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14. ABSTRACT This work was pursued as a supplement to an existing University Nanosat-4 activity (the Akoya/Bandit mission at Washington University), The objective of this work was to develop control theory for operating the 3-kg free-flying Bandit spacecraft, as expressed by two goals: improve the fidelity and performance of our 3DOF hardware testbed and 6DOF simulator; develop, test and evaluate two methods for autonomous multi-vehicle control (behavior-based and waypoint/autopilot). Control theory was developed for teams of fixed-thrust (constrained-actuator) space vehicles, culminating in one doctoral dissertation (with two more in progress). The 6DOF simulator was greatly enhanced in both fidelity and operational effectiveness. The new 3DOF hardware testbed did not work as intended, for reasons that will be explained.					
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Objectives

This proposed work revises the ongoing activity, “Scarab/Bandit-C: Automated Object Interception and Robotic Servicing on a University Nanosatellite”. Under that AFOSR contract, the Aerospace Systems Laboratory at Washington University is training the next generation of spacecraft engineers by developing Bandit, an under-5-kg cold-gas-propelled drone spacecraft and Akoya (formerly “Scarab”), a 25 kg host vehicle. That contract calls for Bandit/Akoya to be completed by June 2007 as part of the AFRL/NASA/AIAA University Nanosat-4 competition. The baseline Bandit mission is to demonstrate key enabling technologies for on-orbit servicing using extremely small drones: launch containment, an on-orbit soft dock, means to transfer power and/or data, proximity operations and control of an under-5 kg vehicle, and image-based navigation.

As we developed a Bandit concept of operations and ground operator terminals, it became clear to us that there has been insufficient research in the area of automated control of teams of mobile/agile spacecraft in close proximity, especially in conditions of constrained operator time and communications bandwidth. Therefore, we proposed to revise our AFOSR activity by supporting graduate/faculty research in methods for autonomous, multi-vehicle control and enhanced operator workstations. The work would be evaluated/demonstrated on both a 3DOF hardware testbed and a 6DOF simulator.

3DOF Hardware Testbed. It was proposed to improve the 3DOF testbed for evaluating both control algorithms and user workstations. The improvements would consist of building an 8' x 12' forced-air table (using porous plastic for near-continuous flow) and adding a dedicated overhead camera system. As will be explained below, the forced-air system did not work and the existing system has proven too erratic to justify the expense of the camera system.

6DOF Software Simulator. The existing Java-based graphical 6DOF simulator was to be improved for this proposed work in the following ways:

- Moving the simulator to a dedicated server to increase speed. Part of this process will be to ensure that the simulation core can be migrated to the Media and Machines cluster.
- Creating real-world thruster models to account for misalignment, thermal behavior, noise, etc.
- Creating real-world sensor models to account for noise, bandwidth restrictions, digitization, etc.
- Adding Sun/Moon/Earth objects to improve operator context/situational awareness
- Incorporating orbital lighting issues (shadows, reflections, eclipse)
- Adding impact dynamics between vehicles and between the drones and host
- Converting the core modules from Java to C++ to improve speed.

As will be noted, based on the changes identified during development of the simulator, some of these objectives were set aside and others put in their place.

Autonomous Control of Spacecraft Teams. We extended potential functions to autonomously arrange teams of Bandit-like vehicles into several types of motion primitives, allowing complex behavior to be assembled from building-block functions. The potential theory was also extended to prove convergence and to identify optimal thruster configurations.

In particular, we wanted to develop potential functions with limited system knowledge (e.g., where only the distance/direction of nearby objects is known, in body coordinates), and especially to develop estimators to respond to limited state knowledge (both in terms of unobservable states and slow update rates).

Review of Efforts

As noted above, the 3DOF testbed objective was not met. The initial concept was to force air through a flat, smooth porous plastic surface to create a large table with uniform lifting flow. The concept worked in small proof-of-concept systems (1' x 1' test sections) but did not scale favorably to a production design. Specifically, we had difficulty finding air pumps with the flow rate and back pressure necessary to provide sufficient lift on a Bandit-sized test object on a 4' x 6' surface. Significant difficulties were encountered in securing the porous plastic to the table, generating uniform flow in the plenum underneath the table, sealing the edges of the plastic, and finding a powerful-enough air pump.

