Propellant-less Atmospheric Differential Drag LEo Spacecraft (PADDLES) Mission

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ABSTRACT

Differential drag has been considered as a method of controlling small spacecraft, and presents the dual advantages of covert operation and the elimination of propellant usage, while still allowing traditional maneuvering methods. Propellant-less Atmospheric Differential Drag LEo Spacecraft (PADDLES) is anticipated to be launched in 2016 and will use differential drag to effect in-plane orbital re-phasing maneuvers. Varying the drag will be done by varying the cross wind area using a patent-pending repeatedly deployable and retractable drag sail subsystem in the anti-ram face of the satellite intended for use on CubeSats. This paper describes the hardware and software used, as well as the mission overview and projected maneuvers.

INTRODUCTION

Motivation

The PADDLES mission has a dual engineering and scientific motivation. The purpose of PADDLES is to create rendezvous maneuvers using differential drag. These rendezvous maneuvers allow spacecraft to perform maintenance, assembly, and refueling while in orbit. Because the financial and fuel costs of refueling are very high, a new source of control forces is needed. Drag forces in LEO are an alternative to thruster maneuvering, presenting the dual benefits of lack of traceability and no fuel consumption. With differential drag techniques, propellant-free control is possible, since electrical power can be used to vary the cross-wind area to vary drag. Obtaining this power through solar energy allows for indefinite operation as long as sufficient orbital altitude is maintained. As the control force involved is only present in the orbital plane, the use of differential drag is restricted to in-plane maneuvers and has no effect on cross-track motion.

PADDLES will also measure atmospheric density while in orbit. A dedicated atmospheric density sensor will be used in the front of the spacecraft, allowing it to collect measurements in real time. The ability to measure density, and therefore drag, while in orbit allows closed-loop maneuvering using the drag force as an input. Additionally, the density measurements can be used to improve existing atmospheric models by providing additional data points.

PADDLES Operational Concepts

Based on Systems Tool Kit (STK) lifetime simulations, the optimal initial altitude for PADDLES is 350-500km. This corresponds to a lifetime of 2-3 months, long enough to perform maneuvers, but not high enough that maneuvers will take weeks. The International Space Station (ISS) is anticipated to be used, as its orbit and equipment are well-suited for PADDLES, since the control algorithms work best in a near-circular orbit.

Since the cross-wind area of PADDLES is affected by its pitch and yaw rotation, PADDLES requires precise attitude control. Additionally, the ram-face density sensor and GPS antenna both require pointing accuracy of 3 degrees or better for accurate operation. The onboard star tracker has less stringent requirements, but still must be pointed into space to operate properly.

Previous Work

As mentioned previously, Pérez has performed simulations of maneuvers using differential drag[1]. His work has shown that differential drag can successfully actuate in-plane maneuvers. Some previous work has also been done using STK to simulate differential drag maneuvers[2,3,4].

Performing relative maneuvers using differential drag has also been addressed using independent controllers for secular motion and oscillation reduction[5]. Additionally, other methods of actuating the differential drag have been proposed. JC2SAT uses rotation of the satellites to vary the cross-wind area and effect relative maneuvers[6]. Finally, the issues with modeling

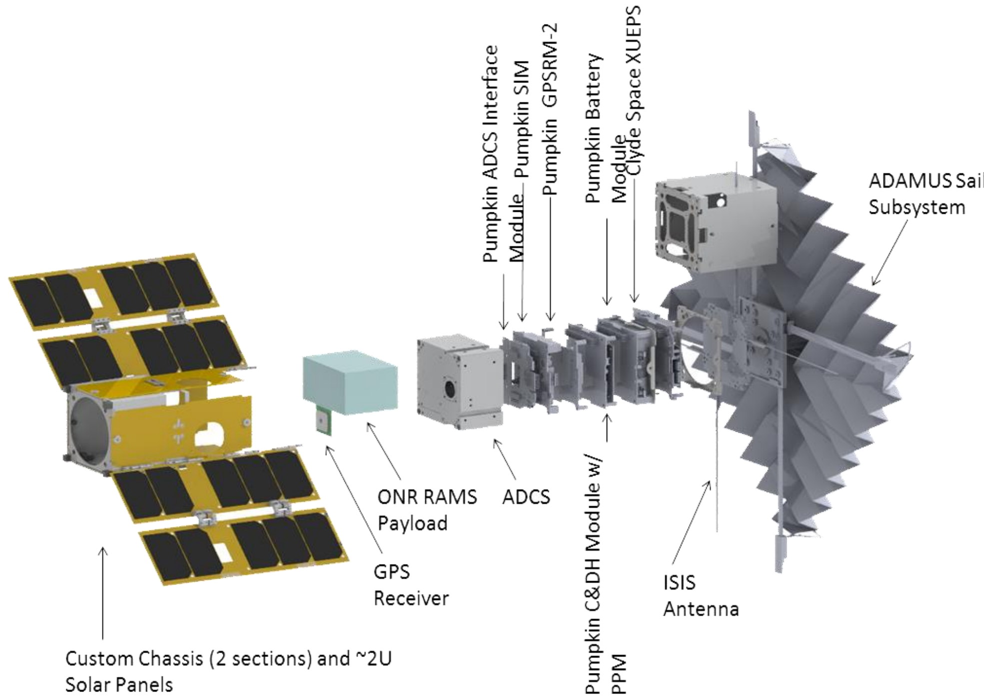

Figure 1: PADDLES Exploded View

atmospheric drag and effects each one has on the overall prediction are summarized in Vallado et al[7].

