CubeSat based Rendezvous, Proximity Operations, and Docking in the CPOD Mission

John Bowen, Marco Villa, Austin Williams
Tyvak Nano-Satellite Systems Inc.
15265 Alton Parkway, Suite 200, Irvine, CA 92618; (949) 753-1020
john.bowen@tyvak.com

ABSTRACT

The CubeSat Proximity Operations Demonstration (CPOD) mission led by Tyvak Nano-Satellite Systems leverages several formation flying techniques to enable rendezvous, proximity operations, and docking with two identical 3U CubeSats. Tyvak developed a unique relative navigation payload that includes delta GPS, inter-satellite link with radio ranging, two infrared imagers, and two visible imagers. A cold gas propulsion system is integrated into the vehicle for translational maneuvers. A high performance attitude determination and control system was developed to enable maneuvering and relative pointing. While cost was kept low with the use of commercial off the shelf components and selective redundancy, the integration of new rendezvous and docking components necessitated a significant investment in testing and integrated system performance verification. Approach trajectories remain passively safe through the use of "walking safety ellipses" that include radial and cross track orbital offsets. This paper presents the challenges of rendezvous, proximity operation, and docking for CubeSat vehicles, lessons learned from the CPOD mission, and an update on CPOD mission status.

INTRODUCTION

Tyvak Nano-Satellite Systems Inc. (Tyvak) has completed the development of the CubeSat Proximity Operations (CPOD) vehicles, qualification of the Engineering Unit, and is well underway with acceptance testing the flight units. The CPOD mission utilizes a pair of identical 3U CubeSats for maturing rendezvous & proximity operations, docking (RPOD) techniques and associated propulsion technologies for nano-satellites. The mission will validate and characterize a suite of sensors for RPOD including visible imagers, infrared imagers, sub-meter GPS solutions, and radio ranging. The mission also utilizes enabling techniques including onboard image processing (bearing, range, and pose), magnetic docking, cold gas propulsion, and autonomous maneuver planning.

The CPOD mission leverages prior work performed by Applied Defense Systems (ADS), one of its partners, that enables advanced RPO and docking capability to be hosted on a CubeSat platform. [1, 2]

SYSTEM DESCRIPTION

The CPOD Mission uses two identical 3U CubeSats to demonstrate rendezvous, proximity operations, and docking. Each CubeSat is comprised of three primary internal modules that include the bus, propulsion system, and RPOD module (Figure 1).

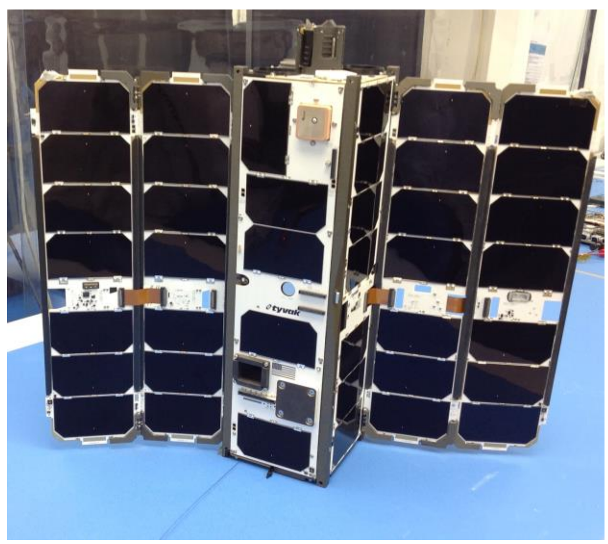


Figure 1 - CPOD Vehicle Configuration

The Bus contains the communication systems (UHF uplink/downlink, S-band downlink, inter-satellite link), battery module, and inertial reference module (IRM). The highly integrated IRM includes both attitude determination & control system (ADCS) and command and data handling (C&DH) functionality. It houses three reaction wheels, two star cameras, MEMS IMU (3-axis gyroscope and 3-axis accelerometer), three torque coils, and both the ADCS and C&DH processors. The propulsion system includes a liquid fuel tank, gas plenum, control/management circuitry, and 8 nozzles to support full 3-axis translational control. The RPOD module includes two visible and two infrared cameras, the inter-satellite link (ISL) patch antenna, docking electro-magnet, fiducial LEDs, docking mechanism, and the guidance, navigation and control (GNC) and image processing (IP) processors. Two deployable solar arrays generate the power to support all mission phases.

