Prox-1: Automated Proximity Operations on an ESPA Class Platform

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ABSTRACT

The Georgia Institute of Technology Prox-1 mission is an ESPA-class, student-designed, student-built satellite mission designed to demonstrate automated relative trajectory control in conjunction with a semi-cooperative target in Low-Earth Orbit. It is scheduled for launch in September of 2016 aboard the Department of Defense Space Test Program (STP-2) mission as a secondary payload. The primary mission of the spacecraft is to perform flight qualification and performance validation of experimental flight hardware; to deploy The Planetary Society's LightSail mission, an internally housed 3U cubesat; and to perform relative trajectory control with respect to that target utilizing passive thermal imaging and automated on-board guidance algorithms. Several subsystems are integrated to accomplish this mission, and a description of the subsystem components is detailed in this paper. An overview of the concept operations is also presented here. For the automated proximity operations phase of the mission, Prox-1 will demonstrate an advanced Guidance, Navigation, & Control subsystem. This subsystem will combine GN&C algorithms and filters developed in-house and based on reference literature. This paper will provide an overview of the Prox-1 mission and the advancements it brings to the small satellite community.

INTRODUCTION

The Georgia Institute of Technology Prox-1 mission is a student-designed, student-built mission designed to demonstrate automated relative trajectory control in conjunction with a semi-cooperative target in Low-Earth Orbit. The Prox-1 mission is currently scheduled for launch in September of 2016 aboard the Space Test Program (STP-2) mission as a secondary payload. The spacecraft is an ESPA-class satellite tasked with the deployment of an internally housed 3U cubesat and relative trajectory control with respect to that target utilizing passive thermal imaging and automated on-board guidance algorithms. The 3U satellite deployed from Prox-1 will be The Planetary Society's LightSail spacecraft, a solar sail demonstration mission. The Prox-1 mission will launch on board a SpaceX Falcon Heavy through the United States Department of Defense Space Test Program. Once Prox-1 separates from its launch vehicle, it will begin a startup phase, powering vital subsystems and proceeding to de-tumble. After angular rates are nulled and batteries fully charged, the spacecraft will establish a communication link with the ground station and relay vital information. A checkout phase will verify the health status and validate the performance of the system. This includes the flight qualification and characterization of several new technologies, including Honeybee Robotics' Tiny Operational Responsive Control moment gyroscope (TORC), the Jet Propulsion Laboratory's Advanced Micro Sun Sensor, a thermal imager custom-built by Arizona State University's Mars Space Flight Facility, and a cold gas thruster developed at the University of Texas at Austin. The mission will begin its next phase by ejecting the LightSail spacecraft. Prox-1 will rendezvous with LightSail, targeting a range of 100 m in a trailing orbit. Autonomous proximity operations will begin with automated rest-to-rest maneuvers, and continue with natural motion circumnavigation maneuvers with respect to LightSail. Prox-1 will also conduct on-orbit inspection of LightSail's solar sail upon deployment. For the automated proximity operations mission, Prox-1 will demonstrate an advanced Guidance, Navigation, & Control subsystem. This subsystem will combine GN&C algorithms developed in-house and based on reference literature. The algorithms are integrated in a Six Degree-of-Freedom simulation environment in MATLAB/Simulink for development and testing before being autocoded into C/C++. The C code is then integrated with custom-built flight software based on NASA's Core Flight Software System. For navigation, Prox-1 will make use of custom-built image processing algorithms and Extended Kalman Filters (EKFs) for relative orbit determination with respect to the target satellite and another EKF for inertial attitude determination. Prox-1's guidance algorithms will combine relative orbital elements with artificial potential functions for maneuver planning and collision avoidance.

Prox-1 is the winner of the 7th edition of the United States Air Force Research Laboratory's University Nanosatellite Program flight competition for the microsatellite category. Besides its goal of demonstrating innovative technologies, Prox-1 is also the first spacecraft mission holistically developed at the Georgia Institute of Technology. While this fact gives rise to some challenges, it also allows for the furthering of the education of several hundred undergraduates involved in the project at one point or another. This paper will provide an overview of the Prox-1 mission and the advancements it brings to the small satellite community.

SYSTEM AND SUBSYSTEM DESCRIPTION

System Description

Prox-1 is an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter-class (ESPA) satellite. In its launch configuration, Prox-1 has a wet mass of 66.5 kg, which includes 2.2 kg of propellant and a 4.5 kg contribution from LightSail. The outer envelope of the spacecraft is 24 by 28 by 12 inches. Most of the spacecraft's mechanical structure is made out of 6061-T6 aluminum alloy and machined using both manual and computerized numerical control lathes and mills. The spacecraft will be placed in a circular orbit of 720 km of altitude with an inclination of 24 degrees in the maiden flight of the SpaceX Falcon Heavy rocket. Although maneuvers during the proximity operations phase of the mission will introduce small perturbations to the orbit, it will not reenter the atmosphere during the duration of the mission.

