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A Performance-Driven Experiment Framework for Space Technology Development Using the International Space Station

by

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Abstract

Space systems are inherently difficult to verify prior to launch due to the challenges of replicating the space environment through ground testing. The SPHERES testbed on the International Space Station has provided a risk-tolerant test facility for evaluating enabling technology. The operational execution of the SPHERES facility has resulted in the development of best practices for working with experiments in the operational space environment that can be continually refined through successive generations of SPHERES projects. This thesis presents an experiment framework for developing space technology using the International Space Station that focuses on incrementally building toward technology demonstration through the achievement of specific results at each step that are designed to enable an effective demonstration. The operational nature of the ISS constrains both the time available for testing and the control that the scientist can exercise over the experiment. Therefore, this framework addresses the need to design experiment campaigns that can efficiently achieve the desired results using data gathered from tests that exhibit unexpected behavior in addition to the tests that exhibit expected behavior. The framework is inspired by the lessons learned from the RINGS project, an attachment to the SPHERES facility that tests Electromagnetic Formation Flight using electromagnetic coils attached to the vehicle. The RINGS experiment campaign is reviewed with a focus on the lessons learned from the operational phase of the project. From these lessons, the experiment framework is developed and presented so that researchers can have a guide in the planning and designing of their experiments for use on remote, operational facilities. The framework is then applied to the next-generation SPHERES project, the Universal Docking Port, as well as the RINGS project, in order provide examples of how this framework can be implemented.

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Chapter 1

Introduction

1.1 Motivation

Space system failure can have catastrophic effects due to the high cost associated with individual missions, the loss of the high-value capability that space assets typically offer, as well as the negative impact a failed spacecraft can have on other vehicles on orbit acting as space debris. As a result, space systems are developed with a near-obsession on risk mitigation by investing large sums of money into analysis and testing to reduce the probability of failure as much as possible. Space systems have been difficult to test prior to launch because of the many environmental properties that are difficult to fully test on ground testbeds or simulations. As the complexity of space systems increases, simulations and ground tests become less capable of accurately characterizing performance in the space environment.

In contrast, giant corporations such as Coca-Cola, MetLife, General Electric, IBM, Mondelez International, Cisco, and Tyco International have begun over the past few years to infuse into their culture some of the characteristics of the startup and venture capital world that have enabled rapid growth and progress that these corporations seek to emulate. The most notable characteristic is the near veneration of risk-taking, failure, and the lessons that can be drawn from it [1]. The result of the risk-taking culture is that these companies have been able to innovate quickly as they learn from their mistakes and ultimately increase the quality of their products.

The risk adverse mindset that exists within the space systems community contributes to
a relatively slow technology development cycle because stakeholders do not want to shoulder the risk of using a new technology on their system until it has been proven on other systems in space. Though systems have gotten smaller and cheaper in the recent years as more and more CubeSats and NanoSats are developed, the risk-adverse culture can still permeate the design and development of many of these systems. In order to support higher rates of technological progress in space systems, the technology should be developed in an environment that encourages risk-taking while placing a strong emphasis on learning from failures.

The SPHERES testbed on the International Space Station offers such a facility. It was designed in the 2000s as a way to conduct dynamics and controls experiments in an environment that more appropriately represents the environment in space while balancing that risk tolerance and testing duration more favorably than ground testbeds, RGA flights, and systems on orbit. The SPHERES facility is a test environment that could be used to learn from failure in a risk-mitigated way in order to push space technology forward. The relatively low cost of failures in the ISS environment is necessary in the advancement of technology through this risk-taking culture, but is not sufficient in the absence of an emphasis and plan for learning from those failures. It does not matter how low-cost the failure is if the team is not prepared to learn and benefit from the it. Thus, this thesis presents an experiment framework for planning and designing experiment campaigns that advance space technology through the incremental achievement of results that are designed to lead to the successful demonstration of the technology in a microgravity environment. The framework uses both the successes and the failures of tests in the microgravity environment to achieve the desired results by using successes to confirm an understanding of the technology in a certain application and environment, and the failures to help uncover characteristics of the technology that were previously unknown. Both drive towards a greater understanding and ultimately greater technological progress for space systems.

The framework itself was also developed using lessons learned from the RINGS project, an addition to the SPHERES facility used to test electromagnetic formation flight in the microgravity environment. The RINGS project experienced many challenges during its experiment campaign, creating an opportunity to learn from failure on a project where the loss from failure is minimal. The RINGS operational campaign went from August 2013-July
2014, spanning the height of operational intensity for the SPHERES facility as shown by the disparity in personnel and operational sessions that occurred during that time (Figure 1-1). The manner of personnel working on the project also had an effect, because the team had complete graduate student turnover at the RINGS project level right before the operational campaign began. The RINGS project was also the first in the SPHERES facility to be led outside of MIT, making it more difficult to transfer knowledge from prior experiences working with the facility. These factors brought to light many of the challenges that research teams face when experimenting with emergent technology in an operational environment. The experiment framework presented in this thesis addresses these challenges and will help teams to plan and design their test campaigns to leverage the benefits of the operational environment while acknowledging the constraints.

1.2 SPHERES Facility Overview

The SPHERES satellites are designed to model the behavior of formation flight spacecraft and contain a satellite bus complete with propulsion, navigation, avionics, power, and communications subsystems. The SPHERES satellite structure is held together by six aluminum rings that are aligned in pairs along each of the three axes. The entire system is then encased using two molded Lexan shells as shown in Figure 1-2 from Saenz-Otero [3].
The satellites use twelve cold-gas thrusters fueled by liquid $CO_2$ that enable controllability in all six degrees-of-freedom. The propulsion subsystem is described in detail by Chen [4]. The navigation subsystem provides real-time state (position, velocity, attitude, angular rate) information to each satellite using three body-axis IMUs and range measurements from external ultrasonic beacons to update the state estimate. The navigation subsystem and estimation algorithm development is described in detail by Nolet [5].

The satellite avionics contain a TI C6701 Digital Signal Processor (DSP) and a Virtex FPGA to interface between the DSP and the propulsion and navigation subsystems. Two sets of eight AA batteries provide power to all satellite components for approximately two hours. The satellites communicate with a laptop through RF communication. All SPHERES satellites share the same frequency using a TDMA scheme that splits the communication period between all satellites involved in the formation and the laptop ground station. The avionics, power, and communications subsystems are all described in detail by Saenz-Otero [3].

The SPHERES satellites also contain an expansion port that enables the SPHERES satellite to carry payloads in order to test and verify different mission applications. The expansion port, shown in Figure 1-3, enables a structural and an electrical connection between the payload and the SPHERES satellite though a 50-pin serial connection [6].

Figure 1-2: Structure of the SPHERES Satellite
The upgraded expansion port was first used on the International Space Station to connect to the VERTIGO payload. The VERTIGO payload upgraded the SPHERES facility through the addition of stereo cameras and additional onboard computational power in order to enable the testing and evaluation of new algorithms and approaches for computer vision-based navigation [7]. The VERTIGO program has completed five test sessions aboard the International Space Station from February 2013 to July 2014 that are described in detail by Tweddle [7] and Setterfield [8] [9] [10].

The next SPHERES payload launched to the International Space Station was RINGS, a system that is used to test control algorithms for electromagnetic formation flight. The RINGS payload is introduced in the next section and its operational campaign will be described in detail in Chapters 2 and 3.

Other SPHERES payloads launched to the International Space Station are: FIT’s Slosh
experiment used to study fluid dynamics in microgravity [11] and the NASA AMES Smartphone payload used to provide additional functionality such as a camera, extra sensors, powerful computing, and a Wi-Fi connection [12]. The InSPIRE-II payloads, the UDP and the Halo, are expected to begin operations in the summer of 2015 and are described more thoroughly in Section 1.4.

1.3 RINGS Payload

The Resonant Inductive Near-Field Generation System is an actuator that provides electromagnetic forces and torques on each satellite depending on the separation distance and relative orientation of the two units. RINGS was sponsored by the Defense Advanced Research Project Agency (DARPA) to test electromagnetic formation flight (EMFF) and wireless power transfer (WPT) capabilities. In its EMFF mode, the RINGS units generate a synchronized alternating magnetic field that can attract, repel, and torque each unit. In this mode, both the amplitude and the phase of each unit can be independently controlled. In the WPT mode, one unit generates an alternating magnetic field while the other unit receives power via a load resistor placed in line with the circuit that dissipates the transferred power. Figure 1-5 shows a RINGS flight vehicle with major components labelled.

![Figure 1-5: RINGS Flight Vehicle](image)

The RINGS circuit coil contains five layers of 20 turns of 6061 aluminum that are stacked on top of each other and connected in series. Each RINGS unit has a diameter of 0.62m and a mass of 17.1 kg. The resonant coil drive circuitry uses an COTS H-bridge in order
to generate the alternating current. Three Hall Effect sensors, placed in series with the coil circuit, are used to measure the current in the coil. The RINGS housing contains an LCD so that diagnostic messages about the RINGS hardware can be accessible during operations. The resonant coil, electronics, and wiring are enclosed in a polycarbonate shell that is semi-translucent. To regulate the temperature of the system, a system of cooling fans, fin walls, and diffuser ports are used to dictate air flow within the housing. Power is supplied to the RINGS units through two DeWalt 18 V, 36 W-Hr lithium-ion rechargeable batteries connected in series. In EMFF mode, the RINGS units operate at a frequency of 85 Hz and can generate a maximum 18 Amps.

A microcontroller made by Microchip is used as the RINGS processor central to hardware operation. It has a 32-bit core processor, 80 MHz primary oscillator, 16 channels of 10-bit analog-digital converter channels, and 512 KB of flash memory. The microcontroller receives commands from the SPHERES satellites and sets the desired operations mode and regulates the H-bridge accordingly. The microcontroller sends command feedback data to the SPHERES satellites in addition to data that the SPHERES downloads to the laptop. Additional digital outputs are used to configure the hardware and monitor health status.

Electromagnetic Formation Flight requires the ability to control satellites using the relative forces generated by driving current through electromagnets on each vehicle in the formation. Elias first developed a non-linear model for EMFF dynamics assuming a fully controllable dipole and that the satellites operated in the far-field region (>3 coil radii) [13]. A fully controllable dipole in 6-DOF is achieved by using three orthogonal coils attached to each vehicle enabling the system to point its magnetic dipole in any direction by varying the current through the each coil. The far-field assumption enables the EMFF dynamics to simplify to the interaction of two or more bar magnets in determining the relative forces.

Schweighart takes EMFF dynamics further in his work by developing a model that captures the near-field dynamics [14]. From his model, he is able to characterize the relationship between the forces and torques produced by the coils, the separation distance, and the relative orientation. Biot-Savart’s law and Ampere’s law are combined to form Equations 1.1 and 1.2, where Figure 1-6 from Eslinger [15] defines the terms in the equations.
\[ \vec{F}_2 = \frac{\mu_0 i_1 i_2}{4\pi} \oint \left( \oint \frac{\hat{r} \times d\vec{l}_1}{r^3} \right) \times d\vec{l}_2 \]  \hspace{1cm} (1.1) \\

\[ \vec{\tau}_2 = \frac{\mu_0 i_1 i_2}{4\pi} \oint \vec{a}_2 \times \left[ \left( \oint \frac{\hat{r} \times d\vec{l}_1}{r^3} \right) \times d\vec{l}_2 \right] \]  \hspace{1cm} (1.2)

Figure 1-6: Definition of the EMFF Two-Coil System

Though the EMFF equations have no closed-form solution in the near field, Schweighart was able to derive far-field approximations that have been used for a number of different EMFF controls approaches including:

- A non-linear control law for multi-satellite systems, while using Legendre Pseudospectral Methods to generate optimal trajectories developed by Ashun [16].

- A ‘token’ approach where only one satellite actuates at a time developed by Ramirez-Riberos [17].

- A non-linear control method for docking satellites developed by Zhang [18].

These methods are not entirely applicable to the RINGS system because they often assume a fully controllable dipole and operations in the far-field region. Control approaches for the RINGS system were developed by Buck [19] and Eslinger [15]. Buck develops a numerical simulation based off of the near-field equations, 1.1 and 1.2. He also developed a feedback control law to theoretically demonstrate position control of the underactuated system while a separate actuator is used for ‘dipole steering’ attitude control. Unfortunately,
the controller was designed using the far-field equations and was never demonstrated in the near-field. Eslinger reformulated the RINGS control problem and performed state reduction for different applications in order to demonstrate the feasibility of dynamic programming methods for satellite control with electromagnetic forces. Both Buck and Eslinger developed promising control strategies for the RINGS system, but unfortunately neither of the methods were ready for immediate implementation with the testbed when operations began. The time required to develop and test the software for these approaches was greater than the time available in between test sessions aboard ISS. Finally, Alvisio’s work [20] covers the first few operational test sessions aboard the ISS and uses some of the data to validate the RINGS simulation for different translational and rotational test cases in the near-field.

1.4 UDP Payload

The Universal Docking Port (UDP) is an upgrade to the SPHERES facility aboard the International Space Station that provides the satellites with docking and undocking capability. This upgrade enables the SPHERES facility to be used as a testbed to address many of the challenges or reconfigurable spacecraft including relative sensing, dynamics characterization, and control of the reconfigured system. An understanding of these challenges is important to space mission such robotic servicing and assembly, orbital debris-removal, and asteroid sampling.

![Figure 1-7: Integrated SPHERES-UDP Vehicle](image)
A pair of docking ports are capable of rigidly connecting two SPHERES satellites using a protruding lance and a mating hole with a motor mechanism that is used to secure the inserted lance from the other docking port. The docking ports are also equipped with cameras and visual markers that can be used to determine the relative distance and angles between the satellites to assist with the docking maneuver. The UDP attaches to the satellite through the VERTIGO Avionics Stack (VAS) and a standoff as shown in Figure 1-7 from the UDP Phase III Safety Presentation [21]. More detailed information about the UDP can be found in Miller [22].

As part of the InSPIRE-II program, the UDPs will be joined on station by the Halo payload that provides a structural and electrical connection for up to six peripherals that would normally attach to the SPHERES satellites through the expansion port. The Halo will enable testing of more complex docking and reconfiguration architectures by adding docking ports at various positions and orientations as well as by adding different sensors and actuators to the system (see Figure 1-8 from McCarthy [23]).

