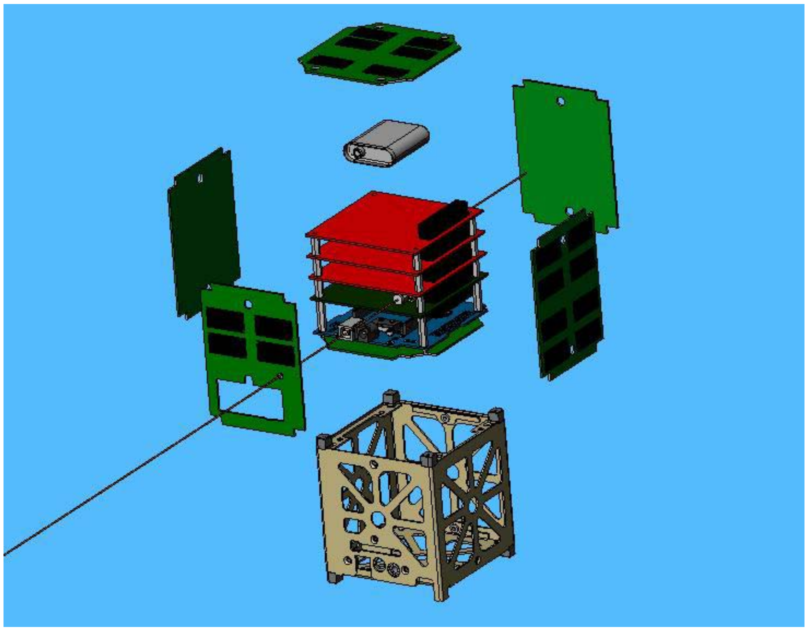
A Survey of Micropropulsion for Small Satellites



10x10x10 cm. CubeSat

William Storck, Olivia Billett, Mitul Jambusaria, Andy Sadhwani, Pierric Jammes, Professor James Cutler
Space Systems Development Laboratory (650) 838-0948
Durand 269, Dept. of Aero/Astro, Stanford University
Stanford, CA. 94305-4035 USA
(E-mail: william.storck@lmco.com, obillett@stanford.edu, mhj@stanford.edu, sadhwani@stanford.edu, pjammes@stanford.edu , jwc@stanford.edu

ABSTRACT

The Stanford Space Systems Development Laboratory (SSDL) is developing several CubeSat missions (including KatySat) that can benefit from onboard propulsion systems. CubeSats are generally one to two kilograms and made of one to three units of 10 cm cubes. The small size puts a premium on real estate and power. Onboard thrusters would have to be compatible with these restrictions. Ideally, a thruster system could provide thrust for attitude control and primary propulsion for docking/rendezvous, observation/inspection, and formation flying. A survey is presented of existing technology driven by the following primary requirements: I_{bit} less than 1mNs, mass less than 1kg, and size less than one 10cm cube unit. Some of technologies reviewed include Vacuum Arc Thrusters (VAT), resistojets, MEMs microresistojets, Pulsed Plasma Thrusters (PPTs), cold gas thrusters, monopropellant thrusters, bipropellant MEMS thrusters, and solid propellant MEMS thrusters. These systems were reviewed for a variety of possible applications for small satellites.

INTRODUCTION

Satellites rest at the cutting edge of technology today as computers did a generation ago. CubeSats, the standardized university nanosatellites, have revolutionized this realm of science by allowing students to apply new theories and venturesome applications to satellites.

The majority of CubeSat missions have used magnetic rods to provide orientation with the Earth's magnetic field. Future CubeSats, however, may incorporate three-axis control and even orbital changes through the implementation of micro-thrusters. While researching micro-thruster technology, we found that many universities and companies are developing experimental systems to provide three-axis control on CubeSats. This is particularly difficult due to size, weight, and power restrictions present on CubeSats that are not as prevalent on larger-scale satellites. Our trade study of micro-thrusters includes many developmental technologies such as micro-colloid thrusters, micro-vacuum arc thrusters, micro-pulsed plasma thrusters, MEMS devices, micro-water jet thrusters, and cold gas thrusters. It would be beneficial for the CubeSat community to learn of the success and failures of the various technologies.

This paper will outline the general theory behind each micro-thruster technology as well as their application history and drawbacks. This information has potentially high payoff if shared with the Small Satellite community; the development of micro-thrusters will not only broaden the scope of mission capabilities for small satellites, but for larger satellites as well. This paper will address both electric and chemical propulsion options for nanosatellites.

ELECTRIC PROPULSION

The Vacuum Arc Thruster (VAT)

The Vacuum Arc Thruster (VAT) is manufactured by Alameda Applied Sciences Inc and has been developed for flight on a nanosatellite by both the University of Illinois and Michigan Tech University. The VAT is sized at 4 cm x 4 cm x 4 cm, and weighs 150g. [22] The University of Illinois measured the impulse to be on the order of 1 µNs/pulse. Though the magnitude of the I-bit is small enough for precision maneuvers, the size eliminates the possibility of three-axis control as it is currently designed. Thus this propulsion technology can be characterized as suitable for primary propulsion and single axis attitude control. For larger satellites, however, full precise attitude control fits in the scope of the VAT.