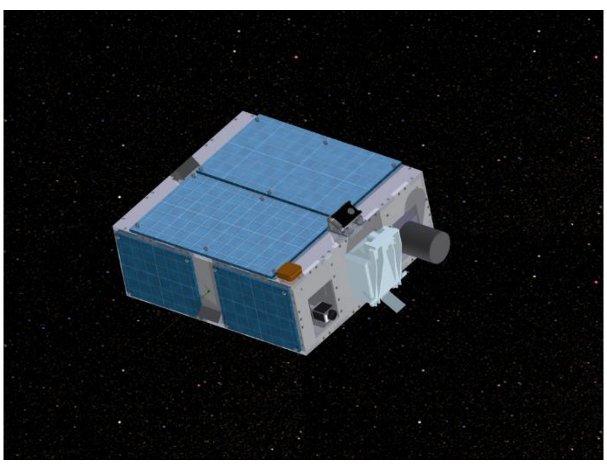

Figure 1: Model of Prox-1 Spacecraft

Attitude Determination and Control Subsystem

Attitude determination in Prox-1 is accomplished with four types of sensors. One is the 3-axis-accelerometer and 3-axis-gyroscope integrated into the Analog Devices ADIS16365 Inertial Measurement Unit (IMU). The second sensor is the SpaceQuest MAG-3 magnetometer, which provides a source to measure the spacecraft's orientation with respect to Earth's magnetic field. To determine the attitude of Prox-1 with respect to the sun, two different types of sun sensors are utilized. Coarse determination is achieved with three units of the ELMOS 986.10 sun sensor. The Advanced Micro Sun Sensor, provided as a flight test unit by the Jet Propulsion Laboratory, accomplishes fine sun vector determination. The state vector necessary for precise orbit determination is given by a SpaceQuest GPS-12 receiver processing unit and antenna suite.

Attitude control is achieved by a set of torque rods and control moment gyroscopes. The three torque rods were designed and manufactured by students at Georgia Tech, are mounted orthogonally to each other, and their design specification of producing a dipole moment of 10 A-m^2 has been verified experimentally. These torque rods will be used for coarse attitude control while de-tumbling and for stabilization during the control moment gyroscope's desaturation. The Honeybee Robotics' Tiny Operational Responsive Control moment gyroscope (TORC) unit will provide the fine attitude control necessary to accomplish precise pointing and agile maneuvering during proximity operations.

The subsystem interfaces with the flight computer via two microcontrollers with an ATmega2560 processor, four custom hardware circuit boards, and a specialized set of harnessing. Software libraries for most of these components were developed in-house.

Electrical Power Subsystem

Power is generated aboard Prox-1 by seven body mounted dual junction solar panels spread across four faces of the spacecraft for a total power generation during nominal operations of over 50 Watts. These solar panels were designed and fabricated by student personnel.

Power generation and storage is regulated by a ClydeSpace Ltd. 3U Flex EPS and Power Distribution Module. These units have been modified to accommodate a total of 18 battery charge regulators (BCRs) for Prox-1's large power generation needs. The EPS system also provides the spacecraft with 5V, 7V, 12V and 28V power rails. Energy is stored via the use of three 30 W-Hr ClydeSpace Lithium Polymer battery packs.

Thermal Control Subsystem

Multi-layer insulation sheets are installed in faces of the spacecraft's exterior not covered by solar panels for passive thermal control. Active thermal control is achieved by 4 Omega Engineering's polymide film flexible insulated heaters. Thermal modeling for nominal mission scenarios was done in conjunction with Air Force Research Laboratory personnel, and placement sites for the 4 heaters selected. The spacecraft is equipped with 24 thermistors to provide temperature sensing in critical areas or in the vicinity of critical components. An Arduino Mega2560 with a custom hardware interface shield are used to communicate between the subsystem's hardware components and the main flight computer.

Telecommunications Subsystem

The spacecraft utilizes two different bands of the electromagnetic spectrum to communicate with the ground station. Uplink (telecommanding) is carried in the ultra-high frequency (UHF) band, receiving with a SpaceQuest RX-445 UHF receiver through two monopole antennae. To downlink health telemetry and imagery, the spacecraft takes advantage of the higher data rates enabled by S-band. A SpaceQuest TX-2400 S-band transmitter is utilized to radiate via a monopole antenna. A Kantronics KPC-9612 terminal node controller is used to modulate and demodulate the signal, and manage the output to and input from the flight computer.