The CPOD on-orbit demonstration (Figure 2) will incrementally validate the key technologies, algorithms, and operations by gradually increasing operational complexity and utilizing on-board autonomy to identify and respond to key abort situations. The two 3U vehicles are designed to launch as a secondary payload in a 6U deployer. In launch configuration, the CubeSats are attached together via standoffs, separation springs, and a tie down mechanism to form a single 6U vehicle. After ejection from the deployer, the vehicles undergo an initial checkout in the attached 6U configuration to verify proper communications, power generation and storage, attitude determination and control functionality, and communications between application specific processors. One solar panel array on each vehicle will be deployed to maintain a positive energy balance during this mission phase.

Upon successful vehicle checkout, the conjoining tie down is cut and the vehicles drift apart from the force of the separation springs. The first complete propulsive maneuver is performed soon after separation to minimize distance between vehicles. From this initial configuration the rendezvous, proximity operations, and docking phases are carried out starting with passively safe maneuvers and transitioning to a non-passively safe final approach. An example of this incremental approach is the use of simple high intensity LEDs to provide target aids during initial operations and to validate sensor operations under on-orbit lighting conditions. These LEDS will be disabled in later scenarios to fully evaluate sensor capabilities for relative navigation.

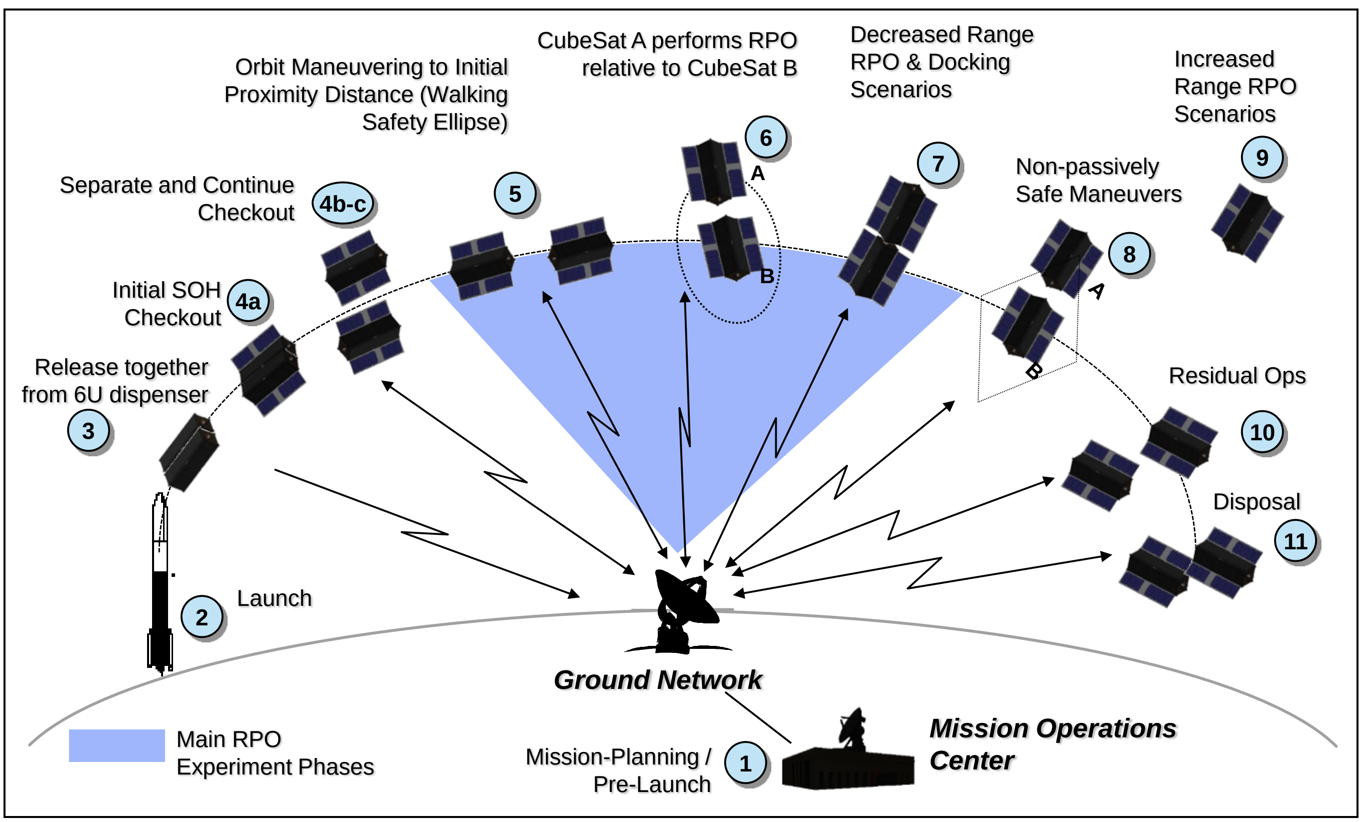


Figure 2 - CPOD Concept of Operations

During the final approach maneuver, the docking unit will use electro-magnetic forces to attract the two vehicles together and close the final 0.5 meter separation. Once in contact, the docking mechanism firmly attaches the two vehicles with mechanical fingers. Similarly, the vehicles can undock and separate by using a combination of magnetic and propulsive systems.

