Active Solar Sail Designs for Chip-Scale Spacecraft

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ABSTRACT

Centimeter-scale spacecraft, known as "Chipsats," have very high surface-area-to-mass ratios, which accentuates solar radiation pressure (SRP) effects. In contrast to traditional. large solar sails, chip-scale solar sails have the potential to be highly agile in terms of attitude because of their structural rigidity and low moments of inertia. This ability to easily reorient a solar sail greatly expands the orbits that a solar-sail spacecraft can achieve. Solar sail actuation through electrochromic surfaces or MEMs mirrors represents an interesting, low-power way to further extend the capability of chip-scale solar-sail spacecraft. However, there remain a number of challenges. In particular, most of these technologies are on/off and have limited, highly nonlinear behavior. Ensuring that an active solar sail of this type performs as desired demands a systems-level perspective on dynamics and control design.

INTRODUCTION

Chip-scale spacecraft offer the prospect of unique and novel exploration missions. The low cost per spacecraft of manufacturing and launch allows a highly redundant mission architecture. By expanding chip-sat actuation capabilities, we can enable mission architectures such as stochastic exploration [1] and swarm sensor networks. For certain science objectives, this mission architecture could be a very cost effective.

A key challenge for this scale of spacecraft is trajectory control. The severely limited mass and size motivate propellantless actuation. A number of solutions for navigation have been explored, such as Lorentz force augmentation [2] [3] and electrodynamic tethers. [4] Such solutions would make sense for missions near the earth or other planetary bodies,[5] but rely on effects not applicable to a generic heliocentric orbit.

Fortunately, the high ratio of surface area to mass naturally makes radiation pressure a viable control force. A solar sail on this scale is free from many of the control challenges that need to be overcome by larger scale space, since it is essentially a rigid, planar body. However, any thrust is highly coupled to the spacecraft attitude. There are various techniques for created passively stable sun-pointing chip-scale spacecraft outlined in Atchison and Peck, 2010,[2] along with various orbital maneuvers utilizing a constant force due to solar radiation pressure (SRP). Here, we examine reflective surfaces that are pixelated and controllable, along with various micro-electromechanical systems (MEMs) to achieve more general actuation.

Chipsats as a class are uniquely adapted to using radiation to advantage. The natural high surface area to mass ratio combined with natural structural rigidity avoids many of the difficulties that larger solar sail designs must overcome. Large sails are unfurled after launch, and held taut generally with booms or through spinning and edge weights. These designs allowa substantial, unpredictable wrinkling in the sail surface. Attitude control may be accomplished by shifting the center of mass relative to the center of pressure [6], but must be done carefully to avoid overwhelming the tensioning system. Chipsats can withstand much faster slews without concern for changing topography.

SOLAR SAILING

Solar radiation interacts with a surface through a number of mechanisms. Each of these interactions vary substantially by wavelength of incoming light as well as material properties. For our purposes, we can model these interactions as specular reflection, diffuse reflection, absorption, and transmittance. The difference between specular and diffuse reflection is shown in Figure 1 and Figure 2. Specular reflection preserves the angular relationships of incoming light beams, so the outward light maintains the incoming image.[7] Diffuse reflection does not preserve angular relationships, usually due to surface scattering,

