MicroVacuum Arc Thruster Design for a CubeSat Class Satellite

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Abstract

This paper describes the University of Illinois 2-cube CubeSat (10 x 10 x 20 cm) designed for April 2003 launch. The Illinois Observing NanoSatellite (ION) includes a scientific mission to view the airglow layer of the atmosphere and a CMOS camera for space and Earth photography. ION will also be used as a test bed to demonstrate a number of technologies including an active 3-axis attitude control system, with a new propulsion system used for both attitude control as well as orbital maneuvers. The new vacuum arc thruster (VAT) propulsion system produces ion velocities of up to 30,000 m/s, driven mostly by local pressure gradients. A 12 V inductive energy storage circuit is used to provide the initial breakdown and to sustain the plasma. Four thruster heads can be controlled individually to produce arc pulses with adjustable pulse width and repetition rate. Size and mass have been driven by the CubeSat requirements and amount to 4 x 4 x 4 cm and 150 g, respectively. Thrust to power ratios are expected to be ≈10µN/W. The individual impulse will be close to 1µN-s/pulse. Challenges to the design and integration of the VAT into a CubeSat size satellite are presented. On board diagnostics and methods used to verify operation of the VAT are discussed.

Introduction

The Illinois Observing Nanosatellite (ION) is a 2 kg, dual-cube, CubeSat-class satellite currently under construction at the University of Illinois at Urbana-Champaign. The satellite was designed, and is being built by a student group at the U of I, under faculty supervision, as part of the larger CubeSat program. This group consists of roughly 25 graduate and undergraduate students, drawn from various engineering disciplines, who are in charge of all aspects of satellite design, construction, and testing, as well as program management.

The U of I program was initiated in the Fall of 2001. Analysis of existing and planned CubeSat missions identified several objectives with potential to provide significant contribution to the overall CubeSat program and small satellite community. A satellite mission was constructed around these objectives in an effort to provide such a contribution. Mission objectives include both technological and scientific goals. Objectives include: 1) acquisition of data on the Earth's airglow layer via photo-multiplier tube instrumentation; 2) development of a magnetic 3-axis attitude control system; and 3) space qualification of a miniature electric propulsion system. All objectives are described in further detail in the following sections.

Satellite design was completed in the Spring of 2002 with transition to satellite fabrication and systems testing occurring late Spring and

Summer 2002. The current timeline targets satellite delivery in January 2003. The University of Illinois has partnered with CubeSat Launch Corporation to deliver ION to orbit.

Science Objectives

The main science objective for ION is to study the airglow layer of Earth's upper atmosphere. This layer is located approximately 100 km above the Earth's surface. The airglow phenomenon is caused by atomic oxygen-driven chemistry that emits light at a wavelength of 760 nm. At this wavelength, light is absorbed by Earth's lower atmosphere, preventing study by Earth-based sensors. ION will study the airglow phenomenon using a photo-multiplier tube (PMT). The PMT is treated as the main payload for ION. Upon delivery, ION will use the PMT to study the airglow phenomenon from low Earth orbit; specifically, the imaging and tracking of wave-like structures ranging from 20 to 200 km in size that are created in the airglow layer by atmospheric winds.

As a secondary mission, a complimentary metal-oxide semiconductor (CMOS) camera will be utilized for earth imaging. While successful implementation of the CMOS camera is primarily a technology validation objective, it is hoped that data collected from this sensor can be used for atmospheric study as well.

Technology Objectives

ION Technology objectives include the development and/or space qualification of several components. The on-board CMOS camera is one of these components. It is hoped that successful utilization of this sensor will enable future use for Earth-observing missions, as well as the potential use of similar CMOS devices for on-board star tracking. High-efficiency solar cells provided by the Emcore Corporation will also be flown and demonstrated. In addition, the flight computer being used on ION is also being flight validated. The small integrated data-logger (SID), supplied by Tether Applications Inc., will be space qualified for future use in small satellites. The U of I team is also in the process of developing an active, magnetic three-axis control system using free-air torque coils as actuators. Three mutually orthogonal torque coils will be combined with a three-axis magnetic sensor and mathematical models to interact with Earth's magnetosphere and control ION's attitude via SID.

The primary technology mission for ION, however, is the space qualification of a micro vacuum arc thruster (μVAT) propulsion system. This propulsion system is being developed cooperatively with Alameda Applied Space Sciences Corporation. The propulsion system aboard ION will consist of one power-processing unit (PPU) that supplies power to four μVAT thruster heads. The μVAT thrusters work in a manner similar to a spark plug, with an electric arc being created from anode to cathode. The interaction between electric arc and cathode results in cathode material being ejected from its surface at high velocity. This produces a highly efficient, low-thrust method of propulsion. In the case of ION, the aluminum frame of the satellite will serve as the cathode material (with the electric arc localized to specific areas), effectively utilizing the frame as propellant in a self-consuming fashion.

