Pico-Satellite Orbit Control by Vacuum Arc Thrusters as Enabling Technology for Formations of Small Satellites

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5th International Conference on Spacecraft Formation Flying Missions and Technologies,
Munich, Germany

May 31st, 2013

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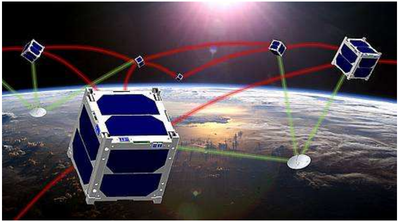
Introduction

- In the last years, considerable attention is given toward lowering cost and time in development of Earth observation and communication satellites
- One possible method of addressing these needs is the development of a distributed small satellite system to replace a single large spacecraft

TanDEM-X, DLR



proposed NetSat, Wuerzburg University

Introduction Cont.

- A minimum requirement for a formation, for example, is to keep the spacecraft range bounded, within line of sight of each other and the ground, maintaining relative distances below 1500 km throughout the mission duration (few months)
- Currently, the smallest satellites that can be considered for formation flying are in the pico scale. Important widespread platform is the 1U CubeSat $\sim$ 1 kg, 10 cm X 10 cm X 10 cm
- This minimum mission scenario needs to be analyzed in order to evaluate if a propulsion system can be fitted

Photograph of CubeSats after deployment from the ISS

Electric Propulsion Benefits and Limitations

- Higher propellant velocity V_{ex} (1×10^4 - 3×10^4 m/s) than conventional chemical rockets ($\sim 4\times10^3$ m/s) - saves mass $m_f = m_0 e^{-\Delta V / V_{ex}}$
- Low thrust

electric propulsion missions

Mission	ΔV	**flight time**
Orbit insertion	2000-5000 m/s	$<$ 180 days
Moon probe	$\sim$ 4000 m/s	$\sim$ 500 days
Station keeping	10-100 m/s	periodic
Drag compensation	10-1000 m/s	periodic

- Requires additional power source. Small spacecraft have limited available power due to mass and surface area restrictions

pico, nano, micro and mini- satellites features

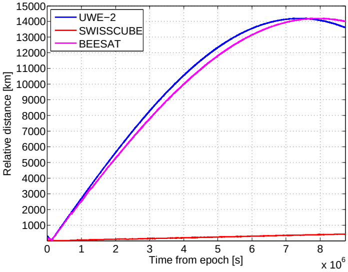
	Pico	**Nano**	**Micro**	**Mini-Small**
Spacecraft mass	$<$ 1 kg	$<$ 10 kg	$<$ 100 kg	$<$ 450 kg
Payload mass	$<$ 0.1 kg	$<$ 1 kg	$<$ 30 kg	$<$ 200 kg
Power generated	$<$ 2 W	$<$ 20 W	$<$ 200 W	$<$ 600 W

Mission Scenario

We examine a deployment scenario: a group of four CubeSats launched in 2009 to a sun synchronous circular orbit at an altitude of ≈ 715 km

- The orbit of each satellite is naturally evolving (no propulsion)
- Although the CubeSats where released from the same launcher they display strong differences in drift rate
- One pair has relatively small relative drift while the two other satellites are drifting rapidly to thousands of kilometers
- Conclusion: in order to maintain a satellite formation in low Earth orbit (LEO) some degree of orbit control is required

Relative distance between four CubeSats, taken from TLE data



Orbit Control using Very Low Power EP

Orbit Control using Very Low Power EP

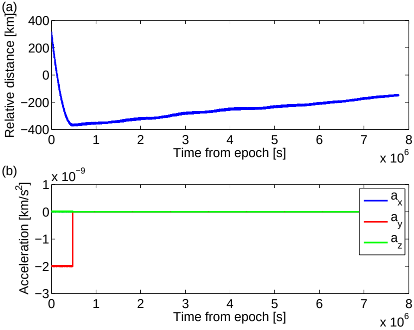
- To reduce the secular drift between satellites an energy matching principal can be employed
- In the case of a circular orbit, the energy principle degenerate to minimization of the difference in the semi-major-axis (SMA)
- In-track thrusting is selected as the control strategy for formation keeping: increasing/decreasing the deputy spacecraft SMA, without affecting other orbital parameters

Phasing Maneuver

- The applied control has to match the deputy's SMA to that of the chief's
- A thrust control can be manually computed assuming complete knowledge of both orbits and the rate of change in the differential SMA Δa versus the thrust applied
- By performing the maneuver as close as possible to the formation deployment epoch small relative distances can be easily maintained throughout the mission

Phasing Maneuver Cont.

