Jacob Simmonds

11/8/2017

Pre-generals PhD Committee Meeting Research Abstract

Miniaturization of Low Power Hall Thrusters

I. Background

Satellites have enabled a great variety of scientific and commercial opportunities in the last half century, however launch costs are prohibitive and until recently only several nations have been capable of launching satellites into orbit. CubeSats and other small satellites have recently experienced an explosion of use as components have been miniaturized and confidence in small satellites has increased. As such, industry has responded and new nations and companies around the world are building rockets specifically to launch these small satellites – Spaceworks' market review reported over 450 satellites have been launched in between 2013-2016, which is more than twice the total launches before 2013. [1] CubeSats have enjoyed this success for two primary reasons: they are a fraction of the mass of a typical satellite while demonstrating similar capabilities.

With this surge in CubeSat use the subject of satellite formations has gained increased traction. Formations of satellites can enable even more ambitious missions, such as a constellation providing internet around the world, a grid of satellites that can measure space-resolved space plasma properties, or a space-based array of satellites that could form a telescope with much higher resolution than achievable on Earth. However, formations of satellites require a great deal of technological advancement to be viable, namely laser communications, better pointing control, and a small low power propulsion system to move the satellites and maintain formation in the presence of orbital perturbations. The optimization of this low power propulsion is the focus of my research.

Propulsion can be separated into electric and chemical propulsion, where electric propulsion uses onboard power to accelerate a propellant using electromagnetic forces while chemical uses the propellants to chemically react and provide the acceleration for the propellant. Chemical propulsion has hard limits on the specific impulse, which is a measure of how much energy a particle of propellant can achieve and is related to the fuel mass needed to perform an orbital maneuver. Electric propulsion has much higher specific impulse limits and so needs less fuel, and as such is viewed as the best way forward in small satellite propulsion.

II. Thrust Density

A common theme between most plasma thrusters is low thrust and thrust density (thrust per area). As a preliminary idea, the fundamental thrust density limits for electrostatic, hall, and electromagnetic thrusters are shown in Figure 1 along with values from several high TRL thrusters. There it can be seen that Hall Thrusters currently have the highest working thrust density of any thruster, but are still well below their fundamental limit. This limit can be obtained by looking at how thrust is generated inside a Hall Thruster and assuming a maximum magnetic field of ~1000 Gauss, which is about the maximum B field that can exist in an air-gap in a magnetic circuit with iron.

$$j_\theta = \nabla \times B_r/\mu$$

$$\frac{Thrust}{Volume} = j_\theta \times B_r = (\nabla \times B_r/\mu) \times B_r = \frac{B_r}{\mu}\frac{\partial B_r}{\partial z} = \frac{\partial\left(\frac{B_r^2}{2\mu}\right)}{\partial z}$$

$$\frac{Thrust}{Area} = \frac{B_r^2}{2\mu} = 3778\ N/m^2$$

The resulting expression is roughly equal to magnetic pressure,[2] but the best Hall Thruster is still two orders of magnitude below that limit. To increase thrust one would have to correspondingly increase mass flow rate, which would increase density in the thruster. However this leads into problems involving collisionality and diffusion. As electrons diffuse towards the anode and across magnetic field lines the electric potential profile inside the plasma changes, lowering the thrust. Classical electron diffusion predicts a $1/B^2$ proportionality, however experimentally the diffusion has been shown to be proportional to ~1/B. There is no theoretical model for this diffusion, but there is strong experimental evidence that the spoke instability plays a large part,[3] and this instability appears to get worse for smaller thrusters.

III. Orbit Application

In order to understand the application a miniaturized thruster with high thrust density could have we need to do some basic mission analysis to determine how thrust density affects capability. This capability can be split into 3 areas: orbital change maneuvers, maintenance of formation geometry due to orbital radii, and maintenance of formation geometry due to perturbations. While using DeltaV approximations can be useful to determine the orbital maneuvers, response time and position error can be very important to formation maintenance, and so some numerical simulation is necessary to understand how thrust can control formation. Some preliminary work has been performed for a satellite formation of 1km separation at 63,000km altitude using current Cylindrical Hall Thrusters, and thrust-time and position-time plots can be found in Figures 2 and 3. Furthermore, changing the thrust density and efficiency has an effect of mission time resulting in some optimal thrust density, an example of which can be seen in Figure 4.