Docking missions generally have five parts: the rendezvous with the target, proximity operations, the docking, manipulation of the target, and undocking. The UDP payload (and later the Halo) provides researchers the capability to test control algorithms in each of these areas in the dynamically authentic environment of the ISS. The SPHERES program
has had a strong history in working with algorithms that support these applications. For proximity operations, Tweddle [24] developed a Multiplicative Extended Kalman Filter for Vision-Based Relative Navigation using known fiducial markers. Nolet [5] completed a comprehensive review of GN&C algorithms for autonomous docking that includes estimation, control, and path-planning algorithms. Fejić [25] expanded Nolet’s work and developed algorithms for autonomous docking to different cases of tumbling satellites. Mohan [26] used the SPHERES satellites and a prototype version of the Docking Port to develop reconfiguration method known as the business card approach for adjusting to the new physical properties of the reconfigured system. Jewison [27] expanded that work by developing a method for selecting thrusters when trying to control the reconfigured spacecraft. Much of the early operations conducted with UDPs will be based on the methods developed by these team members.

1.5 Thesis Outline

This chapter discussed the motivation of the thesis and introduced the SPHERES test facility aboard the International Space Station with more detailed information on the two payloads used in this work, the RINGS units and the UDPs. The remainder of the thesis is described below.

- Chapter 2 details the operational campaign for the RINGS project by going through the development and results of its first four test sessions after the payload’s integration to the ISS facility.

- Chapter 3 summarizes the lessons learned from the RINGS campaign so that future ISS flight projects can be improved and avoid some of the challenges faced by the program.

- Chapter 4 presents an experiment framework for operational space technology development that focuses on incrementally advancing new technology by clearly defining success criteria for each increment and designing experiments to meet that criteria.
• Chapter 5 provides an example of the framework from Chapter 4 using an upcoming payload for the SPHERES facility, the UDP.

• Chapter 6 uses the framework from Chapter 4 to discuss how the RINGS project can be used to further Electromagnetic Formation Flight considering the lessons learned on the first campaign.

• Chapter 7 concludes the thesis by summarizing the material presented and presenting recommendations for future work.
Chapter 2

RINGS Operations Campaign

2.1 Experiment Campaign Overview

The RINGS test sessions under its initial DARPA contract were focused on the development and testing of control algorithms for electromagnetic formation flight. Using an incremental approach that is common among SPHERES projects, the RINGS team planned their test sessions according to this pattern by starting with simple maneuvers and adding complexity with each test session. Table 2.1 shows the plan for science development aboard ISS according to the RINGS research proposal [28]. The following sections in this chapter present the results of each test session.

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<tr>
<th>Session</th>
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<th>Goals</th>
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<td>Checkout</td>
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<td>Run hardware checkout algorithms that validate operation using information gathered by the expansion port</td>
</tr>
<tr>
<td>Science 1</td>
<td>1 Week</td>
<td>Wireless Power Transfer and Relative Stationkeeping Maneuvers</td>
</tr>
<tr>
<td>Science 2</td>
<td>6 Weeks</td>
<td>Rotational Control Algorithms</td>
</tr>
<tr>
<td>Science 3</td>
<td>6 Weeks</td>
<td>Optional: Re-run tests to ensure completion of all objectives</td>
</tr>
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2.2 System Checkout

The RINGS Checkout session occurred on August 27, 2013 and was operated by Astronaut Karen Nyberg. The checkout session was used to update the RINGS PIC firmware, conduct Wireless Power Transfer (WPT) experiments, and to evaluate the performance of the RINGS current driving circuitry at different operating frequencies and duty cycles. For each test, the astronaut would use a push-button to cycle through the LCD messages on the RINGS hardware and read those messages to the ground crew at MIT and NASA AMES. The content of these messages would indicate to the ground team that the hardware was functioning properly [29].

For the WPT tests, the RINGS units were set up facing each other near the center of the test volume at approximately 50cm apart. After three trials, the RINGS units successfully transferred power from one coil to the other coil. The Hall-Effect sensor measured 5A of current on the transmitting coil and 4.1A of current on the receiving coil. A linger shows that the RINGS coils have an impedance of 1.9 Ω for a 40 % duty cycle [30]. Therefore, the power generated and received by each coil can be calculated using Equations 2.1 and 2.2.

\[ P_{TX} = I_{Coil}^2 \times Z_{Coil} = (5A)^2 \times (1.9\Omega) = 47.5W \quad (2.1) \]

\[ P_{RX} = I_{Coil}^2 \times Z_{Coil} = (4.1A)^2 \times (1.9\Omega) = 31.9W \quad (2.2) \]

The power dissipated by the load resistor(2Ω) can be calculated using Equation 2.3.

\[ P_{Load} = I_{Load}^2 \times R_{Load} = (4.1A)^2 \times (2\Omega) = 33.6W \quad (2.3) \]

Assuming that the other power losses due to the circuitry of the RINGS hardware are negligible, the power input is relatively equal to the power dissipated in the two resonant coils and the load resistor [31]. Therefore, Equation 2.4 can be used to calculate the power transfer efficiency.

\[ \eta = \frac{P_{Load}}{P_{TX} + P_{RX} + P_{Load}} = \frac{33.6W}{47.5W + 31.9W + 33.6W} = 30\% \quad (2.4) \]

30
The EMFF checkout tests did not go as well as the WPT tests did. When testing in EMFF mode at a specified duty-cycle, the measured RMS current fluctuated between 5 and 15 Amps rather than remaining constant as expected. Furthermore, closer examination of the instantaneous current measurements of both coils in Figure 2-1 shows that there was an offset in synchronization between the two coils [31].

![Figure 2-1: Instantaneous Current in Both Coils](image)

When the primary SPHERES satellite emits an infrared pulse to begin its global metrology period, the RINGS units should use that signal to synchronize their alternating current signals. Keeping the RINGS units synchronized is essential in maintaining the correct magnitude and direction of the induced electromagnetic forces. The Checkout Session report explains that the synchronization error was caused by a firmware bug that was fixed prior to the first science session [31].

2.3 Science 1

The first RINGS science session was the first occurrence of electromagnetic formation flight in 6-DOF. In addition, system identification experiments were conducted to verify previous experimental results from the Reduced Gravity Aircraft (RGA) campaign conducted prior to the launch of the testbed. As shown in Figure 2-2 from NASA [32], a tether was used to restrain one of the RINGS coils during the electromagnetic formation flight experiments. The experiments were conducted by Astronaut Michael Hopkins on November 4, 2013.
2.3.1 System Identification

System Identification tests were conducted to determine the mass and inertia properties of the system in addition to the effective forces generated from each thruster. Each thruster was fired four times for 600ms at 1 second intervals before transitioning to the next thruster. IMU data was recorded at 1kHz and state estimation was conducted during the 400ms period of each second in which thrusters were not being fired. Each thruster characterization test was conducted successfully resulting in 4 measurement opportunities per thruster. The samples were used to determine the average values for the physical properties and the thruster forces.

The data is analyzed using a least-squares system identification tool developed by Christopher Jewison that filters the IMU data using a moving average filter, determines the measured linear and angular acceleration from each pulse shown by the accelerometer measurements, determines the center of gravity using the gyroscope measurements, and calculates the true linear acceleration by subtracting the calculated angular acceleration from the measured acceleration (Figure 2-3). Table 2.2 shows the center of gravity and inertia results from the test session compared to expected values derived from Eslinger’s analysis [15] of the RINGS system.

Once the physical properties were determined, the linear acceleration from each thruster firing could be determined by subtracting the angular acceleration from the accelerometer
measurement. Converting these acceleration values into force enabled the team to gain further insight into the control authority that the system has when using thrusters. The force values for each thruster firing are shown in Table 2.3. The cells highlighted in red show impingement of the thrusters covered by the RINGS hardware. These thrusters are nominally the X and -X body thrusters on the SPHERES satellite. Though some of the other thrusters do not provide the expected 0.098N of force, Thrusters 0, 1, 6, and 7 are clearly more severely impinged. Looking at Figure 2-4, it can be seen that the impingement comes from two places: the misalignment of the clamp and the blockage from either the avionics box (+X) or battery packs (-X).

### 2.3.2 Open-Loop Electromagnetic Formation Flight

The open-loop electromagnetic actuation tests were used to demonstrate the system’s capability to generate electromagnetic forces and torques with different variations of thruster
Table 2.3: Effective Force of Thruster Firings (N)

<table>
<thead>
<tr>
<th>Thruster</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.011</td>
<td>-0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>1</td>
<td>0.022</td>
<td>0.014</td>
<td>-0.004</td>
</tr>
<tr>
<td>2</td>
<td>0.013</td>
<td>0.097</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>0.005</td>
<td>0.082</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>-0.002</td>
<td>-0.008</td>
<td>0.075</td>
</tr>
<tr>
<td>5</td>
<td>-0.002</td>
<td>0.004</td>
<td>0.093</td>
</tr>
<tr>
<td>6</td>
<td>-0.008</td>
<td>-0.011</td>
<td>0.008</td>
</tr>
<tr>
<td>7</td>
<td>-0.012</td>
<td>-0.003</td>
<td>-0.001</td>
</tr>
<tr>
<td>8</td>
<td>0.008</td>
<td>-0.050</td>
<td>-0.002</td>
</tr>
<tr>
<td>9</td>
<td>-0.010</td>
<td>-0.074</td>
<td>0.002</td>
</tr>
<tr>
<td>10</td>
<td>0.002</td>
<td>0.016</td>
<td>-0.070</td>
</tr>
<tr>
<td>11</td>
<td>0.001</td>
<td>-0.022</td>
<td>-0.095</td>
</tr>
</tbody>
</table>

Figure 2-4: SPHERES Thrusters Impinged by the Battery Packs and Avionics (L) and the RINGS Clamp (R)

stabilization. The these tests contained two parts:

1. **Initial Positioning:** SPHERES-RINGS vehicle uses thrusters to maneuver toward specified position within volume in front of the tethered satellite.

2. **Electromagnetic Actuation:** RINGS payload applies open-loop electromagnetic forces and torques, while SPHERES thrusters provide different levels of thruster stabilization.

Different levels of thruster integration were used because closed-loop thruster control of the SPHERES-RINGS system had yet to be demonstrated on orbit. In the event that the use of thrusters decreased stability of the system, alternative tests with varying degrees of thruster involvement could be used.
Analysis of the initial positioning of each test provides insight into the controllability of the system using the SPHERES thrusters. Figure 2-5 shows the position of the free-floating vehicle during the initial positioning maneuver. During this test the vehicle was oriented such that the global $x$-axis is along the axial line of motion and the impinged thrusters for both units are along the global $y$-axis.

![Figure 2-5: Initial Positioning Results](image)

It is clear from this data, that the impinged thrusters had an impact on the controller’s performance. The position error in the impinged axis is an order of magnitude greater than the unobstructed axes showing that the hardware impingement does have a significant impact on the performance of the controller in the relevant axis. The initial placement by the astronaut has a greater importance in this axis due to the limited control authority of the SPHERES thrusters.

Analysis of the open-loop electromagnetic actuation maneuvers verifies that the system can generate both attractive and repulsive forces while firing thrusters for stabilization. Figure 2-6 shows the position of the free-floating vehicle in all three axes subject to different variations of thruster stabilization using the same commanded current. The electromagnetic force acts in the $x$-axis to attract and repel the vehicle in all three tests. In the 5-DOF thruster control case, the free-floating vehicle is able to complete both the attraction and the repulsion maneuver as shown by the green line in the top subplot. The ability to complete the repulsion maneuver appears to degrade as thruster stabilization is removed.
The \( y \)-position drifts in all three cases as a result of the impinged thrusters, while the \( z \)-position is well controlled throughout the majority of the test in all three cases. A plot of the attitude error for the same tests, shown in Figure 2-7, yields consistent results.

Open-loop electromagnetic actuation tests were also performed in the shear configuration, where one coil is set perpendicular to the other producing torque and lateral force. Figure 2-8 shows the attitude and position of the free-floating vehicle as a result of electromagnetic
forces and torques in the shear configuration. The top subplot shows that the RINGS vehicle almost makes two full 180-degree rotations as a result of the electromagnetic torque generated from the coils.

The first science session for RINGS was successful in demonstrating the potential for electromagnetic formation flight through its display of attraction and repulsion maneuvers from both axial and shear configurations. In addition, the system identification tests were consistent with prior analysis and microgravity experimentation on the RGA flight. The results of the open-loop electromagnetic actuation tests were used by Alvisio in the verification and validation of the SPHERES-RINGS dynamics simulation that can be used for further control algorithm development on the testbed [20].

2.4 Science 2

The second RINGS Science session occurred on February 11, 2014 and was operated by crew members Michael Hopkins and Koichi Wakata. The objective of the test session was to demonstrate closed-loop control maneuvers using electromagnetic actuation with two vehicles that were both free to move within the test volume. The team was unable to use the control methods developed by Buck [19] and Eslinger [15] in this test session because they were not ready for implementation in the near-field and on the SPHERES-RINGS system.

Figure 2-8: Motion of Free-Floating Vehicle during Electromagnetic Actuation from a Shear Configuration
Instead, the team focused on a closed-loop controller for the simple axial case that uses the near-field dynamics model that Buck developed in his work. To simplify the experiments, electromagnetic force controllers were designed for the axial configuration assuming that the thrusters could be used to maintain the alignment of the coils so that there were no electromagnetically induced torques.

![Figure 2-9: RINGS Science 2](image)

### 2.4.1 Position Control Law Development

For the axial case, the only degree of freedom that needs to be controlled by the coils is the one along the line connecting the two satellites. The goal is to use the electromagnetic force generated by the coils to control the separation distance. Figure 2-10 shows a diagram that can be used to develop the control law. The symmetry that results from the conservation of energy in the two-coil system enables the control to be executed from the reference of the

![Figure 2-10: RINGS Position Control Formulation for the Axial Case](image)
primary RINGS (red) unit while the secondary RINGS unit (blue) completes the complementary motion. The control input is the force generated by the coils, shown as positive for a force that increases the separation distance. The state, $x$, is defined by the half of the separation distance that the primary RINGS unit is responsible for. The transfer function that describes the dynamics of the primary RINGS coil is shown in Equation 2.5.

$$G_p = \frac{x}{F} = \frac{1}{ms^2}$$

A PD controller was used to determine the force required to correct the separation error. This controller was selected because of its heritage on the SPHERES testbed as well as its fast response time and low overshoot. The PD control law is shown in Equation 5.1 where $K_p$ and $K_d$ are the position and derivative control gains, and $x_e$ and $\dot{x}_e$ are the primary unit’s half of the separation distance and separation velocity errors.

$$F = K_p x_e + K_d \dot{x}_e$$

The gains were selected using MATLAB’s PID tool function using the plant transfer function shown in Equation 2.5. Two different sets of gains were selected to create a ‘fast’ case and a ‘slow’ case. Though the faster performance is preferred, it was a concern that a fast moving system would prevent the 1Hz frequency of the RINGS mixer from updating the actuator dynamics appropriately. Table 2.4 summarizes the gains chosen and their expected performance.