The underlying principle of the VAT is producing ionized micro-plasma that expands into vacuum at high velocities resulting in thrust. The VAT operates by discharging ionized metal plasma from a macroscopically cold cathode. This plume attains a streaming velocity of 1 -3 x 10^4 m/s depending on the element used as the cathode, as seen below.

Table 1 [25]

Element	Streaming velocity (10^4m/s)	Arc current (A)
Al	2.99	60-120
Ti	1.67	60-120
Ag	1.25	60-250
Ta	1.11	60-120
W	1.43	60-120

This also allows for a wide range of specific impulses from 1000 to 3000 s. The thruster is designed by placing a metal rod cathode of 3mm diameter inside a small ceramic tube which is then centered in another metal tube of 6mm serving as the anode. In order to discharge an arc at voltages as low as 100V, a thin film of the cathode coats the insulator to provide triggerless ignition. Pictures of the VAT and circuit, provided by Michael Keidar, (University of Michigan) are shown below,

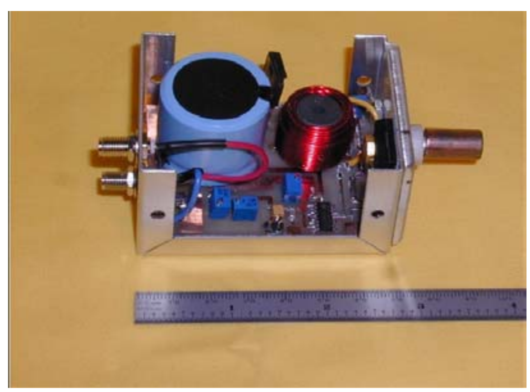
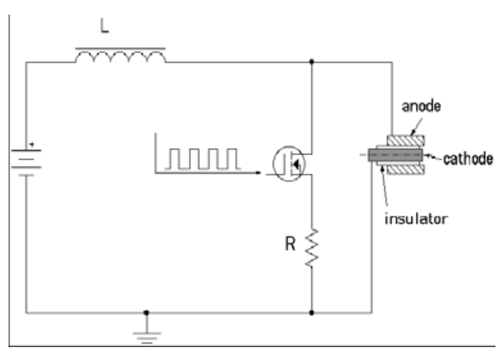


Fig 1

VAT system including PPU (thruster head is on the right).

Fig 2



The arc currents range from tens to multiple kA. The pulse length can also be varied from a few microseconds and above, and pulse frequencies can reach as high as a few hundred per second. In short, this allows for a greatly varied thrust range from the VAT- which also implies that a great range of maneuvers is possible.

The low mass of the system is achieved by using an inductive energy storage system in the PowerProcessing Unit (PPU). An inductor is charged through a semiconductor switch, and discharges when the switch is opened, releasing a voltage peak which breaks down the insulator surface at voltage levels of approximately 200V. When the switch opens, the current that was flowing through it is transferred to the vacuum arc, and currents of 100 A for a couple hundred milliseconds are conducted with ~30V. [22]

An interesting alteration to the regular VAT design is the magnetic VAT. By applying a magnetic field to the plasma plume, the thrust to power efficiency has been shown to increase by 50%. The magnetic field concentrates the plume created, making it easier to point as well as avoid contamination to the neighboring satellite hardware. Another added benefit of the MVAT is an increase in exit velocity. The exit ion velocity has been shown to increase by 30%, which also correlates to an increase in specific impulse. [24]

This technology was given to the University of Illinois, Urbana-Champaign and Michigan Technological University with testing as part of their cubesat missions aboard ION and HuskySat, respectively. Currently, ION is scheduled to launch in 2006 with four vacuum arc thrusters for translation and two-axis control. The system is driven by Cubesat requirements and resulted in a volume of 64 cm^3 and a mass of 150g. The thrust to power ratio was estimated to be 10 μN/W, with each impulse delivering 1μN-s/pulse. A summary of the specifications of VATs and a comparison to other electric propulsion systems can be found in Table 2. [22]

A simplified model was generated by ION's team, which showed the effect of the thrusters on the satellite dynamics. It provided an estimate of thrust with an aluminum cathode to be 13.5 μN-s/W^4. The moment of inertia was modeled as 8.3×10^{-3} kg-m^2 based on uniform block density. Their findings showed thruster firing at 4 Watts, producing 54 μN of thrust, and a torque of 5.4×10^{-6} N-m producing an angular acceleration of 6.56×10^{-4} rad/s^2. The model thus showed that a continuous firing of four seconds results in a 90 degree turn in 10 minutes. [22]

Michigan Technological University will not be flying the VAT technology on HuskySat and are currently seeking another test bed to fly their VAT in space.