PADDLES SUCCESS LEVELS

1. **Bare Minimum Success:** S/C tumbling and RAMS working, collecting sporadic measurements and relayed to ground.
2. **Additional Success:** above PLUS neutral density measurements feed density prediction algorithm/s[4]
3. **Additional Success:** S/C is attitude stabilized but sail does not operate. RAMS collecting measurements at all times.
4. **Additional Success**: differential drag controller operates without info on density, execution of desired maneuvers without propellant[4]
5. **Additional Success**: above PLUS information fed to differential drag controller, execution of desired maneuvers without propellant[1]
6. **Additional success:** above PLUS density prediction algorithm/s and comparison between maneuvers and prediction match with certain approximation[4]
7. **Additional success:** above PLUS "sudden" density changes are detected by the sensor and by the maneuver detection algorithm, and they match within certain accuracy
8. **Additional success:** above PLUS the sensor measures additional quantities (temperature, ions densities, etc.)

PADDLES HARDWARE

The PADDLES Exploded View is shown in Figure 1. Some subsystems are still under development, and are represented by blocks with the same overall dimension.

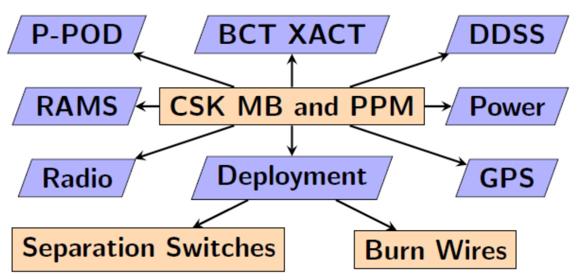

Figure 2: Hardware Organization

CubeSat Motherboard and PPM

PADDLES is controlled by the CubeSat motherboard and PPM, both provided by Pumpkin[8,9], which connect through the CubeSat bus to all the other subsystems, as shown in Figure 2. These run the Salvo Pro operating system for priority-based action and fast software development. Development was further enhanced by utilizing an electrically identical development board (also provided by Pumpkin) test environment for debugging. The motherboard leverages hardware compatibility with the PC/104 footprint and includes a

USB interface so that software can be updated after the initial hardware build.

ADCS

The BCT XACT system is used as the Attitude Determination and Control System (ADCS) for PADDLES. To provide full 3-axis control, a combination of reaction wheels and magnetorquers, which can de-saturate the wheels, are mounted along each body axis[10]. This is integrated into the CubeSat Bus using a proprietary connector provided by Pumpkin.

Drag Sail System

Sail Subsystem

Figure 3: Sail Subsystem

The sail subsystem shown in Figure 3 is used to control the cross-wind area of the spacecraft. The sail is based on an existing origami pattern but driven in reverse[11]. Figure 4 shows the folding pattern used; red and blue lines indicate opposite direction folds. Rotating the center, while constraining the corners to linear paths, allows a unique surface area to be mapped to a rotation angle of the center. The rotational limit is set by the number of folds in the sail and the maximum deployed area is linked to the size of the folds and is not linearly linked to the folded size. Over-rotation of the sail can result in failure of the sail material though tearing or failure of the sail geometry through crumpling.

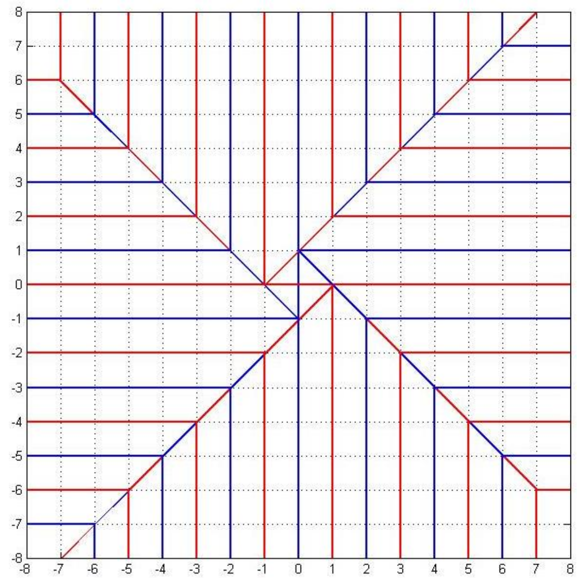

Figure 4: Drag Sail Folding Pattern

The sail is constructed in house from space-qualified Mylar[12]. A slider is attached to each corner of the sail (Figure 5), which constrains each corner to move radially along the booms. Angle changes between the corners of the sail and the boom are mitigated by using swivels on the sliders, allowing low-friction motion. These are pressed between two layers of Mylar and bonded using a UV-cure adhesive. At its center an aluminum motor attachment plate is adhered to the sail in a similar manner.