My research will be split into three components: the first is an experimental campaign to determine parametrically how miniaturization changes the loss mechanisms, and so the thrust density. To do this we will conduct performance tests on several identical Cylindrical Hall Thrusters of different scales. The second is a simulation campaign to understand how the magnetic field is changed with size, as magnetic field saturation becomes a problem which changes the field geometry. The third campaign is an orbital analysis to understand what small satellite formation missions are possible with different thrust densities to provide an understanding of what capabilities our new thrusters would have.

IV. References:

1. Doncaster, B., Williams, C., and Shulman, J. “SpaceWorks Nano and Microsatellite Market Forecast 2017.” http://spaceworksforecast.com/2017-market-forecast/, 2017.
2. Raitses, Y., Fisch, Nathaniel. “Parametric investigations of a nonconventional Hall thruster.” Physics of Plasmas, 8, 2579 (2001).
3. C. L. Ellison, Y. Raitses and N. J. Fisch, “Cross-field electron transport induced by a rotating spoke in a cylindrical Hall thruster,” Physics of Plasmas 19, 013503 (2012).

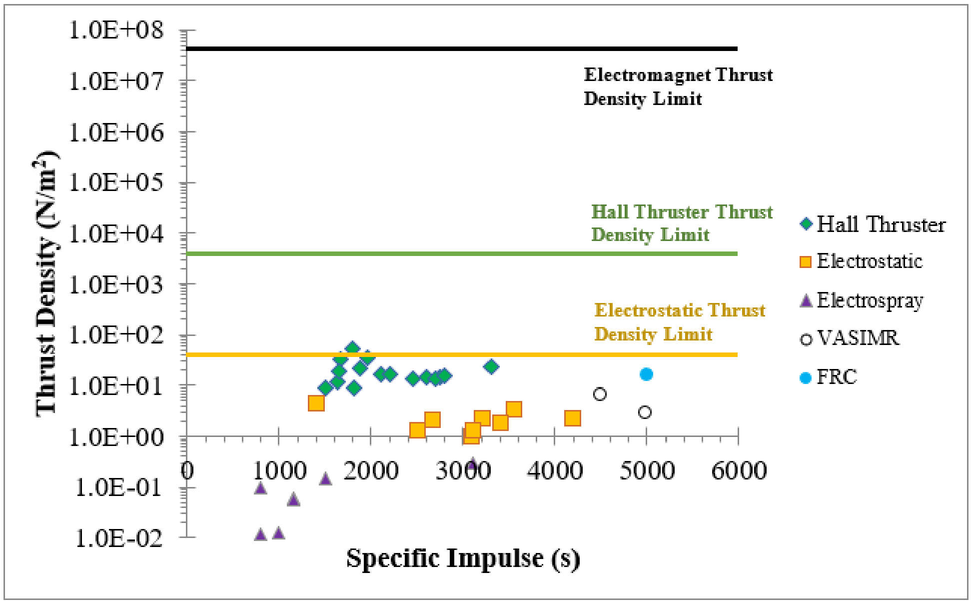

Figure 1. Thrust Density vs Specific Impulse for High TRL Thrusters

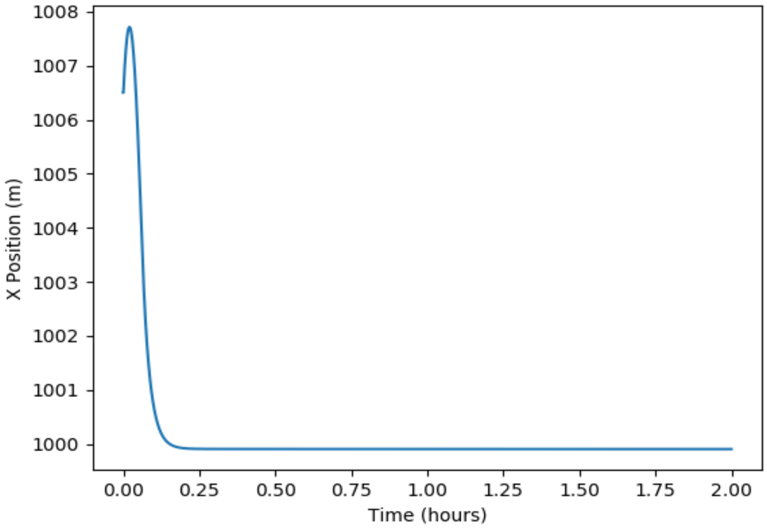

Figure 2. Position vs Time for a binary satellite formation with 1km vertical separation and 63,000km altitude.

