Development of the µPPT propulsion module for STRaND a 3U CubeSat

Peter Shaw, Vaios Lappas, Craig Underwood
Surrey Space Centre, University of Surrey, Guildford, Surrey, UK, GU2 7XH
p.shaw@surrey.ac.uk

CubeSats to date have shown an excellent potential in providing quality science and demonstrating the use of COTS technology in space applications. A next stage in the evolution of CubeSat technology is the ability to demonstrate useable on board propulsion. Following on and building on the success of previous missions (CanX-2, ION etc), Surrey Space Centre has designed, developed and is in the process of manufacturing the propulsion flight module that will be able to provide pitch, roll and yaw around a central axis and translational movement in two axes. The module comprises of eight breech fed micro Pulsed Plasma Thrusters (µPPTs). To aid in the miniaturisation there have been two significant changes. The first was a replacement of the typical sparkplug with a contact trigger mechanism that initiates a discharge. The second was the removal of the typical Teflon™ propellant used in PPTs between the discharging electrodes. In studies at the Surrey Space Centre it was shown that discharges without the presence of Teflon™ produced ~60-75% the impulse/bit then discharges with the presence of Teflon™ at the parameters that were tested. The mass eroded for the plasma production was theorised to originate from the electrodes, which is similar in the mechanisms of operation to the Vacuum Arc Thruster (VAT). The module is split into three PC104 boards, two boards house four µPPTs on them and the third board is the power unit. The power unit uses award winning voltage multipliers that take the 5V CubeSat bus voltage and transforms this to 700V for the PPT high voltage capacitors. This paper focuses on the developmental work that has been conducted to construct a propulsion module for the Surrey Training Research and Nano-satellite Demonstration (STRaND) 3U CubeSat, which is due for launch in November 2011.

Nomenclature

- \( h \) Electrode separation (m)
- \( I \) Current (A)
- \( I_{bit} \) The impulse generated per discharge (Ns)
- \( w \) Electrode width (m)
- \( \mu_0 \) Magnetic permeability of free space (NA\(^{-2}\))
**Introduction**

The CubeSat is a disruptive technology; with its low production cost and ever-increasing payload capability this technology has the possibility of seriously impacting the economics of space. Surrey Satellite Technology Limited (SSTL) will be developing and exploiting CubeSats as a relatively cost effective approach to provide training and demonstration of new technologies on a 3U CubeSat platform. The Surrey Technology Research and Nanosatellite Demonstration mission (STRaND-1) will be a precursor technology demonstration mission for a series of follow on missions. To increase the satellites in-orbit lifetime a propulsion system needs to be developed to compensate for atmospheric drag. The SSTL in-house $\mu$-resistor jet with propellant tank and feed lines proved to be too cumbersome for a full axis control system. Surrey Space Centre (SSC) offered an alternative in the form of a $\mu$PPT and it was accepted as part of the ADCS system. The current launch date is scheduled for the winter of 2011.

The first flight of a pulsed plasma thruster was on the Zond-2 satellite in the 1960’s. Throughout the past 50 years the PPT’s popularity has varied, originally sidelined for its low performance efficiencies (typically below 20%) the PPT has made a recent comeback for a low cost, low power solution for small satellite propulsion, as seen in recent PPT hardware developments such as the EO-1 PPT experiment\(^{[1]}\), Dawgstar PPT module\(^{[2]}\), SIMP-LEX\(^{[3]}\), and JOSHO\(^{[4]}\) that have all been developed and in the case of the EO-1 PPT flown, in the past decade. PPT’s remain popular within University group’s world wide due to a PPT’s compatibility with small satellite mission requirements, its relative ease of construction and its perceived simplicity in operation.

**Fundamentals**

The pulsed plasma discharge process is explained in terms of a nominal PPT with a capacitor as an energy storage device, the electrodes are in a parallel plate configuration where the electrode separation is larger than the electrode width, the electrodes have a Teflon\(^{\text{TM}}\) propellant bar in between them and the discharge initiator is a sparkplug, see Figure 1. The process described is for a single pulse of a PPT discharge. The process starts with a power unit supplying electrical energy to a discharge capacitor until it becomes saturated. The energy supplied to the capacitor over time (or power) dictates the speed that the capacitor charges up at and hence the frequency that the PPT can be discharged at.