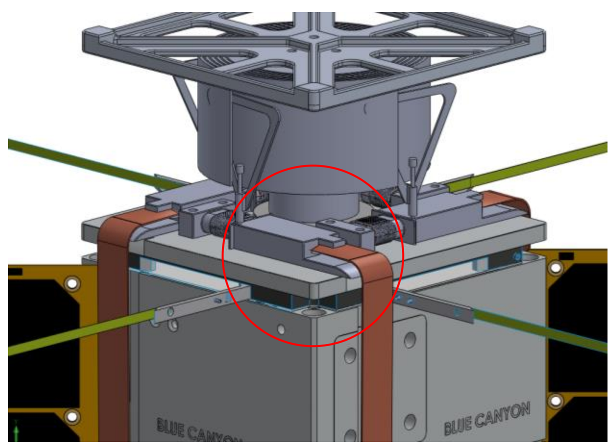

Figure 5: Boom Detail View with Slider Circled

As the sail will be opening and closing many times per maneuver[4], fatigue was thought to be an issue. Assuming a worst-case scenario of essentially continuous opening and closing (which would likely drain the battery), PADDLES would only last a few weeks because the average drag would be much larger than that in the closed configuration. Even with opening and closing the sail on the order of tens of cycles per hour, (which presents the same average drag as continuous opening and), PADDLES still does not have time to open and close more than several hundred times before de-orbiting. Excluding manufacturing defects and control errors, the sails have been shown to last for thousands of cycles without any noticeable fatigue wear, suggesting fatigue will not be an issue[13]. Sails were mounted to the rails shown in Figure 6, and cycled to determine the wear experienced. Of the six sails tested, three are still working after 2000 cycles (one reached 4000), and the other three worked properly for several hundred cycles, until a faulty command tore each one[13].

Further testing is necessary to ensure this fatigue life holds true under conditions encountered in space. The sail will be run through a similar open-close fatigue test under vacuum conditions while varying the temperature to match the anticipated in-orbit radiation–induced temperature profile.

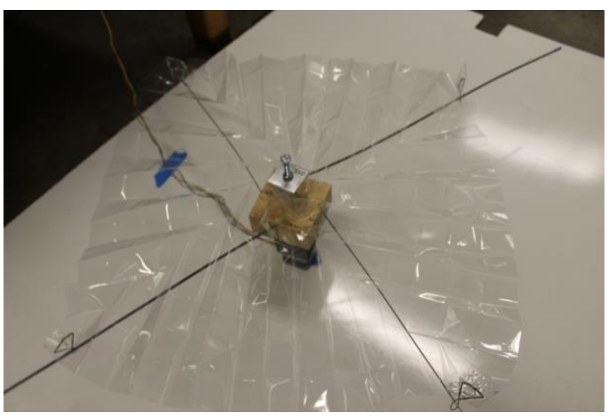

Figure 6: Fatigue Fixture Used to Test Drag Sail

Motor Subsystem

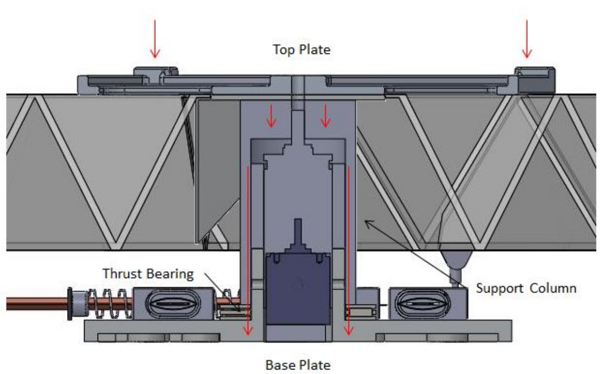

Figure 7: Motor Subsystem Load Path

During fatigue testing, the sail was mounted on a test fixture to determine the torque required to open and close it. 100 mN-m was found to be sufficient to open and close the sail in all cases. A 200 mN-m space-qualified Faulhaber 1516SR Series 12V DC brush motor fitted with a 900:1 reduction gearbox was specified to run the motor in the most electrically efficient power range and provide sufficient torque to ensure the sail would reliably open in all cases[14]. This motor was also chosen for its dimensions; the space allotted for the motor was a cylinder of 36mm diameter and 45mm length.

