

PROGRESS ON COLLOID MICRO-THRUSTER RESEARCH AND FLIGHT TESTING

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ABSTRACT - Electric propulsion devices are known for their high specific impulses, which makes them very appealing to space mission requiring ultimate utilization of the limited resources on board the spacecraft.

Advances in microelectronics have allowed increased functionality while reducing the sizes of the spacecraft. However this has not been entirely true for propulsion units. Colloid Micro-Thruster held the promise for micro- and nanosatellite propulsion application because of their size, low cost, integrated package, high efficiency, and custom configurability to fit a specific application.

This paper outlines the renewed research efforts on Colloid Thruster, in an attempt to understand the underlying principles and to uncover its true potential. A one-nozzle and a 100-nozzle prototype have been built and tested. A flight thruster subsystem is under development for proof-of-concept flight testing on board a 15-kg university nanosatellite project called Emerald.

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1. INTRODUCTION

Space mission designers have long been relying on electric propulsion because of its characteristic of high specific impulse, allowing higher total delta-V, which makes it suitable for long space missions or for spacecraft with limited fuel storage capacity. Despite of this advantage, the high power consumption and massive power supply requirements have made electric propulsion option unattractive for 100kg-class microsattellites and 10-kg class nanosatellites.

Colloid Micro-Thruster technology is expected to satisfy the need for high-performance propulsion units for small spacecraft. Recent study by Mueller, 1997 [1] concluded that "... of all micro-electric primary propulsion options reviewed, Colloid Thrusters are quite possibly the most suited for microspacecraft propulsion applications." Previous research have shown that Colloid Thruster technology hold great promise, however it is also evident that much of the work on characterizing its operation is yet to be done. Current as well as future work are motivated primarily by the need from the micro- and nanosatellite community, and to a larger extent, by the need from the general space industry for a high-performance yet cost-effective propulsion option for a faster, better, yet economical missions.

Part of the research effort is concentrated on validating the technology. The flight demonstration of the Thruster takes advantage of the Emerald Nanosatellite project [2,3].

The Emerald project is intended to promote and support Distributed Space Systems. This approach distributes the space system's functionality throughout a fleet of microsattellites. The Colloid Thruster technology, promising low-cost, high-performance, custom configurability and reconfigurability, are deemed critical to the success of the Distributed Space Systems missions for commercial as well as military applications.

2. BACKGROUND

WORKING PRINCIPLE

Colloid Thruster works by accelerating charged liquid particles using an electrostatic field, as shown in Figure 1. Glycerol is commonly used as propellant, and is sometimes doped with salt to increase their conductivity.

From the reservoir, the liquid is channeled out through a capillary. At the back opening of the orifice, a high electrostatic field is applied causing imbalance of surface forces due to accumulation of charge on the surface of the liquid. This caused the liquid to breakdown to small charged droplets. The same electrostatic field then accelerates these droplets, thus creating thrust.

The charge that accumulates at the surface of the liquid propellant depends on the electric field that exists at the surface. By using the

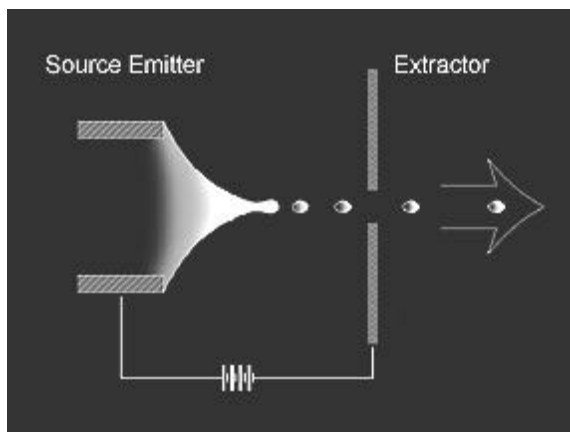


Figure 1. Basic Principle of Colloid Thruster.

appropriate field different particle polarity can be generated.

The particle can also be tuned to follow a specific trajectory by effecting the appropriate accelerating field.

BENEFITS

Colloid Thruster technology opens possibilities that offer many benefits to fulfill the different needs of the various sector in the space industry [3,4].

1. Size

The simplicity of this technology permits miniaturization to work, taking advantage of commercial microelectronics and micro-technology.

2. Power

The energy required to break the surface tension are minimal compared to what is required to maintain chemical reactions, resulting in a high overall efficiency.

