Quad Confinement Thruster.

**Figure 3**: Specific impulse versus applied anode power for the QCT-200.
been designed to allow operation at higher powers. Data obtained through experimental campaigns using the QCT-200 has allowed increased understanding of QCT operation. As a result, the quadrupole field strength was identified as a key parameter in the control of QCT performance and the QCT-1500 has been designed to allow operation over a broad range of field strengths. Other performance related parameters have been identified, such as the plasma channel pressure and quadrupole field geometry and have remained unmodified in order to allow performance comparison and extrapolation from QCT-200 operation data. The input (anode) power density of the thruster has been increased slightly at the maximum operating set point to allow investigation of operation at higher input power densities. The QCT-1500 has been designed to allow all the desirable physical parameters to be achieved, while also incorporating mechanisms to ensure easy operation and longevity of the thruster in the lab. The thruster is constructed mainly from aluminium in order minimise the total weight of the system. A cooling circuit has been integrated into the thruster structure and is designed to transport heat generated by the 8 electromagnets when running at full power in steady state. Thermocouples have also been strategically placed to ensure that any permanent magnets do not exceed their curie point.

The projected performance of the QCT1500 has been estimated based on extrapolations of data collected during the QCT200 experiments. In order to allow such an extrapolation, a number of parameters have been fixed in an attempt to recreate the physical processes present within the QCT200. Based on the QCT200 data, the input power required to achieve a specific impulse of 1600 s was calculated at 1000 W. A thrust level of 50 mN was then selected as a nominal maximum thrust and together with the specific impulse, the required flow rate of xenon was calculated as $3.19 \times 10^{-6}$ kg/s (30 sccm). The QCT-1500 is currently undergoing
performance evaluation, using the SSC pendulum thrust balance \cite{2} and results will be the subject of near term publications.

**QCT-40**

The QCT40, shown in Fig.\ref{fig:qct40} is the smallest of the QCT family and exchanges the mass, volume and steerable nature of the plasma plume for permanent magnets that provide a higher field and no power requirements. The QCT 40 also uses a novel corona discharge effect to replace the Hollow Cathode as a neutraliser. Concept study tests have been conducted and further thrust tests will be performed during 2013.

![QCT-40 hardware and during initial start up testing.](image)

**THE HELICON DOUBLE LAYER THRUSTER (HDLT)**

The Helicon Double Layer Thruster (HDLT) is the focus of development efforts and scientific investigation due to the innate design advantages of the technology which lends itself to efficient plasma generation and long life. The thruster can operate in a range of source plasma modes including low power capacitive and higher power helicon coupling. The plasma can then be accelerated by an spontaneously forming an electrostatic double layer. The HDLT has demonstrated a large range of scalability with the capability to operate at RF input powers of tens of watts up to kilowatts.

The Helicon Double Layer Thruster is an electromagnet electric thruster that accelerates ions across a double layer in order to generate thrust. The double layer forms spontaneously in the presence of a diverging magnetic field within a pressure range of approximately $2.7 \times 10^{-4} - 2.7 \times 10^{-3}$ mbar (0.2 – 2.0) mTorr for argon discharges \cite{5}. The double layer may be described as a rapid potential drop occurring over a finite region no larger than a few centimetres thick. The physics of double layers pertaining to plasma propulsion is not fully understood, existing theories which do not explicitly include the influence of magnetic field topology describe the region using a four particle model \cite{6,7}. The current free i.e. zero net charge, double layer is sustained by four groups of ionised species. Downstream of the double layer trapped low energy ions are present and trapped low energy electrons remain upstream. Free electrons and ions possessing higher energies than their trapped counterparts traverse the double layer moving from the low potential to high potential sides (downstream to upstream of the DL) and from high potential to low potential sides of the double layer respectively. An ion beam is the result of the acceleration of the high energy ion population across the double layer, which is thought to be the main thrust generating mechanism for the HDLT. As the thruster plume contains both accelerated ions and trapped electrons the resulting beam is self neutralising. Therefore an external cathodic neutraliser is made redundant. The thruster design also eliminates grids by accelerating ions across a naturally occurring potential difference. As a result the HDLT removes the components which are responsible for limiting the lifetime of established electric propulsion technologies such as electron bombardment ion thrusters and Hall effect thrusters \cite{8,9,10,11}.