![Figure 1: The traditional view of the Pulsed Plasma Thruster in its constituent parts](image)
A sparkplug is used to initiate a discharge between the main parallel electrodes by field emission, where electrons tunnel quantum mechanically through a strong potential barrier near the surface of a metal. The electrons being emitted then augment the electric field between the parallel electrodes creating a conductive path, into which the main discharge then occurs. High speed photography taken by the Tokyo Metropolitan Institute of Technology\cite{5}, shows that initially the conductive path occurs across the surface of the Teflon\textsuperscript{TM} via an unconfirmed mechanism but most likely some form of electron avalanche through the surface layers.

Once the discharge is initiated a conductive path between the charged plates of the capacitor via the discharge chamber electrodes through the plasma is established. This is known as the current loop. The electrodes that make up the discharge chamber have an inductance associated with them and as current begins to flow through the system, energy from the capacitor is stored within the magnetic field around the inductor. The resistance within the conducting loop is small (≤1Ω) which gives rise to large discharge currents in the kilo ampere range and strong magnetic fields form around the electrodes.

As the energy of the capacitor is transferred to the magnetic field of the inductor the voltage across the capacitor drops and eventually all the charge on the capacitor will diminish and the potential difference across the capacitor plates will tend to zero. However the current will continue to flow because inductors try to resist change in the current. The energy used to keep the current flowing is extracted from the magnetic field, which will then begin to diminish. The current will charge the capacitor with a voltage of opposite polarity to its original charge. When the magnetic field is completely diminished the current will stop and the charge will again be stored in the capacitor, with the opposite polarity as before. Then the cycle will begin again, with the current flowing in the opposite direction through the inductor. The charge flows back and forth between the plates of the capacitor through the discharge electrodes (inductor) and the plasma. The energy oscillates back and forth between the capacitor and the inductor until resistances within the plasma and electrodes cause the oscillations to die out.

This assumes a conductive path is maintained during the discharge process and for this to occur in the discharge chamber plasma needs to be created and maintained. The mechanism of plasma production is under development with advanced models being presented to explain the Teflon\textsuperscript{TM} propellant-plasma interaction\cite{6}. In the instance of the model presented by Keidar et al. it is assumed that there is a plasma-Teflon\textsuperscript{TM} interaction each time the capacitor reverses polarity, but high speed photography shows this is only the case for the first half cycle of the discharge\cite{5}.

The plasma itself has been shown to contain species of carbon and fluorine of various ion charge states. Collected RFEA data from the University of Washington observed that probe current production was still occurring on its collector grid when a repelling grid had a 199V potential difference put across it. This would indicate that the maximum ion charge state being produced could be C\textsuperscript{4+}, F\textsuperscript{6+} or Cu\textsuperscript{9+}.

It is also of interest that above 199V no current was observed and that 199V coincides exactly with the 9th level of ionisation of Copper\cite{7}. High speed photography images show that bright spots can be seen on the surface of the electrodes (predominantly the cathode) with plasma filaments or jets originating from them which are bent (or canted) in the direction of the plasma flow\cite{5} \cite{8} \cite{9}. Mass erosion has been identified in experiments as coming from the Teflon\textsuperscript{TM} surface and from the electrodes. The exact nature on how electrode erosion occurs
in a PPT is not well defined. It is this area which was explored in earlier work in which a model for the electrode erosion occurred by the process of cathode spots and cathodic arcs.\(^{[10]}\)

Once the plasma bulk is established, current will begin to flow through the electrodes, which act as inductors and establish a magnetic field. The current will flow through the current loop and due to the low resistance of the plasma large currents and hence large magnetic fields will be produced. The strong current densities flowing through the plasma interact with the strong magnetic fields and a force is produced, otherwise known as the Lorentz force. The force pushes and accelerates the plasma particles along the force vector and when seen on the larger scale this is seen as the entire plasma bulk being accelerated along and out of the discharge chamber.

To complicate the situation the inductance and resistance of the electrodes is continually changing as the plasma bulk propagates down the discharge chamber. The current loop will try to follow the path of least resistance and so as time elapses the current path follows the ever expanding propagation of the ion sheet until the ion sheet leaves the chamber. As this current loop expands the effective volume of the inductor increases. This alters the overall inductance of the circuit and due to the current having to physically pass through more material the electrode resistance also rises.