The need for a low mass propulsion system was the main driver for the creation of the VAT technology. Where electric thrusters are difficult to reduce in size, thrust and power, the micro VAT operates under 100W without losing efficiency. It is not practical to scale down Xe- ion engines and hall thrusters to the order of 10W and still maintain efficiency. For gases, you need to store propellant, a tank, and piping, and for Hall thrusters, increasing the magnetic field with a decrease in size is difficult. In Pulsed Plasma Thrusters, scaling down is possible, but the bulky PPU means that the thrust to mass ratio significantly decreases. The micro-VAT has a low mass alternative PPU by utilizing inductive energy storage. This reduced mass PPU allows for a propulsion system under 300g.

The VAT system is also desirable for its low operating voltage requirements that make it ideal for small satellite missions. In addition to low mass and low voltage requirements, the VAT offers a range of candidates for the cathode, producing a range of high exit velocities and high specific impulses. The VAT is also unique in its simple and scalable thrust design (without efficiency loss) that opens the doors for orbital maneuvers for future cubesat missions. For orbit transfers and orbital maneuvering, high thrusts can be produced, and for station keeping and attitude control smaller thrusts are also available. The combination of these two capabilities means that satellites with this technology can be launched in non-ideal orbits and is versatile for small and big satellites.

The VAT, conversely, is a fairly new technology since it has not been flight proven yet. Though two Universities have designed their cubesats with VAT's on board, they remain to be tested in space. Thus, though the VAT has attractive characteristics, it is still an untested and unreliable system. In terms of performance the VAT maybe undesirable for the high EMI produced by high peak currents and fast switching. The exhaust plume is also not concentrated and runs the risk of contaminating neighboring sensors, solar panels, and other hardware.

The benefit of electric propulsion for the reduction of spacecraft mass is more significant for mass limited missions such as those undertaken by cubesats. The VAT has a simplified structural design that is favorable for both mass and size reduction. It can provide throttleable thrust for precision maneuvers or orbit changes. Capabilities such as pointing, rendezvous, station keeping, satellite observation, would all be possible with such technology on a satellite.

Resistojets

Resistojets are electrothermal propulsion systems that operate by passing gaseous propellant through an electric heater. The super-heated propellant is then expanded through a conventional nozzle to create thrust.

Resistojets have often been used as enhanced chemical propulsion systems where electric heating is used to further expand and accelerate propellant that has already undergone a chemical reaction. However, they can also be used as a primary propulsion system, using propellants as various as Nitrous Oxide, Helium, Ammonia, Carbon Dioxide, Hydrogen, etc. Water is a particularly attractive non toxic and environment-friendly propellant, especially for small university satellites. Water is indeed cheap, non hazardous, easy to handle and, being stored non-pressurized in the tank, it easily satisfies the safety requirements for launch.

Large resistojets have been used for stationkeeping on communication satellites for several decades. With the growing interest in small satellites, research has been conducted in the past decade to develop small resistojets and especially water resistojets for nanosatellites. Two main technologies have been designed and are under development: macroscale resistojets that are essentially smaller replicas of the traditional larger ones, and microscale resistojets (MEMs) designed using CMOS (complimentary metal oxide semiconductor) processes.

Engineering unit for MIGHTYSAT II programme
Picture: property of SSTL

Fig 3

Micro resistojet flown on UK-DMC
Picture: property of SSTL

Fig 4

Macroscale Rresistojets

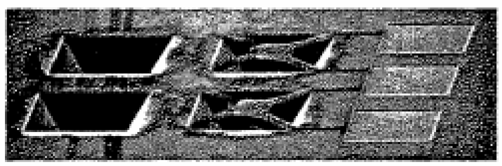
The main achievements in this domain have been obtained by Surrey Satellite Technology Limited and the University of Surrey, UK (Sweeting et al. [29], Lawrence et al. [30], [31], and [32])

SSTL first came up with a small resistojet, which was launched and successfully operated on UoSAT-12 in April 1999. The propellant was Nitrous Oxide, but the resistojet was also designed to work with de-ionized water. The diameter is 95mm and the length 160 mm, the total weight 1.24 kg. The measured thrust was about 100mN (45mN is expected for water) and the Isp of 127s (152s for water) ([32]). However, the main drawback of the system remains its power consumption, 100W, which is not acceptable for nanosatellites.
SSTL also developed an experimental micro resistojet that was flown on UK-DMC satellite in Sept. 2003. The miniature resistojet, weighing 13 grams only, uses 3W of power to heat the water used as propellant. With such features, the 10 cm long resistojet could possibly be flown on CubeSats. However, the experiment was not as successful as expected. The propulsion system fired its 2.06 grams of water and experienced 3.3mN of thrust over a 30 second period ([32]), which means the resistojet had an effective Isp of only 5 seconds. This may be due to propellant leakage, or bad pre-heating of the water. Because of this result, research was not continued on this resistojet.