3. Inert Propellant

Such propellant allows for easy ground handling and reduced risk during ground engineering as well as to the launch vehicles, leading to cost savings for the overall space mission.

4. Flexibility

Custom configuration, such as different specific impulses and thrust levels, are easily achieved by adjusting the working parameters, as demonstrated by Perel et al., 1967 [5] “...no other thruster system offers the potential capability of operating in such a broad range of specific impulse and variable thrust”

5. Increased System Reliability

At the subsystem level, simplicity leads to reduced risks, therefore increasing reliability. At the system level, new options such as thrust vectoring allows significant reduction in thruster count and system complexity. Thrust vectoring capability also permit for real-time system reconfiguration to account for unexpected thruster failures or other system discrepancies.

6. New Possibilities

This technology offers propulsion option for microspacecraft, and encourages development and application of Virtual-

Spacecraft technologies and Distributed Space Systems architecture for more advanced space missions.

It is also worth noting that the benefits of this thruster technology allow for a low-cost, rapid prototyping and proof-of-concept flight test.

3. RESEARCH ACTIVITY

The activities during the early phase of the research were aimed to recreate the past findings [4]. This is to help identify potentially interesting phenomenas and to create guidance to the subsequent research and development phases.

EXPERIMENTAL APPROACH

The experimental approach involves the construction of 1-nozzle (shown in Figure 2) and 100-nozzle colloid emitters (shown on Figure 3) [6]. The prototype consists of two 3 x 3-cm brass plates, the source or emitter plate and the extractor plate, which are separated by a 0.5-cm thick boron nitride insulator. The nozzles protruding from the emitters plate is aligned to 0.5-mm holes on the extractor plates. The distance from the tip of the needle to the extractor is 1-mm, as maintained by the boron-nitride insulator.

The nozzles are made out of stainless steel capillary having 0.006" outer-diameter and 0.002" inner-diameter. They are held on to the emitter plate using electrically conductive adhesive.

The source plate is connected to a positive high-voltage variable power supply, and extractor plate is connected to negative high-voltage variable power supplies. These power supply can be controlled manually as well as through a microprocessor. Note that the latter option is also used to simplify integration and testing with the satellite bus.

The experiments use unseeded glycerol and unseeded isopropyl alcohol as propellant, and was run in atmospheric condition.

Results showed stream currents in the order of several picoamperes, detected through a picoammeter that is connected to a particle collector plate.

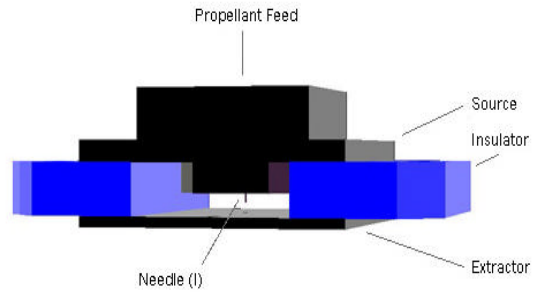


Figure 2. Schematic Illustration of the 1-needle prototype

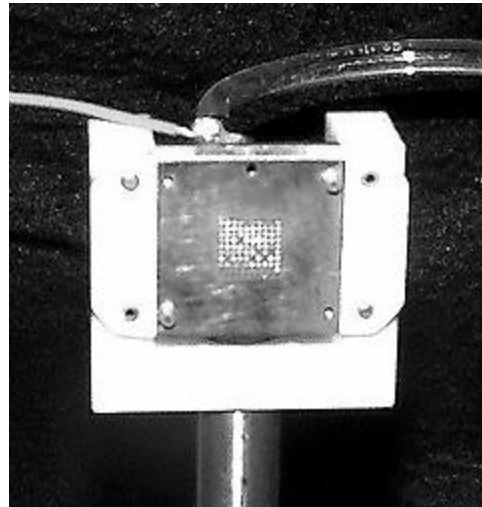


Figure 3. 100-nozzle Thruster Prototype.

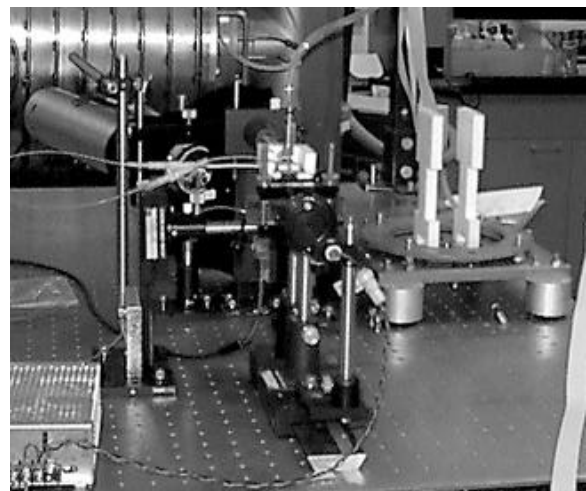


Figure 4. The Experimental Facility.