Space qualification of the system will be accomplished by verification of successful firing using various on-board diagnostics. Validation of this system will enable its future use for attitude control, orbit maintenance, and perhaps even orbital maneuvers such as orbit raising/lowering and de-orbit. Such capability opens the door to missions that were previously impossible for satellites of ION's

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size, and provides the promise of lower launch costs and increased launch opportunities by allowing CubeSat-class satellites to piggy-back on vehicles with non-ideal orbits, followed by transfer to final desired orbit.

Specific details of the propulsion system are provided in the following sections. The basic theory of vacuum arc thrusters is discussed first. This is followed by a description of components specific to ION and specifications of their design. Operation and control are also discussed. On-board diagnostics and methods for space qualification are then explained, with conclusions following.

Vacuum Arc Thrusters

Basic Theory

The initial μVAT design was coaxial. The cathode was a 3 mm diameter metal rod inserted into a small ceramic tube which in turn was inserted into a ~6 mm diameter copper tube, serving as the anode. The insulator is coated with a thin film of the cathode material to provide the 'self-triggered' or 'triggerless' operation. This kind of operation allows for an arc to ignite at voltages as low as 100V. More detailed information about this process can be found elsewhere[1,2,3]

Use of the self-triggered vacuum arc enables use of a low mass PPU that utilizes inductive energy storage (IES). Figure 1 shows a schematic drawing of μVAT. A semiconductor switch is triggered to draw a current I from a DC power supply (5V-35V) through an inductor L. The moment the switch opens, a voltage peak L dI/dt is produced which ignites the arc by driving current through the thin-film coating on the ceramic between anode and cathode. Subsequently, plasma is established at a hot spot at the cathode-coating interface and the stored energy in the inductor supports the plasma.
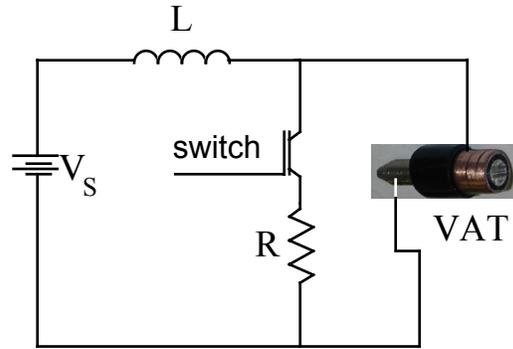
Figure 1 Principle schematic of the coaxial vacuum arc assembly

After the initial vacuum arc formation, a fully ionized metal plasma is produced from a macroscopically cold cathode. The metal plasma plume, produced at cathode spots in a way reminiscent of laser plasma production, streams outward to achieve velocities of 1-3 $x10^6$ cm/s over a wide range of elements from Carbon to Tungsten, making the μVAT suitable for 1000-3000 s specific impulse missions. Time-of-flight measurements of the charge state distributions have shown that the ions are predominantly of charge states 1^+ to 3^+ depending on the metal species used and the arc current density.[1] Arc discharges are produced with arc currents from tens of amperes to many kA. Pulse lengths can be from a few microseconds upwards, and the pulse repetition rate can readily be up to a few hundred pulses per second. This implies a very wide dynamic thrust range. The μVAT can be operated in a pulsed mode with an average power of 1-100 W and masses of about 0.1 kg. For orbit transfer and orbit maneuvering of a satellite, high thrusts are desired to save time, while for station keeping the required thrusts are relatively low. The μVAT has the potential of providing a wide dynamic range of thrusts without efficiency loss for these missions.

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ION Design

Power Processing Unit

The University of Illinois power processing unit, designed and built by Alameda Applied Sciences Corp. and shown in Figure 2 incorporates the same inductive energy storage design. The ION PPU was designed to control 4 thrusters individually. The PPU has a modular design (Figure 3) with one main board housing the inductor and timing circuit. Each thruster is connected to a separate control board which houses the semiconductor switch used to control the current through the inductor. PPU size and mass have been driven by the CubeSat requirements and amount to 4 x 4 x 4 cm and 150 g, respectively. The PPU is powered from a 12-24 V power bus.