KEY MISSION ENABLERS

Several key technologies and techniques enable the CPOD mission, including miniaturized advanced avionics, miniature relative navigation sensors, and a multi-thruster cold gas propulsion system. Key techniques include the use of passively safe rendezvous orbits, mission assurance testing, and integrated closed-loop testing approaches.

Miniature Avionics

The Tyvak Endeavour avionics line has been developed in parallel with the CPOD mission to meet the CPOD mission requirements and general requirements for high performance CubeSats. Low size, weight, and power is a key enabler to performing the CPOD mission in a 3U CubeSat form factor.

Command and Data Handling—The Command and Data Handling (C&DH) module is a CubeSat-compatible processing board designed to support a wide range of computational requirements while maintaining low power consumption. The C&DH module permits dynamic power management to optimize overall energy consumption, enabling low-power idle modes down to 20mW and high-performance modes within 200mW.

Attitude Determination and Control System—With one dedicated control processor, two star trackers, IMU, three reaction wheels, GPS receiver, Sun sensors, magnetometers, and three torque coils, the ADCS subsystem provides attitude knowledge of better than 0.15 degrees three sigma, and attitude control (knowledge and control error) of better than 0.18 degrees (3-σ). The ADCS and C&DH combine to form the IRM (shown in Figure 3).

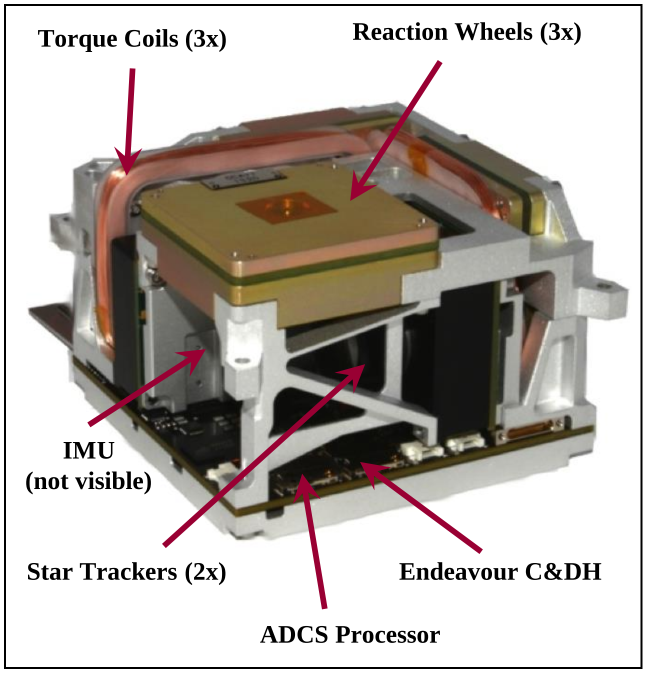


Figure 3 - Inertial Reference Module (IRM)

The star sensor processor is capable of producing a valid quaternion from a single camera at up to 6Hz. The star sensor software has two operating modes: Lost in Space (LIS), and Recursive. The LIS mode can determine vehicle attitude with no attitude knowledge (full catalog search), while the recursive method utilizes previous attitude information to reduce match time and increase confidence. The performance of the star tracker has been validated using Earth's rotation as reference and shown to provide 10 arc-second knowledge (1-σ in pitch/yaw). Two star trackers are included in the design for robustness from mechanical and electrical failures and to improve star-field availability. Additionally, fusing data from two orthogonal star trackers removes the less precise reading of roll about a star sensor axis. Star sensor and IMU data are processed in an extended Kalman filter at 10Hz.

A triad of orthogonal reaction wheels enable precision slewing and pointing control. Tyvak developed the reaction wheels specifically to support the needs of agile CubeSats while being scalable for varying vehicle inertias and agility requirements. Each wheel provides velocity control—allowing for graceful resets—while the ADCS processor commands target velocity. Torque coils are used for wheel desaturation in addition to vehicle detumbling.