Simplified laser scattering experiments showed charged particle being generated. It also showed the effects of Rayleigh critical charge limit, as witnessed by particle break up as it evaporates along its trajectory. The experimental setup is shown in Figure 4.

NUMERICAL APPROACH

Numerical analysis was also performed in parallel with the experimental activity [6]. A particle trajectory simulation was performed by applying the equations of motion to the particle as it travels through the electrostatic field. It assumes a particle of known charge originating at the edge of the emitter. Further simplification was made by assuming that the field was not distorted by the presence of these charged particles. This assumption was made due to the low particle loading in the field.

The simplified numerical analysis provides a significant insight to several important phenomena that have important impact to the overall system.

There is evident of significant velocity drop as the particle exits the extractor plate, as shown in Figure 5. The velocity drop effectively reduces the specific impulse, therefore reducing the overall system efficiency.

Particle stream divergence was found to depend on the source-extractor geometry, with increased divergence as the gap between the source emitter and the extractor plate was reduced. Figure 6, showing the particle

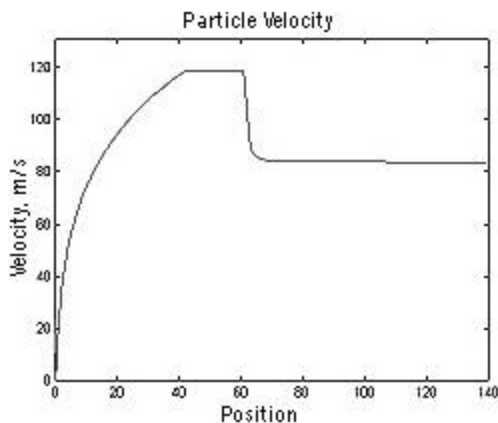


Figure 5. Particle Velocity Profile.

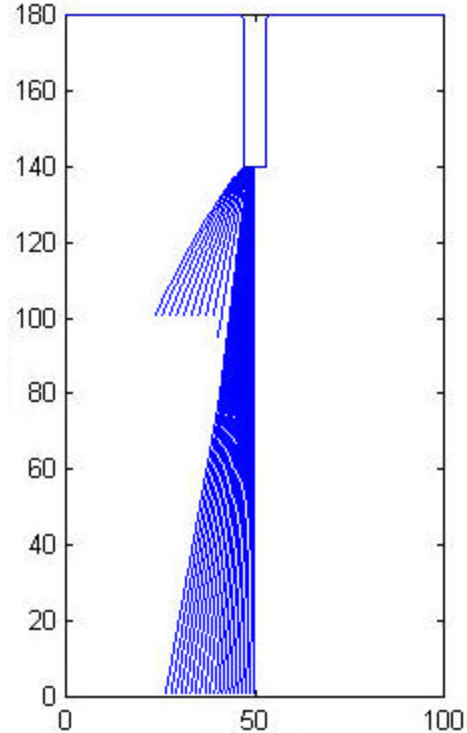


Figure 6. Particle Trajectory

divergence, also reveals additional problem in which the particles strike the extractor grid.

4. FUTURE RESEARCH

The future research will address the recently discovered characteristics, and will in turn develop the tools that will adequately address these issues [6]. The approaches that will be taken are structured to complement one another with no or minimal interdependence, to allow for cross checking of the results that is obtained from the different methods.

EXPERIMENTAL APPROACH

The experimental approach will include the development of an optical measurement system. A Dual-Laser Time-Of-Flight (DLTOF) velocimetry setup based on the Mie scattering will be developed to allow for non-intrusive measurements of the particle velocity. The DLTOF velocimetry setup is shown in Figure 7.

5. FLIGHT TESTING

The Colloid Micro-Thruster will be one of the payloads on board one of the Emerald nanosatellites being built jointly by the Space Systems Development Laboratory at Stanford University and Santa Clara Remote Extreme Environment Laboratory at Santa Clara University [2,6]. Emerald Nanosatellite mission is depicted in an artist's illustration shown in Figure 8.