Finally, after burning out two motors and failing to generate enough lift for even a large piece of paper, the porous plastic table was abandoned. In fact, after discussions with Peter Will at USC/ISI, it was learned that even a normal air hockey table generates considerable noise/disturbances due to uneven flow up and around the sides of the floated objects, causing them to abandon their own table work in 2003 in favor of self-floating objects. (An example of the unbalanced disturbance can be seen at ISI's website: http://www.isi.edu/robots/movies/Diagnol_Across_Table.mpg.)

Returning to the original granite 3DOF table, we encountered similar problems with the unbalanced flow control and, especially, the problems inherent to the extremely low-thrust thrusters used on Bandit. Therefore, we chose to suspend work on the 3DOF table in favor of a short but 6DOF demonstration on NASA's C-9 "Microgravity University" in Spring 2006. The C-9 activity itself (student travel, testbed materials) were funded through the NASA Missouri Space Grant, while the Bandit spacecraft used in the experiment was partially funded by this supplemental grant; we decided it was a more appropriate use of equipment funds than to build the proposed camera system for a nonfunctional table. The C-9 final report is enclosed.

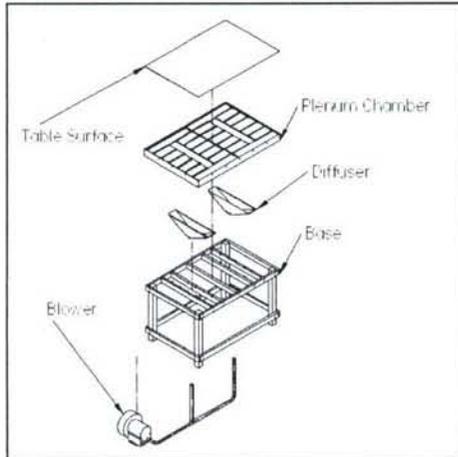


Figure 1. Forced-air table schematic



Figure 2. Students aboard the NASA C-9 flight

By contrast, the 6DOF simulation was much more successful. The PI and Sara Scarritt continued development of the simulator. All of the original objectives were at least partially achieved. Three were fully completed: Creating real-world thruster models; creating real-world sensor models; adding Sun/Earth objects; incorporating orbital lighting issues. The objectives to improve simulation speed was achieved, though not by the intended methods; instead of a dedicated server or converting to C++, the Java code was scrubbed to improve memory usage, algorithms were reworked to run more quickly, and a non-graphics version of the code was developed to allow for background runs to perform at approximately 30 times faster than real-time. With this change, a dedicated server was unnecessary, as the code could run adequately on each client machine. The impact-dynamics objective was partially

accomplished in that the simulator has a crude docking-detection algorithm to indicate when a Bandit has impacted the docking ball. The benefits of further improvements to impact dynamics were not viewed to be worth the significant increase in code complexity and (especially) the significant increase in processing cycles.

During the course of the development process, we identified and added five useful features: the ability to change spacecraft autopilots on the fly, a socket link to our ground station software (so that command & state information to/from the ground station is displayed in the simulator, enabling "shadow" operations), multiple "camera views" within the simulation, the ability to record/replay a simulation run, and a tunable estimator embedded to the spacecraft object.

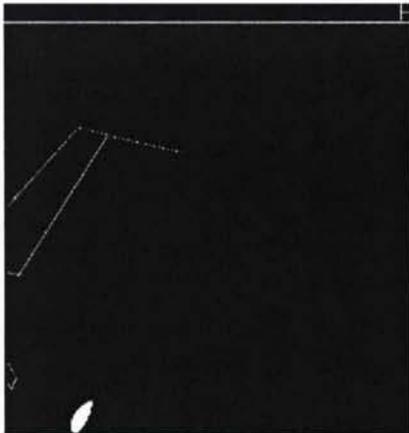


Figure 3. Docking process as viewed from host spacecraft "camera". Note the faint outline of a wireframe Bandit, which indicates the estimated position