Communications—The vehicle utilizes several systems to support telecommand, mission data downlink, and the inter-satellite link (ISL). The main vehicle communications system leverages a UHF radio daughterboard similar to the design used with Tyvak's Intrepid system board, which has successfully flown on several missions including the Cal Poly IPEX mission [4]. The miniature unit requires only 130mW in receive mode, and can support up 1.5W RF output. The UHF radio is completely compatible with Tyvak's mission operations center. The UHF radio is paired with an omnidirectional L-dipole antenna. A separate S-band downlink that is compatible with several existing ground networks is utilized for high-speed downlink of data-intensive telemetry and mission data. Two switched patch antennas support the S-Band downlink. The ISL utilizes a 2.4Ghz ISM transceiver which provides both data transfer and radio ranging. The ISL has an operational range of multiple kilometers, enabling far field operations (before optical data products are available). Figure 4 shows the primary RF module which houses the UHF transceiver, UHF antenna, and S-band transmitter.

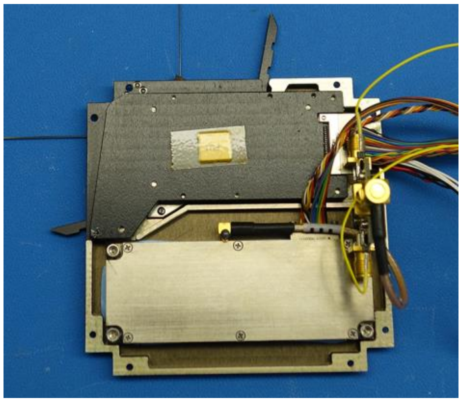


Figure 4 - UHF Transceiver with Deployable Antenna and S-Band Transmitter

Electrical Power Subsystem—The Electrical Power System (EPS) follows a distributed architecture composed of Point-Of-Source (POS) solar array Peak Power Tracking (PPT) and Point-Of-Load (POL) power regulation. Nominally 11.1V unregulated battery power is routed throughout the spacecraft bus, which minimizes line loss and wire harnessing overhead. The battery module includes protection circuitry and heaters (Figure 5). This approach facilitates system flexibility where additional loads and sources can be added to the spacecraft with minimal impact to the core design.

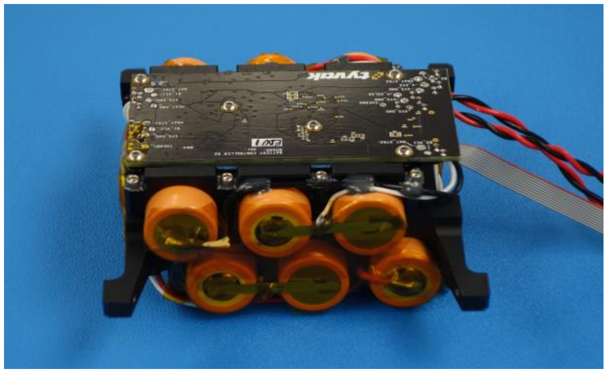


Figure 5 - 60Whr Battery Pack in a 3S2P Configuration with Battery Heaters

Additionally, POL regulation provides opportunity to fine-tune regulation to specific load profiles of a given subsystem. Regulator efficiency may be optimized for a nominal current draw to minimize conversion losses. This topology inherently supports fine-grained power control allowing subsystems to be powered down when unneeded to reduce power consumption and vulnerability to single-event latch-ups.

A common PPT regulator design has been developed to serve both large deployable and small fixed UTJ cell arrays. Independent solar arrays are geometrically arranged to minimize shading and thermal gradients to maximize power output (Figure 6).

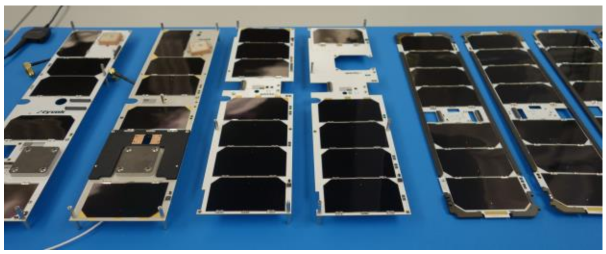


Figure 6 - Fixed and Deployable Solar Panels with PPTs, Antennas, and Umbilical Interfaces

Relative Navigation Sensors

The RPOD payload utilizes several different sensors to support the range of operating distances. The narrow field of view visible imager detector is common with the Tyvak star tracker but utilizes optics with a longer focal length. The RPO image processing and control software is common to both visible and IR cameras with only minor changes needed. The RPOD module houses the four imagers (narrow field of view visible, wide field of view docking visible, wide field of view IR, and narrow field of view IR), fiducial LEDS, as well as the docking mechanism, and electronics for image processing. The RPOD module is shown in Figure 7.