As seen in Figure 7, mounting space was a major concern in the motor choice. Approximating the folded sail as a cylinder, the folded height of the sail decreases exponentially with increasing folds per edge (i.e. smaller square size). However, the folded width reaches a minimum at approximately the pattern used for the sail, as the width depends on both the square size and the number of folded layers. The possible sail size and folding pattern were studied in an attempt to increase the space available; it was found that the existing pattern already matched the available motors. Eqn. 1 describes the overall size of the sail when folded.

$$d = \sqrt{2}\frac{L}{2N} + \frac{2Nt}{p_f};\ h = \frac{L}{2N} \tag{1}$$

Where d is the diameter of the cylinder, h is its height, 2N is the number of squares on the edge of the full sheet (as seen in Figure 4), L is the edge length of the sheet, and t is the thickness of the sheet. The packing factor p_f represents the ratio between the minimum theoretical packed thickness and the actual packed thickness[13]. This was experimentally determined to be approximately 0.25.

Because solar power will not always be available, the motor must work off the voltage provided by the battery and EPS board, as connecting it directly to the solar panels was not an option. This is accomplished through the use of a motor control board, which attaches to the CubeSat bus. This board allows for rotational control, and includes logic to deal with limit switches at the end of the rotational range.

Guide Rail Subsystem

As mentioned, the guide rails constrain the corners of the sails to radial motion, mapping a rotation angle of the motor to a unique cross-wind area. These booms are manufactured in-house using 304 austenitic stainless steel. The nonmagnetic properties eliminate magnetic interference with the antennae, and the large increase in yield strength with cold work allows for easy forming, while ensuring the shape does not easily change after manufacturing[15]. Using a curved cross section similar to that of a tape measure, as seen in Figure 8, the booms will tend to snap into the correct shape when released. During launch, the booms are wrapped under the solar panels, and deploy immediately after the panels. Once the booms deploy, the sail may open when given the correct control input.

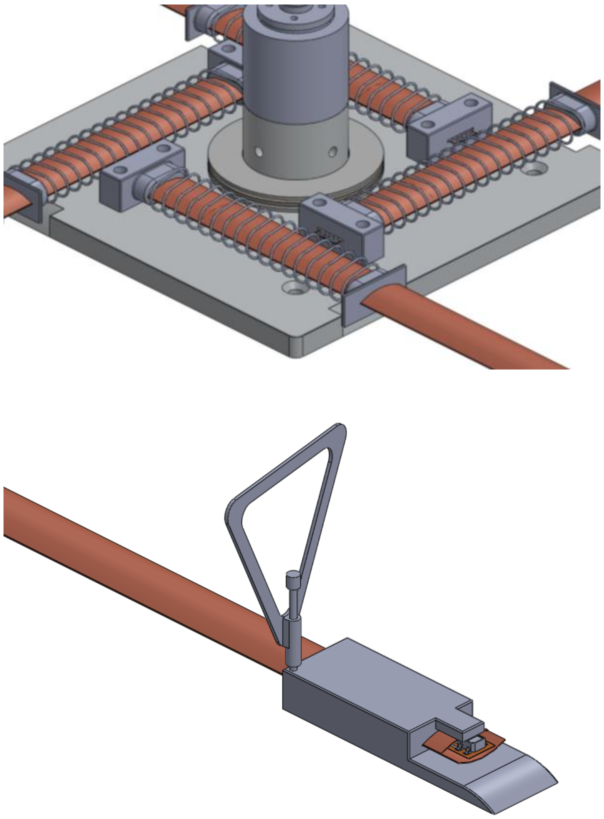

Figure 8: Guide Rail Subsystem and Slider Detail

As PADDLES is compressed while in the P-POD due to the deployment spring, the drag sail system must support the load[16]. The load path shown in Figure 7 shows the load path through the drag sail subsystem. The top plate presses directly against the P-POD door, and rotates with the motor. However, the motor is located inside a column, which passes between the top plate and the thrust bearing at the bottom, supporting the load. The effect is that the motor is only required to support rotational torque, and is not placed under an axial load.

Power System

PADDLES runs at a slight power deficit due to attitude and mounting constraints. Suntracking is used to mitigate the deficit when possible. The panels are arranged in what is denoted a Ø arrangement, as shown in Figure 9. Arranging the panels in this way provides the optimal balance between suntracking capabilities, panel size, and FOV of the BCT XACT ADCS. Originally, it was proposed to use four smaller double-sided panels in an X-configuration, but this was shown to waste much of the solar panel area. Since the sunlight can only come from one direction at a time, it is better to suntrack and orient all the solar cells in the same direction to save weight. PADDLES rotates about the ram axis to maximize sunlight. Assumptions and design parameters used to estimate the power requirements are shown in Table 1 in the Appendix. Note that the peak power requirement represents all systems running at peak, and cannot actually be reached. Further analysis is currently being performed using the solar panel analysis tool in STK.