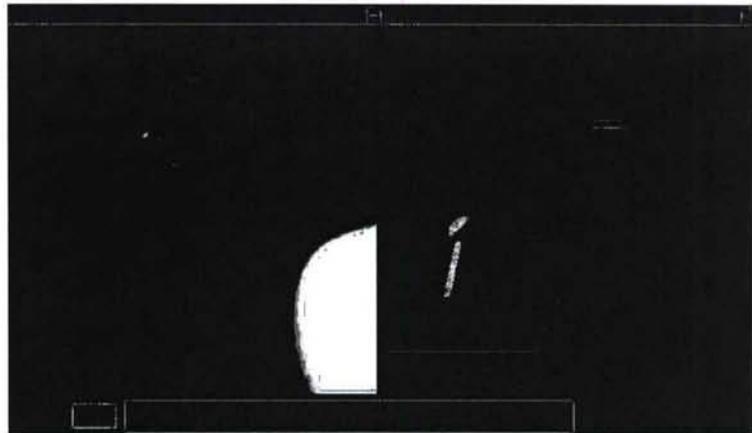


Figure 4. Simulation run as viewed from Bandit (left) and host spacecraft (right). Note the visual enhancements to aid in operational training: the exaggerated red cones from thrusters firing, the foreshortening of the right image (calibrated to match the actual host camera parameters), the body-fixed coordinate frame attached to the free-flying spacecraft, and the illuminated Earth in the background.

Finally, development of the flight control algorithms was continued by four people: the PI and three Masters/doctoral research students (Jeremy Neubauer, Sara Scarritt and Stephen Forbes). Neubauer & the PI did the initial work on potential function control, with Scarritt extending the basic work to consider matters of incomplete state knowledge and data dropout. In particular, she examined control systems where high-accuracy image-based updates were available, but in high-lag (20 seconds) and with very slow refresh rates (1/20 Hz). Attitude rate data was available at near-real-time. Forbes acted as the project manager for the Bandit spacecraft development in the C-9 activity, and his doctoral work is to extend Neubauer's work for new mission applications, and to consider matters of robustness.

Accomplishments/Findings

The main accomplishments of this activity were the upgrades to the 6DOF flight simulator, development and refinement of the potential function control methods, and the construction of a flight-equivalent Bandit spacecraft for testing in the NASA's C-9 Reduced Gravity aircraft. The overall accomplishments and summaries from above:

- Forced-air tables are not cost-effective designs for 3DOF microgravity testbeds. (They are not particularly effective by any measure.) In addition to the challenges of generating sufficient flow, flow over the sides of the floating objects is typically unbalance, leading to Bernoulli-effect-driven disturbances.
- Instead of the forced-air table, the student and equipment resources were redirected towards completion of the propulsion system and flight unit for the Bandit spacecraft. Because of these

added resources, two proto-flight Bandit units were completed. As supplementary material, the Overview Document from our satellite project is enclosed.

- Potential function-based controllers show promise for robust operation of teams of Bandit-class vehicles. In particular, very simple motion primitives can be combined to form complex behaviors. For example, we developed functions to maintain separation distance from an object, circulate around an obstacle, and approach along a fixed closing vector; when combined, these functions could create behaviors for docking and waypoint-based navigation.
- Defining the potential functions in terms of generalized velocities (instead of position/attitude) allows one to define convergence criteria. These potential functions are also very effective at overcoming the constrained-actuation problem.
- The 6DOF simulator was greatly enhanced, especially in the ability to run tests in faster-than-realtime cases. (This was quite literally a four order of magnitude increase in simulation speed over our previous system.) The simulator is now used in controls research, training spacecraft operators, and in developing flight procedures for the Bandit mission.

Personnel Supported

Supported Personnel. The following personnel received direct support from this contract:

- Dr. Michael Swartwout (PI) – 1 summer month.
- Stephen Forbes (Student Project Manager and Graduate Research Assistant) – 6 months support
- Sara Scarritt (Graduate Research Assistant) – 6 months support
- Forrest Rogers-Marcovitz (Electronics & Software Lead) – summer intern
- Graham Walker (Bandit propulsion engineer) – summer intern, 2006

Associated Personnel. The following students were funded to participated in contract activities, with the funding coming from other programs:

- Erin Beck (Student Project Manager, 2006-2007).
- Megan Sheridan (Bandit Propulsion Lead)
- Jeremy Neubauer (NDSEG-funded doctoral student)

Key Students. In addition to the students listed above, the following students made key contributions to the project as the C-9 experiment and flight test team: Fiona Turett (lead), Justin Char, Jessica Kirsch, Molly McCormick, Elaine Cheng, David Miller and Elaine Bourne.

Publications

No peer-reviewed publications came out of this activity. Jeremy Neubauer's doctoral dissertation covers the development and first analysis of the potential function methods.¹ Conference publications are discussed in the next section.