Microscale Rresistojets (MEMs)

The most promising solutions might be the MEMs microresistojets, whose scale is more adapted to nanosatellites. The idea is to design and build a full propulsion system on a single silicon chip/die of a few mm on a side, including both the resistojet (propellant inlet, plenum, heater, channels, and nozzle) and the driving electronics. Those chips are designed and traced using CMOS processes. Most of these resistojets were tested with water as propellant, but other propellants are also conceivable.

In 1999, the Aerospace Corporation, USA, (Center for Microtechnology) developed a 3 Watt CMOS resistojet on a 2.2mm-square die, that also incorporates a flow rate monitor based on micro flow sensors and micro power transistors. The trickiest part of the development seemed to be the creation of the heater (suspended mesh over the plenum). Characterization of the latter is still going on. (Janson et al. [33], [34])

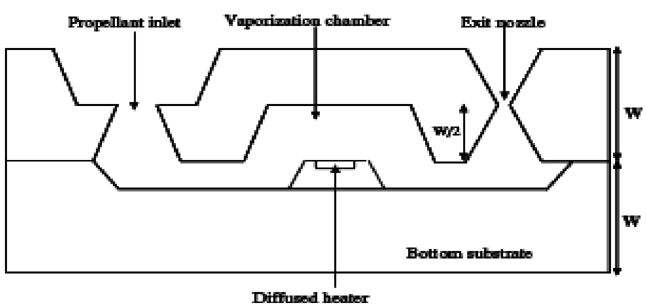


SEM photograph of EDP-etched structures in a CMOS-processed silicon die.

Fig 5

In 2000, Ye et al. at Tsinghua University in China developed arrays of 4 CMOS resistojets on 10 x 10 x 1mm silicon chips [35]. Different design parameters were tested and the optimal performances were obtained by pulsing the thrusters at 30 Hz with 0.9ms pulses. The thrust achieved was 3μN, the minimum impulse 2.6×10^{-9} Ns, and the total impulse achieved was 0.2 μNs. The estimated Isp is about 190s. However, the power consumption remains high (30W), but might still be achievable since it is only required over the short duration of the pulse, 0.9ms. [35]

In 2004, Maurya et al at the Indian Institute of Technology developed a similar CMOS resistojet (VLM), but used a different heater in order to optimize the performances. It was shown that the microthruster could produce a varying thrust from 5 μN to 120 μN with low power consumption, from 1W to 2.4W. Those values look promising but information on the propellant consumption (Isp) is lacking. [36]



. The cross-sectional view of the VLM (not to scale).

Fig 6

Ketsdever et al. [37] at the Air Force Research Lab (AFRL) designed a Free Molecule Micro-Resistojet (FMMR) which relies on the same principle as the previous ones, except that it operates at exceptional stagnation pressures from 50 to 500 Pa. The propellant cannot be considered as a continuum anymore and the behavior of the free molecules has to be considered. This design both increases propellant tank mass and valve leakage requirements and reduces intermolecular collisions which limit the overall efficiency. The result is that the effective Isp of 45s (taking into account leakage, residues, etc.) is higher than a standard micro-resistojet, and the volume and mass of the tank can be consequently reduced. Thrust of the order of 0.25mN can be achieved.

In conclusion, it is clear that MEMs resistojets would of course be ideal in term of mass and size requirements for nanosatellites. Other performance characteristics such as power consumption, thrust, Isp, and I_{bit} are promising for some systems. With low minimum impulses, such arrays of micro-resistojets could be used to create a full system of 3-axis attitude control. Unfortunately, those systems remain for now at the stage of research and none of them are currently ready to be implemented on a satellite and fly. This is a definitely a technology to keep an eye on.

Micro Pulsed Plasma Thrusters

Pulsed plasma thrusters (PPTs) have been used aboard satellites since the 1960s, however, their smaller counterparts, micro pulsed plasma thrusters (micro-PPTs), have been an active area of research since the late 1990s. An advantageous feature of this technology is that it is scalable to the size of the satellite. This section will focus on micro-PPTs suited for Cube Satellites. [26]

Advantages of micro-PPTs are their simple design, ease of manufacturing, virtually unlimited shelf life, flight durability, and reliability. Their drawbacks include low efficiency, electromagnetic interference, and high operating voltage.

A micro-PPT is composed of 3 main parts: 1) a DC-to-DC converter that raises the bus voltage from a few volts to a few kilovolts, 2) a high voltage capacitor which stores the charge, and 3) a coaxial tube which receives the capacitor’s discharge and is composed of an outer conductive electrode (such as copper) that is grounded, an intermediate Teflon™ electrode, and an inner conductive electrode (such as copper) which is connected to the capacitor. When the charge from the capacitor is dumped onto the coax, a low energy discharge occurs between the inner electrode and the intermediate Teflon™ layer. This serves as a catalyst that enables a high-energy discharge between the intermediate Teflon layer and the outer electrode.

