Reflective Control Device Trade Study

Introduction

Solar sails are attractive for cost-effective CubeSat missions because they eliminate the need for thrusters and chemical propellants by generating thrust using solar radiation pressure. However, attitude control and steering of solar sails remains reliant on traditional methods such as reaction wheels and the ejection of propellant. The objective of a reflective control device (RCD) for solar sails is to reduce the weight and cost of the spacecraft by controlling the orientation entirely using the pressure of sunlight. The premise of a RCD is that by altering the reflectivity of small patches placed on opposing corners of the solar sail, the spacecraft can be steered by the control torque generated by the difference in force exerted on the patches. Reflective control devices for limited attitude control were successfully demonstrated by the IKAROS mission carried out by the Japan Aerospace eXploation Agency (JAXA).

The current material under consideration for the RCD is polymer dispersed liquid crystal (PDLC) film, a type of liquid crystal device that can be switched from an opaque to a transparent state with the application of an external electric field. PDLC films are composed of liquid crystal microdroplets suspended in a polymer matrix and can switch states without the need of a polarizer. The RCD device must generate a large enough torque to control the attitude of the spacecraft but also must not significantly increase the mass and the power consumption of the spacecraft. Consequently, there exists a trade-off between the area of the RCD and the thickness of the PDLC with regards to power consumption, mass, and control authority. Employing PDLC patches on a NEA Scout-like solar sail would allow for propellantless attitude control, thereby extending the science capability and dynamic performance of the spacecraft.

Background

This report investigates five different thicknesses of PDLC to assess the effect of PDLC thickness on the performance characteristics of an RCD for a solar sail similar to that planned for the NEA Scout CubeSat mission. The five test cases are shown in Table 1[1]. p_on and p_off represent the fraction of the photon momentum that the RCD transfers when the RCD device is switched on and off respectively. p_diff represents the difference in the fraction of photon momentum transfer between the on and off state of the RCD and is a measure of the effectiveness of the device. In order to quantitatively compare the test cases, a Figure of Merit was defined as the difference in fraction of photon momentum transferred divided by the product of power and area density:

$$FOM = \frac{p_{diff}}{(power * area\ density)} \tag{1}$$

	Thickness (um)	p_on	p_off	p_diff	Power (mW)	Area Density - Just PDLC(kg/m^2)	FOM
A	35	0.432	0.869	0.437	1.559	0.040	7.090
B	22	0.404	0.782	0.378	1.196	0.025	12.701
C	15	0.394	0.676	0.282	1.270	0.017	13.093
D	8	0.394	0.597	0.203	0.592	0.009	37.859
E	5	0.387	0.529	0.142	0.423	0.006	59.281

Table 1: PDLC Thickness Study Results

Although the difference in momentum transfer between the on and off state of the RCD decreased with decreasing PDLC thickness, the power usage and the area density also decreased. Combined, these effects lead to the Figure of Merit increasing as the PDLC thickness decreases, indicating that the thinner material is preferable in terms of weight and power consumption.

Results

The five PDLC thicknesses were evaluated for the required area to generate a minimum control torque at a distance of 1 Astronomical Unit (AU) from the sun. The desired torque was set at 5 μN m as that is the largest torque that NEA Scout is expected to experience during its mission. The force exerted by the RCD is given by:

$$F = p_{diff} * P * A \tag{2}$$

where F, the force, is in N, p_diff is difference in fraction of photon momentum transferred, P is the solar radiation pressure at 1 AU in N/m^2, and A is the area of the RCD (accounting only a single patch in one corner). The torque can be expressed:

$$T = F * r \tag{3}$$

where T, the torque, is in N m, and r is the moment arm of the RCD in m. The RCD is placed at the end of the boom, and hence the moment arm is:

$$r = b - \sqrt{\frac{A}{2}} \tag{4}$$

where b is the length of the boom in m which was determined from the finite element model of the sail. The required area to achieve the desired torque of 5 μN m at 1 AU from the sun is can be calculated for all of the PDLC thicknesses. Once the necessary area of the RCD had been determined, the mass and the power could be calculated from the area density and the power density values[2] with the results shown in Table 2.

Case	**Thickness (um)**	**Force (N)**	**Moment arm (m)**	**Required Area (m^2)**	**Mass (kg)**	**Power Density (W/cm^2)**	**Power (W)**
A	35	8.12E-07	6.16	0.411	0.0164	4.45E-04	1.83
B	22	8.16E-07	6.12	0.478	0.0119	3.42E-04	1.63
C	15	8.27E-07	6.04	0.649	0.0110	3.63E-04	2.36
D	8	8.42E-07	5.94	0.918	0.0083	1.69E-04	1.55
E	5	8.63E-07	5.79	1.345	0.0081	1.21E-04	1.63

Table 2: PDLC Thickness vs. Performance Metrics

As is demonstrated by the values, as the thickness of the PDLC decreases, the required area to achieve a given control torque increases. However, the area density of the PDLC also decreases with decreasing thickness with the combined effect being a lower mass at thinner PDLC films. The power requirement for the devices is nearly flat with changing thickness and does not disply a clear trend. These results are shown in Figure 1 and Figure 2.