Interactions/Transitions

The PI presented a paper at the 2006 Responsive Space Conference in April 2006 in Los Angeles, CA on the design and operation of the Bandit spacecraft.² At the conference, he discussed issues of control and operation of small inspector-class spacecraft with members of Lockheed-Martin's XSS-11 team.

The PI and all supported students attended the 20th Annual AIAA/USU Conference on Small Satellites in August 2006. They presented the Akoya & Bandit prototypes as well as an early version of the 6DOF simulator. A significant fraction of the small satellite community attends this conference. In addition, Jeremy Neubauer presented a paper on the potential function method, earning 2nd place in the student competition.³

The PI attended DARPA's Fractionated Systems Workshop in Colorado Springs, CO, in August 2006, where he talked with researchers about other swarm/team-based control missions (especially the SPHERES group at MIT and Peter Will at USC).

Sara Scarritt presented a paper at the 30th AAS Guidance and Control conference in Breckenridge, CO in January 2007 on developments in the potential function control system with incomplete state knowledge.⁴ She presented a follow-on paper at the 2007 ISSFD Conference in Greenbelt, MD.⁵

New discoveries

The potential function controller and related analyses are new discoveries. More detail is available above, and in references 1, 3-5, below.

Honors/Awards

The overall spacecraft project earned 2nd place in the University Nanosat-4 competition (March 2007). Jeremy Neubauer earned 2nd place in the student paper competition of the 2006 Conference on Small Satellites (August 2006).

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1. J. S. Neubauer, "Controlling Swarms of Micro-Utility Spacecraft," DSc dissertation, Washington University, August 2006,
2. M. Swartwout, "Bandit: A Platform for Responsive Educational and Research Activities," Proceedings of the 4th Responsive Space Conference, Los Angeles, CA, 26 April 2006.
3. J. S. Neubauer, "Controlling Swarms of Bandit Inspector Spacecraft," Proceedings of the 20th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 14-17 August, 2006.
4. M. A. Swartwout, S. Scarritt, and J. S. Neubauer, "Potential Function Controllers for Proximity Navigation of Underactuated Spacecraft," Proceedings of the 30th Annual AAS Guidance & Control Conference, Breckenridge, CO, 3-7 February, 2007.
5. S. Scarritt and M. A. Swartwout, "Proximity Navigation of Highly-Constrained Spacecraft," Proceedings of the 20th International Symposium on Space Flight Dynamics, Greenbelt, MD, 24-28 September, 2007.

Washington University in St. Louis RGSFOP Mission
April 19-28, 2007

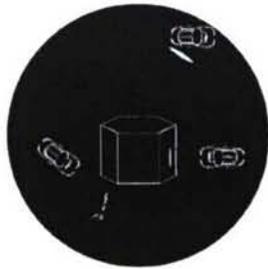


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RGSFOP Overview

The Reduced Gravity Student Flight Opportunities Program is sponsored and run by NASA's Johnson Space Center, as a combined effort between the Reduced Gravity Office and the Higher Education Office. The program allows university teams to submit a proposal for an experiment to test in the C9 aircraft. If selected, the team prepares the experiment for parabolic flight to simulate microgravity. Four undergraduate students fly with the experiment. A Test Equipment Document Package (TEDP) is submitted six weeks before flight containing a detailed explanation of the experiment, analysis of the test structures, and a safety evaluation. During flight week, the team is at Ellington Field for 9 days and participates in many different activities, including a seminar with an astronaut, information about NASA internship and co-op positions, and physiological training prior to flight. The Washington University in St. Louis proposal suggested testing Bandit, a 3-kg nanosatellite, in the microgravity environment to verify the propulsion system.

Mission Objectives

At the time of the proposal, our mission objective was to use Bandit's vision system to locate a simulated Akoya dock, re-orient to face the dock, and move towards the target. The images were to be analyzed by Akoya's image processing capabilities, after which the auto-pilot would attempt to orient Bandit so that he could dock. This would allow us to verify both that the vision system works successfully and that Bandit is capable of reorienting with 6 degrees of freedom, verifying the propulsion system.