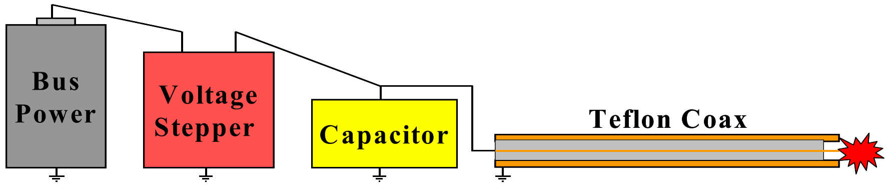


Fig 7- PPT

During the discharge, plasma is formed at the exit of the Teflon™ coax and is expelled through thermal expansion and electromagnetic propulsion at velocities on the order of 3 km/s. The discharge is mainly composed of carbon and fluorine. Around 10 micro-Newtons of thrust and 300 s of specific impulse are generated. The impulse bit is about 30 micro-Newton-meters and 10 micrograms of Teflon™ is emitted per pulse, where the pulse rate is about 1 Hz when fired in a vacuum. A salient feature of the micro-PPT is that its small impulse bit allows for precision pointing or docking. [27]

The micro-pulsed plasma thruster is self-triggered and fires continuously as long as energy is supplied to it. Carbon buildup at the end face of the coax can short out the electrodes thereby limiting the life of the micro-PPT. [28]

A micro-pulsed plasma thruster was developed at the Stanford Space Systems Development Laboratory (SSDL) largely in part by John Ellis, a consultant to the lab. The prototype, shown below, was developed using commercially off the shelf parts, including a neon light voltage stepper, a high voltage 0.15 microfarad capacitor, and a telecommunications coaxial tube. The voltage stepper raises an input voltage of 5 volts at 0.03 amps to an output voltage up to 3000 volts. Taking advantage of electronics flea markets, the net cost of the system was only $15.

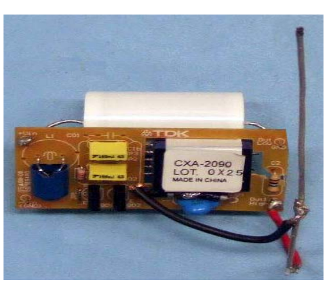


Fig 8- The Micro-Pulsed Plasma Thruster

While the pulsed plasma thruster fires 6 times per second, each pulse only lasts about 50 ms which releases 1500V at 1000 A in an estimated 10 nanoseconds. Its life span in air is 200,000 + pulses. Unfortunately the prototype did not fire consistently when tested in a vacuum. This is attributed to a higher breakdown voltage being required.

In addition, when the micro-PPT fired in the vacuum, it did not generate significant thrust. This is attributed to the coax design that was used. The coax is arguably the most important design feature of the micro-PPT. The Air Force Research Laboratory has invested heavily into designing the coax alone.

An important concern raised by a micro-PPT being placed aboard a small satellite is the electromagnetic interference generated by the micro-PPT. The EMI can reset the satellite's microprocessor. Interestingly enough, the SSDL micro-PPT prototype was found to interfere with the operation of a handheld multimeter at close range, but not a CubeSat's MSP430 microprocessor.

Measuring the thrust of the micro-PPT is no small task, especially when measuring the performance in a vacuum chamber. Torsional thrust stands are often used in this area, where the natural frequency of the torsion spring is tuned at the firing frequency of the micro-PPT.

After additional research, SSDL decided to abandon work on micro-PPTs due to the amount of development work remaining and also due to the limited vacuum chamber time available. While regular-sized PPTs have been flown on numerous large satellites, the author does not know of any nano or picosatellites that have flown micro-PPTs. The only small satellite equipped with PPTs that comes close to the weight of a CubeSat is the 13 kg Cornell Dawgstar satellite. This satellite, however, is still awaiting launch.

Colloid Micro-Thrusters

Colloid thrusters derive thrust from a stream of ions and droplets. These devices rely on the principle of electrostatic extraction, using a charge to break down the surface tension of a conductive liquid to release droplets and ions. The liquid is fed through a capillary to a fine tipped needle. The potential acting on the liquid at the tip of the needle causes a cone to form from which the droplets are extracted. The induced field also releases ions.

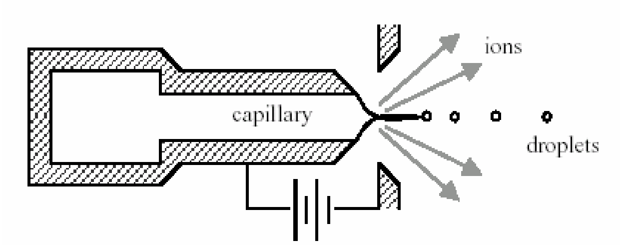


Fig 9- Colloid Micro-Thrusters

Applying power in the range of 1.5 kV to 20 um emitter is a reasonable operating configuration. Varying the current determines whether ions, droplets, or both are produced. A low current produces droplets only and a low Isp. A high current produces high ion fractions for a high Isp. This would allow for fine maneuvering of a spacecraft.