Using the worst case relative drift ($\Delta a = 2000$ m) and SGP4 position estimates as initial conditions, a high fidelity simulation was carried out. A phasing maneuver was performed with the deputy decelerating in the in-track direction at 2×10^{-9} km/s^2 for 5.5 days with a total $\Delta V \approx 1$ m/s. The stability of the new orbit is clearly shown - keeping the relative distance less than 300 km for the three months duration



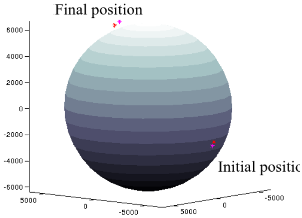
Phasing Maneuver Cont.

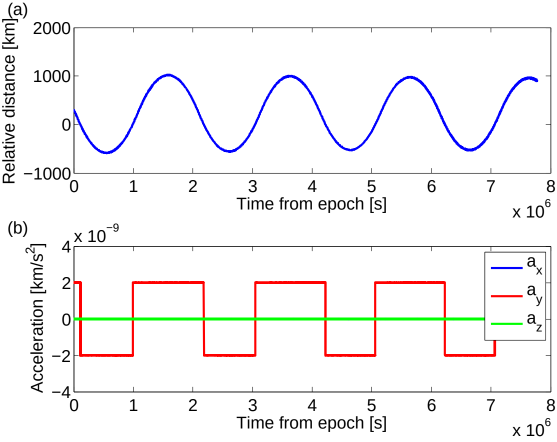
- The phasing maneuver, although efficient, requires accurate knowledge of the orbital parameters of all the spacecraft in the formation
- For a pico-satellite with limited power and sensor capability this is not currently possible
- Instead of measuring the orbital position on-line, the orbital elements can be provided from TLE data
- However, TLE data set accuracy may be insufficient for the phasing controller, with SMA errors as large 1–2 km with and update rates of 1 - 2 days

Simple Orbit Controller

- A simple off-line orbit control law is suggested that do not require high precision orbit measurements
- A bang-bang type control is followed, where the thrust command direction is determined from the in-track relative distance. The control changes signs at moments of closest approach
- Using the same initial condition as in the phasing controller, high fidelity orbit-propagator results show that the motion is bounded and the controller is able to keep the deputy at a relative distance of less than 1000 km from the chief. For three months a total $\Delta V = 15$ m/s was required
- Similarly, using acceleration of 10^{-6} m/s^2 and a total $\Delta V = 7.5$ m/s, a relative range of less than 1500 km was kept

Simple Orbit Control Performance Cont.





Propulsion System

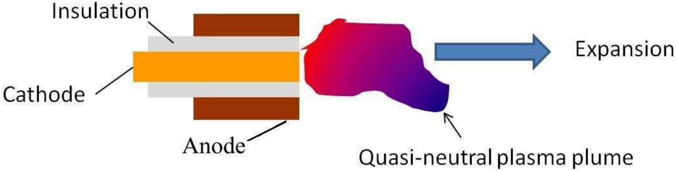
Vacuum Arc Thruster

- Volume, mass, and power constraints in pico-satellites require the use of innovative propulsion solutions
- Only handful state of the art propulsion systems are currently suitable
- The vacuum arc thruster (VAT), an electric propulsion device, was selected for the UWE-4 CubeSat project of Wuerzburg University*
- The VAT is a solid state ablative pulsed thruster. It is simple, scalable, and has adequate performance in very low power operation

*Funded by the Bavarian Space Technology Program

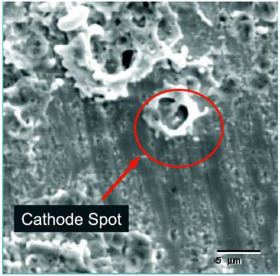
Vacuum Arc Thruster Operation

- An arc discharge that burns in metal vapor liberated from the cathode into an inter-electrode gap initially at vacuum
- Combination of Joule heating and ion bombardment heating sustains the temperatures to vaporize cathode material
- The plasma is generated by explosive emission from cathode spots
- Fully ionized high velocity and directional plasma flows are produced
- No external magnetic field is needed for operation