<table>
<thead>
<tr>
<th></th>
<th>Gains</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Case</td>
<td>0.238</td>
<td>5.355</td>
</tr>
<tr>
<td>Slow Case</td>
<td>0.080</td>
<td>2.408</td>
</tr>
</tbody>
</table>

Throughout the maneuvers, the secondary RINGS unit is held to a constant current, $i_2$, while the electromagnetic mixer is configured to output the desired current of $i_1$ in response to the commanded force and current separation distance. The purpose of the mixer is to account for the nonlinear dynamics of the system so that the linear PD control could be used.
The RINGS mixer is a function $i_1 = f(F, d_{rel})$ that is derived from the RINGS near-field model. The function is created by using a polynomial fit of data from the RINGS axial case generated by Alvisio [20] and Buck [19]. Figure 2-11 shows a diagram of this control scheme.

![Figure 2-11: RINGS PD Control Strategy](image)

The two different sets of control gains were included in the test plan for this test session in order to determine which performed better in the flight environment. For each set of gains, the current on the secondary coil, $i_2$, needed to be set low enough that the controlled current, $i_1$, didn’t exceed the current limit for the hardware. Conversely, an $i_2$ value that was too high would result in $i_1$ operating at very low currents throughout the test.

### 2.4.2 Attitude Control Law Development

In order to maintain the axial configuration, the attitude control law is designed to maintain an attitude that keeps the vehicles facing each other. Though thrusters are used for attitude control on the SPHERES satellites, this strategy could be implemented using a reaction wheel assembly or control moment gyroscopes on future electromagnetic formation flight vehicles.

In order to keep the coils facing each other, the attitude controller was designed to align each satellite’s y-body axis with the line between the two satellites as shown in Figure 2-12. The red line on Figure 2-12 is the difference between the global position vectors of
the two satellites. Using the rotation matrix shown in Equation 2.7, this center-line vector can be converted into the coordinate frame of the SPHERES satellite using the quaternion components of its state vector.

\[
M_{12B} = \begin{bmatrix}
q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\
2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 + q_1q_4) \\
2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2
\end{bmatrix}
\] (2.7)

With the target vector in the coordinate frame of the SPHERES satellite, the rotation error becomes the rotations needed to align the y-body axis with the center-line vector. Figure 2-13 diagrams this process using a 321-Euler Angle rotation. The first section on the left shows a projection onto the XY-plane. From the projection it is easy to see that the first rotation is the arc tangent of the x and y components of the target vector in the body frame. Therefore the first rotation about the z-axis is \( \theta_{Z_e} = -\text{atan2}(X_{tgt}, Y_{tgt}) \). The y-rotation is chosen as zero because rotations about this axis do not help the RINGS units face each other. The section on the right of Figure 2-13 shows the system projected into the
Y’Z-plane where Y’ is the y-body axis of the vehicle after the first rotation (shown in the second segment of Figure 2-13). The relationship between Y’ and the original Y axis is used to determine the final rotation as \( \theta_X = \text{atan2}(Z_{tgt}, Y_{tgt}\cos(\theta_Z)) \). The rotation error is then converted into a quaternion using Equation 2.8.

\[
q_e = \begin{bmatrix}
q_{e1} \\
q_{e2} \\
q_{e3} \\
q_{e4}
\end{bmatrix} = \begin{bmatrix}
sin(\theta_X/2)\cos(\theta_Z/2) \\
sin(\theta_X/2)\sin(\theta_Z/2) \\
cos(\theta_X/2)\sin(\theta_Z/2) \\
cos(\theta_X/2)\cos(\theta_Z/2)
\end{bmatrix}
\]  

Equation 2.9 shows how the error quaternion and angular rates can be used in a quaternion feedback-controller developed by Wie [33] where the control gains are developed using the same linear methods used for the PD position controllers.

\[
\tau = \begin{bmatrix}
\tau_x \\
\tau_y \\
\tau_z
\end{bmatrix} = K_{3x3} \begin{bmatrix}
q_{1e} \\
q_{2e} \\
q_{3e}
\end{bmatrix} + C_{3x3} \begin{bmatrix}
\omega_{xe} \\
\omega_{ye} \\
\omega_{ze}
\end{bmatrix}
\]  

2.4.3 Experimental Results

The RINGS Science 2 session encountered many difficulties in obtaining clear results due to a combination of a software bug affecting the initial positioning maneuver and a data downlink failure on tests conducted between two satellite resets. From the data that was gathered, the controller results show that the separation distance and relative attitude can only be controlled for short amounts of time before becoming unstable.

Figure 2-14 shows the relative separation and attitude of the two satellites during an attraction maneuver. As the satellites approached their target separation distance, their relative attitude became more unstable due to electromagnetic torques that overcame the thruster attitude control. In the repulsion case, the opposite is true. As the satellites approach their separation target, the attitude error converges to zero as shown in Figure 2-15. There are two main reasons for this difference. The first is that the electromagnetic torques generated by the RINGS coils are higher at closer separation distances. Therefore,
the magnitude of the torques that the thrusters need to overcome increases in the first case yet decreases in the second case as the satellites approach their respective targets. The second reason comes from the force needed to slow the vehicles down as they approached their targets. In the first case that force is a repulsion force and in the second it is an attractive one. In order to understand the impact of this distinction on attitude control, it is useful to look at a simplified equation derived from Schweighart’s [14] far-field EMFF equations. The torque in any axis can be generalized as shown in Equation 2.10 where \( f(\theta_e) \) is some function that depends on the relative angular error in the same axis as the torque.

\[
\tau = -\frac{1}{4\pi} \frac{\mu_0 \mu_A \mu_B}{d^3} f(\theta_e) \tag{2.10}
\]
From Equation 2.10 the relationship between the angular error and the sign of the torque can be determined for both attraction and repulsion cases. A summary of these relationships is provided in Table 2.5. The pattern shown by Table 2.5 is that when attraction is used to slow the system down, the induced electromagnetic torque stabilizes attitude by opposing the angular error. When a repulsive force is used, however, the electromagnetic torque destabilizes attitude by contributing further to the angular error. In future control development, it is important that boundary conditions be placed on the induced electromagnetic torques so that the supplemental attitude control can compensate effectively. Instead of assuming that electromagnetic torques are zero, calculating the expected induced torque and feeding that forward to the attitude controller would also improve the attitude control performance in maintaining the axial configuration.

The results of the test session reveal that the team was trying to take too far of a step forward in its development. Using two free-floating satellites and attempting closed-loop control with the coils increased the complexity of the problem in a way that the team was unprepared to manage in the available time. Furthermore, the absence of a validated model resulted in control strategies that were not entirely thought out as well as ground verification that was not thorough enough to catch a software bug that negatively affected the session and its results.

### 2.5 Science 3

The third science session took place on July 10, 2014 and was operated by crew members Alexander Gerst and Gregory Reid Wiseman. The goal of this test session was to gather the remaining data needed to finish the validation of the dynamics simulation and begin
retesting closed-loop control methods that were revised from the previous session. In order
to reduce the complexity of the tests, one of the vehicles was restrained with a tether.

The data gathered during the first science session was unable to completely validate the
dynamics simulation because of a firmware error that prevented the coils from maintaining
their phase during a repulsion maneuver. After the firmware error was corrected, data
needed to be gathered to complete the simulation validation process. Open-loop electromagnetically actuation tests were planned for repulsion and attraction at different separation
distances. Detailed information on the validation of the RINGS simulation can be found
in Alvisio’s thesis [20]. To incorporate the lessons learned from the second science session,
closed-loop tests were planned that involved incrementally progressing from initial positioning
with thrusters to a position hold using the coils, followed by a small step input using the
coils. These tests were designed to be repeated at different separation distances.

2.5.1 Experimental Results

During the test session, the free-floating satellite had trouble positioning itself in front of the
tethered satellite using the thrusters. It was determined that this only occurred in tests that
used relative positioning rather than absolute positioning, revealing that the underlying issue
was in the state estimation of the tethered satellite. Post-processing of the data confirms
this as the cause. Figure 2-16 shows one of these tests during the initial positioning phase.

The red line shows the estimated position of the Red SPHERES Satellite (free-floater),
while the blue line shows the estimated position of the Blue SPHERES Satellite (restrained).
The target state for the Blue Satellite is 80 cm separation in the x-axis and alignment in the
y and z-axes. From the plot it can be shown that the Red Satellite is correctly positioning
itself relative to the Blue Satellite according to the estimated state of the Blue Satellite. In
the test configuration, the Blue Satellite is restrained so that its position should not change.
The motion of the Red Satellite shown in the plot is consistent with the motion of the Red
Satellite shown in the video feed from the test, confirming that the state estimation of the
Red Satellite is functioning correctly.

In the y and z-faces, it is possible that the RINGS hardware blocked the direct path
from certain beacons to receivers on the restrained satellite as shown in Figure 2-17. To
mitigate the state estimation instabilities caused by ultrasound outliers, Nolet implemented
pre-filtering rules that removed outliers among the 24 measurements collected for each beacon
ping [5]. Of these rules, the ones most applicable to this case are:

1. If the angle between each receiver and the line-of-sight to the beacon exceeds 35 degrees,
it discards the corresponding measurements.
2. If fewer than three valid measurements are collected on one face, it discards all four measurements on that face.

3. It keeps only the ones corresponding to the face closest to the beacon (which presents the lowest TOF data).

From Figure 2-17 it can be seen that both Beacons 1 and 5 should have consistent, successful ultrasound measurements on the forward face. With Beacons 2, 3, and 4, however, it is unclear how consistent successful measurements are. Each beacon would need to have 3 successful measurements on one out of two faces that are each obstructed in some way by the RINGS hardware in order for that face’s measurements to be passed to the estimator. If only measurements from Beacons 1 and 5 are accepted, then the satellite can estimate its position on any point along a circle created by the intersection of the two range measurements. In this case, it is expected that the state estimate will vary in the Y and Z-axes much more than it does in X-axis, and that those variations will be symmetric. The data shown in Figure 2-16 follows this pattern.

It is important to note, however, that this anomaly only appeared in the Science 3 session and was not apparent in the Science 1 session where one satellite was also tethered. Figure 2-18 shows that the position estimates of both satellites during a RINGS test from the Science 1 session are stable throughout both the thruster positioning phase ($t < 75s$) and the electromagnetic actuation phase ($t > 75s$).

![Figure 2-18: RINGS Science 1 Position of Both Satellites](image-url)
In addition, similar estimation anomalies occurred with the Zero Robotics (TS61) and VERTIGO (TS63) projects before and after the RINGS session (TS62). Such anomalies in these sessions point to a cause other than ultrasound obstruction because VERTIGO has ultrasound bypass lines to the satellite and Zero Robotics uses only the SPHERES satellites. In TS66, Metrology Checkout, it was discovered that one of the recently updated GLAs (General Luminaire Assemblies) was emitting an infrared signal that was interfering with the satellite’s metrology. The offending GLA was turned off for the Zero Robotics Middle School Finals, as well as the High School Unit Tests, Dry Run, and Finals, with successful results. It is unclear whether or not this change will solve the estimation instabilities completely, because a test has not been run with RINGS on ISS since the third science session. It is possible that in certain positions, the SPHERES-RINGS system will still experience estimation instabilities due to hardware obstruction.

2.6 RINGS Campaign Summary

The RINGS testbed was the first long-duration, microgravity testbed for electromagnetic formation flight control algorithms and the first to demonstrate the potential for the technology in the 6-DOF environment. In addition to the complexity of these control methods, there were also many programmatic challenges that the project faced in its pursuit of its science objectives. Table 2.6 summarizes the results of each RINGS test session relative to

<table>
<thead>
<tr>
<th>Gap (Weeks)</th>
<th>Plannned</th>
<th>Actual</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Checkout</td>
<td>N/A</td>
<td>N/A</td>
<td>Hardware Checkout using Expansion Port Data, Hardware Checkout, Wireless Power Transfer</td>
</tr>
<tr>
<td>Science 1</td>
<td>1</td>
<td>10</td>
<td>Wireless Power Transfer, Relative Stationkeeping, Mass/Thruster ID, Axial &amp; Shear Open-Loop Electromagnetic Actuation Tests</td>
</tr>
<tr>
<td>Science 2</td>
<td>6</td>
<td>14</td>
<td>Rotational Control, Axial Closed-Loop Electromagnetic Actuation Tests</td>
</tr>
<tr>
<td>Science 3</td>
<td>6</td>
<td>21</td>
<td>Finish Objectives, Additional Model Validation Tests, Axial Closed-Loop Electromagnetic Actuation Tests</td>
</tr>
</tbody>
</table>

Red: Objectives that were not successfully accomplished.
the planned objectives in the project contract. Each test session required more time than originally planned and, in most cases, the objectives were reduced in scope. Even with the reduced scope, some of the goals in each test session were not achieved. The RINGS testbed failed the Checkout session because the tests revealed that there was a firmware error preventing the RINGS units from synchronizing with each other. The session was also incomplete in that it did not comprehensively test the operational modes that were needed for future science sessions. The research team was able successfully demonstrate Wireless Power Transfer capability using the RINGS coils during the Checkout session. The Science 1 session was successful in executing the system identification and open-loop electromagnetic formation flight tests. The second science session faced more challenges in successfully demonstrating closed-loop control with electromagnetic actuators. The electromagnetic torques induced by the RINGS coils overcame the attitude controller’s ability to maintain stability. The Science 2 session also faced challenges due to the absence of a validated simulation and the presence of a firmware error that degraded repulsion performance, revealing the accumulating consequences of unresolved errors from the previous two sessions. Finally the third science session showed that even when the test session is well planned to achieve its objectives, well tested on the ground hardware, and is simulated on the simulation, the success of the session can still be compromised by external factors in the environment that the testbed operates in. The next chapter focuses on identifying the underlying causes in the development and execution of the test campaign that led to these results so that lessons can be learned and applied to future flight programs.
Chapter 3

Lessons Learned from the RINGS Project

3.1 Overview

The purpose of this chapter is to identify the decisions, habits, and practices that led to the results of the RINGS operational campaign so that future flight projects can benefit from the lessons learned. The following sections provide more detail into each test session and the lessons that can be learned from their execution. There is also a section on ground testing lessons learned that express the importance of preparing for flight success using comprehensive verification in conditions that are as close to the operational conditions as possible.