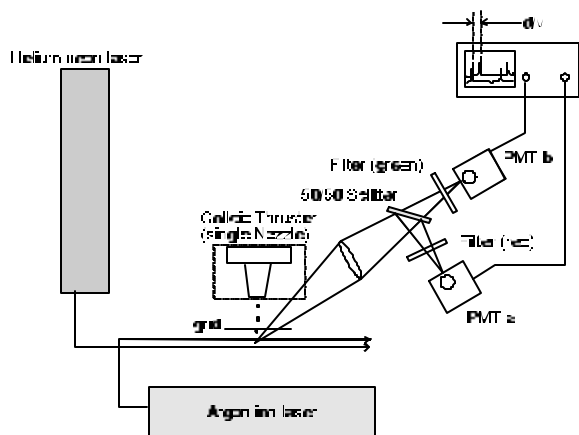


Figure 7. The Dual Laser Time-Of-Flight velocimetry setup.

This setup involves two laser sheets of different wavelengths, having a known spacing between them. A two-photomultiplier tube setup, each responding to one of the laser wavelengths, will be used to monitor the scattered laser. A particle travelling through the two laser sheets will be recorded as a pair of events the photomultiplier tube pair. The velocity information is then extracted by auto-correlating the events, taking into account the known spacing between the two laser sheets.

A 'high-speed' picoammeter has been developed and is currently under testing to determine its actual performance. This apparatus will be used to do a conventional Time-Of-Flight analysis on the charged stream to determine the velocity of the particle stream.

NUMERICAL APPROACH

The next step in the numerical analysis is to incorporate the liquid surface charging and break-up to predict the shape of the liquid surface and the particle generation.

The particle trajectory calculation will be refined to include the disturbance to the electric field caused by the charged particles. This will be extended further to simulate the exhaust stream neutralization process.

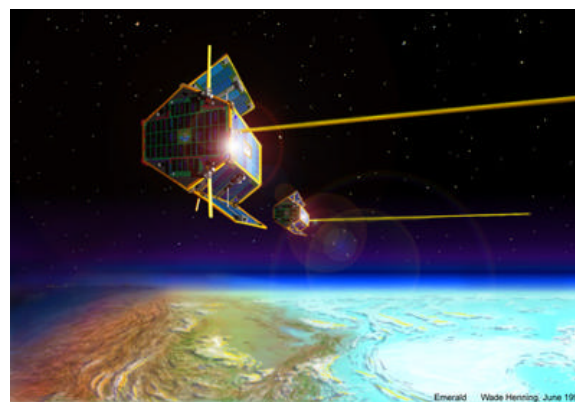


Figure 8. The Emerald Nanosatellite pair on orbit.

MISSION APPROACH

Emerald is a low-cost, high-risk mission that is schedule driven. To minimize the impact of the mission principle to the mission success, the development of the Colloid Micro-Thruster payload is structured using a building-block approach.

MISSION OBJECTIVE

The Mission Objective for the Colloid Micro-Thruster experiment will be to conduct a test firing on orbit and to validate it through sensor readings. The mission is divided into three, step-by-step, major phases. The objectives are structured with a building block approach, with the simple and basic experiment forming the foundation for a more complex experiment. This will ensure that only minimum satellite resources are required for success of the mission. The three major phases in the Colloid Micro-Thruster mission are:

1. Initial Phase

This study will concentrate on the survival and operation of the Colloid Micro-Thruster immediately after launch. This is to confirm whether the Colloid Micro-Thruster subsystem, along with its support electronics and propellant system, can withstand the rigorous launch environment and exposure to space environment. This will be done by various system and telemetry checks throughout the thruster subsystem following the activation of the satellite after deployment from the launch vehicle.

2. Operational Phase

This phase of the mission will study the operations of the Colloid Micro-Thruster by firing the thruster and monitoring the pico-ampere current that is induced by the charged particle stream. This also establishes the Minimum Success Criteria for the Colloid Micro-Thruster Experiment.

3. Technology Demonstration Phase

The final phase will involve firing the Colloid Micro-Thruster unit to attempt to change the spacecraft attitude, namely the rate of spin of the spacecraft. The spin up is induced by offsetting the thrust vector from the spacecraft's center of gravity. Measurement of the spin rate will be done using the attitude sensor on the spacecraft, and will be coordinated by the spacecraft's main processor. This final phase will also study on the particle stream neutralization.

Mission Success is achieved by successful completion of the Operational Phase. The Technology Demonstration Phase is intended to demonstrate the application of Colloid Micro-Thruster for micro- and nanosatellites supporting Distributed Space Systems and Formation Flying. This will be an added bonus to a successful Operational Phase.