Different researchers have reported generating various specific impulses. Perel developed an Isp of about 1500 sec and thrusts of the order of 1 mN using an extraction voltage of 13 kV.[38] The liquid was glycerol. Kidd and Shelton built a prototype array with 36 needles and ran it for 4350 hours. Operating voltage was 12kV with 130um diameter needles, and the fluid again was glycerol. [38]

Work on colloid thrusters was first started in the early 1960's with big satellites in mind, but those efforts failed and the work was abandoned. With the interest in micro and nano-satellites, and the inherent power and size constraints, there is belief that colloid thrusters could be scaled for this application. Advances in micro-machining add to the feasibility.

Table 2: Summary Estimates of EP Data

Program (Satellite)	SSTL micro resistojet (UK-DMC) [32]	Tsinghua University (China) [35] CMOS resistojets	Indian Institute of Technology [36] CMOS resistojet (VLM)	Micro Vacuum Arc Thrusters Alameda-UIUC Ion	SSDL Micro-Pulsed Plasma Thruster (Stanford)	Colloid Micro-thrusters
Dry mass (kg)	0.013	Not available		0.300	0.1	Not available
I_{bit} (mNs)	Notavailable	2.6 *10-6	Variable according to thrust	Not available	Not available	Variable
Thrust (mN)	3.3	0.003	Variable: 0.002 to 0.120	Variable: 10 mN/W	0.006	Variable: 1
Isp (s)	5	190	Non available	1000-3000	300	Variable: 1500
Avg Power (W)						
Peak Power (W)	3	30	1 to 2.4	100	1.5	Variable
Size (mm)	100 long * 5-10 diameter	4 resistojets on 10*10*1 chip	Micro chip	40x40x40	40x30x20	Variable
Availability	One try only Research stopped because of poor Isp	Research stage only, for now	Feasibility study only, for now	Research Stage Alameda	Research stage only	Research stage only

CHEMICAL THRUSTERS

Cold Gas Thrusters

Cold gas thrusters are a reliable propulsion option with an extensive flight history on larger spacecraft, and are also capable of being miniaturized to meet the constraints imposed by the larger end of the nanosatellite range. Commercial micro cold gas thruster valves are available with thrust levels on the order of milliNewtons and have already been used by some missions to create a nanosatellite propulsion system. Advantages of a micro cold gas thruster system for CubeSats include simplicity of design, ease of handling when using benign propellants, flexibility of continuous and pulsed operations, as well as low power requirements, all of which promote the use of micro cold gas thrusters for primary propulsion, and possibly single axis control.

However, the propellant tanks required to feed the system quickly overwhelm the size constraints on most CubeSats, making them a less favorable option for attitude control. Reichbach et al [2] discusses the required mass and sizing of micro cold gas thruster valves, tanks, and feed systems for accurate attitude control. In addition, the minimum I_{bit} is constrained by the response time of the valve system, and is frequently too high to produce accurate attitude control for nanosatellites

As a rough requirements estimate for impulse bits, Reichbach suggests :

$$\frac{{I_{bit}}^{2}}{F_d m \Delta x} \approx 2 \qquad (1)$$

Where F_d is the constant (or average) disturbing force, m is the spacecraft mass, and Δx is the required deadband. Other disadvantages of micro cold gas thrusters include a very low Isp, valve leakage, fuel sloshing, and potentially significant center of mass changes due to the large amount of propellant expelled during firing.

Micro-cold gas thrusters have been developed into propulsion systems by several agencies. Most recently, NASA's ST-5 mission, launched in March 2006, tested a cold gas system based on microvalves produced by Marotta [5]. The characteristics of that system are summarized in Table 3, and more information on Marotta's cold gas microthruster valves is available at their website [16]. Similar microthrusters are available from other commercial propulsion companies and can be used to develop custom propulsion systems. For example, the University of Toronto Institute for Aerospace Studies (UTIAS) modified COTS solenoid microvalves to create a sulfur hexaflouride-based nanopropulsion system ("NANOPS") for their CubeSat mission CANX-2 [19]. Characteristics of two sample cold gas micro-thrusters produced by Moog Systems Group are also included in Table 3 for reference.

Another notable COTS-based micro-cold gas thruster was developed by Surrey Space Systems Limited (SSTL) for the SNAP-1 satellite. SNAP-1 was designed to be an inspector nanosatellite while employing as many COTS pieces as possible, thereby lowering the cost and shortening the design phase [1][10]. SNAP-1's propulsion system consisted of a butane-fueled thruster, using a solenoid operated valve from Polyflex Aerospace and an innovative tank design that stored the propellant in 1.1m of coiled tubing (65 cc). The mission was launched in 2000, the results of which are summarized in Table 3.