3.2 Checkout

The purpose of a checkout session is to verify the proper functionality of the system and its potential to complete future science objectives. The test plan for the checkout session included tests were only designed to accomplish the first half of that purpose [29]. During the session, the hardware failed the functional tests because the RINGS units were unable to synchronize their current waves properly using the infrared pulse from the SPHERES satellite when in electromagnetic formation flight mode. More importantly, the functional
tests were incomplete because they did not include tests that verified that the phase of the current was executed as commanded by the software in repulsion mode.

The results of this session were caused by a focus on task-completion without a strong understanding of the purpose of those tasks. The test session was developed and tested by two graduate students, one with six months on the project and the other with 5 weeks. More important than the time on project, though, was the nature of the experience that focused on execution at a detailed level rather than a holistic understanding of the project. The two graduate students who led the project for the previous two years were unable to transfer enough of their project-level knowledge during the overlap period or in the documentation such that new students could effectively lead the project’s operations. This lack of understanding of the purpose for their tasks led to a test plan that didn’t directly push towards the completion of the objectives. **It is important to emphasize the purpose of the tasks within a project rather than simply emphasizing the completion of tasks.** The task-focused mentality caused the two students to base their tasks off of the primary source of documentation they had on a RINGS checkout, the Flight Hardware Assembly Checkout [34]. Developing a checkout session for its own sake meant that tests were designed to accomplish many of the same functional checks that were previously completed prior to flight hardware delivery without direct connection to future sessions and science objectives.

Hindsight reveals that these tests didn’t completely verify the functionality of the hardware because it did not catch firmware error that overwrote the phase value during repulsion maneuvers. Both the ISS checkout and the Flight Assembly Checkout didn’t verify that the RINGS units could command current magnitude and phase correctly. This occurred because of an implicit assumption that the attraction and repulsion case are similar enough that directly verifying either case is sufficient to verify both cases (See Section 3.6: Ground Testing). The discovery of the synchronization error in the firmware might have flagged the team to revisit the assembly checkout and ISS checkout to look for other aspects of the system that were not adequately checked, specifically checking for items related to the current phase. Instead, the team only used tests in attraction mode to debug and ‘patch’ the synchronization error because there was not enough time to exhaustively investigate the firmware as development of the next session had already begun.
3.3 Science 1

The Science 1 session was successful in accomplishing all of its objectives during the test session. All of the Mass Identification tests were successfully executed and the Open-Loop Electromagnetic tests were executed with all three variations of thruster stabilization. In this test session, the team learned the importance of utilizing ‘back-up’ tests that enable the completion of objectives in the event that the nominal tests do not perform as planned. For the Open-Loop Electromagnetic tests, the back-up versions included different profiles of commanded current that could be used if the units collided or didn’t move far enough during the nominal case.

Though the test session went well, the team had difficulty in drawing conclusive results from the data after the session. In order to maximize operational time, tests were designed that included combined use of attraction, repulsion, and thruster forces. Though this improved the overall stability of the system, having all three force factors in the same test made it difficult to determine which one was responsible for the output effects. This difficulty delayed the simulation validation process because the team spent more time trying to determine the reason why the flight data did not match the simulation data. This experience stresses the importance of designing tests that help the researcher quickly analyze the data and generate clear results. In order to maintain the time advantage that comes with combining multiple factors into a single test, the RINGS project could have maintained independence by downlinking data that allowed the team to distinguish between attraction, repulsion, and thruster forces such as the thruster firings times, or the current phase angle. If the data downlink bandwidth is a limiting factor, the test could have separated the maneuvers by including a ‘coasting’ maneuver for a few seconds that would appear in the position data as a linear slope.

3.4 Science 2

The second science session was unable to meet its objective of demonstrating system stability using closed-loop electromagnetic control. The simplifying assumption to de-couple the
position and attitude control proved to be inadequate as the electromagnetically induced torques often overcame the thruster attitude controller. Furthermore, inadequate ground testing resulted in a software bug in initial positioning that made it very difficult to control the initial conditions of the electromagnetic actuation maneuver. This session is significant because it shows the results of accumulating deficiencies from previous sessions. Going into Science 2 the RINGS project lacked a complete system checkout and a validated simulation, both of which should have been completed at this point.

The validation of the simulation using Science 1 data was taking longer than expected, prompting the graduate student team to split and have one continue working with simulation and the other work on controllers and test designs in order to deliver on time for the Science 2 deadline. The issue with this is that the controller development was completed without the simulation, requiring a simplification of the problem that wasn’t appropriate for electromagnetic dynamics. Since the simulation wasn’t ready by the flight software delivery deadline, the controllers were never evaluated thoroughly prior to delivery and the simplifying assumptions were never tested. The pressure to deliver the next test session by the given deadline resulted in an attempt accomplish the next objectives despite the inability to complete necessary steps to build off of the results from previous testing. Figure 3-1 shows a control block diagram that highlights how the Science 2 session focused on designing the controllers (orange) without fully characterizing components used by the controllers to affect system plant.

Much of the pressure came from a focus on data acquisition rather than data analysis and results. The iterative research process, however, requires both the acquisition of data and the analysis of data to generate useful results that feed into the next test session iteration. Estimating the time required to generate those results can be difficult, especially when the actual results deviate from the expected results. Due to the ISS office preference for planning sessions before the data was gathered and analyzed, the estimated development timelines for each session only accounted for results analysis in the nominal case plus an added buffer that was not enough to complete an in-depth analysis of the data when unexpected results surfaced. Successful data acquisition became synonymous with successful test session, assuming that successful results would inevitably follow. In many cases the timelines were so
tight that the research team had already been deep into the development of the next session before data from the previous session had even reached them. Figure 3-2 shows a comparison of each activity and its desired result based on relationships shown in Figure 3-1. Comparing each activity with its result highlights the issue in the trend towards defining success as the completion of the activity rather than the achievement of the result. It is clear to most that it is not the demonstration of open-loop control that enables closed-loop control, but it is the characterization of the system response to the inputs given to the actuator so that that knowledge can be used to design controllers that command inputs to achieve desired system responses. Closed-loop control is enabled by the results of open-loop control not
Experiment campaigns on ISS should be planned based on the results of previous tests not off of their completion.

In order to help shift the emphasis towards results, researchers need to think about how they can reduce the time between test session completion and having confidence in whether their results are expected or unexpected. The RINGS team had a good understanding of what they expected to see, but placed less emphasis on responding to unexpected results. The allocated schedule buffer proved to be insufficient to respond to the unexpected results because the buffer was not determined with specific unexpected possibilities in mind. Had the Open-Loop EMFF test results matched the expectation, the team would have moved on and there would have been less schedule pressure. The problem arose when the results were not consistent with the expectation and the team realized that they had less data than they needed to clearly determine the cause. This realization did not occur until weeks after NASA had already started planning the next session, shifting the pressure and focus to the execution of that session rather than the reconciliation of the working theory with the previous data. By identifying the need for more time earlier in the process, the research team could have requested a delay for the next session before NASA started planning.

Figure 3-3 summarizes these two ideas in the context of the iterative research process. The goal is to shorten or reverse the time between the key points shown by the stars:

![Iterative Research Process](image)

Figure 3-3: Iterative Research Process

NASA’s decision to start planning the next test session and the point where the research team knows whether the hypothesis can be confirmed or not. This should be approached by
both sides in order to be effective. NASA should reframe its definition of success to focus on consistent results, not simply data acquisition, as the condition for moving on. **The research team should design experiments and have a data analysis plan that identifies unexpected results as soon as possible, so that a request for more time could be made during the experiment or very soon after the data acquisition.**

The RINGS project used test result codes to help troubleshoot tests during the session, but all of the error codes were related to the system’s ability to successfully acquire the data not on whether that data was consistent with the expected result. In some cases it will be obvious, such as when the RINGS units are unstable or have crashed into each other or the outside of the volume. For many of the Open-Loop EMFF tests, though, the RINGS units seemed to be performing correctly in the video feed and only analysis against the simulation revealed an inconsistency. Having predetermined error ranges programmed into the test and using result codes to communicate that information to the ground team would enable a better understanding of the session’s success with reference to the expectation rather than simply knowing that the tests proceeded through their steps correctly.

### 3.5 Science 3

Learning from many of the lessons discussed in the previous three sessions, the third science session was designed to gather data for simulation and test closed-loop EMFF in a more incremental fashion. Unfortunately, Science 3 showed that the operational environment can still prevent a team from achieving its goals despite that preparation. It is important, therefore, to spend time understanding the status of the operational testing environment by following the results and challenges of other test projects that utilize the same facilities. In the case of RINGS Science 3, the Zero Robotics Middle School Unit Tests had similar metrology issues that could have given the RINGS team reason to either postpone the session or spend the first part of the session characterizing the facility to determine the cause.
3.6 Ground Testing

In addition to the lessons learned related to flight experiments and preparing for unexpected results, it is also important to acknowledge the lessons learned from ground testing with the RINGS project. In the case of the firmware error, the unexpected results weren’t the result of microgravity dynamics and therefore could have been detected and resolved through ground testing. Though the lessons learned are still valuable for future flight programs, it is obviously preferred that they are utilized for unexpected behavior that occurs from the microgravity environment and not by errors that could have been resolved earlier.

As mentioned earlier, the underlying assumption that prevented the detection of the firmware error was that both attraction and repulsion were the same software function and therefore only needed to be verified in one mode. Figure 3-4 shows the propagation of the firmware through each test session under this assumption. Based on the checkout session, the team thought that the only issue was that the firmware was unable to synchronize the current correctly. In reality, that error existed in addition to an error causing the phase command’s memory location to be overwritten by zero in a non-deterministic fashion. Since zero-phase is attraction, this error was undetectable by running only attraction tests. The error was not detected until after Science 2 when the team used an oscilloscope to measure the instantaneous current driven by each coil. Looking back at the assembly checkout procedure, it can be seen that no repulsion test were run at all. Even for the attraction tests, the only method of verification was through the RMS current shown by the LCD screen providing

Figure 3-4: RINGS Firmware Status by Session
no information about the phase or confirmation that the coils are in attraction or repulsion mode. *To be comprehensive, the ground testing should include all system modes and states that will be used in flight and a verification method that provides enough information to conclusively determine that the tested component or system is functioning correctly.*

As the deadline for the checkout session approached, the team began to defer tasks that did not need to be accomplished prior to flight software delivery to a later date. One of these tasks was the development of the data parsers used to analyze the RINGS data downlinked through the SPHERES satellite. The communication path from the RINGS unit to the SPHERES satellite to the laptop was verified, while the parser was left to be completed in the ‘down’ period between the delivery of the software to NASA and NASA’s delivery of the flight data following the test session. The ground units passed the functional tests already, and it was assumed that the only reason the flight units would not pass during the session was if something was damaged during the launch. The difference between the ISS checkout and the flight assembly checkout, however, was that in the ISS version the RINGS units would save and downlink the entire current waveform at the end of select tests rather than sending the RMS values in real-time as they do in nominal tests. When the data parser was developed during the down period using data generated on the ground units, the team realized that the RINGS firmware was not correctly synchronizing the current waves on each infrared pulse. *End-to-end tests should be completed on the ground that include inspection of the generated data.* This not only confirms that the data is being generated and parser correctly but provides insight into errors that may not be obvious from watching the hardware operating on ground.

Another ground testing lesson that comes from the Science 2 session is that the *ground verification environment should mimic the flight conditions as best as possible.* Even though the team did not have a validated EMFF simulation at that point, there were other ways in which the team could have verified their software that were more ‘flight-like’ than simply using the ground hardware units in a static configuration while watching for thruster firings and timeout conditions. Holding the units in their initial placements and guiding them through their expected motion as thrusters fired would provide the ability
to check both estimator convergence and correct state targets. The size and weight of the
RINGS units was the major hinderance to completing this type of verification because it
was difficult to physically hold the units in the middle of the volume. Considering this
limitation, the SPHERES simulation (with updated physical properties for RINGS) could
have been used to validate the dynamical behavior of every part of each test that did not
use electromagnetic forces without the burden of having to hold the units. This would have
also verified that the software was programmed correctly.

3.7 Summary of Lessons Learned

This section summarizes the lessons learned presented in this chapter from the RINGS
operational experiment campaign. They key lessons learned are:

- It is important to emphasize the purpose of the tasks within a project rather than
  simply emphasizing the completion of tasks. Although this lesson was learned through a
  personnel transition within the RINGS program, it really should be applied to everyone
  on a team that is striving towards the same objective.

- Experiment campaigns should be planned to incrementally improve off of the results of
  previous tests and not simply off of their completion. Though this seems like common
  sense, planning for operational testing often requires large lead times pushing the
  researcher to declare success before the complete results may be known.

- In order to aid the operational planners, the research team should design experiments
  and have a data analysis plan that identifies unexpected results as soon as possible so
  that a request for more time could be made during the experiment or very soon after
  the collection of data.

- To be comprehensive, the ground testing should include all system modes and states
  that will be used in flight as well as a verification method that provides enough infor-
  mation to determine that the tested component or system is functioning correctly.
• End-to-end tests should be completed on the ground that include inspection of the generated data. If you cannot get the data you need from the experiment, then there isn’t much value in running the experiment at all.

• The ground verification environment should mimic the flight conditions as best as possible. Though this is challenging when working with the space environment, hindsight shows that there were more creative ways in which the RINGS program could have verified their flight software prior to flight.

Each step in the technology development process is challenging as the new technology is refined and demonstrated in increasingly more relevant applications and environments. When experimenting in the operational environment for technology demonstration purposes, progress is made by analyzing and responding to behavior that might not have been apparent based on studies outside of the operational environment. The lessons learned from the RINGS project will help future projects better prepare to meet these challenges by focusing on the objectives, learning quickly from the unexpected, and by thoroughly preparing before the flight experiments.
Chapter 4

Performance-Driven Experiment Framework

4.1 Overview

The lessons learned from the RINGS project present a need for a framework for experimentation for space technology development in operational environments such as the International Space Station. This chapter presents an experiment framework for operational space technology development that focuses on incrementally advancing new technology by clearly defining results that lead to the completion of objectives for each increment and efficiently designing experiments to achieve those results. The achievement of results that lead to the completion of the objectives, rather than the schedule, is the primary driver in determining how to progress through the experiment campaign. By reducing the need for re-testing, this framework should result in a completion of the objectives in a shorter timeframe when compared to the schedule-driven approach used in Chapters 2 and 3.