Neutral particles are also produced in the discharge. The neutral particle sheet velocity remains constant as it propagates with a leading edge that is parallel with the Teflon\(^{\text{TM}}\) surface.\(^{[11]}\) The neutral particle sheet is not accelerated by electromagnetic forces and so moves down the chamber at a relatively constant but reduced speed compared to the ion sheet. As the magnetic field around the inductor begins to collapse, current in the system becomes reduced and the ion production is decreased. By the time the capacitor plates have been recharged (at an opposite polarity to the initial state), ion production is at its lowest (but non zero) as current ceases to flow. If able to, a secondary discharge occurs and is referred to as a re-ignition. The re-ignition however does not occur across the Teflon\(^{\text{TM}}\) surface (as the initial discharge did) but occurs at the point where the neutral particle sheet coincides with the cathode.\(^{[5]}\) Either the neutral particle sheet acts as a path of least resistance and breaks down or the sheet promotes some form of activity on the cathode. Either way a current loop is established and the plasma creation and acceleration process begins anew. The re-ignition process reoccurs several times depending on the discharge characteristics of the LCR circuit.

Once the discharge process has been completed and the energy of the capacitor has been depleted additional processes occur. Only a small proportion of the total discharged energy was used to accelerate the ion particles. The energy lost to heating effects is deposited in the discharge chamber walls and propellant surface. If sufficient, the energy causes a transition change and either melts or sublimes the chamber walls and Teflon\(^{\text{TM}}\) surface respectively, creating small and large particulates. These particulates are accelerated by gaseous pressure forces out of the discharge chamber at a speed of 200-300 ms\(^{-1}\). This process happens for a few hundred microseconds.

**Experimental Synopsis**

Experiments conducted at SSC were based on the PPTs shown in Figure 2 with the parameters in Table 1. During experimentation the discharge initiation circuit was altered in several respects (i.e. additional resistors, capacitors etc) with no effect to the overall discharge properties of the pulse. It was only found that it was important to create an arc breakdown
through the vacuum to initiate a discharge but the properties of this initial arc did not appear to be significant.

Table 1: Standard configuration for the PPT test bed

<table>
<thead>
<tr>
<th>PPT Parameter</th>
<th>Experimental PPT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Voltage Capacitor</strong></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>4.06 μF</td>
</tr>
<tr>
<td>Inductance</td>
<td>≈325 nH</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Discharge Initiator (DI)</strong></td>
<td></td>
</tr>
<tr>
<td>Type of sparkplug</td>
<td>NGK</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>30 kV</td>
</tr>
<tr>
<td>DI Capacitance</td>
<td>10 nF</td>
</tr>
<tr>
<td><strong>Electrodes</strong></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Copper</td>
</tr>
<tr>
<td>Width</td>
<td>20 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>10 mm</td>
</tr>
<tr>
<td>Discharge channel length</td>
<td>60 mm</td>
</tr>
<tr>
<td>Separation</td>
<td>30 mm</td>
</tr>
<tr>
<td><strong>Teflon™ (if present)</strong></td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>Variable</td>
</tr>
<tr>
<td>Height</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

Figure 2: SSC PPTs. Top Left: PPT test bed with Ultem™ sidewalls and Teflon™ propellant. Top Right: PPT test bed without sidewalls but with Teflon™ propellant. Bottom Left: PPT test bed without sidewalls and Teflon™ propellant. Bottom Right: Changing the sparkplug to a single Tungsten electrode.
The impulsebit $I_{bit}$ of the discharge can be estimated using the following relationship:

$$I_{bit} = \frac{1}{2} \mu_0 \frac{h}{\eta} \int [I(t)]^2 dt$$  \hspace{1cm} (1)

This method of calculating impulsebit only finds the electromagnetic contribution of the impulse and not that generated from neutral vapour gas dynamic acceleration or macro particle ejection that may be measured by using an impulse balance. Mass erosion experiments were conducted to measure the mass loss of the Teflon$^{TM}$ propellant per pulse discharge. The width of Teflon$^{TM}$ between the electrodes that were investigated were 3.00mm, 3.53mm, 4.00mm, 5.00mm, 6.00mm and 7.50mm. The PPT discharge energy that each Teflon$^{TM}$ sample was subjected to can be summarised in Figure 3 along with a comparison between the mass loss per pulse discharge and PPT discharge energy and a comparison between the impulsebit of the pulse discharge and PPT discharge energy.