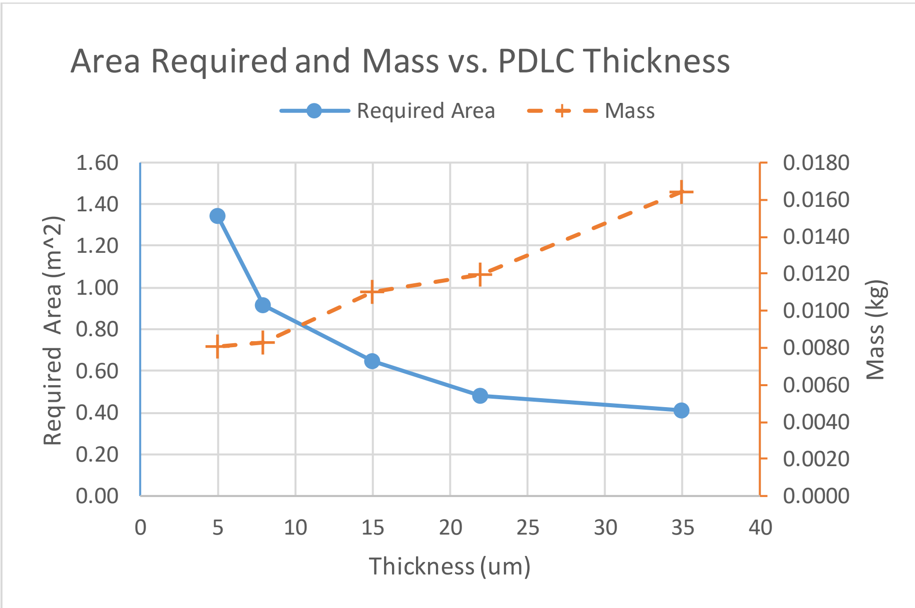

Figure 1: Area Required and Mass of RDC vs. PDLC Thickness

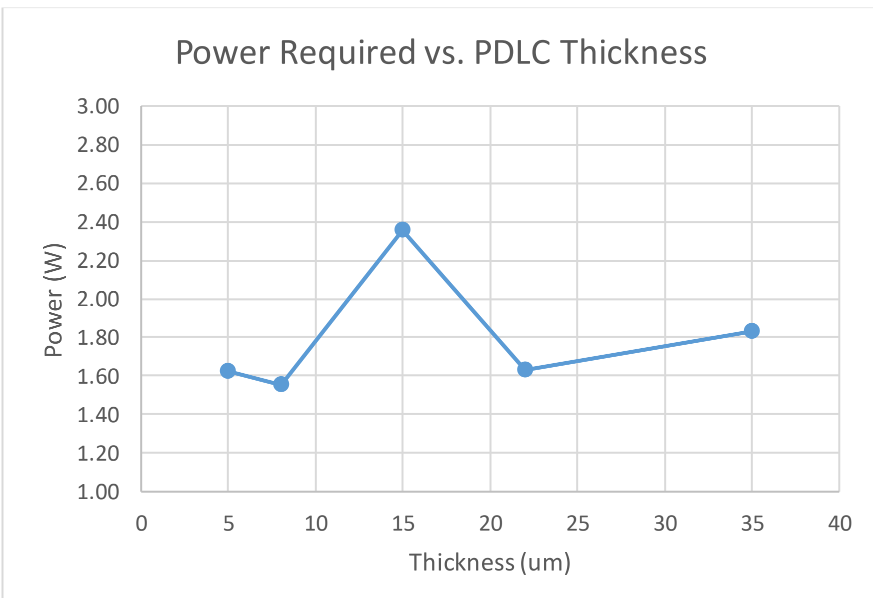

Figure 2: Power Required by RDC vs. PDLC Thickness

Analysis

The primary objective of this study was to determine the feasibility of a reflective control device for use on a NEA Scout-like solar sail mission. Based on the preliminary findings, the mass and power requirements of a RCD needed to achieve a 5 μN m control torque do not place a significant burden on the spacecraft. Using a thicker PDLC film would require less area for the RCD with only a minor increase in the mass of the device. Moreover, the power required for a thicker PDLC does not seem to increase relative to that of the thinner films. These findings would suggest that a thicker PDLC film would be preferable for use in the RCD. Follow on work to this preliminary study should consider the effects of the entire RCD system including associated wiring and housing. Further testing should also be carried out on larger segments of the PDLC film to determine if the intensive properties remain constant at larger areas. Much work remains to be done, but this brief study has determined that a RCD employing PDLC films could be a feasible attitude control system for a solar sailing CubeSat as a follow-on to the NEA Scout mission.

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[1] J. Munday, T. Lockett, M. Nehls, A. Heaton and K. Wilkie, "Propellantless Attitude Control of Solar Sail Technology Utilizing Reflective Control Devices", 2016.

[2] D. Ma, J. Murray and J. Munday, "Controllable Propulsion by Light: Steering a Solar Sail via Tunable Radiation Pressure", *Advanced Optical Materials*, 2017.