In any project the cost, performance, scope, and schedule all need to be traded against each other based on the priorities of the stakeholders involved while also considering the personnel and infrastructure used to accomplish the project. This relationship is shown geometrically in Figure 4-1 in the form of a triangle with performance, cost, and schedule as the sides and the project scope as the area of the triangle. Heagney’s book on project management offers ways to plan projects while trading these four criteria against each other.
This chapter addresses what happens to the cost, performance, schedule, scope relationship during the operational phase of the project, long after the creation of the project plan. Changes in personnel, the funding landscape, and unplanned surprises between the creation of the plan and the project operations all contribute to the plan’s inadequacy to reliably define appropriate priorities. Estimates in the plan based off of specific personnel and knowledge available at the time are guaranteed to be inadequate in the face of these changes.

Once the plan is created, each component is documented in some sort of artifact. For example: the schedule could be in a gantt chart, the cost in a budget, and the performance in a requirements document. Of those three, the requirements are often the most vague and difficult to understand. Pressure from clear deadlines can result in a narrow, task-focused mentality that leads to an interpretation of the less clear expectations for each step that may not actually accomplish goal of the operations campaign. The Performance-Driven Experiment Framework reverses this natural tendency by clearly defining objectives at each step in the incremental technology development cycle, including how each successive increment is enabled by its predecessor, while vaguely defining the schedule so that it enables adequate planning without negatively impacting performance.

The experiment framework can be divided into three major steps which are listed below.

1. **Determine the End Points** by defining the experiment campaign objectives and understanding the current state of the system.

2. **Create an Experiment Campaign Plan** by breaking down the objectives into
tasks using a Work Breakdown Structure, sequencing the tasks, and defining the result required to enable successive tasks.

3. **Design the Test Session** to achieve the next set of results in the plan by developing tests that enable the completion of those results through the gathering of data that can be used to confirm the hypothesis as well as the data to update the theory in response to unexpected behavior.

The following sections within this chapter describe these steps in more detail, drawing on methods from the fields of project management, systems theory, and design of experiments to form a coherent process that guides the researcher from the creation of objectives through the test-level design that achieves them.

### 4.2 Determine the End Points

#### 4.2.1 Define the Objectives

The first step in designing an operational experiment campaign is to develop a shared understanding of where the project is going by developing the campaign objectives. This crucial step is often overlooked because team members tend to overestimate their collective understanding of the project’s destination. People do not want to take time away from real work to discuss something that everybody clearly understands. Individuals’ task lists are already piling up and they don’t have time to discuss goals. This is a mistake because the way in which the problem is defined influences the way it is solved. Different problem definitions among team members, different teams, or departments will result in diverging paths that almost certainly lead to project failure. Furthermore, clearly defined goals allow teams to determine which tasks to engage in and which tasks *not* to engage in. To be effective and useful, objectives must be simple enough to be communicated clearly yet specific enough to be actionable.

For technology development missions, mission objectives can include the demonstration of the technology in applications relevant to future missions, the performance characterization of the technology that shows advantages over current technologies, the validation of the model...
representation for that technology, or any other achievement that would reduce the risk of using the technology by increasing understanding of it. Technological development stages are most commonly quantified using Technology Readiness Levels (TRLs) that measure the maturity of a technology and the associated risks with deploying that technology.

Once the mission objective has been found, it is important that it is translated into an experiment campaign objective and communicated in a way that facilitates a clear understanding among the team. One way to do this is to have each team member reduce the objective statement into the simplest terms by continually asking “what?” at each level. Consider the following objective statement for an emerging technology:

*Mature the technology to TRL 6.*

The first reduction of the objective statement is completed by asking “what does TRL 6 mean?”

*Complete a prototype system demonstration with this technology in a relevant environment.*

At the operations phase it is assumed that the project hardware is already en route to the International Space Station, so the prototype system becomes the project hardware and the relevant environment becomes the International Space Station. Therefore, the following reduction is prompted by asking “what demonstration entails?” This is where individual definitions are likely to diverge depending on their own experience with the project, in this particular research field, and even what section of the project they’re responsible for.

- Is a demonstration of the hardware functioning correctly in the microgravity environment or demonstration of its utility with the integrated system?
- How does the demonstration need to parallel future missions where this technology can be used?
- What conditions and applications best parallel those future missions?

Answers to these questions influence the types of experiments selected, the data gathered, and the time and resources put into the project throughout the experiment campaign. Recall
that objectives specify results that are needed to progress towards the completion of the project mission. Therefore, objectives must be clear enough so that each team member can clearly distinguish what needs to happen for the operations campaign to be successful. In order to review the experiment campaign objectives and ensure that they support the mission objective is to ask “why?” for each campaign objective. The answer for each one should in some way support the mission objective.

4.2.2 Understand the Current State

Once everyone on the team is moving towards the same destination, the next step is to make an assessment of where the system currently is. Specifically, it is important to understand any hardware challenges and the status of software development and testing for the components, subsystems, and integrated system. This becomes critically important if there are new team members working the project, or if there was a handoff from the flight hardware integration phase to the operations phase of the project. Even if the entire team is highly experienced, current state assessment should be performed before launching into the experiment plan.

The time taken for this assessment will vary depending on personnel, but it is important to allocate whatever time is needed even if it means pushing previously estimated milestones back. It should not be assumed that all of the software testing traditionally completed during flight hardware integration and delivery was completed correctly just because the project is no longer in that phase. The project may be under a tight schedule resulting in the attitude that there is no time to do things that were already completed during integration, an attitude that stems from the perception that the team barely has enough time to complete the operations tasks in the operations phase. If that pressure exists within the project’s operations development, it is likely that it also existed in during the flight hardware integration resulting in the deferment of tasks that were not absolutely required for flight hardware delivery. In this case the hardware may be delivered with a prototype version of the software that seems to work but was not exhaustively tested for operational cases that the system is expected to encounter—something that was deferred as an “after-delivery” task.

The goal is the gather documentation from past tests and procedures that allow the team to build an accurate understanding of the capability of the system. Some of the questions
that need to be asked to understand the current state are:

- What are the individual components and how were they verified before flight?
- How are they integrated into subsystems and how were their interactions verified?
- How was the fully integrated system verified?
- What are the differences between the ground and flight test environments?
- Were end-to-end tests performed that use the same input and output interfaces that will be used during the operational test sessions?
- What prior research or demonstrations have been conducted with this technology?
- Is there a simulation or model that has been developed? What are its limitations?

If the project has already had prior flight testing on the International Space Station or on a Reduced Gravity Aircraft, it's important to understand the experiments conducted, lessons learned, and results obtained.

The systems approach is one way to manage complexity and organize all of the information on the project. Ramo characterizes the systems approach as a technique for the application of a scientific method to complex problems that concentrates on the analysis and design of the whole as distinct from the components [36]. In the traditional scientific method, systems are broken into distinct parts that can be examined separately. This analytic reduction assumes that each of these distinct parts are truly independent in that the results are not distorted through the separate analysis of each part. For more complex systems, however, this assumption of independence is often invalid as there are many interrelated components within the system [37]. The general model of complex systems is expressed in terms of a hierarchy of levels of organization. At each level, properties emerge that do not exist at the lower levels. The property of ‘shape’ means nothing at the cellular level of an apple, but only at the level of the apple itself [38]. These emergent properties are lost when decomposing a system through analytic reduction.

Functional decomposition is the most widely used method of system simplification in the systems engineering of space systems. Functional decomposition involves separating
the system into different parts based on function. A satellite bus is broken into power, controls, avionics, structures, thermal, communications, and propulsion subsystems which can then be broken down further into components such as solar arrays, batteries, reaction wheels, gyroscopes, processors, mechanical parts, etc. In traditional systems engineering, requirements are flowed down from the highest level to the lowest level to design the system, and then tested from the lowest level back up to the highest level as the parts are integrated into the whole [39].

The systems approach can be used to develop mental models of the project. Since the models represent complex systems, it is expected that these models will become complex as well. The model can be filtered into application-dependent views that capture the relevant parts of the model while removing the irrelevant. Nightingale and Rhodes developed the use of ‘view-lenses’ that enable the simplification of complex enterprises, while maintaining the fidelity required for adequate analysis [40].

Many space technology development projects that utilize the microgravity environment of the ISS are related to testing new methods of propulsion or sensing and their associated control and estimation algorithms. Figure 4-2 shows an example of a control system view that shows the relationships between the different components. The command and data handling function is included as well because it is important to have a good understanding of how the control process is being commanded and what data is available to the researcher for analysis. The blue boxes highlight some of the questions that can be asked to gain a higher understanding of each component and its relationship to the whole system. It is suggested that each component be explored even further when working with specific testbed projects so that more details can be flushed out to develop an accurate understanding of the project status based on evidence in the form of analysis and prior experimentation.
4.3 Create an Experiment Campaign Plan

4.3.1 Determine Work Breakdown Structure

Armed with the operations objectives and knowledge of the current state of the system, an experiment plan can be developed that advances the technology through test sessions that successively provide more knowledge on the performance and limitations of the emergent technology in various scenarios that reflect future needs.

Starting with each objective, a Work Breakdown Structure (WBS) can be used to identify and organize tasks prior to their integration into a schedule. The WBS is used in project management to subdivide complicated tasks into smaller ones until a level is reached that cannot be further subdivided. For a simple example, Heagney [35] uses the ‘project’ of cleaning a room to illustrate how a WBS works (Figure 4-3). A WBS is primarily concerned with identifying all of the tasks and is less concerned with their sequence. Trying to determine the sequence at this stage can limit the team’s ability to focus on identifying all of the tasks that need to be accomplished.
4.3.2 Sequence Tasks

After the tasks have been identified, then the team can determine the sequence using an arrow diagram. An arrow diagram shows a graphical representation of the project plan while highlighting the sequence and relationships of the activities. Heagney offers two rules of thumb for turning a WBS into an arrow diagram [35]:

1. Choose Appropriate Level of WBS.
   It is not always appropriate to schedule activities at the lowest level of the WBS. Activities should not be scheduled in more detail than can be managed by the team. If the team meets weekly, scheduling tasks with hourly or daily durations does not make much sense. The higher level task is tracked on the schedule, while the responsible engineer for that task manages his or her time appropriately to schedule the subtasks identified at the lower levels of the WBS. That being said, scheduling at too high a level results in ‘back-loading’ the work because team members will believe they have a lot of time to complete that task and put it off in favor of more pressing tasks. Heagney suggests that no task should have a duration greater than four to six weeks.

2. Develop schedule according to what is logically possible, incorporating resource allocation at a later time.
   Though resource allocation is very important in the development of realistic schedules,
it should be ignored at this first stage. This enables the true sequencing of tasks based solely on their dependence from other tasks. If a team had a surplus of personnel, this would be the order in which all tasks could be accomplished.

Figure 4-4 shows an arrow diagram using the room cleaning example. Picking up toys and clothes before vacuuming makes sense so that the vacuum doesn’t pick up anything large that could damage it. Similarly, vacuuming occurs after dusting so that the vacuum can pick up dust that was brushed off of tables and desks onto the floor.

Though cleaning a room is a very simple ‘project’, this task breakdown and sequencing exercise will certainly be more difficult for breaking down space technology development objectives. The mental models developed using the systems approach should be referenced frequently when determining both the WBS and the sequencing of tasks needed to go from the current state to the completion of the operations objectives. These models will organize the relationships between components and subsystems in a way that aids in the task identification and sequencing steps.

4.3.3 Determine Desired Results

In traditional project management, the next step is to turn the arrow diagram into a workable schedule by estimating the durations of each task and using those estimates to determine the estimated completion date of the project. Instead of defining the individual tasks with respect to time, however, they will be defined with respect to their performance criteria.
This subtle difference results in the project being driven by its performance rather than its schedule ensuring that the project doesn’t advance to the next set of tasks without adequate preparation. In the room cleaning example, its likely not important whether the room gets cleaned in 30 minutes or in an hour. It is important, though, that the there are no toys or clothes on the floor so that the carpet can be vacuumed completely—a certain performance is required to enable the future task. It is recommended that performance criteria also be clearly defined for tasks that do not precede other tasks. The criteria will be consistent with the quality required to complete the the operations objectives, the final destination of tasks. For each task then, the success criteria is defined by the results that need to be achieved in order to enable the following tasks which ultimately lead to the completion of the operations objectives.

![Diagram of performance criteria for room cleaning example]

**Figure 4-5: Performance Definition of Room Cleaning Example**

Figure 4-5 shows an example of results for each task in the room cleaning example. Though transition from action to result seems obvious for this simple example, it is necessary to define each task in terms of its result to ensure that that result is actually achieved. The tasks involved with space technology development on the International Space Station are much more complex and it is often difficult to discern the desired result from the ‘action statement’ provided in the schedule. Under pressure from the specific (though estimated) timeline presented in traditional project schedules, the definition of results changes to what
can be accomplished in that time given the available resources as opposed to what needs to be accomplished. In the context of the room cleaning example, this difference can be seen in the choice between washing the walls once or washing the walls until there are no visible stains or streaks.

The same ideas apply in the determination of success criteria for experiment iterations as part of a technology development program. The purpose of an experiment in this context is to confirm predictions about the emergent technology that are based on the analysis, theory, and prior experiments in terrestrial environments. Therefore, the theory needs be updated to be consistent with the data gathered in previous iterations before making testable predictions for the next iteration. Furthermore, the predictions tested in the flight session need to be confirmed by analysis using models based on the updated theory as well as ground testing results (to the extent that this is feasible). Using the system diagrams developed in Section 4.2.2, a confidence check should be conducted on all components and subsystems that are utilized to achieve the next set of objectives. If there is low confidence in one or more components, this should be resolved through analysis, ground, or flight testing prior to moving on to the next iteration.