Payload and Science Instruments

For all intents and purposes, the LightSail spacecraft shall be considered as the payload in the Prox-1 mission. In its stowed configuration, LightSail is a 3U cubesat with a mass of approximately 4.5 kg. A standard Poly Picosat Orbital Deployed (P-POD) developed by the California State Polytechnic University will be used to eject LightSail from Prox-1. LightSail will remain electrically inhibited while inside Prox-1.

The science instrument suite is composed by an infrared imager, a visible light imager, a processing board, and an interface board. Michael Veto, a PhD candidate at the Arizona State University's Mars Space Flight Facility, is the lead designer and integrator of this subsystem. The infrared camera is called THESIS (THErmal-camera System for Imaging Spacecraft) and it has heritage from the THEMIS imager utilized in Odyssey. The visible camera is a Point Grey Chameleon. A MinnowBoard with an Intel Atom dual-core microprocessor will be used to run the Image Processing Algorithms, while a Camera Link frame grabber will interface directly with the memory in the flight computer. The thermal images obtained by THESIS will be used for relative navigation purposes. A representative image capture is shown in Figure 1.

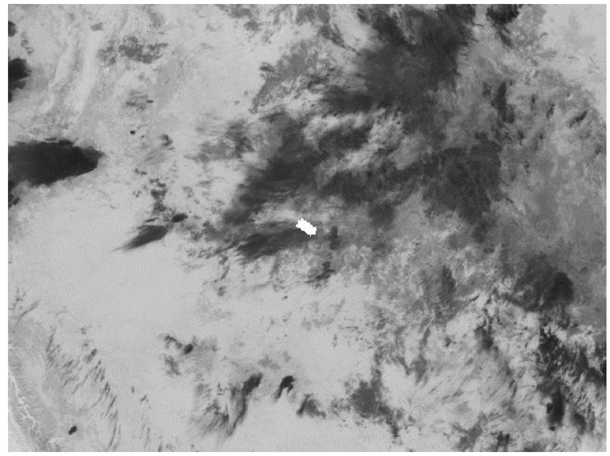

Figure 2: Representative 3U Thermal Image

Command and Data Handling Subsystem

Prox-1 features a principal flight computing element, along with several subsystem microcontrollers. While increasing the need for a well-defined software interface among all components of the system, this modularity allows for rapid development on multiple platforms. The subsystem microcontrollers perform the low-level hardware electrical interface with the components and package the data into a coherent frame for the flight computer to receive. The main flight computer is housed in a Texas Instruments BeagleBoard. Its main functions are to queue information from the sensors, feed and receive data from the advanced guidance and control algorithms, command actuators, monitor subsystem processes and spacecraft health, manage the storage and transmission of telemetry, and process ground commands. Serial communication software libraries and command dictionaries were developed at Georgia Tech and are specific to this system. At a more abstract level, interaction with subsystems and critical watchdog timers are integrated using the NASA Core Flight Executive software. A more thorough overview of the Guidance, Navigation, and Control subsystem will be given in a subsequent section in this paper.

Propulsion Subsystem

The propulsion subsystem for the Prox-1 satellite is a Cold Gas Propulsion Unit, designed and manufactured by the University of Texas at Austin. This thruster uses a non-toxic R-236FA refrigerant as its propellant. The maximum pressure of the engine is 100psi at 56°C and 15psi at 0°C. It delivers a 50mN thrust with 1 second fire- 1 second recharge cycle. The unit has a minimum impulse bit of 0.125 mNs and a firing frequency of up to 50 Hz. The tank, piping, and nozzle are stereolithographically fabricated using Accura Bluestone as a material[1]. Valves are made of steel. Compression fitted O-Rings serve as an interface for pressure and temperature sensors and filling mechanisms. The propellant is stored in a main tank as a saturated liquid, heated into a gaseous state in an expansion plenum when the inner valve opens, and expelled when the outer valve opens. The unit will be flown in other cubesat missions prior to the Prox-1 launch date. The construction materials have been approved by a NASA safety review board. The unit has been successfully tested for bursting, leaking, long-term compatibility, and its low-duration-pulse thrust verified by ballistic pendulum tests in vacuum conditions.