Four TTL level control signals determine which thrusters are operational. Multiple control signals can be sent in order to fire multiple thrusters simultaneously. In this case, the arc will randomly initiate on one of the two thruster heads. Another way to fire two thrusters simultaneously is to alternate the control signal. In this fashion, the relative power ratio going to each thruster can be controlled.
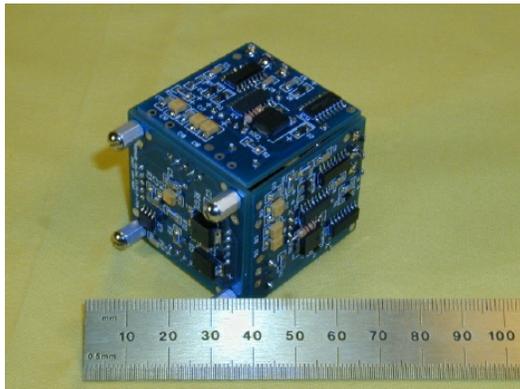
**Figure 2 Vacuum Arc Thruster PPU designed for use aboard ION**

Figure 3 Vacuum Arc Thruster PPU designed for use aboard ION, Open View

The ION PPU can be fired in two modes of operation. First, an onboard timing circuit can be used to fire the thrusters at a pre-set pulse frequency and power. This mode of operation requires only a single activation control signal. The second mode of operation for the PPU is one where the ION on-board computer sends the PPU a square wave signal generated by a pulse width modulator circuit (PWM) to control the switch for each thruster. In this manner, the computer can control the pulse frequency as well as the energy per pulse.

Thrusters

The original μVAT design incorporated a cylindrical thruster. With this design, the thruster was to be placed in the feet of the satellite. It was determined that the cylindrical geometry would require significant insulation, as well as tight tolerance machining to operate reliably. It was also unclear if a cylindrical design would withstand launch vibration. A sandwich or "BLT" geometry was adopted instead. In testing, the BLT geometry proved to be more reliable, as well as easier to manufacture. The first BLT design is a sandwich of copper, ceramic, and titanium. The arc forms between the center (titanium) and outer electrodes. The original BLT design was scaled to approximately a 1 cm wide μBLT.

During the initial design, the high density and high I_{sp} of the tungsten electrode were favored. The tungsten could provide the highest ΔV given a limited mass and volume; however, in order to demonstrate a thruster system with a large volume of fuel for possible future missions, the μBLT thrusters were incorporated into the satellite structure in such a way that the aluminum structure became the fuel. The final design of the μBLT is shown in Figure 4. The anode is separated from the structure (cathode) with two high-alumina ceramic plates. The arc will either attach to the satellite structure or to the aluminum bar used to clamp the μBLT together. When the thrusters are assembled and prepared for operation, the ceramic closer to the aluminum bar will not be plated with the conductive layer, increasing the chance that the arc will form between the anode and satellite structure.
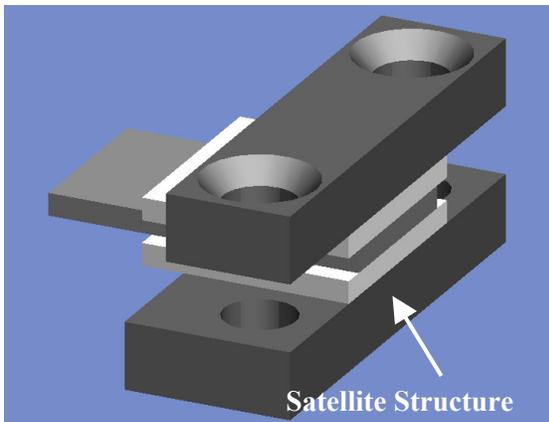

Figure 4 μBLT design incorporated into satellite structure.

The four thrusters are located on the satellite in such a way as to allow both translation and 2 axis rotation. Two thrusters are placed on each of the 10 cm x 10 cm faces of the satellite. Each thruster is in the opposite corner of that face as shown in Figure 5. With this layout, when thrusters 1 and 2 or thruster 3 and 4 are fired simultaneously, the satellite experiences translation. When thrusters 1 and 3 or thruster 2 and 4 are fired, the satellite experiences rotation about one axis. Firing thrusters 1 and 4 or thrusters 2 and 3 rotates the satellite about another axis.

To estimate the effect that the thrusters will have on the satellite, a theoretical analysis was conducted which provided an estimate of thrust with an aluminum cathode to be 13.5 μN-s/W.[4] With this thruster layout, each thruster will have approximately 5 cm of lever arm about the axis of rotation. It is assumed the satellite has the moment of inertia of a uniform density block (8.3×10^{-3} kg-m^2) and the thruster fires at a nominal 4 Watts, producing 54 μN of thrust. The pair of thrusters produce 5.4×10^{-6} N-m of torque. This results in an angular acceleration of 6.56×10^{-4} rad/s^2. This means that by firing the thrusters continuously for approximately 4 seconds, the satellite will turn 90 degrees in 10 minutes.

This estimate is only an approximation to the actual motion of the satellite. Due to the location of the thrusters, torque will not be applied through the center of mass, thus likely resulting in something other than pure rotation. The dynamics of this motion are yet to be simulated; however, the simplified model described above is sufficient to estimate an approximate effect that the thrusters will have.