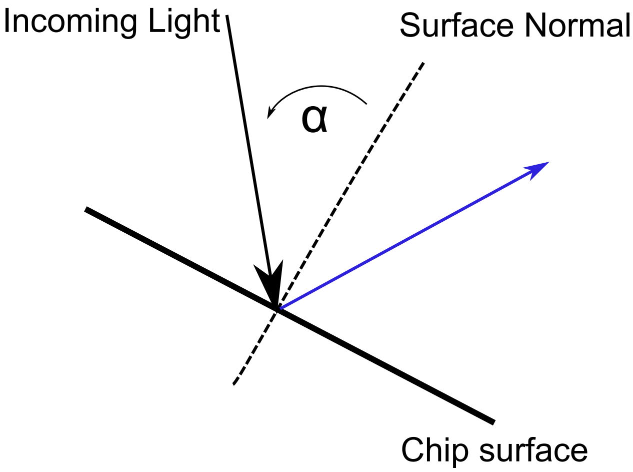

Figure 1: Specular reflection

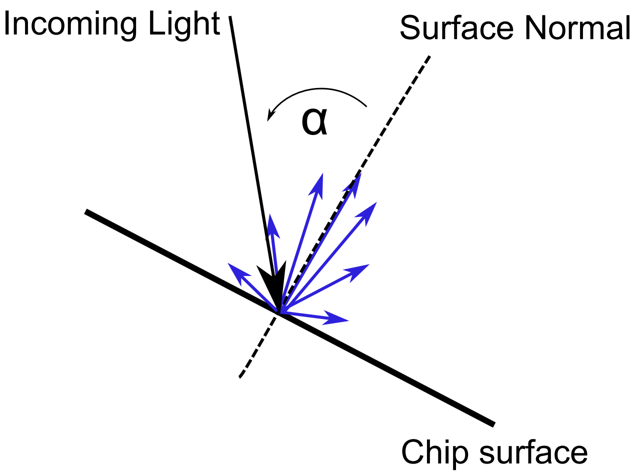

Figure 2: Diffuse reflection

so that the average direction of exiting light is along the overall surface normal.

Since the majority of the sun's power is within the visible spectrum, the interaction can be approximated as an average across these wavelengths, roughly 400 - 700 nm. The solar energy flux for this band taken to be a radiation pressure:

$$\vec{P}_{SR} = \frac{W}{c}\hat{r} \quad (1)$$

where W is the solar energy flux and c is the speed of light. For a reflective flat plate,[8] Equation 1 gives us a force

$$\vec{F}_{SR} = 2PA\cos\alpha * \left[\left(2\eta_{sr}\cos\alpha + \frac{2}{3}\eta_{dr}\right)\hat{\boldsymbol{n}} + (\eta_{ab}+\eta_{dr})\hat{\boldsymbol{e}}_S\right] \quad (2)$$

where η_{sr},η_{dr}, and η_{ab} are the specular reflection, diffuse reflection, and absorption coefficients, respectively and $\eta_{sr} + \eta_{dr} + \eta_{ab} = 1$, meaning all of the incident light has been accounted for. Here, A is the planar area of the chip, so that $A\cos\alpha$ is the effective area projected in to the plane perpendicular to the incoming light. In addition, it is assumed that the energy being asorbed is being reradiated isotropically in the thermal band and so does not affect substantially affect the net force.

Most studied solar sails are large, thin, and flexible in order to maximize payload and allow a more compact form for launch. While this design strategy can provide a very large surface to mass ratio, the smaller scale surface topology is challenging to characterize, and large angle slews must be very slow or risk tangling the sail.[9] Some work has been done for smaller, rigidized solar sails have also been studied,[10] but such designs have not yet been tested.

Altering the SRP force may offer a means to control the attitude of a chipsat. If we consider MEMs actuated mirrors on the chip surface, the solar radiation force due to specular reflection changes in both direction and magnitude according to the new $\hat{\boldsymbol{n}}$ and α. If instead we alter the optical qualities of the surface, the net force direction shifts between the surface normal direction and the vector pointing away from the sun (or other light source). So, while the primary effect is to increase or decrease the magnitude of the force at that surface, there is also a dependence on the relative direciton of the sun. Colombo *et al.*[11] examine how the modulating electrochromic surfaces may enable controlled orbit evolution and swarm characteristics for passively sun-pointing chip swarms.[12]

If the reflective surfaces are shaped appropriately, solar radiation may also provide a "windmill" torque. The problem with a fixed windmill geometry, as discussed in [8], is that the spin will contuinue to accelerate until structural failure. To avoid this failure mode, the applied torque needs to have a spin dependence that will create a maximum spin speed within a safety margin. At faster spin speeds, the torque should decrease to zero, so that the chip no longer experiences angular acceleration around its primary spin axis.

DESIGN SPACE

SRP creates a force by the momentum transfer of photons being reflected or absorbed by a surface. The magnitude of this force depends on the amount of incident light, and the coefficient of reflectivity. So, materials such as electrochromic and thermochromic films can allow some active modulation of this SRP force.[10] The direction depends on the direction of the surface normal relative to the incident light, so both overall attitude of the chip and MEMs control of the surface can provide adjustments to the force direction. By carefully designing these capabilities, we can provide a range of control forces and torques.