Cold Gas MEMs

To achieve 3-axis attitude control of nano and picosatellites, research attention is turning more and more to MEMs devices. Commercial CMOS sun sensors are already available in the mm/cm scale, as are commercial MEMs inertial sensors, making an entire micro-scale propulsion system a viable option for nano and picosatellites [8]. In addition to their small size, MEMs devices hold a number of advantages that make them ideal for nanosatellite propulsion. The thrust to weight ratio increases by up to 2 orders of magnitude as thrusters are scaled down, although that ratio is reduced slightly by additional viscous losses due to boundary layer interactions. In addition, the ability to engineer precise shapes and systems in MEMs devices allows greater design control and a higher level of integration, minimizing interfaces and system weight as well as simplifying the overall design. [9]

MEMs devices are limited to a shorter operating temperature range due to their silicon structure, but research in this area has already begun to strengthen these devices. One solution to this problem that is particularly of interest to university CubeSats is the MicroPropulsion System (MiPS), developed by VACCO Industries for the Aerospace Corporations' inspector nanosatellite MEPSI. Using VACCO's ChEMS^{TM} technology, MiPS is produced by bonding multiple layers of chemically etched metal sheets, creating a more robust device capable of withstanding greater temperature levels as well as more aggressive launch forces. MiPS consists of 5 butane-based cold gas thrusters providing 3-axis control in a 210 cc titanium structure. While butane does have a low Isp, its non-toxicity, extensive flight history, and low pressure make it a leading choice for university nanosatellite propellants. The MiPS prototype was built with a 95 cc propellant tank producing 34 Ns of total impulse with an I_{bit} of about 0.55 mNs (see Table 2). VACCO plans to produce pre-machined propulsion 'kits' for university CubeSats, leaving just the core assembly to be designed and produced for individual systems, thereby cutting the lead time down to 4 months. [3] Similar VACCO valve technology is currently being developed into a flight system at Stanford's SSDL, with an estimated launch date in under a year. Other cold gas MEMs devices include a hybrid system combining 3 different MEMs systems at Uppsala University in Sweden [12], and an experimental nozzled 1mN thruster made from COTS valves at the Aerospace Corporation [17].

Like cold gas thrusters, monopropellant and bipropellant chemical thrusters are proven technologies that have been used on larger scale satellites for years. However, chemical thrusters are much harder to miniaturize, and have essentially no viable options for nanosatellites in their current form. The required size and minimum I_{bit} of traditional chemical thrusters are easily out of the range of constraints imposed by a CubeSat. To overcome this obstacle, MEMs microrockets have been developed in monopropellant, bipropellant, and solid propellant form. Here again the design benefits of MEMs fabrication make microrockets appear to be the future of nanosatellite propulsion.

Monopropellant MEMs Thrusters

Monopropellant thrusters have a number of advantages over other chemical thrusters. Like bipropellant engines, they have greater propellant densities and higher Isps than cold gas thrusters, and require lower power levels than electric thrusters. But they are also much simpler in fabrication and handling than bipropellant engines, and have a greater range of total impulse and thruster levels than either solid or bipropellant thrusters. [7]

Both hydrazine and H_2O_2-based MEMs thrusters have been developed. While hydrazine provides a higher specific impulse, H_2O_2 is generally a better option for university CubeSats due to its non-corrosive nature and ease of handling. While a major disadvantage of H_2O_2 is its short storage life, most CubeSat missions are constrained to one-year missions anyway, mitigating the risk of propellant decay. H_2O_2 thrusters use a catalyzed exothermic reaction to break down H_2O_2 into oxygen and steam, which are then expanded through a nozzle to create thrust. The design of the combustion chamber affects the thrust level produced, so the added flexibility of MEMs fabrication allows for continued research in this area.

Scaling chemical rockets produces a few disadvantages that continue to be areas of research. For one, the increased importance of boundary layer interactions and viscous forces make conventional expansion nozzles less effective. In addition, microrockets have a higher surface-to-volume ratio which increases the heat transfer rate, producing lower combustion chamber temperatures and lowering the Isp [14]. Research at Penn State and Princeton Universities addresses some of these problems, and focuses on the use of green liquid propellants, electrolytic ignition, and increased effectiveness of nozzles. They have developed prototype meso-scale chemical rockets using ceramic stereolithography techniques to create a 3D nozzle, which has both a higher operating temperature range (> 2000 K)and a better efficiency than standard 2D silica nozzles. Stable combustion of hydrogen and air has been achieved with these prototypes, ranging from 10 to 170 mm^3 in volume, under both continuous operation and cycle testing.

Table 3 Cold Gas Thrusters

Program (Satellite)	NASA MCGT (ST-5) [5]	SSTL (SNAP-1) [20][21]	Moog 58E143 (CHAMP, GRACE) [18]	Moog 58X125A (SAFER, Pluto fly-by) [18]	VACCO MiPS (MEPSI) [3]
Dry mass (kg)	0.05	0.422	0.04	0.009	0.456
I_{bit} (mNs)	44		-	-	0.55
Thrust (mN)	445	46	16-40	4.4	55
Isp (s)	-	43	> 60	-	65
Avg Power (W)	< 0.4	3.5-6	< 1	-	-
Peak Power (W)	1	-	< 10	10	-
Size (mm)	-	170x170x100	57 long x 17	38 long x 12	25 x 91 x 91

Development continues to convert these thrusters to a liquid propellant [6]. Research on MEMs H_2O_2 thrusters is also being conducted at NASA/GSFC, where prototypes on the order of a millimeter long are being developed and tested with the goal to provide .5 mN thrust with an Isp of 140-180s [7].