There is likely some concern at this point regarding the absence of deadlines from the operations plan. Parkinson’s Law states that work always expands to fill the time allowed [41]. Leaving the deadline unbounded would result in projects that take longer than they should and therefore cost more due to having to pay for more work-hours. Parkinson’s Law occurs because every person is balancing their own time, performance, resources and scope for each task they need to do in the same way they are balanced for a project. Assuming their resources or abilities are fixed in the near-term, having more time means that they will increase the scope and performance of their work on the task. People will take the time they have to turn in the best possible product for their boss and co-workers. If the performance and scope are defined and fixed, however, the team member will complete each task in the minimum possible time given his or her abilities and resources.

To develop an operations plan, the WBS is used to break down each objective into tasks that are successively broken down until they cannot be broken down further. An appropriate level of the WBS is chosen and those tasks are sequenced based on what is logically possible
resulting in a path the team can take to go from the current status towards the completion of the operations objectives. Finally, each task in the operations plan is defined in terms of the results that are required in order to enable the following steps ultimately leading to the completion of the objectives. The next section discusses the design of test sessions to enable the results needed for the tasks in the operations plan.

4.4 Design the Test Session

The purpose of experiments in the context of space technology development is to confirm a set of predictions about how a technology operates and performs in a specified natural environment. The process is iterative as both the predictions and the experiments are modified until the predictions are reliably consistent with the results obtained from the experiments. Testing in operational environments such as the International Space Station presents challenges to both the time and the manner of experimentation. Testing the full range of factors is infeasible given the high cost of microgravity test time. In addition, the remoteness of the laboratory results in the researcher having less control over the environment relative to terrestrial laboratories. The experiments must be designed to gather the necessary data despite this variability.

Design of Experiments refers to the process of planing, designing and analyzing the experiment so that objective conclusions can be drawn effectively and efficiently. The field originated through the work of Ronald Fisher but has grown over the last several decades into the most popular approach to experimentation. The basic principles of classical DOE methods are [42]:

- **Randomization:** Reduces the effects of experimental bias by averaging out the effects of noise factors that may be present. Randomization ensures that all levels of a factor have an equal chance of being affected by noise factors.

- **Replication:** Allows the experimenter to obtain an estimate of the experimental error as well as a more precise estimate of the factor or interaction effect. Replication achieves this by completing repetitions of an experiment, or a portion of an experiment, under
more than one condition.

- **Blocking:** By organizing experiments into blocks that contain a set of relatively homogeneous experimental conditions, the effects of extraneous variations can be eliminated thereby improving the efficiency and precision of the experiment.

- **Orthogonality:** When each factor can be evaluated independently of all other factors, orthogonal experiments reduce the number of experiments needed to evaluate all of the factors by matching each level of each factor with an equal number of each level of the other factors.

Experiment design for operations focuses primarily on being efficient with test time while ensuring that the necessary data is gathered. For technology advancement, the role of flight experiments is to confirm previous results with new results in a more representative environment or application. Alternatively, flight experiments can be used to discover characteristics about the technology that were undiscoverable in the previous test environments. Therefore the necessary data in each test is the data that enables these two roles. Determining the necessary data can be facilitated through a clear understanding of the following questions:

- What is the expected behavior?
- How will this test confirm that behavior?
- What information is required for confirmation?
- If there is unexpected behavior, what information is needed to update the previous theory?

The principle of *orthogonality* is used to minimize the test time required to meet objectives. Orthogonality enables the evaluation of multiple factors through a single test so long as the effects of each factor on the output is independent from the effects of all other factors used in the same test. Maintaining independence is an important criteria that needs to be met in order for this principle to apply properly. If many different functions of the system are tested simultaneously for the sake of time without maintaining independence, it will be difficult to diagnose the cause of any output that deviates from the expectation.
Each test session contains a set of tests that should advance the team towards the completion of its operations objectives. In order to achieve this, the tests should be linked to the tasks identified by the Experiment Plan derived in Section 4.3. An Objective-Test Matrix supports traceability between each test and the test session objectives defined by the tasks in the experiment plan. Such a matrix is useful in communicating which objectives are being addressed and how they are being addressed by the test session. The Objective-Test Matrix ensures that the entire objective space is covered appropriately by the test session. In addition, the matrix helps to increase efficiency by highlighting redundant testing that can be cut out to save time. For example, Figure 4-6 a matrix for a test plan involving a new robot system that is programmed to complete the room cleaning functions used in the prior examples. The rows show each test in the test session in addition to a summary of previous testing, while the columns show the objectives that the tests are being designed to address. In this example, the test session completes unit testing (one objective per test), then a partially integrated test that involves completing two tasks before beginning the third, and finally a fully integrated test that achieves all objectives in a single test. The Objective-Test Matrix allows the researcher to keep track of which objectives are being addressed in the test session and which tests are responsible for each one.

Figure 4-6: Objective-Test Matrix Example
Using the test plan, each test can be designed to meet their objectives. It is important to consider that the operational environment offers less control over the experiment conditions compared to other testbeds where the researcher has direct access to the experiment. The drive to design a test session to be time-efficient seems to oppose the drive to redundantly design the test session to accomplish its objectives in spite of lower levels of control and higher variability. One way to resolve this contradiction is to first design the test session efficiently and then add ‘back-up tests’ that support adaptability to the operational environment. For example: a test with successive maneuvers can consist of back-up tests that skip the first few maneuvers and start with the initial conditions that would exist if those maneuvers had been executed correctly. There is no need to run the test if the primary one is successful, thereby preserving the efficiency of the session. The key to achieving this is to incorporate real-time feedback in the primary tests that prompts the researcher to use one of the back-up tests because it was unsuccessful in getting the necessary data to complete its objective. A redundant design uses a ‘set it and forget it’ approach that broadly tackles variability by increasing the number and variations of tests to increase the probability of success. The time constraints typical of experiments on the International Space Station require a much more targeted approach that uses a design that supports adaptability and a research team ready to adapt in real time.

A key component of the experiment plan is that each experiment builds off of the results of the previous experiments in the plan. In order for this to happen, result indicators should be placed throughout the experiment that give the researchers insight into the performance of each test within the session. It is important that these result indicators be designed with the success criteria in mind. Using result indicators that confirm that the test was executed correctly does not provide any information on whether or not the data generated during the test supports the hypothesis. If it is not possible to include these feedback indicators on the experiment itself, a plan should be set in place that enables rapid confirmation of the hypothesis using the data. It is necessary that the result be known soon after the session’s execution in order to give the operations team enough lead time to plan a session. It is important to clarify that it is not necessarily the case that the team must rapidly reconcile the unexpected results, but rather report them such that the planning function can be
effective despite having to wait for the results of the session before moving on.

4.5 Summary

Traditional project planning approaches balance cost, performance, schedule, and scope according to the priorities of the stakeholders involved in the project. Due to the inherit clarity in deadlines and budgets relative to the inherit vagueness of performance specifications, projects tend to feel pressure to prioritize their original budget and schedule goals over their performance and scope goals when the estimates that the targets were based on prove to be inaccurate later in the project. This chapter proposes a planning method that clearly specifies the performance goals without specifically defining the schedule to reduce the negative effect that schedule pressure has on performance.

The first step is to develop a shared understanding of the operational campaign objectives that are simple enough to be communicated and specific enough to be actionable. The preferred method for writing objectives may vary among organizations, but the important
thing is that all stakeholders share the same understanding of the definitions and implications of each objective as well as the purpose behind that objective. This is important because the way in which the problem is defined influences the way it is solved. It is also important to have a strong understanding of the current status of the project hardware, software, and research. The systems approach can be used to create and share information about the project so that the capabilities of each component, subsystem, and the integrated system can be understood in with reference to evidence through analysis and testing.

To move toward the destination of the operations campaign, a Work Breakdown Structure can be used to identify tasks by breaking down large objectives into smaller and smaller tasks. These tasks can be sequenced to show the order that the tasks need to be completed in based on their dependency on other tasks. Instead of assigning an estimated duration to each task, it is recommended that success criteria be defined for each task that specifies the results that need to be achieved in order to be adequately prepared for the following tasks. Finally, tests are designed to achieve the results defined by each task on the path toward the completion of the operations objectives. The need to reduce test time on the International Space Station is balanced with the need to be adaptable to operational variability by designing feedback into the primary tests that allow the researcher to respond to the results with alternative tests that accomplish the objectives in a different manner. The feedback also supports rapid confirmation of results to give session planners enough lead time to respond to unexpected results if they occur.

Chapter 5 provides an example of this process on the Universal Docking Port (UDP), an upcoming addition to the SPHERES facility aboard the International Space Station designed to test autonomous docking and reconfiguration of satellite systems in order to support future missions in robotic assembly and repair on orbit. By stepping through each step in the experiment framework, the example provides insight into how the framework can be used to efficiently design an experiment plan that focuses on the accomplishment of its objectives in spite of unexpected results that occur on operations.
Chapter 5

Example using the UDP for Docking and Reconfiguration

5.1 Overview

The six UDP flight units are scheduled to launch in June 2015 with expected operations planned for the following summer. The operations will focus on the development of docking algorithms with some preliminary validation of reconfigurable control algorithms in preparation for the addition of the Halo payload on the International Space Station. Combined, the UDP and Halo payloads provide a test facility for control algorithms and operations concepts to support Robotic Servicing and Assembly (RSA) missions. The development and use of an RSA testbed using these payloads is described in detail by McCarthy [23] and Sternberg [2]. The experiment framework discussed in Chapter 4 is applied to the initial UDP operations campaign to provide an example of its use. It necessary to clarify that this is an example of an experiment campaign using the UDP and not necessarily the operations strategy that will be used. As the experiment campaign develops beyond the submission of this work, it is expected that improvements to each session will be made through the use of this framework.
5.2 Operations Plan

5.2.1 Objective Development

The operations plan details the succession of tasks that need to be accomplished from the launch of the UDPs toward the completion of its operations objectives. In order to develop that plan, an objective is needed that defines the result that must be achieved in order for the operations campaign to be considered a success. To start moving towards the objective, a few “why?” questions can be asked about the project that help uncover its purpose.

- Why does the UDP exist as a project?
- Why is it necessary to test in microgravity?
- Why is autonomous docking capability important for enabling future missions?

Searching for an answer to these “why?” questions leads the team to the Phase III Safety Data Package [21], the most recent published documentation on the project, which lists its objective as:

To help enable the DARPA Phoenix mission (near-term) and provide capability for future studies of reconfigurable spacecraft for new mission architectures.

For the purpose of this example, only the near-term objective will be considered. The DARPA Tactical Technology Office (TTO) lists the goal of its Phoenix program as [43]:

To develop and demonstrate technologies that make it possible to inspect and robotically service cooperative space systems in GEO and to validate new satellite assembly architectures.

This statement can be broken down further by answering a series of “what” questions.

What technologies support inspection and robotic servicing?

The UDP payload provides the capability to develop and demonstrate three technologies that support inspection and servicing: (1) autonomous decision-making algorithms to conduct rendezvous and close proximity operations with the target, (2) high-precision relative guidance algorithms for docking to the target, and
Resource Aggregated Reconfigurable Control (RARC) algorithms for target manipulation and repurposing.

What is a cooperative space system?
There are different interpretations of what it means to be a cooperative space system in this context. For the purposes of this thesis, a cooperative asset is a stable system that is communicating relevant information to the servicer and is capable of being controlled to benefit the servicer. A collaborative system is one that communicates information but is unable to control itself to benefit the servicer.

What are the implications of operating in GEO?
The primary implication from operating in GEO is the presence of orbital debris, though the spatial density is one to two orders of magnitude less than LEO. The relative velocities between orbiting objects and debris is also much less; from 9-10 km/s to 2.5 km/s because most objects are in nearly equatorial orbits [44].

What is satellite assembly architecture validation?
Satellite assembly is accomplished by joining pieces of a spacecraft together on-orbit to create a larger system out of smaller pieces that were either packed separately or launched separately. The pieces can either assemble themselves by maneuvering towards each other and docking or they can be assembled by some robotic manipulator. The first method will essentially be validated by completing a cooperative docking maneuver with two UDP-equipped satellites. The second method can be validated using a Halo equipped satellite with multiple docking ports by docking to a collaborative target and manipulating it so that it docks with another collaborative, UDP-equipped satellite.

This “what” question process can be repeated further until the team is comfortable with their collective understanding of the mission. Based on the answers to these questions, the objective for the initial operations campaign can be defined in terms of the result that must
be achieved:

*Using a UDP-equipped satellite, successfully complete the autonomous rendezvous, docking, manipulation, and undocking of a collaborative, tumbling UDP-equipped satellite.*

### 5.2.2 Current State

At the time of this writing, the UDP flight units were cleared for launch and placed in bonded storage until the launch in late May 2015. During the hardware acceptance testing [45], the flight units completed mechanical and electrical inspection as well as unit testing for the connectors, camera, motor, and override switch. Integrated testing with a VERTIGO Avionics Stack was completed to show that the VAS and PIC software could correctly actuate the motor in response to a photosensor trip, and to show that images could be streamed properly and used to track a fiducial. Integrated testing with a SPHERES satellite was completed to show that the ultrasound could be passed through successfully through the UDP and VAS. More integrated testing was completed after the acceptance testing to show that the photosensor state could be passed to the SPHERES satellite and that the SPHERES satellite could send a command through to open the UDP camera in preparation for an undocking maneuver. Short-duration micogravity testing was also completed on an RGA campaign resulting in the experimental determination of the physical properties and thruster forces in both the docked and undocked configurations. Development is ongoing on the camera calibration procedure, relative guidance algorithms, dynamics simulation, VERTIGO-SPHERES API, docking algorithms, and RARC algorithms.

The current state is summarized using a Control System View in Figure 5-1. The highest confidence level is in the thrusters, plant (physical properties), ultrasound sensors, IMU, and global estimator because those were all integrated and verified in a microgravity environment during the RGA flight campaign. The input/output of the relative estimator and camera have been verified on ground but have not been verified when integrated with the whole system. Finally the mixer and controller, including rendezvous, docking, and RARC, have not been verified in the ground testbed or in a microgravity environment.
Experiment Campaign Plan

A Work Breakdown Structure (WBS) is used to identify all of the tasks that need to be completed in order to achieve the objective. Figure 5-2 shows a WBS based off of the objective derived for this example. The objective is broken down into the different pieces that need to come together in order to achieve its completion. Through analysis, ground testing, and flight testing, the research team will iteratively develop a high confidence of success for each piece building towards the objective. The sequencing of the tasks is shown in Figure 5-3.