Comparing the impulsebit to energy for this set of experiments shows a clear trend. The linear relationship suggests a strong correlation between the impulse of the pulse and the energy supplied by the capacitor. The variation in Teflon$^{TM}$ widths has not had an impact on the impulsebit of the PPT pulse. Comparing the mass loss per pulse discharge to the discharge energy reveals some interesting results.

![Figure 3](image-url)  
**Figure 3**: Top: Matrix showing the conditions for the proceeding experiments, Left: Comparison between the impulsebit and PPT discharge energy, Right: Comparison between the mass loss per discharge and PPT discharge energy
First of all the width of the Teflon™ does not seem to be a significant variable in these experiments. At low energies (below 1J) their is a large scatter in the mass loss per pulse discharge data, with some values being negative. This represents the Teflon™ samples gaining mass. This gain in mass could either be explained by electrostatic interference when using the micro mass balance to measure the samples (but repeated measurements tried to overcome this), contamination of the samples by alien objects (but the samples were cleaned before each measurement), the temperature of the mass balance (but it was in a semi-controlled environment) or carbon build up upon the Teflon™ sample surface.

The large scatter may be an artefact of these measurement errors but at higher energies between 3-8J the scatter of measurements falls close to a trend line, where the mass loss per pulse increases with energy linearly. This would suggest that the procedural process used was adequate and that the results below 1J are indicative of a process that is happening in this regime. The reason for this effect on mass loss per pulse at low energies (less than 1J), could be some form of resonant interaction that means more energy is absorbed into the Teflon™. Therefore when this energy is converted to heat, more Teflon™ macro particles are eroded. An alternative reason could be that at low energies the peak currents are significantly less, meaning that the magnetic fields produced by the flowing currents through the electrodes are also not as strong. This would lead to lower confinement of the plasma by the magnetic fields. If more plasma is distributed evenly throughout the discharge chamber and not confined close to the electrodes then there is more probability for the plasma to interact and erode the Teflon™ surface.

A PPT with sidewalls was also experimented on to see how a confined plasma effects the total mass loss. The PPT was set up in the standard configuration with a 3mm width piece of Teflon™ between the electrodes. The PPT was then enclosed with Ultem™ sidewalls that had a separation width equal to the Teflon™ width, see Figure 2. The PPT in this configuration was pulsed for 178 discharges and an average mass loss per pulse discharge of 0.594 µg was observed. Although this caused a triple fold increase in the mass loss per pulse compared to experiments without sidewalls the impulsebit of the discharge was similar to those from the previous experiments. This suggests that the additional mass lost due to the sidewalls confining the plasma did not impact the performance of the thruster.

The experiment with the sidewalls and measurements of discharges with energies of less than 1J suggest that the additional mass introduced into the discharge process does not affect the current and voltage properties of the pulse discharge. Otherwise there would be observable differences in the trend line of the impulsebit to energy below 1J than between 3-8J, which is not seen.

Further experiments were conducted with the PPT set out in Table 1 with and without Teflon™ at various PPT discharge energies. During the experiments without Teflon™ it was observed that there was a linear trend between the impulsebit and the PPT discharge energy. However when the PPT was setup in the standard configuration the impulsebit to energy gradient was higher when Teflon™ was present to when it was not present, see Figure 4.

The impulsebit of the PPT without Teflon™ is ~60-75% of the impulsebit with Teflon™. From previous experiments it was shown that the Teflon™ geometry and the variation in eroded mass from the Teflon™ surface did not impact the performance. This new result leads to the conclusion that although the eroded Teflon™ itself does not affect the performance of the thruster, the Teflon™ presence between the electrodes acts as a catalyst during the discharge. In effect its presence creates a surface that during breakdown the
discharge can track across more effectively than pure vacuum. This creates an increase in the current flow and therefore an increase in the impulsebit. Removing the Teflon™ from the PPT may cause a reduction in the performance but it will also aid in the miniaturisation of the thruster and remove a major source of carbon that will coat the thruster housing in soot that can cause premature failure.