Of most interest to university CubeSats is a monopropellant milliNewton thruster system developed by Micro Aerospace Solutions, where they have replaced the traditional catalyst bed of iridium-loaded alumina pellets with iridium mesh inside the combustion chamber. The resulting design is a thruster 0.2" long, with a nozzle exit diameter of 0.15" and a 0.015" diameter throat. Using low-cost COTS MEMs valves, the H_2O_2 thrusters have an estimated Isp of 150s and an I_{bit} of 0.17 mNs [15]. In order to create a CubeSat-compatible system, Micro Aerospace has produced a complete flight prototype, with 4 50 mN thrusters and a 2" circular propellant tank, that falls within a university budget. The system has a wet mass of 175 g, including 45 g of H_2O_2 capable of 50,000 firings, and is powered by a 9-volt rechargeable battery. Like the VACCO MiPS, Micro Aerospace's propulsion system is essentially flight-ready and capable of 3-axis attitude control of CubeSats.

Bipropellant MEMS

The thrust capabilities of bipropellant engines are far too high to meet the requirements for CubeSat attitude control, but are potentially useful for primary propulsion on possible interplanetary missions. Research at MIT has included work focused on designing a regeneratively-cooled combustion system for use in a turbopump-fed liquid bipropellant engine. Tests of gaseous bipropellant MEMS rockets have already demonstrated thrust levels ranging from 1 to 3N. [14]

Further research is being conducted at Stanford University, where the Mechanical Engineering Department is currently involved in a contract with Pratt & Whitney Rocketdyne (PWR) to develop technologies relating to the catalytic decomposition of nitrous oxide and very lean nitrous oxide/fuel mixtures. The research supports applications such as small in-space thrusters, propellant tank pressurization systems, and oxygen generators. The program will develop, analyze and demonstrate an effective nitrous oxide catalytic gas generator and explore the effects of scaling down to the micro-scale.

Solid Propellant MEMs

Solid propellant rockets contain many advantages for CubeSat propulsion systems, such as their high propellant density and lack of moving parts, leakage concerns, valves or feed systems. However, the current inability to stop and restart a solid rocket is a major obstacle to its use in satellite propulsion systems.

Joint research at TRW, CalTech and the Aerospace Corporation has managed to circumvent this problem by developing 'digital micropropulsion', which consists of an array of one-shot microthrusters that can be fired in any combination, producing throttleable thrust as well as a method of cycling. These MEMs devices are made of 3 separate layers: a silicon layer of initiators (resistive heaters) overlaid with a glass layer of propellant chambers and covered with a silicon layer of burst diaphragms. Up to 10^6 thrusters can be manufactured on a single chip, each with an impulse bit of 0.1mNs while using lead styphnate as propellant [13]. The flexibility of firing options and low impulse bit make digital micropropulsion systems a highly plausible option for nanosatellite attitude control, although not a likely option for a university budget.

Table 4 summarizes the details of the chemical propulsion options that are currently applicable to CubeSat and essentially ready for flight.

Program	VACCO MiPS [3]	Micro Aerospace	TRW/Caltech/Aerospace Corp
Type (propellant)	Cold gas (butane)	Mono-propellant (hydrogen peroxide)	Solid propellant (lead styphnate)
Dry mass (kg)	0.456	.120	-
I_{bit} (mNs)	0.55	0.17	0.1
Thrust (mN)	55	50	0.1 / thruster
Isp (s)	65	150 s	-
Size (mm)	25 x 91 x 91	51 diameter tank & 5 mm thrusters	1 mm^2 / thruster
Availability	Award basis, possibly future COTS	Commercially available	Custom only

Similar research is being conducted at LAAS in France, among other places, where a prototype 10 x 10 array of solid propellant microrockets has been fabricated on a 24mm x 24mm chip. Initial data indicates an I_{bit} of 6 mNs [11].

For primary propulsion on long-distance missions such as a possible interplanetary nanosatellite, NASA/GSFC has developed miniaturized macro-scale solid rockets. These solid motors are roughly 1 kg, with a thrust level of 290 N and 2554 Ns of total impulse. [5]

CONCLUSIONS

After reviewing the thruster technologies discussed in this paper it became clear that very few of these systems are ready to fly in the nanosatellite environment, and none of those are available as flight-tested options for university CubeSats. The chemical monopropellant and cold gas thrusters are some of the more promising technologies with benign fuels and simple designs. The VACCO cold gas thruster valves are of particular interest and are currently under development at SSDL. PPT's at first look were very promising but need extensive research in order to graduate to flight status. Several MEMS systems appear to be plausible options for nanosatellite attitude control, but are also a long way from production. The VAT technology has been incorporated into several university CubeSats but has yet to fly. The main message is the technology is not mature and presents an opportunity for further research.

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