The control surfaces, for both electrochromic and mirror-based actuation, enable the spacecraft to modulate the force acting on it. For a MEMs mirror design, we can control the cone angle of the mirror. Furthermore, the rest of the spacecraft surface would still be contributing a solar radiation force. For a design with a single perfect mirror, we would have Equation 3

$$\begin{aligned}\vec{F}_{net} = 2PA\cos\alpha *& \\ \left[\left(2\eta_{sr}\cos\alpha + \frac{2}{3}\eta_{dr}\right)\hat{\boldsymbol{n}} + (\eta_{ab} + \eta_{dr})\hat{\boldsymbol{e}}_S\right]& \\ + 2PA_m\cos^2\alpha_m\hat{n}_m& \quad (3)\end{aligned}$$

where now α_m and $\hat{n}_m$ can vary, allowing indirect control of α and $\hat{n}$.[8] Figure 3 shows the available normalized force for a flat plate with cone angle ranging from zero to $\frac{pi}{2}$. The tear drop shape is symmetric about the sun direction e_S, and the maximum force occurs along this axis when $\alpha = 0$. For an actual MEMs mirror, with a limited angular motion, only a small patch of this tear drop surface would be available.

We can also tune the optical parameters. Figures 3 through 6 show how the force due to SRP varies in magnitude and direction through a range of cone angle and reflection fractions. These plots consider a centimeter scale spacecraft near Earth's solar orbit, so $P = 4.56 * 10^-6Nm^{-2}$ and $A = .1cm^2$ Note that there is an angle α where the magnitude of force curves intersect. This means that at certain attitudes, changing the optical properties to transition between these curves will not provide a change in relative force.

MEMs Actuated Mirrors

There are a number of available MEMs mirror technologies. The Texas Instruments DLP chipset has a large array of mirrors with ±15 degree discrete motion. Mirrorcle technologies has a two-axis mirror chip, with analog motion. Their integrated mirror sizes currently range from .8 to 1.7 mm with ± 5 degree. While these technologies are intended for fast scanning and created images, it would not be

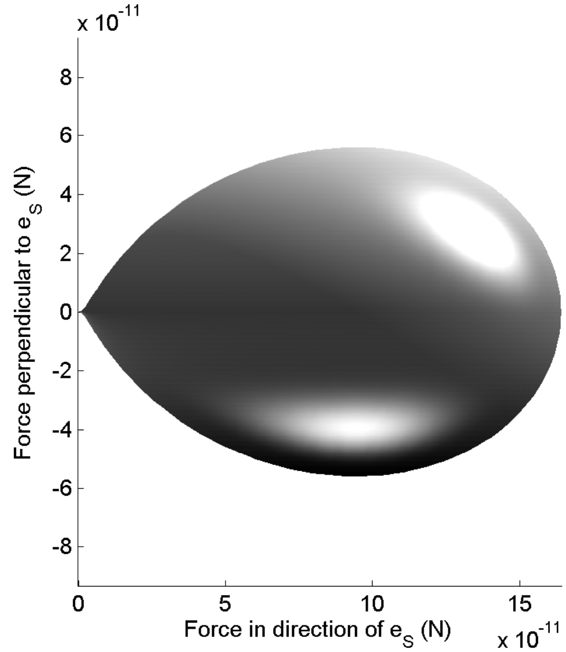

Figure 3: Surface of available force directions from changing the surface normal, with $\eta_{sr} = .8$, $\eta_{ab} = .2$, and A, P normalized to 1. The maximum force occurs along $\hat{e}_S$ when the cone angle α is zero.

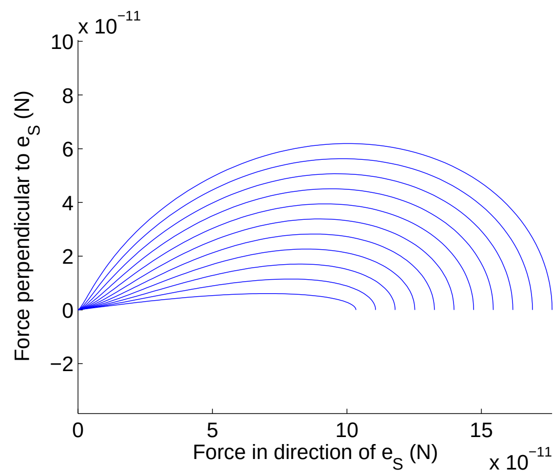

Figure 4: Direction of force available in the $\hat{e}_S$-$\hat{z}$ plane, with $0 < \alpha < \frac{\pi}{2}$ and varying $\eta_s r$ and η_{ab} with $\eta_{dr} = .2$