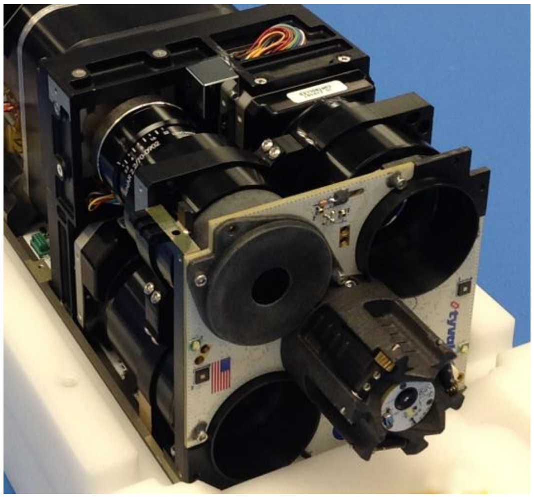


Figure 7 - RPOD Module

The image processing software solution performs relative target range, bearing and attitude based on input from the onboard sensors and an onboard model of the target. The system is able to read and process the images from multiple imaging sensors and execute the algorithms in real-time. The processed bearing, range, and relative attitude data products are output to the RPO computer for relative navigation and trajectory planning.

The onboard model is a rendered catalog of the target vehicle that includes information regarding surface visible and thermal reflectivity. Edge detection and feature comparison algorithms performed on the camera outputs are then matched to the catalog to provide position and attitude information. This onboard database approach provides the added benefit that target vehicles or objects can be easily added, removed, or changed in order to accommodate mission flexibility. Dead pixel maps and new calibration parameters can be uploaded from the ground as needed in order to compensate for sensor degradation or shift in alignment during launch.

At longer ranges, where the target may comprise of only a few pixels, the software system behaves as a point source tracker, providing bearing information as the target moves over a series of frames. As the target gets closer and occupies more of the frame, a stadiometric ranging solution is provided.

Finally, at shorter ranges, when the target occupies a large number of pixels, a relative attitude solution will become available. Silhouette images are created and compared to the on board catalog in order to determine a precise relative attitude solution for the target vehicle. We build upon advances in robotic computer vision algorithms such as the OpenCV computer vision library that is successfully applied in many terrestrial robotics applications. This provides a benefit to the program as it allows rapid development with a well-supported set of tools and libraries. Many OpenCV algorithms have been adopted and optimized specifically for use on low power processors in order to maximize their execution times for our application.

The image processing team has performed a series of lab and high-altitude balloon tests for calibration of cameras and software algorithms. Our test program addresses known sources of error including Sun glint, Earth albedo effects, and other sources of background noise and clutter that are challenging to accurately simulate. A series of imager and software tests have been performed in a well-controlled lighting environment. In addition, a high altitude balloon flight was performed, and the operational experience informed further algorithm improvements.

Cold Gas Propulsion System

The multi-thruster propulsion system () utilizes a mature design that was developed by VACCO Industries and tested extensively (70,000+ firings) in a vacuum by the US Air Force Research Lab. Additionally, the cold gas system traces heritage to DARPA and Aerospace Corp programs. [2] The highly integrated unit utilizes self-pressurizing R134a refrigerant as propellant. R134 is stored as a liquid and provides high volumetric efficiency.