One week before flight, our levels of mission success were as follows:

- 0) Bandit communicates with EGSE
 - a. Thrusters activate
 - b. Continuous communications link established
 - c. Pictures being transferred
- 1) Stick level control of Bandit
 - a. Correct response to commands
 - b. Maneuvers
 - c. Dock
- 2) Successful position determination
 - a. Precise inertial navigation – matching values on estimator and valve impulses
 - b. Successful image of LEDs and accuracy
 - c. Speed of this process
- 3) Autopilots
 - a. Successful “rotate and maintain” –Bandit rotates a set amount and then holds position
 - b. Successful “Timed re-dock autopilot” – Back up and return to same position
 - c. Successful “Track LEDs” – keep Bandit pointed at LEDs
- 4) Autonomous detumble of Bandit
 - a. Angular velocity sensors work
 - b. Bandit counteracts angular momentum

RGSFOP Testbed

In order to increase our chances of our proposal being selected, we contained Bandit inside a box so that the experiment was not free-floating. The testbed consisted of two chambers: the experiment chamber and the equipment chamber. The figure below shows our testbed set-up onboard the aircraft.

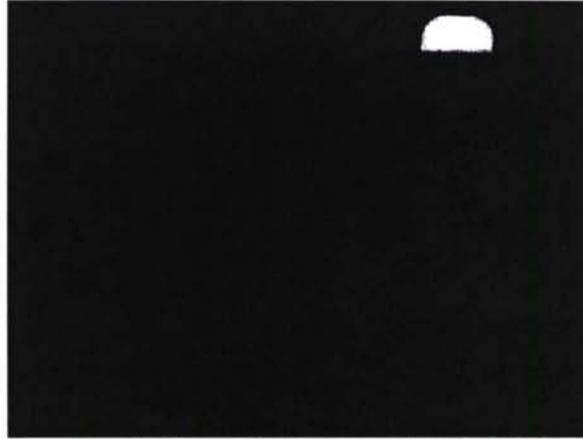


Figure 1: Test equipment set up onboard the C9

The box shown on the left is the experiment chamber, a 24"x24"x36" Lexan box. The box was hinged at the top to allow access to the chamber. Angle aluminum was used to connect the ¼" Lexan. A strut on the bottom allowed for a secure connection to the aircraft. Foam was placed on the bottom to ensure that Bandit was safe during 2G periods. Insulating foam was placed on the front (shown in the picture as left) to meet NASA's impact regulations. The simulated dock is shown on the back plate of the experiment chamber.

Our equipment chamber was a 24" Plexiglas cube, connected with angle aluminum. A strut across the bottom was used for connection to the aircraft. A 6" high shelf was placed in the box. Below the shelf, our outreach experiments were placed and surrounded by insulation foam for protection. The remainder of the box contained our electronics, discussed later in this document. A laptop was secured on top with Velcro to allow for control of Bandit.

Two video cameras were used during flight. The first was placed inside the equipment box, and the other was mounted above the experiment chamber. Due to various issues, neither camera recorded successfully throughout the entire flight.

RGSFOP Outreach

As part of the RGSFOP program, each team is required to perform an outreach project. The project should be designed especially to serve underrepresented communities, if possible. For our outreach, we worked with a local middle school, Brittany Woods Middle School. In early April, our team gave a presentation about space and microgravity to two groups of 7th and 8th grade students. We then supplied the class with plastic test tubes. The students came up with experiments to test in microgravity, and put them in the test tubes. A control set was also used and did not fly so that the student could see the difference.

The experiments included layering different color sand, placing a marble in sand, mixing water and oil, and many other simple experiments. This process allowed the students to feel involved in our microgravity experience, as well as being a good example of the scientific method. After our flight, we returned both sets of test tubes to the students.

RGSFOP Electronics

All our electrical power came from the 115V line within the C9. This was attached to a power strip in our electronics box. The expected schematic, as submitted with the TEDP, is shown below.