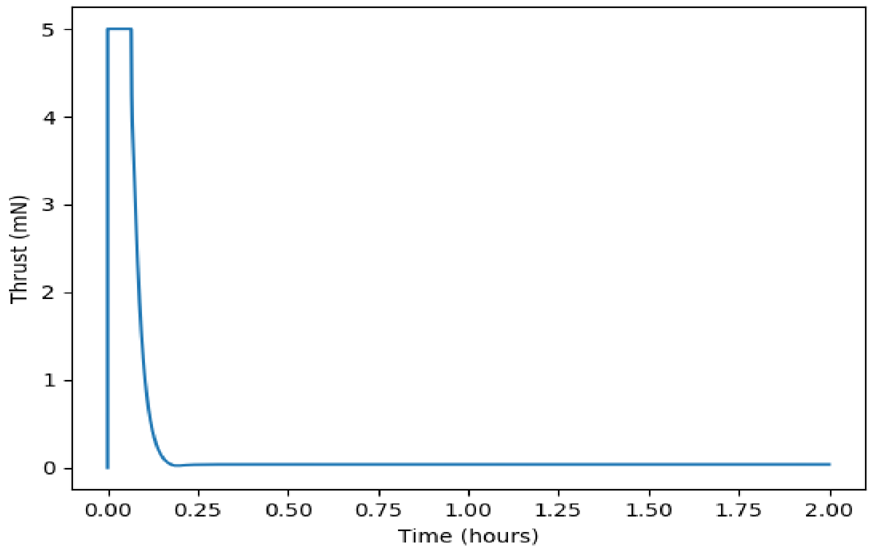

Figure 3. Thrust vs Time for a binary satellite formation with 1km vertical separation and 63,000km altitude.

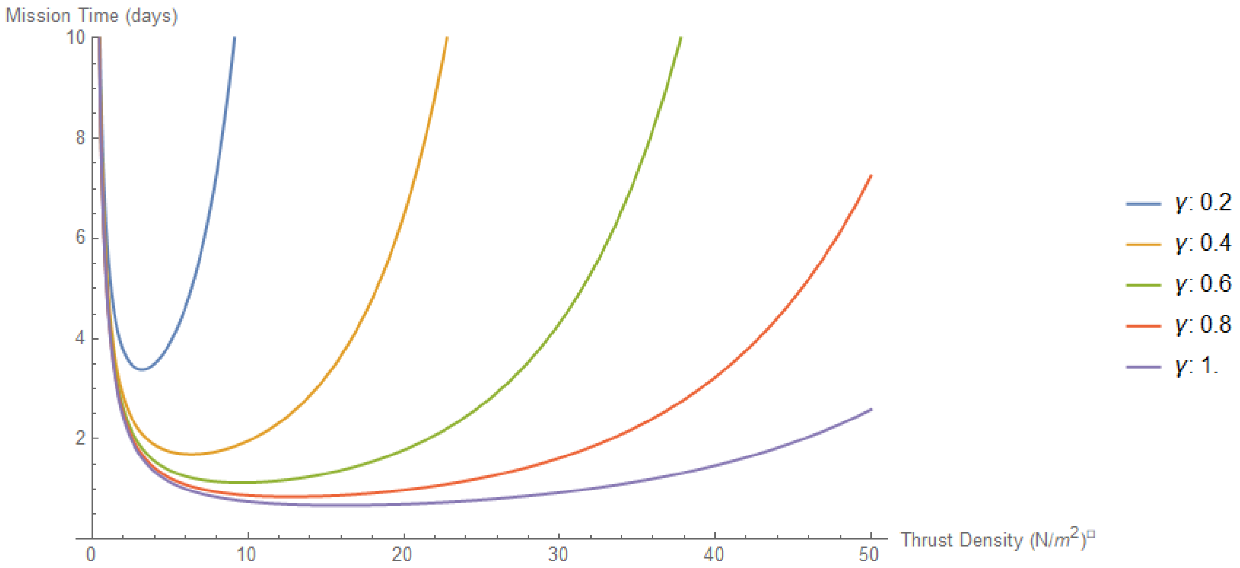

Figure 4. Mission time vs Thrust density for a 3kg satellite with 50W power and DeltaV of 1000m/s, with varying efficiency γ

Figure 4 was generated by incorporating thruster mass into time calculation with relation

$$Time = \frac{2P\eta(m_{craft} + \rho AL)(e^{\frac{\Delta VA\tau}{2P\eta}} - 1)}{A^2\tau^2}$$