Ground Systems

The Georgia Tech Ground Station is located in the Montgomery Knight building in Atlanta, GA. On the roof of said building, the station has a 10 ft. diameter parabolic mesh for S-band downlink that contains 2 low noise amplifiers and a septum feed. A Yagi antenna is used for UHF uplink. These units are remotely controlled via a Raspberry Pi computer by an Array Solutions' OR-2800 controller and AZ-1000/EL-1000 rotators. A Kantronics-9612+ serves as the terminal node controller on the ground side. For radio equipment, the station uses a Kenwood TS-2000X transceiver and an Icom IC-R9500 receiver. SatNet software is utilized for rotator control, Doppler tuning, and data forwarding to local servers for data processing at the Georgia Tech Mission Operations Center.

Verifying the functionality of the ground systems has been accomplished by receiving telemetry from other university satellites currently in orbit. Moreover, the mission operations team and the ground station team have gained a significant amount of experience when supporting operations of The Planetary Society's LightSail-A test mission. Launched in May 20, 2015 as an experimental precursor to the LightSail-B mission that will ride to orbit inside Prox-1, LightSail-A demonstrated successful telecommunication, solar panel deployment, and solar sail deployment in low earth orbit before reentering the Earth's atmosphere in June 14, 2015. Students at Georgia Tech contributed by planning the mission, decoding and analyzing telemetry, and operating the Georgia Tech Ground Station for telemetry reception.

CONCEPT OF OPERATIONS

The Prox-1 mission is divided into seven distinct phases of operation; system checkout, advanced hardware demonstration, rendezvous, Prox-Ops Phase I, Prox-Ops Phase II, LightSail Solar Sail Deployment and Inspection, and finally End-Of-Life Operations.

System Checkout

Upon separation from the launch vehicle, Prox-1 will automatically initiate a startup sequence designed to fully power on the spacecraft, inspect basic spacecraft health, and null spacecraft angular rates in preparation for ground communications. After start-up Prox-1 will monitor its battery levels and will begin transmitting a predefined beacon once they are considered stable. Once initial contact occurs, mission controllers will determine Prox-1's current health status and conduct a series of in-depth tests of the spacecraft's primary systems with the exception of those systems undergoing flight qualification.

Advanced Hardware Demonstration

There are four major components undergoing flight qualification of Prox-1; the JPL Advanced Micro Sun Sensors (AMSS), the Honeybee Robotics Tiny Operationally Responsive Control Moment Gyroscopes (TORC), a thermal imager designed and built by Arizona State University's (ASU) Mars Spaceflight Facility, and a cold-gas thruster built by the University of Texas at Austin. The purpose of this checkout phase is to provide reliable data to ground operators and component manufacturers concerning the true on-orbit capabilities of these devices. Based on the results of these tests, mission controllers will have the ability to update Prox-1's advanced GN&C algorithms to account for any deviations from expected performance.

Testing of the AMSS will primarily consist of significant data collection for comparison with attitude data determined by Prox-1's other attitude sensors.

The Honeybee Robotics TORC unit has been provided by the Air Force Research Lab's (AFRL) Space Vehicle Directorate under a Small Business Innovation Research grant (SBIR). Prox-1 will conduct a series of pre-defined slew maneuvers to verify certain aspects of TORC's performance and nominal operation. This information will be used to qualify the unit for future missions.

The thermal imager developed by ASU's Mars Space Flight Facility will undergo a simple image verification test by taking several images of the Earth to be downlinked for analysis.

Lastly, the UT Austin 3D printed Cold Gas Thruster will be commanded to fire a series of short burns in order to verify its on-orbit thrust performance under orbital thermal conditions. Performance will be verified both through on-board accelerometer measurements and GPS state updates.

Rendezvous

The rendezvous phase of operations will commence with the ejection of the LightSail-B (LS-B) spacecraft from Prox-1's embedded P-POD in the cross-track ejection. The differential J2 forces that result from this event will result in a natural separation between the two spacecraft, mitigating chances of re-contact. Shortly thereafter, Prox-1 will begin a series of automated burns to slowly bring Prox-1 into the same orbital plane as LS-B. Once this occurs, further burns will be commanded to cause Prox-1 to slowly drift to within 150 meters of LS-B at which point, a maneuver sequence will be conducted to stop relative motion. Due to the fact that Prox-1 has no knowledge of LightSail's state, Prox-1 will use dead-reckoning to calculate initial burn sequences. Once mission controllers receive viable ground based estimates of LightSail and Prox-1's post deployment states, updated burn sequences will be uploaded to Prox-1 accordingly. This is the only phase of the mission where Prox-1's mission criteria allow for the use of ground based analysis for maneuver planning and execution.

After a steady relative orbit is obtained, a checkout of Prox-1's relative navigation algorithms will occur using thermal imaging and ground based measurements. It is important to note that during rendezvous Prox-1 does not regain physical contact with LightSail. Rather rendezvous is defined as obtaining a stable relative trailing orbit within 150 meters of LS-B.