FLIGHT HARDWARE

The flight-quality Colloid Micro-Thruster subsystem will be dual polarity. This is accomplished by using two Thruster Modules, one emitting a positive-polarity stream and one emitting a negative-polarity stream to achieve a self-neutralizing operation. Each of the Thruster Modules, like the one shown in Figure 9, will have its own Thruster Module

Controller (TMC) and Thruster Instrumentation Module (TIM). The Thruster Control Unit (TCU) will coordinate the operation of the individual modules via a local I2C serial-bus link. The TCU will also act as an interface to the rest of the satellite bus via the system-wide I2C serial bus. The block diagram for the Thruster subsystem is shown in Figure 10.

The TMC comprise of a PIC 16C74 microprocessor, miniature programmable high voltage power supplies, and propellant flow control. The TMC will handle the system diagnostics, telemetry, high-voltage control, thrust control and propellant flow commands.

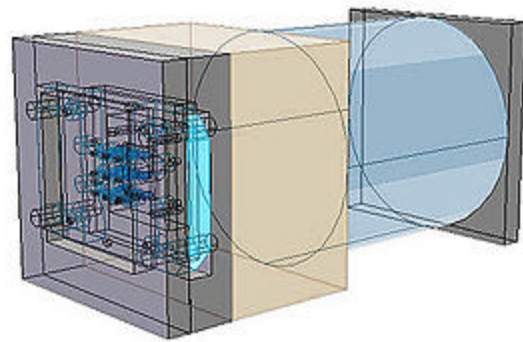


Table 9. The Thruster Module

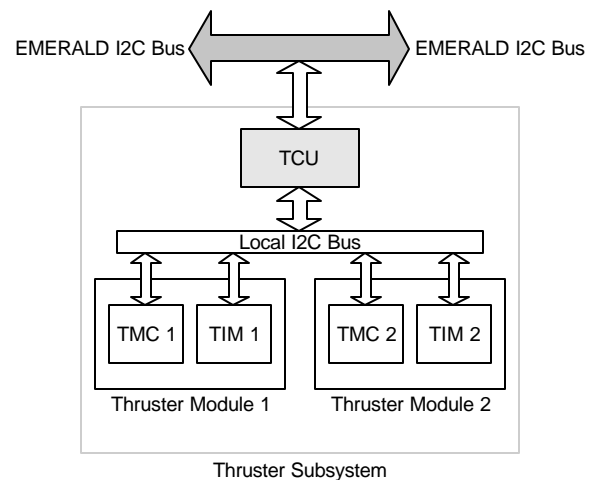


Figure 10. Block Diagram of the Colloid Micro-Thruster Subsystem.

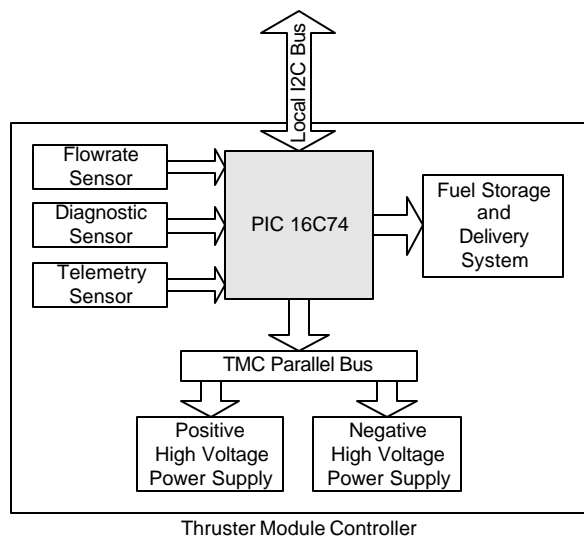


Figure 11. Block Diagram of the Thruster Module Controller.

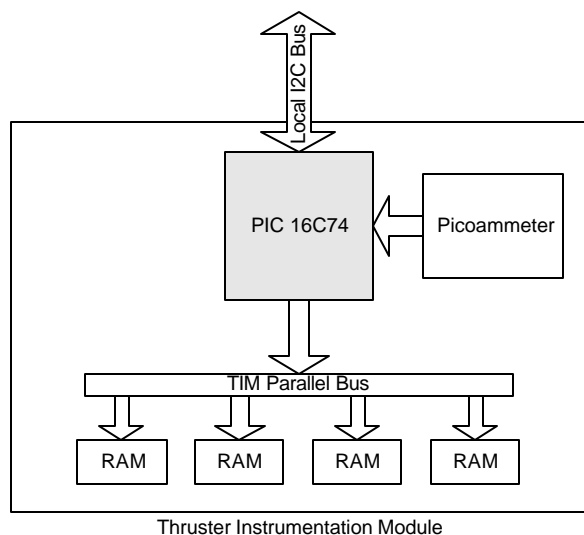


Figure 12. Block Diagram for the Thruster Instrumentation Module.