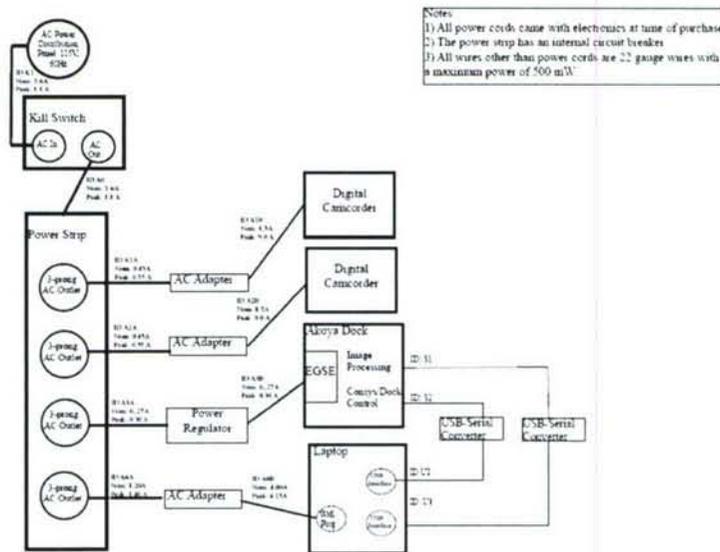


Figure 2: Electrical schematic as submitted with the TEDP

Due to some issues with the power board, this was not our final set-up. The final system is discussed in the pre-flight modifications section of this document.

RGSFOP Communication

The communication system between Bandit and the Akoya electronics was the only radio communication used during our C9 flight. Due to some problems with the gain pattern of Bandit's internal Splatch antennae, modifications were made to the system. With the Splatch antennae, we were only able to receive signal at very short distances and with a certain angle between the two systems.

The changes made are discussed in the pre-flight modifications section of this document.

Pre-Flight Modifications

Before our flight, we had planned on finishing multiple tasks. Upon arrival in Houston, our list of tasks included loading software, verifying communication, finishing the test bed, charging Bandit, checking the propulsion system for leaks, and fueling Bandit. While completing these tasks, however, we discovered multiple issues which we then needed to fix before flight.

As mentioned above, the power board was not working successfully. The board would work fine and draw a normal amount of current (around 600 mA) for approximately 3-5 minutes. After that, there would be a sudden spike up to more than 3 A. This would blow the fuse on the power board and stop the connection. While we are not sure what the exact cause of this problem was, we believe that it was related to the linear regulators. The regulators get very hot during operations, and could possibly have stopped working due to the effects of this heat. Because we did not know exactly what the problem was, it was difficult to engineer a solution. We purchased heat sinks and placed them on the regulators and power board, but this did not solve the problem. We discussed the possibility of using a computer power supply (ATX), but we were not successful with this either. Eventually, we bought separate 5V and 12V power adaptors, attached them to the power cables, and plugged them both in. With the 5V plugged in, the system was stable for an extended period of time. When we plugged in the 12V, however, it stopped working again. We tried placing a diode between the 5V and 12V ground lines to stop them from mixing, but this did not fix the problem. We finally decided to simply use the 5V and forgo the image processing board which ran off 12V. The system did not work without any 12V adapter attached to the wiring, however, so we wired one in. This adapter was never plugged in, and the reason for needing it is still unknown.

Once we had solved the power issue, we began to work on the communications system. We were unable to reliably receive commands, and Bandit would only respond to one command out of approximately 20, or about one out of five if we used the program which repeatedly sent a command. This was at a very short distance, and if we moved further away, we would not receive any commands. After adding length to the antennae on the simulated Akoya, we had no luck in obtaining a better signal. We finally removed the Splat antenna from Bandit and replaced them with quarter-wavelength wire antennae. This solved the problem completely, and we had no trouble sending commands to Bandit at any point during the flight.

Bandit's propulsion system had never been filled away from WashU, and therefore no method was in place to do this. We had made an apparatus to fill Bandit, but it was not secure and the pressure burst the tube. To solve this problem, we needed to purchase stronger tubing. We went to a local auto parts store, and purchased a stronger tube. This was a very secure way to put fuel in Bandit, and caused us no problems throughout the rest of the trip. In this modification, however, we lost the ability to see inside the tube, as the new tube was black. This made it difficult to know how much propellant was in Bandit, and hard to know when to stop fueling.

After fueling Bandit, it was clear that there was a major leak in the propulsion system. We disassembled Bandit and tried to tighten down all the compression fittings. Not all of the fittings were accessible without disassembling most of the system. After tightening down all of the fittings which we could reach with a wrench, we reassembled the spacecraft and tested it again. Still, there was a large leak. After examining the system with a make-shift stethoscope, we established that the problem was not in the screw connection, but rather in the connection between the tubing and the compression fittings. There was no good way to fix this problem, but it was going to end the mission if we didn't. With the leak, propellant only stayed in the tank for under an hour, which was not long enough for us to complete our tests in microgravity. NASA would not allow us to refuel mid-flight, due to the fact that the

propellant would have become an explosive if cabin pressure was lost. We purchased rubber epoxy and applied this to the leak. This solved the problem quite well. We were reluctant to do this because of the possibly damage to the hardware, but we could not find another solution to the problem.