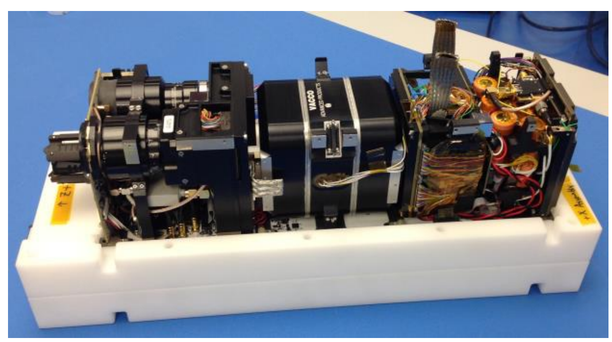


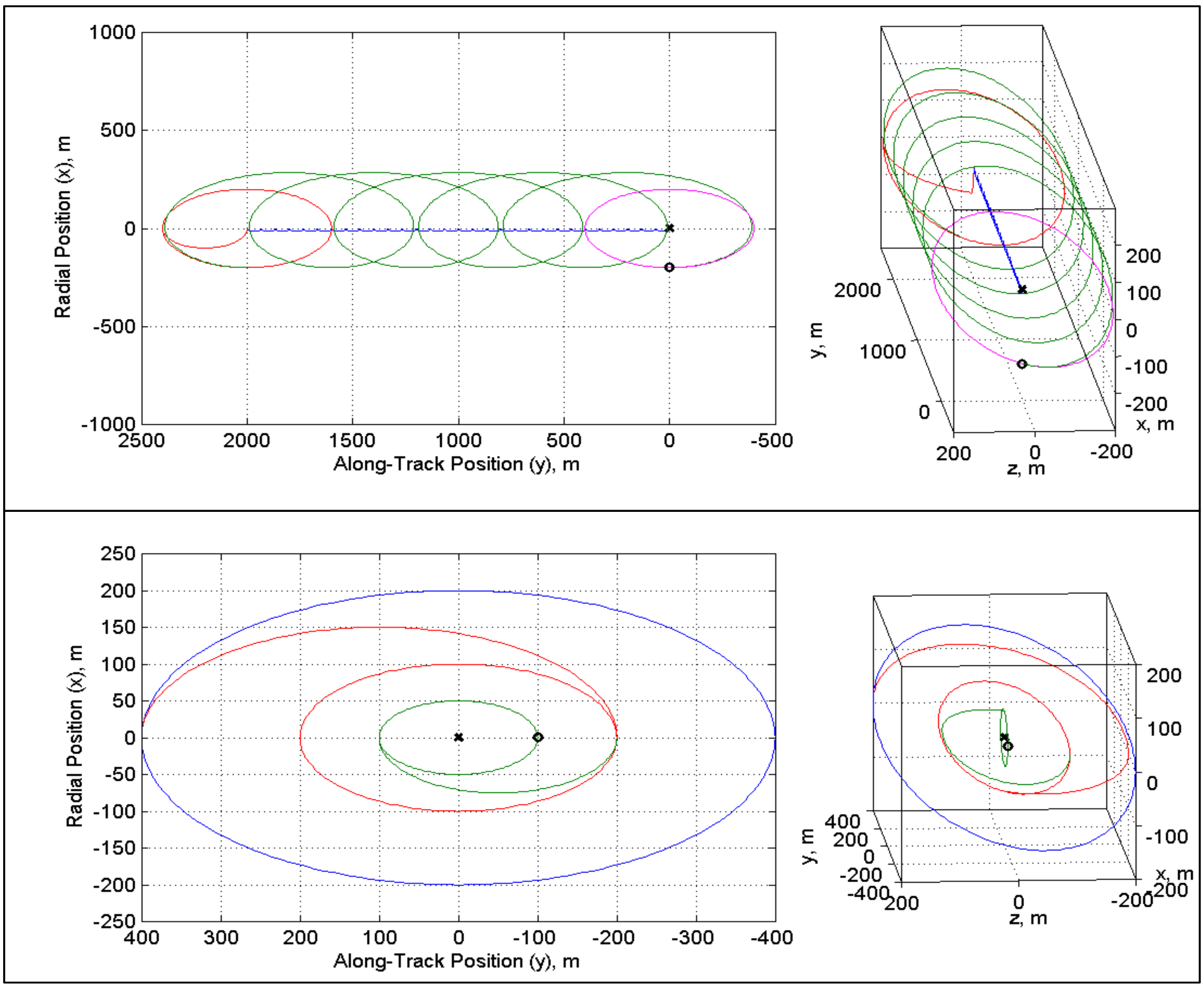
Figure 8 - Internals of CPOD showing 1U of RPOD Payload (Left), 1U of Propulsion (Middle), and 1U of Avionics (Right)

All sensor and control electronics are contained inside the unit and only require external power and data connections. Extensive materials compatibility testing and analyses have demonstrated that the electronics are compatible to being immersed in propellant without issue. The unit was designed specifically to support CubeSat proximity operation missions utilizing 8 thrusters located at the corners of the unit. However, the thrusters are modular units which can be replaced to change orientation; flexibility in nozzle cant angle allowed plume impingement analysis to happen in parallel with propulsion system development. The CPOD configuration provides translational control authority in all three axes while maintaining efficiency for large maneuvers with a primary thruster pair. The baseline design can support a total impulse of approximately 30 m/s for the roughly 5.5kg vehicle.

Passively Safe Rendezvous Orbits

The CPOD mission rendezvous involves a series of passively safe maneuvers to reduce risk of collision during rendezvous and proximity operations. The passively safe nature of the orbits is a product of slight differences between the chaser and target orbits. The selected orbital parameters of the chaser vehicle introduce a natural motion that forms a "safety ellipse" that allows the vehicles to drift past each other without risk of collision (Figure 9).