PADDLES does not suntrack all the time, as this would usually point the star tracked in the ADCS toward the sun or the Earth, and approximately half the time (depending on launch date) there is no sun at all. A battery is used to make up the difference. It is assumed that PADDLES will never draw more than one complete orbit from the battery at peak power, since doing so would indicate a design failure. As an orbit will take approximately 90 minutes, the battery required is approximately 15 W-hr. A Pumpkin 40W-hr battery was chosen instead, as it provides a margin of safety without incurring a weight penalty.

The solar panels used are also provided by Pumpkin. The cells on the panels are arranged in series, which are then arranged in parallel, in two blocks, shown in Figure 12 in the Appendix. The ClydeSpace EPS board used is integrated into the CubeSat bus[17].

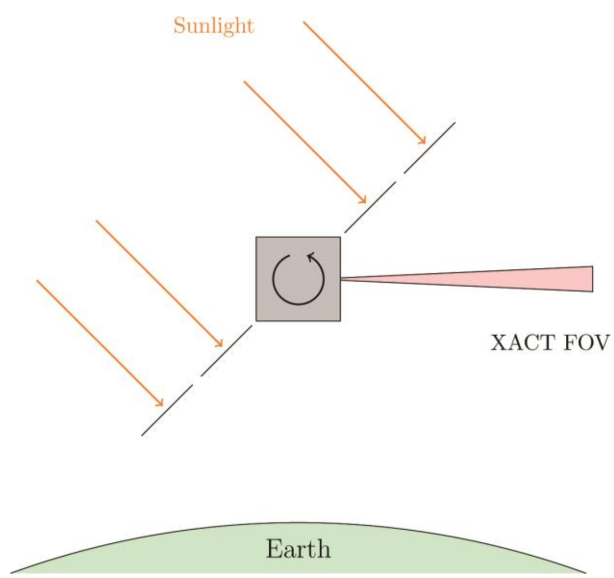

Figure 9: Ø Panel Arrangement

GPS System

The GPS used is a Pumpkin GPSRM-2, integrated into the radio board. Mounted on the ram face of PADDLES is the Taoglas AP.25E.07.0054A GPS antenna[18] which, based on STK simulations, will have access to at least 4 GPS satellites at all times. The GPS board is integrated into the CubeSat bus.

Deployment Hardware

As mentioned, the drag sail booms are wrapped underneath the solar panels during launch. These panels are held in place with a burn wire. 30 minutes after ejection from the P-POD, this burn wire actuates and releases both the panels and booms.

In order to determine when the 30 minutes has elapsed, separation switches are used on the ram face of PADDLES. These are wired in a “NAND” configuration (implemented in the software); both must be released in order to start the timer.

Radio System

As mentioned, the radio shares a board with the GPS receiver. The radio used is an AstroDev Li-1. A quad-monopole ISIS antenna[19] is used to communicate with the ground station. Licensing constraints limit PADDLES to the amateur band, but the exact frequency is yet to be determined.

The ground station network is still under development. It is expected that existing ground stations will be used; however, it is necessary to perform STK simulations to determine the location that gives optimal coverage.

RAMS Sensor

The ONR sensor will be used to measure density while in flight. This is being developed at ONR (United States Office of Naval Research). The ram face-mounted sensor will use the rate of particles absorbed per second to measure atmosphere density. This will be connected to the CubeSat bus.

P-POD Hardware

The P-POD is not formally part of PADDLES, but some CubeSat hardware is explicitly designed to be compatible. The CubeSat Motherboard contains a USB port shown in Figure 10 that can be used to transmit data and commands while PADDLES is in the P-POD. Additionally, a power plug is included to charge the battery before launch. These are located along the CubeSat bus and lined up with a cutout in the P-POD[16].