Proximity Operations: Phase I

Phase I of Prox-Ops will demonstrate both the station-keeping abilities of Prox-1 as well as the ability to transfer between stable trailing orbits. When this phase begins, mission controllers will command Prox-1 to transfer to a stable trailing orbit 50 meters away from LightSail. This is the only information controllers will pass on to Prox-1. The current relative state of LightSail and all burn maneuvers will be autonomously calculated on board and initiated by the flight computer. Once Prox-1 reaches its target destination, it will begin station keeping operations. Pre-defined parameters will determine how much Prox-1 allows perturbations (atmospheric drag, solar radiation pressure, etc.) to alter its relative orbit before the GN&C system re-initiates a burn sequence to return the spacecraft to its nominal position.

Upon satisfactory completion of the rest-to-rest transfer and station keeping operations, Prox-1 will be given a second command to initiate a rest-to-rest maneuver sequence to return to a 150 meter stable trailing orbit.

Proximity Operations: Phase II

Phase II of Prox-Ops will consist of a natural motion circumnavigation (NMC) of the LightSail-B spacecraft. On command, Prox-1 will perform a single burn to place itself into a passively safe orbit around LS-B and begin 360º imaging of the target. The spacecraft will monitor its relative orbit and automatically perform clean-up maneuvers as necessary. Prox-1 will maintain the NMC orbit until ground control determines successful completion of this phase of the mission, at which time, Prox-1 will return itself to a stable trailing orbit.

Prox-1 has extensive fuel margins for all phases of the mission and as such has the capability to repeat both Prox-Ops Phase I and Phase II numerous times. Pending healthy performance of both Prox-1 and LightSail-B, Phase I and Phase II will be repeated as determined by mission control until fuel reserves are depleted.

LightSail-B Solar Sail Deployment and Inspection

By serving as a ride along payload for the Prox-1 mission, LightSail-B has provided a unique opportunity for both missions; the autonomous inspection of a resident space object (RSO) during active operations. Throughout all prior stages of the Prox-1 mission, LSB will be in its stowed 3U configuration. Upon successful completion of Prox-Ops Phase II, mission controllers will command Prox-1 to take up a stable trailing orbit behind LS-B. At this point, LightSail mission control will command the deployment of LS-B's 32 m^2 solar sails. Prox-1 will use both its thermal and visible cameras to capture images of the deployment process and the final sail configuration.

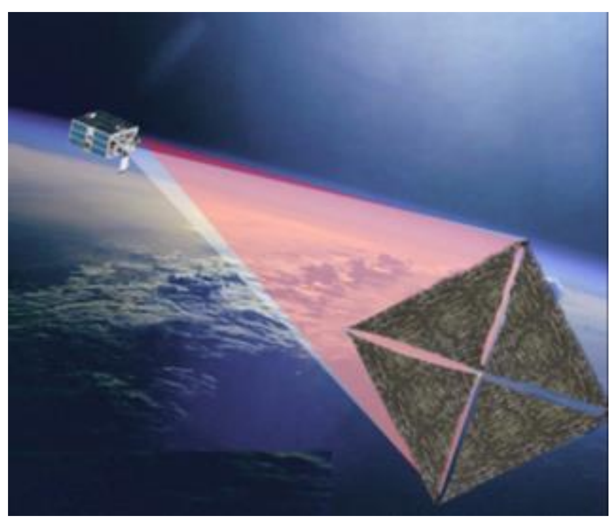

Figure 3: On-Orbit Inspection of LightSail-B

To mitigate any chances of contact with the now deployed LightSail spacecraft, Prox-1 will only maintain visual contact with the target via attitude control and will not perform any further maneuvers. After sail deployment, LightSail will gradually accelerate away from Prox-1. For the next 24-48 hours, LS-B will come into range of Prox-1's cameras approximately once an orbit. During these passes, Prox-1 will continue to capture images of LightSail. After this time, differential drag will have caused significant separation between the two spacecraft preventing further image capture.

End-of-Life Operations

Following the loss of visual contact with LightSail-B, Prox-1's primary mission will be complete. At this point mission management and our mission partners will analyze performance data of all experimental hardware and determine if any further tests should be conducted for research purposes. Post-mission, Prox-1 will primarily serve as an educational platform in conjunction with Georgia Tech's space systems and mission operations classes to give students hands on experience with on-orbit operations. 18 months after launch, the timer on the Tether's Unlimited Tether Tape will expire causing the deployment of its electrodynamic tether. Prior to this event, Prox-1 will undergo end-of-life procedures.