Figure 4: Combined data sets showing how the impulsebit relates to the PPT discharge energy when Teflon™ is present (red) and is not present (black) between the electrodes

µPPT Design Phase
The motivation of the developmental work was to put into practice the knowledge gleaned from previous research. The aim of the STRaND-1 CubeSat PPT was to design and develop a µPPT without Teflon™ for several reasons:

- It allowed the use of the developed SSC PPT model to be used to size the PPT, so when built the PPT could be thoroughly tested and the experimental data could be used to evaluate and validate the developed model further [10].
- The removal of the Teflon™ and propellant feed mechanism saved valuable volume that could be used to place additional PPTs within the system.
- Teflon™ contains a lot of carbon which when broken down would coat the inside surface of the thruster leading to tracking and failure of the µPPT.

The SSC PPT development model was used as a guideline to develop the µPPT. The iterative process began by modelling a PPT that had similar characteristics to the one used in early experiments. A capacitance of 4µF was chosen for the capacitor. The voltage rating of the capacitor dictates its size and the higher the voltage rating the larger the capacitor. A voltage rating of 700V was chosen for the CubeSat PPT as this was the minimum voltage at which the PPT regularly discharged at during experiments. With these values set the SSC PPT model was used to optimise the other parameters of the PPT.
Figure 5 shows the effect on efficiency as the electrode separation distance and the electrode width is varied. When the electrode separation is varied it shows that there is a peak efficiency of 0.15% at around 20mm. When the electrode width is varied it shows that as the width is decreased the efficiency of the system increases dramatically. These results from the model suggest, for the specific model inputs, an optimum electrode separation distance is obtained at 20mm and as the electrodes are thinned the more efficient the system becomes. These two trends suggest a new style of electrode design based on blade style electrodes, see Figure 6.

![Figure 5: Modelled data for a 4µF capacitor at 700V with an electrode thickness of 10mm. Left: Electrode width of 20mm and the electrode separation distance is being varied. Right: Electrode separation of 20mm and the electrode separation distance is being varied.](image)

The bladed electrode concept integrated with the decision not to use Teflon™ was further expanded upon to create a mock up of what a propulsion system may look like, see Figure 7. The propulsion system was initially split into three modules, where eight PPTs where split in to two modules of four PPTs per module and a third module was dedicated to a PPU. The amalgamation of the three modules can be situated within a 2U or 3U CubeSat chassis, with flexible placement of the modules within the chassis to allow for other components and payloads. The design offers control and propulsion in pitch, roll, yaw, X-axes and Y-axes.

To set the total $\Delta V$ of the propulsion module it was thought the plane electrodes could be lengthened to provide more material to be eroded, however CubeSats are designed to be compact. By adding protruding electrodes it would have meant a redesign of the P-POD in which the CubeSat would be stored during launch which would have been both costly and complex. The electrodes were shortened to remain within the CubeSat chassis, this though decreased the amount of propellant available to the system. To overcome this, the electrode
width was increased to 0.5mm which limited the efficiency of the thruster but provided enough propellant to deliver a useable amount of $\Delta V$ for the mission.

During the design phase careful consideration was taken into developing the discharge initiator, in total there were three concepts that were looked into; field electron emission by the traditional spark plug, thermal electron excitation by semiconductor lasers and a mechanical spark gap trigger formed from the breaking of high voltage contacts. Early on it was shown that laser excitation would be too complex a process to procure, build and control so it was dismissed, closer consideration was given to the other two concepts. Initially the field electron emission was thought to be the ideal choice as EMCO High Voltage Inc. sold a 5V DC to negative 10kV voltage multiplier in a 21.6mm$^3$ package. The issue was volume, having one multiplier per thruster sparkplug was an unworkable solution as space was required for other payloads. To try to overcome this a network of reed relay switches linked to...
a single multiplier was looked at, however with each relay being 25 to 30mm long this still took up considerable volume.