The safety ellipse is used in a stationary form when the two vehicles are holding a standoff distance (no relative velocity vector direction drift). The safety ellipse is also used when the chasing vehicle is approaching and



departing, which is known as a "walking safety ellipse." shows both the walking safety ellipse (top) and progressively smaller safety ellipses (bottom). Both the stationary and walking safety ellipses add fault tolerance. For example, if two vehicles are approaching in a walking safety ellipse and the maneuver to stop the approach fails to occur, the approaching vehicle will drift past the target without ever crossing the target's orbit. Similarly, if the chaser is in a stationary safety ellipse about the target and loses control, the vehicles would not cross orbits, even if the lack of station keeping introduced a relative drift.

Ground Based Maneuver Verification

The concept of operation utilizes a sequence of semi-autonomous steps allowing ground operators to verify proper computation of maneuver algorithms prior to actual maneuver execution. The ground approves proposed maneuvers by examining downloaded vehicle state and planned burn sequences, but the actual maneuvers are calculated in near real time autonomously based on current state information. These maneuvers consist of multiple delta-v events, which are carried out autonomously.

Mission Assurance Testing Approach

The CPOD mission requires a balance of thorough testing to reduce risk while keeping costs low and schedule short. The complexity of rendezvous, proximity operations, and docking necessitates testing beyond what CubeSat programs typically undergo; however, the CubeSat form factor and design ease the burden of transportation, testing facilities and support equipment in comparison to traditional spacecraft.

Environmental Testing—The CPOD program utilizes a tailored version of a traditional space vehicle environmental testing flow. The test program includes thermal, thermal-vacuum, and vibration testing at the component, subsystem, and system levels.

High-risk components undergo unit level environmental testing at Tyvak or supplier facilities. The use of COTS components decreases cost and increases performance in comparison to space rated products, but can introduce risk. To mitigate the risk presented by the space environment, some key components (e.g., IMU, reaction wheels, processor system-on-module, and SD memory cards) were put through a survival thermal vacuum and vibration test early in the development cycle to ensure flight worthiness. These tests were performed before the Preliminary Design Review.

Subsystem level qualification testing is performed on key Tyvak built subassemblies that includes the IRM and RPOD modules because of their high level of integration and complexity. The IRM has completed qualification vibration testing, thermal chamber testing, and thermal vacuum testing. Thermal vacuum testing is inherently complex and expensive; therefore, Tyvak performs thermal chamber testing (at ambient pressure) to retire thermal-related risks before thermal vacuum testing. Throughout the development of the CPOD vehicle, the team discovered multiple temperature related issues that were affecting COTS components; the majority of the thermal issues found were repeatable without vacuum, and a thermal chamber was beneficial to resolving them. These tests were performed before the Critical Design Review.

The CubeSat specification [3] requires acceptance level vibration testing of the final vehicle to launch specific levels. This vehicle level vibration testing is typically conducted in a Test Pod that simulates the P-POD; however, the CPOD mission is deployed from the Tyvak 6U deployer. The unique nature of the CPOD configuration—a 6U configuration for launch and a 3U configuration for operations—necessitates testing in a 6U configuration. A single vibration test will qualify both the deployer, and the CPOD vehicle. The CPOD mission includes a single qualification vehicle, so it is paired with a mass model for qualification testing. Flight vehicles will be acceptance tested together. Utilizing the flight like 6U deployer minimizes custom mechanical ground support equipment.

At the integrated vehicle level, only a bake out is typically required for CubeSat missions, but a complete, multi-cycle thermal vacuum test is performed on the qualification vehicle (while powered) to reduce the risk of thermal issues.

The qualification vehicle has completed thermal chamber, thermal vacuum, and vibration testing. shows the EDU unit during integration with the 6U deployer in preparation for vibration testing.

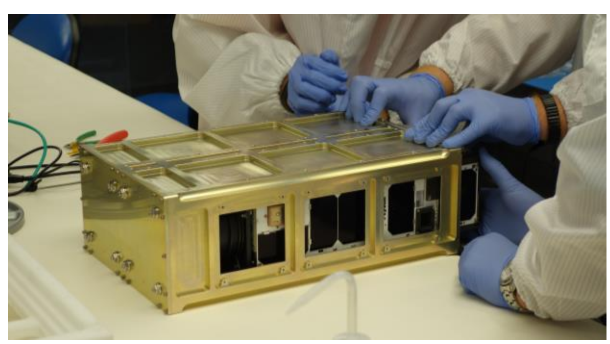


Figure 10 - CPOD Engineering Unit Integrated in Tyvak 6U Deployer for Qualification Testing

Flatsat Testing—The CPOD development includes the build of a complete flatsat. The flatsat has been progressively built throughout the hardware and software development cycles, and it has now been operational for more than one year. Some CubeSat programs perform development on the flight vehicles to reduce hardware costs, but because of the complexity of the CPOD mission and the need to maintain a rigorous software testing approach aimed to retire interface risks as early as possible, a flatsat platform was deemed necessary from the beginning. Many hardware and software issues identified through long duration testing have been resolved on the flatsat, and it has prevented stress on the flight vehicles.