The propellant will be stored in a modified battery-operated insulin pump, which is also controlled by the TMC. The block diagram of the TMC is shown in Figure 11.

The Thruster Instrumentation Module (TIM) will handle data collection and temporary storage. The TIM will incorporate a PIC 16C74 microprocessor, a picoammeter, and RAM. The picoammeter will detect the pico-ampere current induced by the exhaust stream. The microprocessor will then sample

EMERALD	Completion
Mass Model Vibe Test	Aug-99
Working Prototype	Oct-99
Engineering Model	Apr-00
Flight Hardware	Jul-00
Environmental Test	Sep-00
Operations Test	Dec-00
Delivery	Jan-01

Colloid Micro-Thruster	Completion
Prototype Vibe Test	Aug-99
Analysis and Optimization	Dec-99
Support Hardware	Mar-00
Flight Hardware	Jul-00
Environmental Test	Sep-00
Operations Test	Dec-00
Delivery	Jan-01

Table 1. Development Timeline; Emerald (top), Colloid Micro-Thruster (bottom)

the output of the picoammeter and storage to the local RAM. The stored data can be downloaded to the Emerald main computer for downlink for further analysis on the ground. The block diagram of the TIM is shown in Figure 12.

The prototype Thruster is expected to produce 0.1-milli-pound of thrust, while the power consumption for the subsystem is estimated at 4 Watts maximum based on commercial off-the-shelf parts. The overall thruster package is expected to fill 10 x 10 x 20-cm envelope, weighing about 1-kg.

TIMELINE

The Colloid Micro-Thruster will follow development schedule that is similar to the development timeline of the Emerald spacecraft, as outlined in Table 1. This will promote continued cooperation and ensure timely delivery.

The schedule calls for delivery of flight-quality hardware in 12 months and to begin for integration effort and environmental testing. Because of the exotic material and construction techniques being used, incremental testing will be done through out the project to ensure survivability of the Thruster subsystem.

The launch for Emerald nanosatellites is expected to be in the third quarter of 2001.

6. CONCLUSION

The renewed effort into the research on the Colloid Micro-Thruster is geared toward identifying and understanding the underlying theories and key issues that governs the operation of the micro-thruster.

Present findings showed several important characteristics that affect the operations of the Colloid Micro-Thruster. As the research activity enters its second phase, these findings will be closely investigated.

The findings from past research as well as the following research phase will then be brought to the next step by using them as a design tool to engineer a flight prototype that will be used to demonstrate the concept on orbit and to validate the benefits of this new technology.

7. ACKNOWLEDGEMENT

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at Santa Clara University for their continued support to the upcoming flight test on board the Emerald Nanosatellite.

8. REFERENCES

- [1] Mueller, J., AIAA 97-3058, 33rd Joint Propulsion Conference, Seattle, WA, July 1997.
- [2] Kitts, Christopher A., Robert J. Twiggs, Jonathon How, Freddy Pranajaya, and Bryan Palmintier, "Emerald: A Low Cost Formation Flying Technology Validation Mission", In Proceedings of the 1999 IEEE Aerospace Conference, Snowmass, CO, March 6-13, 1999.
- [3] Pranajaya, Freddy M., Carlos Garcia-Sacristan, James Cutler, Bryan Palmintier, Christopher Kitts, and Michael Swartwout, "Micro- and Nanotechnology Applications at Stanford University", Accepted for publication at the 2nd International Conference on Integrated Micro-Nanotechnology for Space Applications: Enabling Technologies for New Space Systems, Pasadena, CA, April 11-15, 1999.
- [4] Cappelli, M., and F. Pranajaya, "Colloid Micro Thruster Research", Research Report, July 1997.
- [5] Perel J., T. Bates, J. Mahoney, R.D. Moore, and A.Y. Yahiku, "Research on Charged Particle Bipolar Thruster", 1967.
- [6] Cappelli, M., and F. Pranajaya, "Colloid Propulsion Development for use in Microsatellite Applications", Research Report, Stanford University, May 1999.