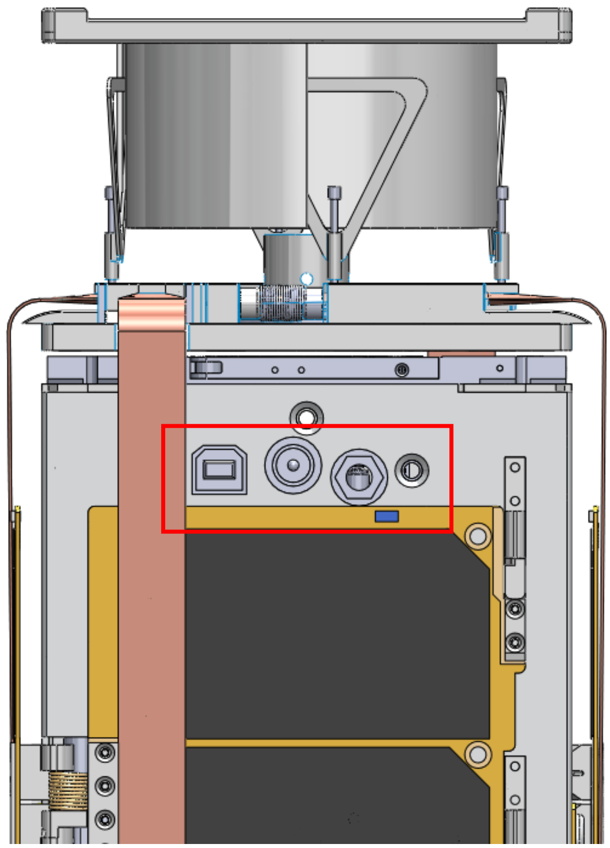

Figure 10: Location of P-POD Connectors

PADDLES HARDWARE AND SOFTWARE MISSION PROFILE

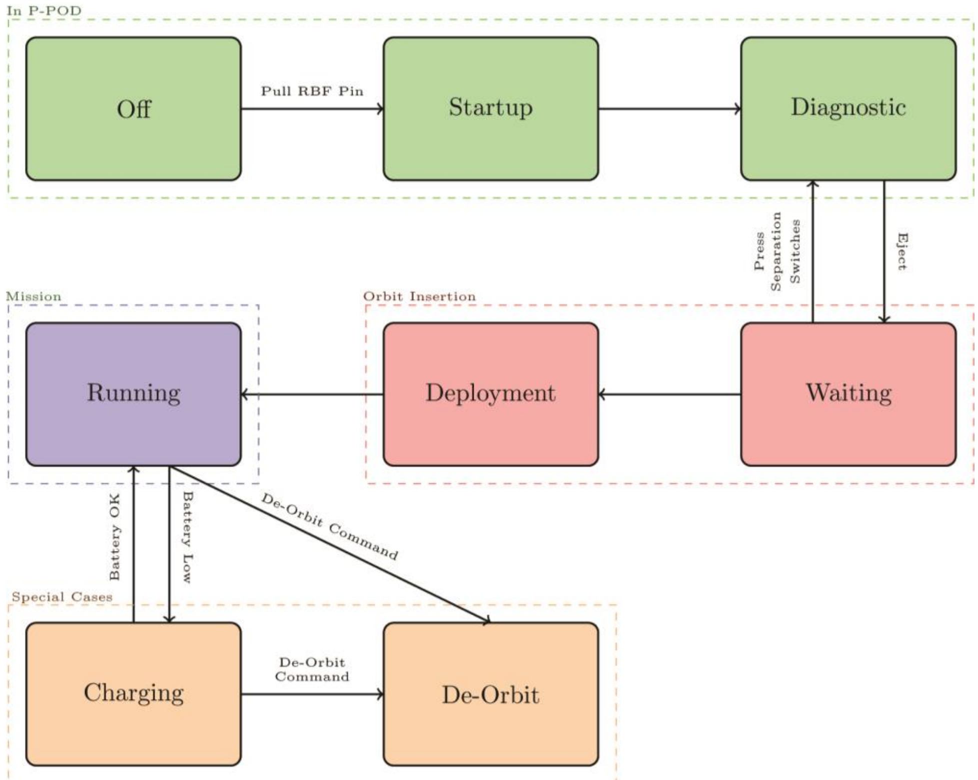

Figure 11: PADDLES Software States Throughout the Mission

The software used in PADDLES is Salvo Pro, provided by Pumpkin. Salvo is intended to run on systems with limited resources, and includes both a Real-Time Operating System (RTOS) and the commands in one executable. Salvo is based on priority levels instead of a superloop, minimizing wasted processor cycles while reducing response time.

In P-POD

PADDLES is anticipated to be launched from the ISS. The anticipated launch timeframe is late 2016. As it is designed to meet the given specifications, PADDLES will be launched using the Poly-Picosatellite Orbital Deployer (P-POD). Launching from the ISS will place PADDLES in a 51.6 degree orbit, at approximately 420 km. PADDLES has no method of enacting plane-change maneuvers, so it will remain in this inclination throughout the mission, except for the effect of perturbations.

While in the P-POD, PADDLES will initially be in the "Off" software state shown in Figure 11. In this state, the hardware is totally off. Removing the RBF pin while in the P-POD bring PADDLES to the "Startup" state. The motherboard will initialize the hardware, software interrupts and software tasks at this point. All software and hardware is ready to be addressed at this point.

The “Diagnostic” state is reached when the hardware is ready. Messages can be sent to USB port, which is still accessible at this point, as PADDLES will still be in the P-POD. Releasing the separation switches, which occurs on release and ejection from the P-POD, transitions PADDLES to the “Waiting State”.

Orbit Insertion

The “Waiting” state can lead either to the “Deployment” state or revert back to the “Diagnostic” state. As the P-POD spec[16] disallows CubeSats from deploying for 30 minutes after release from the P-POD to prevent damage, the “Waiting” state simply maintains the current hardware and software configuration for 30 minutes. This also improves safety; if PADDLES must be removed from the P-POD for any reason, the user has 30 minutes to put the RB pin in or press the separation switches.