Telecommunications satellites may soon be legally required to re-orbit at end of life (EOL) to ensure that inactive satellites are placed at a safe altitude which will not impinge on the orbits of functioning satellites in GEO \cite{12}. Additional costs
relating to the increased propellant mass required to perform the propulsive manoeuvres and the loss of revenue as the satellite mission duration is reduced to allow the transition to the graveyard orbit are both prohibitive factors [?]. Research is currently being performed on an alternative EP device that has a simple robust design that can be easily integrated into satellite architectures, the thruster can operate on a variety of propellant types and does not require a highly pressurised gas supply [?]. The HDLT is seen as a cost effective solution for re-orbiting GEO satellites and may provide mission extension beyond the expected lifetime as the device is able to operate using residual gas. The HDLT is also a candidate for space exploration missions as its design excludes components which precipitate life limiting mechanisms.

MICRO PULSED PLASMA THRUSTER

The Surrey Space Centre (SSC) Pulsed Plasma Thruster (PPT), was developed over a number of years and eventually flew on the STRaND-1 Cubesat mission which was the first to fly a mobile phone and the first UK CubeSat. The PPT hardware is shown in Fig. ?? Unfortunately, six weeks after launch the satellite communications system failed to transmit before in-orbit testing of the system could commence. The flight module flown was designed to be used for fine pointing applications but in the latter stages of putting the satellite together had to be redesigned slightly to perform de-orbiting manoeuvres.

The flight module consists of eight micro Pulsed Plasma Thrusters (PPT), four located at the top of the satellite stack and four located at the bottom. An additional module is the power unit which uses DC to DC transformers to convert 5V satellite bus to 800V. The energy for each PPT discharge comes from the 800V line charging up a high voltage capacitor. Storing energy in a capacitor substantially reduces the power requirements for the thruster, for the STRaND-1 PPT this was 1.5W. The capacitor is then discharged in a discrete train of pulses. Each pulse is a plasma discharge that forms between two metal electrodes, much like an electrical vacuum arc. The arc erodes metal from the electrodes of the capacitor (which forms part of the accelerating mechanism of the thruster) and electromagnetics accelerate the eroded mass out of the nozzle, which produces thrust. The novel aspects of the STRaND-1 PPT module include mass and power reduction techniques. The propellant used in the plasma discharge are also the electrodes which form the plasma discharge in the first instance. As metal has an extremely high density more propellant can be stored in a smaller volume than that of conventional chemical propulsion systems. All in all the propellant weighs about 10g for all eight PPTs in STRaND-1. The second major innovation is the discharge initiation system, in other PPTs the initiation of the discharge is performed by a semiconductor spark plug ramped up to around (2-3kV) to create a spark (a source of electrons). However building a circuit to provide this voltage would be very volume intensive and so a simpler mechanical contact trigger was made using a piezoelectric motor that was only 5mm in length.

Figure 6: The SSC PPT hardware designed for the STRaND-1 Cubesat mission.

The STRaND1 PPT, if successful (i.e. the CubeSat becomes active again), will be the first propulsion system to provide full axis control on this class of satellite. Having an active propulsion system would open up the available mission repertoire a CubeSat could perform in future missions (i.e. rendezvous and docking, flyby inspection etc). The heritage and experience gained in developing a PPT for STRaND-1 has been invaluable and the next step is to create a self contained ‘bolt on’ PPT module that can be integrated onto satellites as an additional mechanism to help with de-orbit requirements.

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SUMMARY

The SSC is heavily involved in the invention, construction and testing of electric propulsion technologies. The development of these technologies has been done in partnership with world leading academic partners allowing high quality basic science investigations to be undertaken. The close relationship with our industrial partners has allowed real world commercial considerations to guide the technology development and has allowed timely flight opportunities to be secured.