The mechanical spark gap trigger formed from the breaking of high voltage contacts was further developed. The system consisted of a contact arm, a lever arm, a torsion spring, an electromagnet and a retaining pin, see Figure 8. The torsion spring is not shown but should be located around the cylindrical part of the contact arm with one spring leg slotting into the cut out section of the lever arm and the other spring leg attached to the thruster housing (not shown). The lever arm and electromagnet was made from steel and was used to create a downward force that pivoted the contact arm to make contact with the grounded electrode. Once the electromagnet was turned off the lever arm was restored to its original position by the torsion spring.

Using the high voltage contact breaking method caused the contact arm to erode and so the separation distance between the electromagnet and lever arm needed to allow for this erosion in its design. The material that the contact arm was made from also affected the erosion rate. By using a material that had a low erosion rate, it would extend the lifetime of the contact arm. Although for bread boarding the contact arm was made from aluminium the actual flight hardware contact arm was made from Elkonite (75% Tungsten, 25% Copper) due to its low erosion rate but relative ease in manufacture (compared to pure Tungsten), see Figure 9.

The capacitor, electrodes, contact arm and created plasma needed to be isolated from the rest of the propulsion module. To do this a thruster housing was designed and built out of Ultem™ which has a high dielectric strength. The design of the thruster housing, capacitor, electrodes and trigger system can be seen in the cut away diagram shown in Figure 10.
The thruster housing measures 40mm x 40mm x 16mm. Four µPPTs can be situated on a single PC104 board in a rotational symmetric off axis configuration, this can be combined with another board of four µPPTs in the opposite rotational symmetric off axis to provide a propulsion module, see Figure 11. The PC104 system requirements specifically relating to board dimensions were adhered to, to ensure smooth integration with other payloads. However there was a design conflict with the structural supports and the thruster housings, so additional PC104 boards were placed above and below the thruster module to ensure integration with other payloads but to allow the structural supports within the thruster module to be relocated.
The PPU was designed to charge up the high voltage capacitors within the eight PPTs. The target was set to charge two 4µF capacitors within 1 second allowing the satellite to fire two thrusters at any one time at a discharge rate of 1Hz. The capacitors were designed to be charged to 700V by using a DC to HV DC multiplier. The multipliers were supplied by EMCO High Voltage Inc. and were packaged into a 12.7mm³ cube. Four multipliers were put into the PPU design. On their input lines 1kV rated diodes were added to provide reverse polarity protection and 10µF capacitors were added to reduce reflected ripple currents on the input supply lines. The PPT capacitors needed to be isolated from each other so when one triggered it would not cause a cascade effect and discharge all the others. To do this low pass filters made from 33nF capacitors and 10k resistors were made. The low pass filters were placed before the 4µF high voltage capacitors. Figure 12 shows the built PPU and PPT module after the design phase but before they were tested in the breadboard phase.

Figure 12: Left: PPU before bread boarding, Right: PPT module before bread boarding

Figure 13: Left: The CR09 Calramic pulse capacitor, 0.76µF at 700V, Right: Modelled data for a 0.76µF capacitor at 700V with an electrode separation of 11mm and an electrode thickness of 5mm. The electrode width is being varied

µPPT Breadboarding Phase
The PPU circuit was modified after bread boarding the initial design. Several flaws were found in the original design. The design was based on a 4µF capacitor rated at 700V, however
the volume available for the capacitors was 3cm³. It was a challenge to find a pulse capacitor that would be rated to high voltages and fit into the available volume. The custom capacitor manufactures Calramic (USA) were able to manufacture two CR09 capacitors fixed by copper tabs in parallel to provide a total capacitance of 0.76µF at 700V, rated for more than 1 million pulses, see Figure 13. The predicted performance of the PPT is also shown using the 0.76µF CR09 pulse capacitor. The trend from the earlier design remains (i.e. as the electrode width decreases the efficiency increases), however at lower capacitance the required width of the electrodes to gain decent levels in efficiency is almost a magnitude smaller.

The model was based on a PPT test bed that used a polypropylene dielectric and not a ceramic dielectric. The difference in the dielectric, capacitor inductance and equivalent series resistance compared to the CR09 capacitor could be significant. The results from the model should be taken cautiously. The µPPTs were built with an electrode geometry of 25mm in length, 5mm in thickness, 0.5mm in width and separated from each other by 11mm. Although the 0.5mm from Figure 13 suggests a low efficiency the electrodes can be thinned during experimental testing to see if an improvement can be achieved.