Once PADDLES is ejected from the P-POD and the 30 minute timer has elapsed, the "Deployment" state is reached. A burn wire releases the solar panels, which allows the booms to deploy. The antennas are then free to deploy as well with an additional burn wire. At this point, the sail can open and close.

A 45-minute timer runs in parallel with the 30 minute deployment timer. Once this timer is elapsed, PADDLES will send a message signaling deployment success.

Mission

PADDLES uses atmospheric density measurements to determine when to effect a maneuver. The "Running" state is used as the normal case for most operation. All hardware is operational in this state.

PADDLES is expected to make two general maneuvers while in orbit. Since only one spacecraft is expected to launch, all maneuvering will be done with respect to a "virtual" spacecraft, represented by a time-series of points. PADDLES will be launched in the same orbit as the virtual spacecraft, but out of phase. PADDLES will then perform two drag-actuated rephrasing maneuvers; one to decrease the relative anomaly, and one to increase it. Each maneuver will decrease the altitude of each spacecraft. More re-phasing maneuvers will take place if altitude permits.

These orbital maneuvers will be detected based on the TLE (two-line element) data received from PADDLES while in flight, as measured by the GPS unit.

Special Cases

Since PADDLES runs at a slight power deficit, at times the mission must be paused to allow the battery to charge. The "Charging" state shuts off the controller, GPS, and sail motor, while still allowing communication. The EPS board monitors the charging state of the battery and returns PADDLES to the "Running" state when the battery is sufficiently charged.

Once the mission is complete, or PADDLES no longer has sufficient altitude to effect any maneuvers, the ground station will send the message to PADDLES to de-orbit. PADDLES will fully open the sail and drop altitude until it burns up in the atmosphere. PADDLES will continue sending radio signals until the necessary hardware burns up. This state can be reached from either the "Running" or "Charging" state.

CONCLUSION

This paper describes the upcoming PADDLES mission, to be launched in 2016. PADDLES uses a patent-pending repeatedly retractable drag sail to actuate in-plane relative maneuvers using differential drag. This drag sail is designed to match P-POD and CubeSat mounting standards, and has the potential to be mounted on future CubeSats. Off-The-Shelf (OTS) hardware was used when possible to minimize costs and development time.

An onboard atmospheric density sensor is mounted on the ram face, capable of taking in-orbit measurements that can then be used to calculate the control input for relative maneuvers. In conjunction with the drag sail, PADDLES can actuate closed-loop maneuvers.

ACKNOWLEDGEMENTS

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REFERENCES

1. Perez, D., & Bevilacqua, R. (2013). Differential Drag Spacecraft Rendezvous Using an Adaptive Lyapunov Control Strategy. *Acta Astronautica, 83*, 196-207.

2. Perez, D., & Bevilacqua, R. (2013). Spacecraft Maneuvering Via Atmospheric Drag Using an Adaptive Lyapunov Controller. *23rd AAS/AIAA Spaceflight Mechanics Meeting.* Kaui, HI: AIAA.

3. Perez, D., & Bevilacqua, R. (2012). Differential Drag Spacecraft Rendezvous Using an Adaptive Lyapunov Control Strategy. *First IAA Conference on Dynamics and Control of Space Systems.* Porto, Portugal: IAA.

4. Perez, D., Wohlberg, B., Lovell, T. A., Shoemaker, M., & Bevilacqua, R. (2014, May-June). Orbit-Centered Atmospheric Density Prediction Using Artificial Neural Networks. *Acta Astronautica, 98*, 9-23.

5. Leonard, C., Hollister, W., & Bergmann, E. (1989). Orbital Formationkeeping with Differential Drag. *Journal of Guidance, Control, and Dynamics*, 108-113.

6. Lambert, C., Ng, A., Nakamura, Y., & Horiguchi, H. (2011). Intersatellite Separation Mechanism for the JC2Sat Formation-Flying Missions. *Journal of Spacecraft and Rockets*, 654-663.

7. Vallado, D., & Finkleman, D. (2013). A Critical Assessment of Satellite Drag and Atmospheric Density Modeling. *Acta Astronautica*, 141-165.