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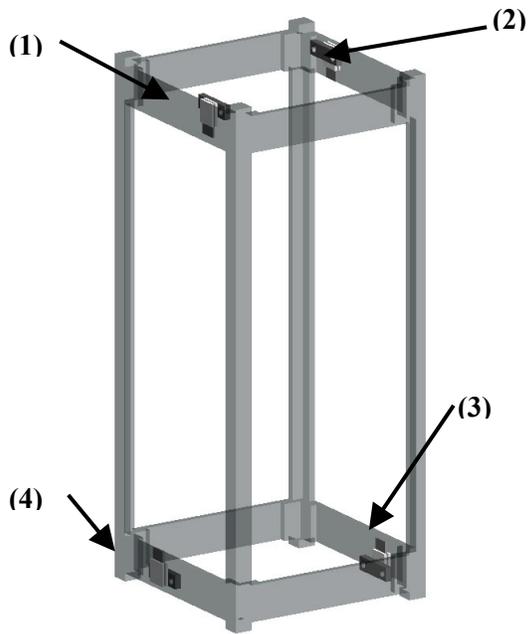
Figure 5 μBLT Thruster locations on Satellite

Diagnostics

One issue that has often confronted mission designers is whether the exhaust from thrusters will redeposit on solar panels or optical experiments. Such deposition can reduce solar panel lifetime and efficiency. In order to estimate this effect, a conductive deposition monitor (CDM) experiment will be flown to help determine the amount of deposition accumulating on the satellite due to the thruster.

The CDM is a 1 cm square ceramic plate, with wire leads attached to opposite sides. As the fuel from the thrusters deposits on the ceramic plate, the resistance between the two wires will fall. A circuit measures the resistance between the leads. Since a very small amount of deposition is expected, the circuit is designed to be very sensitive between infinite resistance and 10 MΩ.

A number of methods have been devised to help verify the operation of the thrusters. At the very basic level, the attitude control system will be able to detect any change in attitude using the on-board magnetometer. Although this is not a direct determination that the thrusters are functioning properly, it is enough to verify that an end has been achieved.

The attitude control system will also be capable of compensating for the thrust with the on-board torque coils. The amount of current through the torque coils necessary to compensate for the thrusters can then be converted into a force or torque produced by the thrusters. This method can be used as an in-flight thrust-stand to measure the exact thrust produced by the thrusters.

The ION computer system is capable of measuring the temperature of the satellite in up to 63 locations. The temperature of the inductor, as well as one of the IGBT switches and it's corresponding thruster will be monitored. This will provide a means to protect the PPU and thrusters from overheating due to normal operation. In case of a failure resulting in a short circuit, the temperature measurement will help to protect and diagnose the system for future operation.

One final diagnostic tool is a Channel Island Circuits model 711B current probe, used to measure the current through one of the thrusters. This current probe is a torroidal inductive probe that measures the derivative of the current between the PPU and the thruster head. A circuit was designed to integrate the derivative signal and return the actual current to the analog input of the computer. This data will be used as a diagnostic tool and possibly in conjunction with a pulse counter.

Conclusions

The University of Illinois has designed the Illinois Observing Nanosatellite (ION), a

CubeSat-class satellite with a scientific payload, an active 3-axis attitude control system, and a 4 vacuum arc thruster propulsion system capable of 2-axis control and orbit translation. This mission is a stepping-stone toward a versatile satellite system capable of carrying a payload, changing orbits, and finely controlling attitude.

Along with it's scientific mission, ION is a technology demonstration mission. The vacuum arc thruster propulsion system consists of a 150 g power processing unit designed and fabricated by Alameda Applied Sciences Corporation (AASC). The PPU controls up to four thrusters, firing any thruster at a pre-set power level, or a power level determined by the on-board computer. The thrusters are a 1 cm wide sandwich (BLT) configuration. The BLT design is a very simple yet robust design, with inexpensive manufacture costs. The thrusters are incorporated into the structure to use the structure as fuel, opening the possibility for large fuel mass missions in the future.

For this technology demonstration, the VATS provide 2-axis attitude control, as well as orbit translation. The VATs, although limited in functionality in this mission, have enormous potential for future flights. The low mass system makes the propulsion system viable for almost any class satellite. The thrust scales with power input which is delivered through a 12-24 Volt bus. This simple yet scalable design makes the system viable for both micro-sats in the CubeSat class, as well as larger satellites.

Vacuum arc thrusters open many doors for future CubeSat class satellites. They will increase launch opportunities by allowing launch on vehicles with non-ideal orbits. They also give CubeSat class satellites a maneuverability previously reserved for much larger satellites.

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