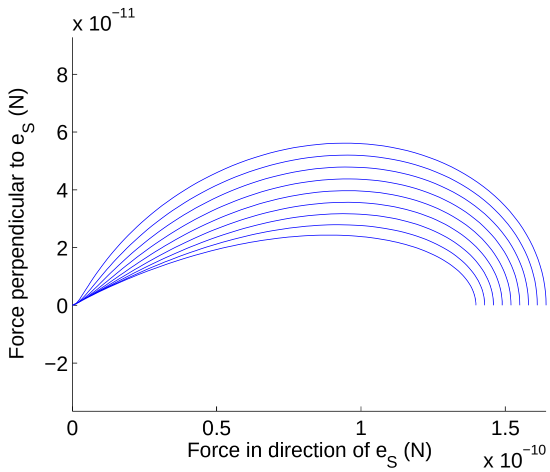

Figure 5: Direction of force available in the $\hat{e}_S$-$\hat{z}$ plane, with $0 < \alpha < \frac{\pi}{2}$ and varying η_{sr} and η_{dr} with $\eta_{ab} = .2$

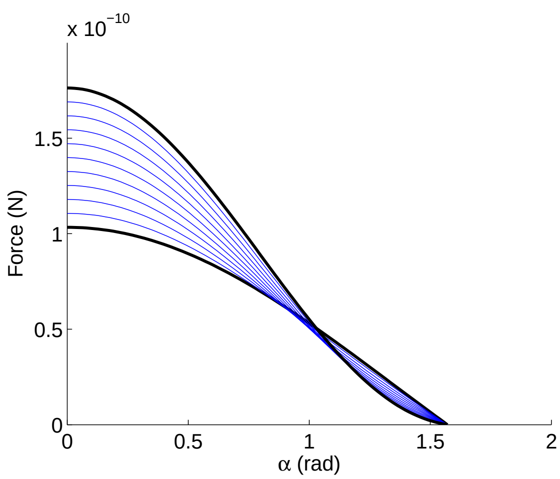

Figure 6: Variation in SRP force magnitude with cone angle α, for a range of values of $\eta_s r$ and $\eta_a b$

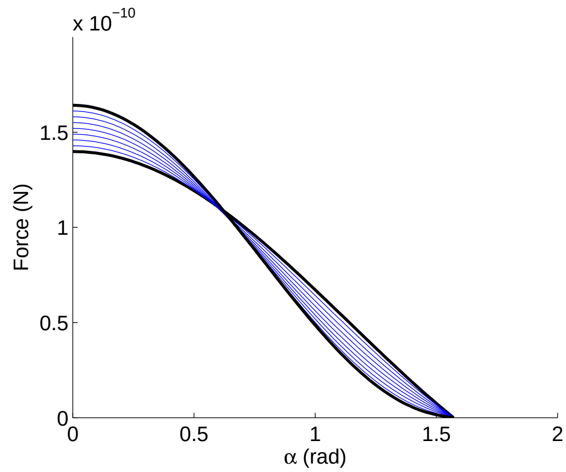

Figure 7: Variation in SRP force magnitude with cone angle α, for a range of values of $\eta_s r$ and $\eta_d r$

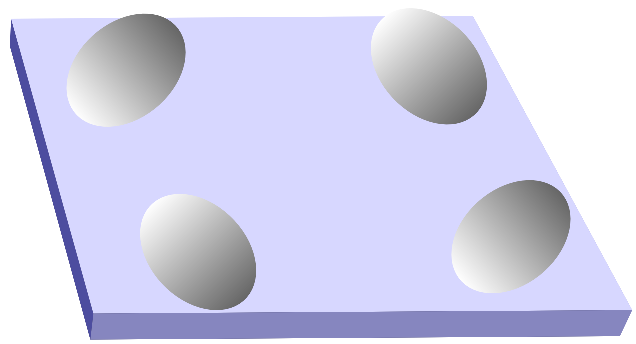

Figure 8: MEMs actuated mirror design showing a pinwheel configuration.