The low pass filter that was designed to isolate the discharging capacitors from each other had a cut off frequency of 482Hz. The PPT has a discharge frequency between 30-200kHz. In theory the filter should have worked but it did not operate satisfactory. Most of the time when one of the capacitors was discharged or one of the triggers operated all of the capacitors in the system discharged. This was initially negated by using a 20M resistor instead of the 10K resistor which reduced the cut off frequency to 4Hz. However this increased the capacitor charge time to around 60 seconds and so was unworkable. The solution was to use a high voltage diode instead of a low pass filter which did not limit the charge time of the capacitor but did stop the transient effects that caused the other capacitors to discharge.

The charge time of the capacitors was an issue, using four EMCO DC to HV DC multipliers and bread boarding the initial PPU with a 2.2µF ceramic capacitor (also from Calramic) showed the charge time was around six seconds, although the CR09 capacitor was only 0.76µF, it was an indication that the PPU would struggle to charge two capacitors in one second. To rectify this the number of DC to HV DC convertors was increased from four to eight, see Figure 14. This was achievable due to the space saved from the removal of the low pass filters.

Figure 14: The revised PPU developed during bread boarding
The working principle of creating a spark by a lever contact mechanism was proved to be a viable option during bread boarding but the design of the original trigger mechanism proved to be troublesome. The original concept used a steel lever arm and electromagnet to provide a downward force and a torsion spring to provide a returning force. When assembled however there were several problems; when compressed the torsion spring would compress on the pivoting arm creating additional frictional forces, the torsion spring stiffness was too high for the electromagnet to overcome, the magnetic field produced by the electromagnet within the set power budget was too weak and magnetic remanence within the steel caused it to become permanently magnetised that would interfere with other systems on the CubeSat.

The electromagnet and lever arm assembly was replaced with a P653 piezo electric motor, see Figure 15. The μmotor from Physik Instrumente (PI) GmbH & Co had a 0.15N push-pull capability with a movement range of 2mm and a power consumption of 0.5W. Compared to the electromagnet and lever arm assembly the μmotor increased the timing accuracy in which discharges could be triggered.

![Figure 15: The redesign of the trigger system using a P653 piezo electric motor](image)

Once the system had been made it was found to be extremely delicate. The holder in which the push rod was mounted was susceptible to getting stuck. In the harsh vibrating environment of a launch, this was an overwhelming risk. Also the holder in general was not stable and so the rod would rub against the guiding holes in the motor mount which caused frictional forces that the motor was not able to overcome. These issues meant that this avenue of development was dropped and other solutions were looked into.

The next candidate was a simple system using Nitinol wire and a returning force spring. Nitinol wire is a shape memory alloy which has the useable property of contracting when heated. The total contraction is around 10% of its total length. Contraction occurs when the crystalline structure in the wire shortens when heat is applied. The wire has a naturally high resistance compared to nominal metal wires and so when a current is passed through the Nitinol wire its own resistance became the source of heat. The Nitinol wire activates and contracts around 70°C. Convection was the main method of cooling the wire down once it had contracted. During the cooling down phase a returning force spring would return the wire to its original length. The movement created was enough to move the contact trigger arm. A system was designed for the μPPT, see Figure 16, which operated nominally in the laboratory environment.
Once placed in the vacuum environment due to the change in the thermal properties of the system a lot less current was required to contract the wire. However the main method in cooling was now conduction through the Nitinol wire structural supports and this took around 20 seconds before the trigger mechanism could be operated again. The Nitinol wire was quite thin and broke on several occasions whilst under high stress conditions, which coupled with the slow repetition rate of this mechanism called into question the survivability of this system during launch.