Cathode Spot

- The plasma originates from small cathode spots (crater radius 1 - 10 μm) that move rapidly and randomly on the cathode surface (1 - 150 m/s)
- Spot motion is the result of the appearance of a new spot and the death of its predecessor
- Electrons are emitted by field enhanced thermionic emission
- A single spot is formed in low current operation (1 - 100 A)
- Spot lifetime is < 0.1 μs

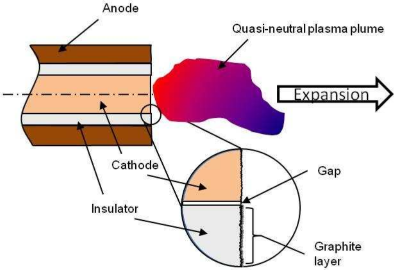


VAT Discharge Characteristics

- Discharge (arc) voltage of 15 - 30 V
- $\approx$ 10 % of the discharge current is contributed by ions
- The ion beam follow cosine distribution perpendicular to the cathode surface (half current at 45 ^{0})
- The plasma is fully ionized and most ions are multiple charged
- Plasma flow velocities of $\sim 10^4$ m/s are produced by gas-dynamic expansion and ion-electron friction
- Cathode erosion rate $\sim$ 10 - 100 μg/C

VAT Triggerless Ignition

- Thin conducting film on the insulator provide high but finite impedance between the cathode and anode
- With few hundred volts between the electrodes breakdown occurs at very small gaps in the thin metal film
- Tiny discharges produce enough metal vapor to initiate the main discharge in the gap
- Metal vapor and droplets eroded from the cathode replenish the thin conducting layer on the insulator



Propulsion System Requirements

The propulsion system has to have sufficient performance while accommodating the power, volume, and mass restrictions of a 1U CubeSat:

- Usable space limited to outer structure
- Mass limited to 150 - 200 g for the whole system
- Input voltage and current limited to 4 V and 0.5 A respectively
- Continuous thrust of at least 1 μN
- Total impulse bit of at least 1 Ns
- Provide for thruster based 2 axis attitude control

Thruster Configuration

The following thruster configuration was selected:

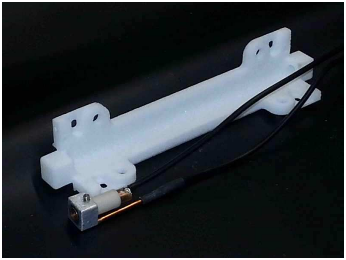
- Four thruster heads, one thruster head per outer rail
- Dimensions: length of 20 mm and diameter of 7 mm
- Combined thrusters mass < 50 g including propellant
- For $\Delta V = 7.5$ m/s, ≈ 1 g of propellant mass is needed (split between four thrusters). Considered cathode materials are titanium (Isp $= 924$ s) and tungsten (Isp $= 1078$ s)

UWE4's Vacuum Arc Thruster

- Simple and robust design
- Efficiency independent of power, $\sim$ 10 W/kg
- Low ignition voltage $<$ 500 V $\rightarrow$ triggerless operation
- Little backflow contamination compared to pulse plasma thrusters

Parameter	μ**VAT**
Thrust, μN	2–10
Specific impulse, s	900–1100
Average input power, W	0.5–2
Total efficiency, %	1–5

micro-VAT for CubeSat application, UWE-4 project
Uni-BwM and Wuerzburg University



Summary

- The feasibility of maintaining a basic formation of pico-satellites using electric propulsion was investigated
- A simple off-line control method was developed. This scheme requires only TLE data with daily ground command
- High fidelity simulations show that in order to maintain a bounded formation of 1500 km, an average ΔV of 2.5 m/s per month is required
- The simplicity of the control law provides important advantage for application in a pico-satellite with extremely limited resources
- It was demonstrated that vacuum arc thrusters can be miniaturized to carry out the tasks. Life time is still a concern

Summary and Standing Issues

- The conductive layer on the insulation is eroded during thruster operation. Therefore a "healing" mechanism is necessary. In addition, cathode geometry may change during operation
- Current design was tested to 10^5 pulses. At least order of magnitude increase is required
- To address these issues two methods are investigated:
  - High power vacuum arc operation - leads to redeposition of the conductive layer by eroded cathode material
  - Use of low melting point materials (tin or indium) to a regenerate the conductive layer and replenish the cathode material by capillary forces (disadvantages of more macro particles and lower Isp $\sim$ 200 s)

Questions?