infeasible to design space-appropriate actuated mirrors. Figure 8 shows a concept design where mirrors could be used to spin up a centi-meter sail spacecraft. When the main face is largely sunpointing, single-axis mirrors with 15° can apply torque per mirror area of around $2 \times 10^{-8} N/m$. If the mirrors are arranged symmetrically, the net torque about the chip surface normal will be

$$\vec{\tau}_{net} = \Sigma \vec{r}_i \times \vec{F})mi \qquad (4)$$

The components of force for each mirror along the surface normal will not produce net torque, but will contribute to the total net force experience by the chip. A centimeter scale, sun-pointing spacecraft with single-axis mirrors could increase spin rate by 3 rpm in under ten hours. A MEMs actuated mirror design could avoid perpetual spin up failure with very minimal sensing of angular velocity, allowing greater flexibility and lifespan.

Electrochromic Materials

There are many types of electrochromic materials. The IKAROS spacecraft, launched by JAXA, used liquid crystal anels to switch between dominantly specular reflection and predominantly diffuse reflection for attitude control. This effect gave the spin-stabilized spacecraft the ability to reorient the spin axis by 1°.[13] This type of optical transition allows torques by shifting the center of pressure away from the center of mass, but also slightly alters the net force direction.

Many materials have been designed for switchable windows, to allow control over reflectivity vs. transmittance for passive control. For example, tungsten-oxide electrochromic windows studied in [14] are switchable between .6-.05 transmittance in the visible band, with applied voltages of 3-5 V, although switching times are on the order minutes to an hour depending on temperature and lighting conditions. Antimony-based films can switch between around .7 reflectance and zero transmittance to .1-.3 reflectance and .5 transmittance, although the performance degrades through switching cycles. [15] An electrochomic film switching between high specular reflectance and high transparency would allow the greatest change in force, but requires that the underlying material is also transparent. However, shifting the light interactions towards transmission instead of diffuse reflection or absorption prevents the controllability problem at relatively high cone angles discussed earlier. There will still be a substantial change in net relative SRP force until new material effects, such as grazing reflections, become significant.

Figure 9 shows how coarsely pixelated electrochromic panels might provide net torque along the chip diagonal. Such a design could provide torque along a number of axes in the chip plane. In addition, the net SRP force could be modulated with symmetric pixel patterns.

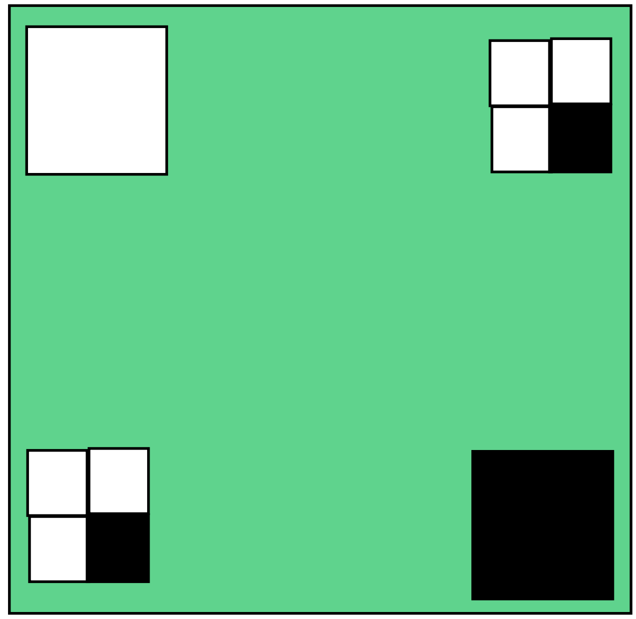

Figure 9: Chipsat with electrochromic panels at each corner.

CONCLUSION

Centimeter-scale spacecraft have exciting prospects. KickSat, a crowd-funded CubeSat project intended to showcase the current abilities of Sprite ChipSat, was launched in May 2014. [16] Developing novel thrust technologies for this spacecraft scale, such as those discussed in this paper, will greatly increase the utility and flexibility of future chip sat swarms.

Active solar sail design also allows more consideration of attitude-orbit coupling. Most solar sail orbit investigations have made strong attitude assumptions, either in absolute orientations or slow slew rates. [17] Chip scale solar sails allow much greater agility, and therefore may also allows novel low-thrust orbital maneuvering techniques.

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