The last system developed returned to the method of using a piezoelectric motor. The SQUIGGLE linear micro motor is manufactured by Newscale Technologies and it uses a system of four pads made from piezoelectric material located around a central threaded rod. The pads are oscillated in such a manner that resemble a ‘hula’ motion that causes the central threaded rod to rotate around its central axis and can be moved up to 6mm. The motor has nanometre resolution, provides a force up to 5N and can change the translation speed of the rod from 1 \( \mu \text{ms}^{-1} \) to 10 \( \text{mms}^{-1} \). The design of this system is shown in Figure 17 with the breadboard concept model. The final mechanism is currently under manufacture and will be ready by early February 2011.
An additional problem with all the trigger mechanisms was the possibility that spot welding occurs. The trigger is charged up to 700V and when brought into contact with the ground electrode caused a spark (a high temperature short lived plasma) to occur that melts the surface of the electrodes and can cause them to bond or weld together. Limiting the current can reduce the chance of spot welding, so a COTS 9 resistor was used, after a few tests this resistor blew and so a 5W miniature 9 resistor rated at 1kV from the Precision Resistor Company Inc. was used. The new resistor worked well in parallel with the motor which provided enough force to overcome any spot welding that occurred.

Due to some power lines being up to 700V the standard PC104 headers were not implemented into the design. The additional space was used to either house a thruster unit or make space for clearances around HV lines located on the PPU board. A harness manufactured by Axon cables was constructed and integrated into the design. The connecting wires were made to ESCC 3901.013.01 standards, with connectors made to MIL-M-24519 standards out of a liquid crystal polymer. The harness was rated to 1kV but when tested in the SSC large vacuum chamber no breakdown occurred up to the maximum test of 2.5kV.

The non high voltage electronics was then developed. A Texas Instruments power distribution switch was used to limit the current into the PPU to prevent the PPT capacitors drawing too much load too fast from the main satellite battery. Another issue was controlling the SQUIGGLE motors. The motors came with their own NSD 2101 drivers that had their own I2C commands, which were incompatible with the satellite I2C commands. A µ-controller was added as a buffer to interpret I2C commands from the satellite and translate these into I2C commands that the NSD 2101 driver could handle. Once the electronics had been selected they were than placed into a PCB layout ready for manufacture, see Figure 18.

![Figure 18: PCB layout of the STRaND µPPT propulsion module](image)
The PCBs should be ready for February 2011 and the integration of all the components should be finished by March 2011. The PPT will then be taken to Stuttgart University and tested on their impulse balance to evaluate the performance. However it is unknown if these results will be conclusive as the movement of the threaded rod on the SQUIGGLE motor may cause enough noise to invalidate the results. Other tests that will be conducted will involve life time tests and the detection and resolution of any electromagnetic interference issues that occur when the PPTs discharge.

After the design and bread boarding phase the CAD model was revised, See Figure 19. The performance design targets of the propulsion system for STRaND-1 were revised based on modelling, see Table 2.

Figure 19: Revised CAD model of PPT propulsion module
Summary
The work conducted to build a µPPT propulsion unit is based on previous research that was completed at the Surrey Space Centre. The experimental evidence showed that the µPPT operated without the use of Teflon™ inbetween the electrodes. It is theorised and supported by initial experiments that the role of the Teflon™ in a PPT is to act as a bridge for an arc breakdown to occur. Removing the Teflon™ does not prevent this arc breakdown to occur but it does hamper the process, limiting the PPTs performance slightly. However removing the Teflon™ does remove a significant source of carbon and removes the need for a propellant feed mechanism, which significantly aids in miniaturisation.

The STRaND PPT propulsion module is being developed for launch in late 2011, this work shows the current status of the project, which is nearing the integration phase of components onto an engineering/qualification model and will be ready to perform performance tests by March 2011. The propulsion module comprises of eight µPPT units situated on two PC104 boards and a third board which acts as the power unit for the whole module. The propulsion module is designed to provide pitch, roll, yaw, ±X axes and ±Y axes manoeuvres. If successful the STRaND PPT propulsion module will be the first electric propulsion device to operate on a CubeSat platform in space and will be the first propulsion module to be used specifically for precision attitude control on a CubeSat.

Author Information
Peter Shaw is currently an experimental officer at the Surrey Space Centre, University of Surrey, UK, where he works on researching and developing CubeSat micro-pulsed plasma thruster propulsion. He is currently finishing a PhD in Astronautics from the University of Surrey, in the field of Pulsed Plasma Thrusters for small satellites in particular studying and modelling the electrode erosion mechanism.

References