MISSION SUCCESS CRITERIA

The Prox-1 mission has four primary mission objectives with two entailing mission success and two more required for full mission success.

Minimum Mission Success

After initial acquisition and system checkout, the first mission objective will be addressed; the in-depth testing of the TORC unit, JPL AMSS sun sensors, ASU Thermal Imager, and UT Austin 3D Cold Gas Propulsion Unit. The results of these test sequences is vital to our numerous mission partners as well as to the success of the overall mission. Mission controller will take special care to ensure full completion of all test procedures. This constitutes the completion of Prox-1's first mission objective.

The second portion of minimum mission success will entail the deployment of LightSail. When LS-B is deployed, both Prox-1's thermal imager and visible camera will be active. The automated image processing and relative navigation algorithms onboard the spacecraft will capture LightSail as it drifts away from Prox-1. Minimum mission success and the completion of the mission's second objective will be achieved when Prox-1 autonomously recognizes LS-B and obtains an initial relative orbit estimate.

Full Mission Success

The first full mission success criteria and third mission objective will require the rendezvous of Prox-1 with the LightSail spacecraft. Once Prox-1 has arrived in a stable trailing orbit, the imagers will be switched on and tasked with locating LS-B. After LS-B has been located, it must be autonomously tracked for at least one orbit and a relative state estimate generated. GPS measurements from Prox-1 and ground based laser ranging measurements of LightSail-B will be used to validate the spacecraft's estimation performance.

The mission will complete all success criteria and its final objective with the completion of both Phase I and Phase II of Prox-Ops. This entails a single rest-to-rest maneuver sequence during Phase I as well as a single natural motion circumnavigation of LightSail in Phase II. Subsequent iterations of Prox-Ops a Phase I and Phase II as well as the imaging of LS-B's solar sail deployment are not required for full mission success.

ADVANCED GUIDANCE, NAVIGATION, & CONTROL (GN&C)

One of the key technology advances of the Prox-1 mission involves the use of an Advanced Guidance, Navigation, & Control (GN&C) algorithm suite. Each of the GN&C algorithms is developed individually in a MATLAB/Simulink environment. Then, all GN&C algorithms are integrated together in Simulink and tested thoroughly. Finally, the integrated GN&C algorithm suite is auto-coded from MATLAB/Simulink into C/C++ and integrated with the rest of the Prox-1 flight software architecture as a single monolithic function.

One unique feature of the GN&C subsystem is the use of a tool in Simulink called Stateflow, which allows the satellite to operate autonomously in various modes based on conditions detected by the flight software. Once the ProxOps phase of the mission begins, there will be no detailed commands sent from the ground. The GN&C subsystem will perform autonomously, only pausing at certain key points to request permission to proceed.

GN&C Algorithm Description

The GN&C algorithms can be broadly separated into three categories: navigation algorithms which use sensors to determine the absolute and relative state of the spacecraft, guidance algorithms which plan the actions Prox-1 should perform, and control algorithms which execute commands using the actuators. This suite of algorithms is arranged as shown in Figure 4, which illustrates how the algorithms are connected with one another and with various hardware components. Brief descriptions of the algorithms are provided here, and further information can be found in previous works on the Prox-1 GN&C system[2,3].

For navigation, Prox-1 makes use of two Extended Kalman Filters (EKFs) which determine the attitude of Prox-1 and the relative position and velocity between Prox-1 and LightSail. The first key component is the inertial attitude determination (AD) filter. This algorithm estimates the attitude quaternion and angular velocity of Prox-1. The AD filter employs an algorithm developed by Crassidis and Junkins[3]. Inertial orbit determination is accomplished using the internal filtering of the Prox-1 GPS receiver. The thermal imager described earlier is then used to take images of LightSail for relative navigation. These images are fed through the Image Processing Algorithms, which determine a relative position vector based on the size and position of LightSail in the image[5]. The resulting relative position measurements are then fed into the Relative Orbit Determination (RelOD) filter, another EKF that computes the estimated relative state vector (position, velocity, and relative orbit elements)[5].

Next, guidance algorithms take the results from the RelOD filter and determine maneuvers to perform based on a set of desired relative orbit conditions. The guidance algorithms combine the use of relative orbit elements for maneuver planning with artificial potential functions for collision avoidance[6].