8. Kalman, A. (2009, July 13). *CubeSat Kit Pluggable Processor Module (PPM) D1 Hardware Revision A.* Retrieved April 18, 2014, from CubeSat Kit: http://www.cubesatkit.com/docs/datasheet/DS_CSK_PPM_D1_710-00527-A.pdf

9. Kalman, A. (2009, August 8). *CubeSat Kit Motherboard (MB).* Retrieved April 18, 2014, from CubeSat Kit: http://www.cubesatkit.com/docs/datasheet/DS_CSK_MB_710-00484-D.pdf

10. Blue Canyon Technologies. (n.d.). *BCT XACT.* Retrieved April 18, 2014, from Blue Canyon Technologies: http://bluecanyontech.com/wp-content/uploads/2012/07/BCT-XACT-datasheet-1.5.pdf

11. Shafer, J., & Palmer, C. (n.d.). *Iso-Area Flasher*. Retrieved from Bay Area Rapid Folders: http://www.barf.cc/FlasherIsosimp.pdf

12. duPont de Nemours, E. I. (n.d.). *Melinex 454.* Retrieved September 18, 2013, from DuPont Teijin Films: http://www.dupontteijinfilms.com/FilmEnterprise/Datasheet.asp?Result=Print&ID=689&Version=US

13. Mason, C., Tilton, G., Vazirani, N., Spinazola, J., Guglielmo, D., Robinson, S., et al. (2013). Origami-based Drag Sail for CubeSat Propellant-free Maneuvering. *The 5th Nanosatellite Symposium.* Tokyo, Japan: The 5th Nanosatellite Symposium.

14. Faulhaber Group. (n.d.). 1516-012SR + 15/8-900:1.

15. ASM Aerospace Specification Metals, Inc. (n.d.). *AISI Type 304 Stainless Steel.* Retrieved April 18, 2014, from ASM Aerospace Specification Metals, Inc.: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQ304A

16. Cal Poly SLO. (2014, February 2). *http://www.cubesat.org/index.php/documents/images/developers/cds_rev13_final.pdf.* Retrieved April 18, 2014, from CubeSat: http://www.cubesat.org/index.php/documents/images/developers/cds_rev13_final.pdf

17. ClydeSpace. (2012, June 8). *CubeSat EPS Overview.* Retrieved April 18, 2014, from ClydeSpace: http://www.clyde-space.com/cubesat_shop/eps/365_flexible-eps-6-x-12w-bcr

18. Taoglas Ltd. (2012). *Taoglas AP.25E.07.0054A.* Retrieved April 18, 2014, from Taoglas Antenna Solutions: http://www.taoglas.com/images/product_images/original_images/AP.25E.07.0054A.pdf

19. ISIS-Innovative Solutions in Space. (n.d.). *Deployable UHF and VHF Antennas.* Retrieved April 18, 2014, from ISIS-Innovative Solutions in Space: http://www.isispace.nl/brochures/ISIS_AntS_Brochure_v.7.11.pdf

APPENDIX

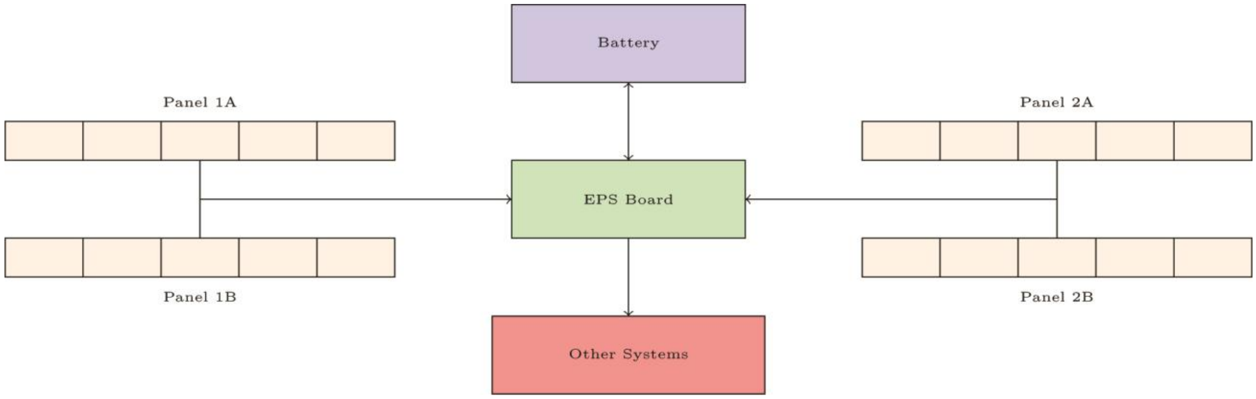

Figure 12: Electrical System Arrangement

Table 1: Power System Data and Design Criteria

System	Peak Power	Average Power	Steady-State Power	Assumptions	Data Source
Drag Sail	0.27W	0.013W	0W	On for 5% of orbit, 5 changes per hour[4]	Faulhaber data[14]
Radio	5W	0.0092W	0W	Based on one ground station	AstroDev data
Motherboard & PPM	0.25W	0.25W	0.05W	Always on	Pumpkin[8,9]
GPS	1.03W	0.535W	0.04W	50% duty cycle	Pumpkin
EPS	0.1W	0.1W	0.1W	Always on	ClydeSpace[17]
ADCS	2W	2W	0.5W	Always on	BCT data[10]
RAMS	1.5W	1.5W	1.5W	Always on	NRL
Total	**10.15W**	**4.408W**	**2.19W**		