While reassembling the satellite after tightening compression fittings, we saw some smoke coming out of the electronics when we were attempting to reattach the battery plate. After frantically blowing on the smoking resistor and detaching the plate, we tried to figure out what had gone wrong. We noticed that one of the wires attaching to the batteries had been slightly stripped in one place. After ruling out all other possibilities, we realized that that wire had been pinched between two metal objects during reattachment. This closed the battery circuit, and had power running through one resistor and then back to the batteries. After replacing the resistor and adding electrical tape to the wire and surrounding metal, we carefully reassembled Bandit without issue. Later, we realized that the charging circuit no longer worked due to this problem. For the rest of the trip, we had to directly attach the power supply to Bandit and monitor it, but we were still successfully able to charge Bandit for both flights.

Flight Performance

Bandit performed as well as could be expected during flight. We were unable to complete most of our mission objectives, both due to spacecraft issues and the nature of the C-9 microgravity environment. The plane does not experience steady zero-gravity, but there is some noise. This was enough to make Bandit move around the testbed without any commands, and made it much more difficult to record data.

Each parabola, we sent a steady stream of one command to Bandit. On some parabolas, we were able to see a clear response from Bandit. Often, it was easier to see rotation than translation, and so we focused on that. It was clear that rotation was easier around certain axes due to the moment of inertia differences.

Overall, the data gathered during flight proved to be rather insignificant compared to the amount of lessons learned throughout the week.

What Was Learned

Operating Bandit showed us both the strengths and the flaws of the satellite. After working with the satellite, the largest issue was the difficulty in disassembling the system and working with the subsystems. Bandit fits together very tightly, which doesn't lend well to quick repairs. A modularized system would make this much easier to deal with. While this is not completely possible, there is definitely room for improvement on this matter and it would make the spacecraft much more user-friendly.

The propulsion system could also be improved upon. The ability to reach each valve and fitting would be extremely helpful for servicing. The current layout does not allow easy access to most of the valves, and some are simply impossible to access. Also, although we established a reliable system for fueling Bandit, the addition of a pressure gauge would be useful. This does not need to be permanently attached to the satellite, and can simply be part of the fueling system.

As discussed earlier, the Splat antennae had a very weak gain pattern and were not sufficient for operations. New antennae would be necessary to ensure a good communications link between Bandit and Akoya. The whip antennae worked very well, and could be attached to the inside of Bandit.

Lastly, less sharp edges would be beneficial for wire protection. In situations where time is short, it is very easy to accidentally short a circuit by pinching a wire. If this were impossible to do, then there would be no issue. Removing sharp edges and shielding wires from possible problem areas would make the spacecraft safer to work with.

Implementation of RGSFOP Lessons on NS-5

Depending on the budget and man-power for the Nanosat-5 competition, these improvements could be made to the system. Any of them would improve the quality of the vehicle and make Bandit easier to work with and safer to fly.

An improvement to antennae is essential to a successful mission, as is a leak-proof propellant system. Without these two improvements, the satellites would fail within minutes of deployment. Bandit would be out of fuel long before entering orbit, and the mission would fail immediately due to the lack of propellant. The new antennae would allow us to communicate reliably with Bandit, ensuring that the satellite did not simply float away for lack of controls.

Conclusion

Despite the numerous issues which arose during the trip, I consider the trip a success. The process of troubleshooting and repairing Bandit throughout the week was both educational for the team members, and necessary for finding flaws in the system. Although we were not able to collect as much data accurately as we hoped, we verified that the propulsion system does work and visually saw Bandit respond to commands.

If we were to propose another experiment to fly on the C9, the scope and mission objectives would have to be carefully examined to fit the constraints of the plane. Flying a free-flying experiment would have helped us, because then we would have had more room to work with and Bandit would not have hit anything as soon. There are risks associated with this and a large amount of safety consideration is necessary. With the experience of flying once, I am confident that a useful experiment could be conducted as long as the constraints were considered while designing the experiment, not during the final week before flight.