Finally, multiple control algorithms are used to provide commands to the actuators. A Slew and Tracking Controller (STC) has been implemented to generate torque commands for the TORC unit to obtain desired attitudes and angular velocities during ProxOps mode. When thruster burns are commanded by the guidance algorithms, the STC will slew to the proper attitude and hold until the thruster controller has completed the thrust maneuver. The Target Acquisition Controller (TAC) also commands the STC in order to locate LightSail when it is not in view of the Prox-1 thermal imager. TAC will first enter into a search mode to locate LightSail when ProxOps mode begins. Once LightSail is found, the TAC then continues to track it to keep it in view of the imager. Custom-built torque rods are used for secondary attitude control when the TORC unit is unavailable because of power restrictions. The torque rods also perform some other tasks such as de-tumbling initial angular rates after Prox-1 is jettisoned from the launch vehicle and performing desaturation maneuvers for the TORC unit.

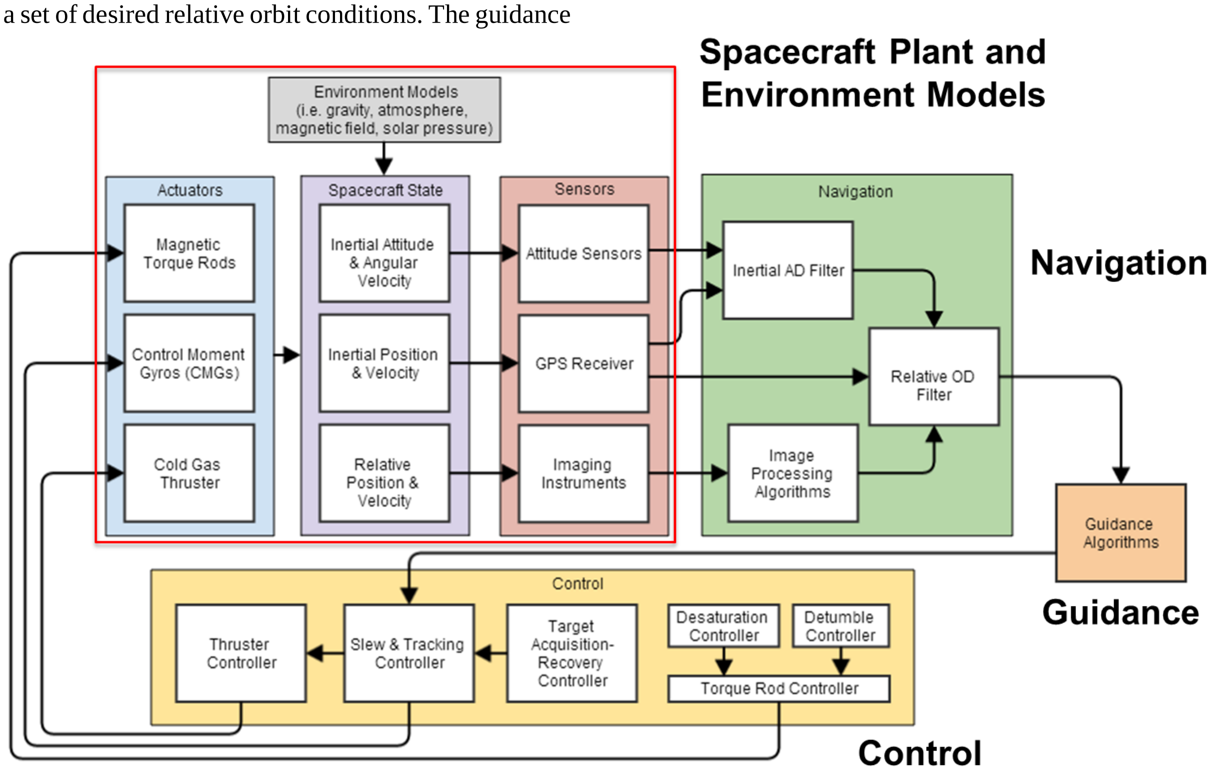

Figure 4: Flowchart showing final GN&C subsystem. Items shown boxed in red represent hardware components rather than algorithms[1].

GN&C Simulation Integration and Testing

Each of the GN&C algorithms is developed in MATLAB/Simulink using a Six Degree-of-Freedom (6DOF) simulation environment. The 6DOF sim models orbital mechanics and perturbations such as atmospheric drag, solar radiation pressure, non-spherical Earth effects, and third body effects which impact the translational and rotational dynamics of the spacecraft. The sim also includes hardware models for sensors and actuators that simulate the performance of the actual components, including sensor noise and non-idealized execution of actuator commands. These spacecraft plant and environment models are shown boxed in red in Figure 4.

Once the individual algorithms have been developed, they are integrated within the 6DOF environment so that the interactions between the algorithms can be understood. After a complete integrated GN&C algorithm suite is developed, it is thoroughly tested in Simulink to ensure that the system is able to perform the Prox-1 mission within any set of expected mission conditions. The simulation also allows the Prox-1 team to determine the robustness of the GN&C system to hardware failures or other unexpected conditions.