*Hardware in the Loop Testing—*The CPOD mission includes an agile control system, a guidance and maneuver planning capability, and real time image processing. A hardware in the loop (HITL) test platform was developed to facilitate real time testing of these coupled systems. The HITL centers around a computer that runs a real time operating system and hosts dedicated interface cards. For the CPOD mission the emulated interfaces include SPI, I2C, RS485, and analog I/O. The dynamics modeling is based on the real time actuation over the flight like interfaces. This allows for the simulated dynamics to include reaction wheel, torque coil, and propulsion system interface overhead. Simulating the dynamics in real time allows for the sensors (i.e., star cameras, IMU, sun sensors, GPS, and magnetometers) to be simulated in real time and fed to flight like processors over the flight interfaces. Additionally, the maneuver planning and image processing can be brought into the loop. HITL testing has been invaluable to exercising the systems in a flight like way and presents another example of how the CPOD mission spans a gap between traditional and CubeSat missions. However, the HITL platform development was accelerated with the use of modern tools including model based design, autocoding, and FPGA driven interfaces.

*Air Table Testing—*The dynamics of docking two spacecraft presents unique challenges, some of which are better explored with real world tests rather than simulation. To verify the CPOD mission docking mechanism design and operation, an air table system was developed. A docking mechanism attached to an air bearing with several degrees of freedom allowed characterization of acceptable docking orientations. Multiple iterations of the docking mechanism design were quickly tested on the air table, allowing for quick development without difficult analytical modeling of contact dynamics. Once the qualification vehicle was complete the air table testing was repeated to verify the docking mechanism worked appropriately with flight like inertias. An image of two systems docking and latching is shown in Figure 11.

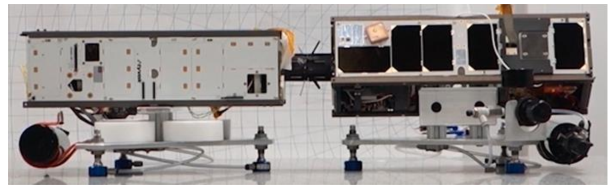


Figure 11 - Air Table Testing

FUTURE APPLICATIONS

The techniques and technologies utilized to perform RPO and docking with CubeSats in the CPOD mission open many possibilities for CubeSats. The cooperative aspects of the CPOD mission lend themselves to satellite self-inspection and servicing. For example, the international space station (ISS) currently lacks the ability to thoroughly assess damage from micrometeorites, orbital debris, and environmental degradation; an RPO capable CubeSat could be deployed from the ISS to perform periodic inspections or in the event of an incident. The non-cooperative aspects of the CPOD mission lend themselves to rendezvous and inspection of unknown targets, for example, asteroids. The formation flying techniques lend themselves to artificial aperture techniques, reconfigurable swarms, and complex constellations.

CONCLUSION

The Tyvak approach to RPO and docking with CubeSats has been successfully proceeding to flight vehicle assembly, integration, and test for the CPOD mission. This paper provides several lessons learned from development of the CPOD vehicles as well an explanation of the key enabling techniques and technologies. The balance between traditional space vehicle development and typical CubeSat approaches, along with the combination of several specific techniques and technologies, has opened the door for a broad range of RPO and docking missions.

REFERENCES

1. Hinkly, David. "A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites." 22nd Annual USU Conference on Small Satellites, Logan Utah, August, 2008

2. Roscoe, Christopher WT, et al. "Formation Establishment and Reconfiguration Using Differential Elements in J2-Perturbed Orbits." analysis 26: 27.

3. Cubesat.org [homepage on the Internet]. CubeSat [updated 02 September 2010; cited 6 October 2010]. Available from: http://cubesat.org/images/developers/cds_rev12.pdf

4. S. Chien, J. Doubleday, D. Tran, D. Thompson, K. Wagstaff , J. Bellardo, C. Francis, E. Baumgarten, A. Williams, E. Yee, D. Fluitt, E. Stanton, J. Puig-Suari, “Flight Validating the Proposed HypIRI Intelligent Payload Module: Results from Intelligent Payload EXperiment (IPEX) Cubesat Operations,” HyspIRI Data Products Symposium, Greenbelt, MD, June 2014.