The team should develop confidence in the system from left to right, using the results
from each step to improve their understanding in preparation of future steps. For example, the Extended-Kalman Filter (EKF) will use the system physical properties, thruster forces, and sensor measurements to estimate the state of the satellite. If the EKF does not achieve the expected result, it will be helpful to have already characterized the thrusters, physical properties, and sensors of the system so that the research team can focus their attention on the algorithm in order to improve the results. This does not mean that these need to be done in separate operational test sessions. An EKF can be designed based on expected results derived from analysis and ground testing for the thrusters, physical properties, and sensors so that both steps can be tested in the same session. Table 5.1 shows the desired result for each task in the UDP campaign that is sequenced in Figure 5-3.

<table>
<thead>
<tr>
<th>Task</th>
<th>Desired Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrusters</td>
<td>Determination of forces and torques generated during thruster firings used to update dynamics model for controller development.</td>
</tr>
<tr>
<td>Physical Properties</td>
<td>Determination of system mass, inertia, and geometric properties of integrated vehicle used to update dynamics model for controller development.</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Verification that ultrasound receivers correctly pass time-of-flight measurements to the global estimator.</td>
</tr>
<tr>
<td>Lineage</td>
<td>Details</td>
</tr>
<tr>
<td>-------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Global Estimator</td>
<td>Determination of estimator accuracy at different positions throughout the test volume and at different relative orientations with another integrated vehicle. Needed to perform closed-loop control during the rendezvous phase.</td>
</tr>
<tr>
<td>Rendezvous Controller</td>
<td>Demonstration of a position and attitude controller that can rendezvous with the target satellite. The controller needs to be fast enough to complete a rendezvous with the target satellite from up to a meter away within a couple of minutes. The chaser cannot overshoot the target position due to the close proximity of the target satellite.</td>
</tr>
<tr>
<td>Camera Calibration</td>
<td>Determination of the camera’s intrinsic parameters such as the scaled focal length, principal point, tangential distortion coefficients, and the radial distortion coefficients.</td>
</tr>
<tr>
<td>Relative Estimator</td>
<td>Demonstration of an algorithm that can determine the relative state between the UDP-equipped satellites using the camera and the known fiducial. The relative estimator must provide a position estimate that is accurate within 1cm and an attitude estimate that is accurate within $2^\circ$ [22].</td>
</tr>
<tr>
<td>Docking Controller</td>
<td>Demonstration of a relative position and attitude controller that can successfully dock two satellites together in a steady manner that allows the motor to close properly. The controller must reduce the position error to less than 1cm and the attitude error to less than $2^\circ$ in order to achieve docking. The target satellite can communicate with and support the servicer.</td>
</tr>
</tbody>
</table>
Demonstration of a relative position and attitude controller that can successfully dock two satellites together in a steady manner that allows the motor to close properly. The controller must reduce the position error to less than 1cm and the attitude error to less than 2° in order to achieve docking. The target satellite can communicate with but not support the servicer.

<table>
<thead>
<tr>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docking Controller (Collaborative)</td>
</tr>
<tr>
<td>Motor Close (Photosensor)</td>
</tr>
<tr>
<td>Thrusters (Docked)</td>
</tr>
<tr>
<td>Physical Properties (Docked)</td>
</tr>
<tr>
<td>Ultrasound (Docked)</td>
</tr>
<tr>
<td>Docked Estimator (Individual)</td>
</tr>
<tr>
<td>Docked Estimator (Integrated)</td>
</tr>
<tr>
<td>Docked Controller (Collaborative)</td>
</tr>
<tr>
<td>Docked Controller (Cooperative)</td>
</tr>
<tr>
<td>Motor Open (Switch)</td>
</tr>
<tr>
<td>Motor Open (Command)</td>
</tr>
</tbody>
</table>

Verification that the motor closes in response to a photosensor trip.

Determination of forces and torques generated using thruster firings after the system has been docked together.

Determination of mass, inertia, and geometric properties of docked vehicle.

Determination of ultrasound receiver measurements quality at different areas within the test volume for the docked system.

Determination of estimator performance in the docked configuration without integrating the target satellite’s resources.

Determination of estimator performance in the docked configuration when integrating the target satellite’s resources.

Demonstration of controller that can successfully maneuver the docked system using thrusters from the servicer satellite by adjusting for the new properties of the system.

Demonstration of controller that can successfully maneuver the docked system using thrusters from both satellites and adjusting for the new properties of the system.

Verification that the motor opens in response to the override switch.

Verification that the motor opens when commanded by the SPHERES satellite.
Separation

Demonstration of a sequence that successfully undocks the two vehicles.

Table 5.1: Desired Results for Each Task in UDP Experiment Campaign

The sequence of events then need to be broken down into operational test sessions that fit within the NASA ISS schedule. A general rule is to flight test everything that the researcher has a high-confidence in plus one more step. High-confidence comes from the results of prior analysis, ground tests, and flight tests. At the beginning, it is likely that many steps will be tested in the same session because those tests will build off of results from ground testing and analysis. As the campaign progresses, each session will need to build off of flight results leading a progression closer to one step per session. Figure 5-4 shows how this method is applied to the UDP tasks. The ISS Checkout session goes out to the 3rd or 4th step in many cases because the previous steps can be largely verified in the ground environment due to few changes in implementation between ground and flight tests. The demonstration of the steps identified in green and red will also be tested on the 3-DOF ground environment to reduce risk, but their success on the ground testbed does not result in high-confidence because of

Figure 5-4: Test Session Targets for UDP Campaign
implementation changes that occur when moving to the flight testbed. The second session only progresses one step in each area because each one builds off of the flight results of the first session. Each ‘task’ on the experiment campaign plan shown here becomes a test session objective that pushes the tests within the test session to focus on the completion of the campaign objective.

5.3 Checkout Session

5.3.1 Test Session Objectives

Objectives for the ISS Checkout session can be broken down into two sub-categories: functional and science preparation. Functional objectives are similar to the tests performed in the Flight Hardware Acceptance Procedure [45] and focus more on verifying that the hardware operates correctly. Since these components were all verified prior to flight hardware delivery, the main purpose of these tests will be to verify that nothing changed as a result of the launch and delivery of the hardware to the International Space Station. The functional objectives for the checkout session are:

- Motor Open (Commanded)
- Motor Open (Switch)
- Motor Close (Photosensor)
- Camera Calibration
- Ultrasound/Infrared Passthrough

The second section of checkout objectives are focused on gathering data that will help the payload complete its science objectives. The science preparation objectives for the checkout session are:

- Physical Properties
- Thrusters
- Global Estimator
- Relative Estimator
- Rendezvous Controller
- Docking Controller
- Separation
- RARC (Docked Controller)

5.3.2 Test Plan

After the test session objectives are determined, test plan can be designed to achieve them. Figure 5-5 shows an Objective-Test Matrix for the UDP Checkout session that connects each test with the objectives that it is designed to test. The test session objectives are colored as they were in Figure 5-4 in order to emphasize that the test session objectives come from the experiment campaign plan. The tests listed below the bolded line are back-up or extra tests that are not required to have a successful test session. A one-line summary of both the Flight Hardware Checkout and the Reduced-Gravity Assist (RGA) Flight are also included to provide a reference of what was already verified in each environment.

1. Camera Calibration

**Overview:** A camera calibration procedure will be executed on each unit in order to determine the camera’s intrinsic parameters such as the scaled focal length, principal point, tangential distortion coefficients, and the radial distortion coefficients [24]. The calibration process for the UDP payload is described in detail by Duncan Miller [22]. The switch will also be used in this test to manually open and close the motor to verify that the switch functions properly.

**Result Indicator:** The camera calibration will provide feedback to the astronaut during the test regarding the quality of the images. The functionality of the switch will also provide a clear result during the test.
2. Absolute Calibration

**Overview:** The absolute calibration test will be used to determine changes in the camera’s position relative to the UDP system. This will be completed by docking the UDP to another unit, taking an image of the fiducial, and comparing that image to similar images taken prior to the launch. This test will also be used to verify the functionality of the photosensor and ‘open motor’ command used during the docking process.

**Result Indicator:** Result feedback will be provided during the test through the GUI to confirm that the image was taken correctly. The results of the photosensor and undocking command verifications will be evident to the astronaut during the test and communicated to the ground team.

3. SPHERES Checkout
Overview: The SPHERES Checkout test verifies the functionality of the metrology subsystem, thrusters (open-loop), and closed-loop controller by proceeding through each one systematically, one satellite at a time.

Result Indicator: Result codes are used to determine if certain beacons are placed incorrectly or if the satellite is unable to receive ultrasound signals from those beacons. The closed-loop maneuver is successful if the satellite points its tank toward’s the STBD wall while pointing its expansion port towards the AFT wall—something the ground team can verify through the video feed in real-time.

4. Mass Identification Test

Overview: In order to confirm the mass properties of the system, each thruster will be fired sequentially for 400ms with 600ms of coasting in between for 3 cycles while the acceleration and angular rate are measured using the IMU.

Result Indicator: Result codes during the test will be used to verify successful data acquisition. The IMU data will be post-processed using the MATLAB data parser developed by Chris Jewison for the RGA flights. The parser uses a least-squares system identification method to determine the center of mass, inertia properties, and the linear and angular acceleration that results from each thruster. The results will be compared to the RGA and CAD results so that the differences could to be resolved prior to the next test session.

5. ‘Clean’ Metrology Dock

Overview: In this test, the chaser satellite will rendezvous with the target satellite during a position hold. When the satellites are near each other, the chaser satellite will switch to a docking controller while continuing to use the same estimator. After the docking maneuver, the satellite will command the UDP to open its motor and complete and undocking maneuver. The UDP camera will be capturing images during this test, but those images will not be used for navigation.

Result Indicator: The ground team will be able to visually determine whether the rendezvous controller successfully maneuvers the satellite into place, as well as whether or not the satellites dock and undock successfully. The controller’s performance will
be compared to the expected simulation data once the flight data is made available to
the research team. Ultrasound receiver data, IMU data, and thruster times should be
downloaded to help diagnose any unsuccessful rendezvous or docking attempts. The
reasons for the unsuccessful attempts should be identified and resolved prior to the
next session.

6. **‘Dirty’ Metrology Dock with RARC**
   
   **Overview:** This test is similar to the previous one, except that the combined satellite
   system will perform a series of RARC maneuvers following the docking maneuver
   before executing the undocking maneuver. The RARC maneuvers will be similar to
   maneuvers performed on the ARMADAS ground experiment for robotic assembly and
   servicing [2] [23].
   
   **Result Indicator:** The RARC maneuvers will include a translation and a rotation that
can be somewhat verified visually through the video feed with a final confirmation
made through a comparison to simulation data after the session. Ultrasound receiver
data, IMU data, and thruster times should also be downloaded during this test to help
characterize the performance of the estimator when using the docked configuration.
The modeling methods used to predict the dynamics of the combined system should
revised based on the results of this test so that those rules can be applied to RARC
on the Halo system.

7. **Basic Camera + Metrology Dock**
   
   **Overview:** The chaser satellite will complete a rendezvous with a target satellite in
position hold. When the satellites are sufficiently close and the UDP camera has a
lock on the target fiducial, the satellite will switch its controller and estimator to
the docking controller and the mEKF. After the satellites dock successfully, they will
execute an undocking maneuver.
   
   **Result Indicator:** The ground team will be able to visually confirm the success of
the rendezvous, docking, and undocking maneuvers. The performance of the controller
relative to expectations after the data is given to the research team. Ultrasound receiver
data, IMU data, and thruster times should also be downloaded in this test in addition
to raw images from the camera to help diagnose unsuccessful docking attempts. The reasons for the unsuccessful attempts should be identified and resolved prior to the next session.

There are also back-up tests included in the test plan to achieve objectives in the event that challenges occur on the primary tests. The RARC Test (start docked) will be used to gather data on RARC maneuvers if Test #6 has trouble successfully completing a dock. Metrology Dock (No Camera) and Metrology Dock with RARC (No Camera) are back-up tests for Tests #5 and #6 in the event that the camera doesn’t initialize properly. Relative Approach, Rate Damp and Relative Approach, Global Hold are used to gather data on the camera and the relative estimator in cases where the satellites are unable to complete a successful rendezvous or in cases where the team is nearing the end of the test session and needs to run a shorter test.

5.3.3 GN&C Approach for the Docking Tests

The docking tests in this test session are important in verifying the testbed’s capability for completing the science objectives in the following sessions. Various control and estimation algorithms are used for each stage in the docking sequence in order to appropriately meet performance needs that vary from stage to stage. The docking tests begin by waiting for global estimator convergence following the initial deployment by the astronaut. After estimator convergence, the satellites begin the rendezvous phase by pointing towards each other so that their docking ports are aligned on an axis that connects the two satellites. During the second part of the rendezvous phase, the target satellite maintains a position hold while the chaser satellite approaches its target. When the chaser is close to the target, the satellite enters the docking stage by switching to the relative estimator and the docking controller. After the target satellite has been captured, a translation and rotation maneuver are completed to demonstrate RARC capability.

The rendezvous controller needs to be fast enough to complete a rendezvous with the target from up to a meter away within a couple of minutes without overshooting its target position and crashing into the target satellite. The PD controller can be designed to meet
this criteria and has a history of implementation on the SPHERES platform. The controller calculates the control input using the state error and gains designed to meet certain performance criteria as shown in Equation 5.1.

\[ u = K_p e + K_d \dot{e} \]  
(5.1)

For the position controller, the gains are determined using Equations 5.2 and 5.3 where \( \omega_n = 0.200 \text{ rad/s} \) and \( \zeta = 1 \) and \( m \) is the mass of the system.

\[ K_p = \omega_n^2 m \]  
(5.2)

\[ K_d = 2\zeta \omega_n m \]  
(5.3)

For the attitude controller, the gains are determined using Equations 5.4 and 5.5 where \( \omega_n = 0.400 \text{ rad/s} \) and \( \zeta = 1 \) and \( I \) is the inertia of the system about the axis being rotated.

\[ K_p = \omega_n^2 I \]  
(5.4)

\[ K_d = 2\zeta \omega_n I \]  
(5.5)

The global estimator used during the rendezvous phase is the SPHERES Extended Kalman Filter described by Nolet [5] that uses the external beacons, on-board IMUs, and a dynamics propagator to determine the state. To account for the changes introduced by the UDP, the EKF was updated to account for the new system mass, inertia, thruster forces, CG, and U/S receiver offset in the +X face.