Autocoding and Integration with Flight Software

After the integrated GN&C algorithms have been thoroughly tested, they are autocoded into C/C++ for integration with flight software (FSW). The Prox-1 team has developed a process to adapt the Simulink models for autocoding. This involves setting configuration parameters for the models and arranging all of the algorithm blocks within a single monolithic subsystem. Simulink Coder is then used to obtain a set of C/C++ code that can be called as a function from the Prox-1 FSW. The process of developing GN&C algorithms in Simulink and autocoding to FSW has been developed by several previous missions. Prox-1 used some methods and processes similar to the Orion project at NASA's Johnson Space Center[7].

Prox-1 utilizes NASA's Core Flight Executive (cFE) as the foundation for its FSW architecture[9]. To integrate the GN&C autocode with the rest of the FSW, a cFE app is created, which collects sensor data and other commands for the GN&C algorithms. The app calls the autocoded GN&C function using the proper input data, then collects output commands from GN&C and sends them to the appropriate hardware components. The embedded GN&C algorithm performance is validated using a real-time hardware-in-the-loop test, which will connect the flight processor and FSW to the 6DOF simulation models in an operational scenario.

TEAM ORGANIZATION AND SYSTEMS ENGINEERING

As of May 2015, the team boasts with 57 undergraduate students, 9 graduate students, 2 technical advisors, and 1 faculty advisor. Students span multiple backgrounds and disciplines, including aerospace engineering, mechanical engineering, electrical engineering, and computer science. The Principal Investigator for this mission is Dr. David Spencer, Professor of the Practice at the Georgia Institute of Technology's School of Aerospace Engineering. A student project manager leads the day-to-day progress of the mission and sets the schedule, allocates resources, and liaisons with external agencies and contractors. Each subsystem also has at least a subsystem lead engineer, who are themselves experts in their own subsystems, interface and manage individual subsystem engineers, and also advise the project manager on project-wide decisions. The team also has several technical advisors who, although graduated, conserve their ties to the team because of their expertise in specific subjects of study and their involvement of the early phases of system design. External sources of expertise are also provided via collaboration with the University Nanosatellite Program and its partners, as well as with component vendors and contractors.

Systems engineering is executed via a dedicated team of student engineers. This team is responsible for the project's requirements validation and verification, which includes test planning, test execution, and documentation. This team is also responsible for documenting the electrical, mechanical, and data interfaces between subsystems and ensure a smooth flow of information between them. The project has three phases for validation and verification: component (Phase A), subsystem (Phase B), integrated system (Phase C), and Day-In-The-Life operations (Phase D). During Phase A, all of the hardware components and low-level microcontroller interfaces are tested to ensure performance in compliance with project requirements and expected scenarios. Subsystem-level executive software and its interface to the main flight computer is tested during Phase B. An integrated test of the flight computer commanding all subsystem hardware and software is performed during Phase C, to the extent that laboratory resources allow. Phase D is concerned with performing a full simulated run of operations and contains an over-the-air Simulated Communications Test to verify ground station and telecommunications capability, a Lifecycle Charging Test to verify battery performance with flight-like loads, a Command Execution Test to ensure any ground commands are properly interpreted by the flight software, and a Day-In-The-Life test that executes a nominal concept of operations across a radio link, just as it would occur in orbit. Environmental testing (i.e. thermal, vacuum, vibration) will occur at the Air Force Research Laboratory facilities in Kirtland, NM.

CONCLUSION

The Prox-1 spacecraft signifies a major advance in the capabilities of small satellites with the demonstration of complicated automated trajectory control maneuvers on a small, low-cost platform. The algorithms and technologies to be demonstrated on Prox-1 will be a major step forward in the advancement and proliferation of small spacecraft within the satellite community. By bringing together dozens of students across many disciplines, Prox-1 has already had a major impact on the spacecraft industry by helping to produce the next generation of engineers.

Acknowledgments

The authors would like to acknowledge all of Prox-1's mission partners; the Planetary Society, NASA Jet Propulsion Laboratory, Arizona State University, the University of Texas at Austin Texas Spacecraft Laboratory, and Honeybee Robotics. We would also like to acknowledge the Air Force Research Lab's University Nanosatellite Program without which Prox-1 would not be possible as well the Department of Defense Space Test Program which has provided us with a launch opportunity. Lastly we would like to thank the dozens of current and former students at the Georgia Institute of Technology whose hard work and dedication have been essential to making this mission a reality.

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