In order to successfully dock the two satellites together, the docking controller needs to reduce the position error to less than 1cm and the attitude error to less than 2°. Due to the steady-state error that can occur using PD controllers, a PID controller is a preferred choice for a docking controller in order to achieve the accuracy required. Equation 5.6 shows the general equation for a PID controller.

\[ u = K_p e + K_i \int e \, dt + K_d \dot{e} \]  
(5.6)
For the position controller, the gains are determined using Equations 5.7-5.9 where $\omega_n = 0.200 \text{ rad/s}$, $\zeta = 1$, $\tau = 20s$, and $m$ is the mass of the system.

\begin{align*}
K_p &= m(\omega_n^2 + 2\zeta \omega_n / \tau) \quad (5.7) \\
K_I &= m(\omega_n^2 / \tau) \quad (5.8) \\
K_d &= m(2\zeta \omega_n + 1 / \tau) \quad (5.9)
\end{align*}

For the attitude controller, the gains are determined using Equations 5.10-5.12 where $\omega_n = 0.400 \text{ rad/s}$, $\zeta = 1$, $\tau = 20s$, and $I$ is the inertia of the system about the axis being rotated.

\begin{align*}
K_p &= I(\omega_n^2 + 2\zeta \omega_n / \tau) \quad (5.10) \\
K_I &= I(\omega_n^2 / \tau) \quad (5.11) \\
K_d &= 0.75I(2\zeta \omega_n + 1 / \tau) \quad (5.12)
\end{align*}

Nolet determined the factor 0.75 in Equation 5.12 through multiple experiments with the SPHERES testbed involving PID position and attitude controllers used simultaneously.

In addition to the control law requiring low steady-state error, the estimates that the controller uses also need to be very accurate in order to enable a successful docking maneuver. The relative estimator is an Unscented Kalman Filter (UKF) that uses camera measurements of known fiducial markers. When compared to the Multiplicative Extended Kalman Filter (mEKF), the UKF has significant advantages in the presence of nonlinearities. Both the mEKF and UKF, in addition to the Montecarlo simulations and testbed data used to validate the estimators, are described in detail by Duncan Miller [22].

In the ‘Dirty’ Metrology Dock with RARC test, the satellites will perform a series of RARC maneuvers after the completion of the docking phase. The business card and thruster selection logic reconfiguration method developed by Chris Jewison [27] will be used to share knowledge of physical parameters and thruster capabilities between the two satellites. Using knowledge of the combined physical parameters and resources of the new system will enable an update to the control laws that are used.
5.4 Summary

This chapter provided an example of the Performance-Driven Experiment Framework using the Universal Docking Port payload in the SPHERES facility. The objective is reduced and defined to specify the result that is required by the end of the first two test sessions in order to adequately prepare the researchers for the arrival of the Halo payload. The current state of the project is assessed using documentation from the assembly testing and results reports from the project’s Reduced Gravity Aircraft campaign. A Work Breakdown Structure is used to break the objective into sub-tasks that need to be accomplished in order to achieve the objective. A campaign plan is formulated by sequencing the tasks towards the completion of the objective and the required results are defined for each task based on what is required to move on to successive tasks in the campaign plan.

Using the framework, the functional and science preparation objectives of the UDP Checkout Session are completed using only seven tests (with five requiring the SPHERES satellites). The Objective-Test Matrix provides a reference on which tests are responsible for each objective, while the arrow diagrams and objectives table provides an explanation of each objective and how they are interrelated. Finally, each test is designed to provide an indication of the results with respect to the expected behavior as soon as possible so that that information can be used to schedule the next test session appropriately. This section does not cover the research and development involved in each task in the campaign such as mEKF, docking controller, and RARC, nor the ground testing required to prepare each test for ISS. The time required for these activities will fluctuate depending on the team and the expertise in the relevant areas and with the hardware. Nonetheless, this process provides a good guide through the planning and designing of the UDP experiment campaign so that the technology can be iteratively developed through the results of successive experiments.
Chapter 6

Planning for Future EMFF Development with RINGS

6.1 Overview

The RINGS program ended in an unfortunate way as the last ISS session on the initial contract was met with facility challenges that were largely out of the control of the research team at the time. Nonetheless, data from the session led to the validation of the EMFF dynamics simulation that can be integrated into the end-to-end SPHERES simulation to develop EMFF control algorithms that can be tested on the RINGS hardware that is still on the ISS. This chapter uses the Experiment Framework discussed in Chapter 4 in order to develop an experiment campaign plan for further EMFF research with the RINGS testbed on ISS.

6.2 Operations Plan

6.2.1 Objective Development

In order to develop an operations plan for continued research with the RINGS testbed, it is first important the the objective of such a campaign be clarified and understood. Here it is important to understand why EMFF development is important and why it is important
to test in a microgravity environment. Electromagnetic Formation Flight offers the same benefits of formation flying in remote sensing, fractionation, and robotic assembly but uses a sustainable power source and does not cloud optics. Due to the dependence on induced electromagnetic forces and torques on the relative position and attitude of the satellites, it is necessary to validate the technology in a full 6-DOF environment so that the affects on the system from changes in each DOF, and their combinations, can be evaluated. So the objective becomes:

To demonstrate stability and control in full 6-DOF using the electromagnetic actuation capability of the SPHERES-RINGS testbed.

Though this is a good start, it is important to become more specific so that team members know what it is that they are pursuing in order to have a successful campaign. This can be accomplished by answering a few “what” questions.

What are the performance requirements for stability and control?
The mission applications for formation flying satellites such as sparse aperture and robotic assembly, require control with a high level of accuracy with respect to its target. Since the SPHERES estimator has an estimated bias of \( \pm 1 \text{cm} \) and \( \pm 3^\circ \), that is the maximum performance that can be expected from the EMFF control laws. The goal would be to develop EMFF control algorithms that can achieve the highest level of accuracy that the SPHERES-RINGS testbed can demonstrate indicating that similar control algorithms would perform even better on future spaceflight programs that utilize more accurate sensor platforms.

How can a single-coil system achieve full 6-DOF?
Due to the dynamic constraints of a single-coil system, the RINGS testbed will be unable to operate in a 6-DOF environment without the use of a supplemental actuator for attitude control. The SPHERES thrusters will be used as attitude controllers that work with the EM coils to achieve 6-DOF stability and control.
This “what” question process can be repeated further until the team is comfortable with their collective understanding of the mission. For the purpose of this example, the objective for the operations campaign is defined as follows:

**Successfully demonstrate the ability to maintain stability and relative control within ±1cm and ±3° using two RINGS-equipped SPHERES satellites and reference inputs that require changes in all 6-DOF.**

After the objective statement, the next step is to take some time determining the current state of the project so that the campaign plan can be developed.

### 6.2.2 Current State

At the time of this writing, the RINGS project hadn’t been used on the ISS since its first operational campaign described in Chapters 2 and 3. Reviewing those chapters will provide a good background in the current state of the project. Figure 6-1 shows a control systems view that summarizes the current state. The RINGS payload itself will likely need a firmware overhaul as recommended by Alvisio [20]. He suggests that the RINGS firmware be migrated to a Real-Time Operating System (RTOS) that can more efficiently use the micro-controller resources, ease the characterization of the application’s performance, and shorten the debugging and testing time for test session development. The impingement of
the thrusters in the body-x direction caused by the RINGS coil housing severely limits the amount of control authority that those thrusters have. The characterization of the system plant was verified using state data from the third science session and comparing that to data from the simulation data that uses the dynamics model. Though the estimator had instances of instability during Science 3, it is unclear how much of that was caused by the GLAs on ISS and how much was caused by U/S obstruction caused by the coils. Finally, the control strategy used in Science 2 for the axial configuration needs to be revisited to better account for the electromagnetic torques generated by misalignment between the two coils.

6.2.3 Experiment Campaign Plan

A Work Breakdown Structure (WBS) is used to identify all of the tasks that need to be completed in order to achieve the objective. Figure 6-2 shows a WBS based off of the objective discussed in the previous section. Using the WBS as a reference, an arrow diagram can be

![Figure 6-2: Work Breakdown Structure for RINGS](image)

organized that sequences tasks in order of their logical dependencies. An overview of this sequence is shown in Figure 6-3. Starting from the left, a team should develop confidence in the system using analysis, ground testing, and flight testing. The results from each step will improve their understanding in enabling the completion of future steps. The tasks in the campaign plan will guide the objectives of the test sessions and therefore need to be expressed in a way that highlights the desired results needed to move onto the next step. Each task on the campaign plan is summarized below in terms of its desired result and any
Thruster Force Characterization

Result: For the team to have a high confidence in their knowledge of the force exerted by each thruster while it is open. These values are necessary for the thruster controller to properly actuate the system and for the estimator to accurately propagate the dynamics. High confidence will come from consistency between CAD and analysis, the RGA campaign, the first ISS campaign, and additional tests at the start of the future campaign.

Challenges: The primary challenge will be gaining confidence in the force values of the impinged thrusters. For the other thrusters, the team should already have a high confidence in the force values based solely on CAD and analysis, the RGA campaign, and the first ISS campaign. It is predicted, based on data from different test sessions, that the force of the impinged thrusters vary based on how carefully the SPHERES satellites were placed in the RINGS units during setup. At the start of the next RINGS campaign, its is important that an emphasis is placed on this setup so that the astronaut can see the truster holes through the RINGS clamps, and that thruster force characterization tests be re-run to capture their capability when setup more carefully.

Testing: These tests need to be performed on ISS because the force of gravity will saturate the accelerometers.

Physical Properties

Result: For the team to have an accurate understanding of the physical properties (mass, CG, inertia) of the system so that the controller and estimator can be designed considering
those values.

**Challenges:** There are no predicted challenges with these tests because flight data following the update of the physical parameters in the flight software have consistently matched the state data generated by the RINGS simulation. The data generated from the thruster force characterization tests can also be used for this purpose.

**Testing:** These tests will also be performed on ISS.

**Ultrasound**

**Result:** Confirmation that the ultrasound receivers on the SPHERES satellites are able to gather measurements from the beacons at different locations within the volume. This will help ensure that the estimator will function properly when used with the RINGS payload.

**Challenges:** Based on the Science 3 session, it is possible that there are certain ‘blind spots’ in the volume where the satellites are unable to gather enough measurements to accurately determine their position. In these locations, it is possible that certain orientations of the satellites result in ultrasound signal impingement due the coil housing.

**Testing:** Downloading the raw ultrasound data roughly doubles the test time making it difficult to balance the value of having the data and the time taken away from other valuable things that can be tested on ISS. Therefore, this task should be completed on the ground testbed as much as possible by holding the RINGS units in different static configurations in predicted ‘blind spots’. Flight tests can include an option to download the raw ultrasound data in the event that unexpected estimation behavior is seen. If the estimator functions properly, as is expected based on the static ground testing prior to the session, time isn’t taken away from the other valuable tests that should be executed in microgravity.

**Hall-Effect Sensor**

**Result:** Confirmation that the Hall-Effect Sensor correctly measures the current wave moving through the RINGS coils and outputs that information correctly through the data downlinked at the end of each test. This is important in having confidence in the current measurements that are used in the data analysis and in the proper functionality of the current controller.

**Challenges:** The primary challenge is that the RINGS units need to be opened up and measured during tests using an oscilloscope. That data should be compared to the sensor data that comes through the data downlinked at the end of each test.
**Testing:** This functionality should be confirmed and verified on the ground hardware so that
time isn’t taken during the session to download the entire current wave. This process was completed prior to the Science 3 session and is documented by Alvisio [20].

**IR Rcv**

**Result:** Confirm that the infrared receivers on the RINGS units correctly receive signal emitted from the Primary SPHERES satellite during its metrology cycle. This will ensure that the hardware functions well enough to enable the RINGS firmware to synchronize the current of each coil based on this signal.

**Challenges:** There are no expected challenges as the team never experienced issues with the IR receivers during the first RINGS campaign.

**Testing:** These tests should also be completed completely on the ground.

**Current Controller**

**Result:** Confirm that the current controller correctly achieves the current commanded by the SPHERES satellites. This will ensure that the proper current is running on the coils, inducing the correct electromagnetic forces and torques used by the controller to actuate the system.

**Challenges:** Currently the current controller is a PID controller that has a relatively slow response and some overshoot before settling on the commanded current. This delay is currently not accounted for in the control algorithm nor the SPHERES-RINGS simulation. The assumption is that the coils immediately actuate the RMS current that is commanded by the satellites. The simulation shows that the difference is negligible when running open-loop EM tests, but the effects of the delay and overshoot should be considered when trying to execute closed-loop control using the EM forces and torques. .

**Testing:** These tests should all be accomplished on the ground hardware

**Phase Sync**

**Result:** Confirm that the firmware is able to reliably synchronize the current between the two coils in both attraction (0°) and repulsion (180°) modes.

**Challenges:** The main challenge faced when trying to confirm the phase synchronization in the first campaign was the assumption that synchronization in attraction and repulsion was the same. Tests should be conducted in both modes and at different levels of current for each
coil, including cases where the coils are driving different levels of current from each other.

**Testing:** These tests should all be performed on the ground hardware. If they are performed after the Hall-Effect sensor tests and the coils are still open, they can be verified with an oscilloscope and the sensor data. If the Hall-Effect sensor is already verified and the units are closed up, the sensor data will be sufficient to confirm that the coils are synchronizing correctly.

**EM Force/Torque Characterization**

**Result:** Gain a high confidence in the understanding of the forces and torques induced by the coils as a function of their relative position and orientation. In addition to enabling the EM controller, understanding this relationship is key in enabling the correct feed-forward terms to the estimator and the thruster-based attitude controller.

**Challenges:** Alvisio showed that by gathering data using open-loop currents to generate electromagnetic forces and torques and comparing that to simulation output that uses the near-field EM dynamics equations, an accurate understanding of the EM actuator can be achieved. The big challenge is that the model that describes the dynamics utilizes a numerical simulation that needs to integrate over 50 segments of each coil twice, calculating the force at each segment and summing the results to achieve the net force. Without the capability to reduce this model such that it accurately conveys the dynamics in the near-field, it is not possible to provide the relationship necessary to enable an EM controller, nor provide the required feed-forward terms to the attitude controller and the estimator.

**Testing:** These tests will need to be tested in 6-DOF because of the effect that rotation plays in electromagnetic dynamics.

**Estimation**

**Result:** Confirm that the estimator provides reliably accurate state estimates within the operational volume for ISS testing. Having accurate state estimates enables both the thruster and EM controllers to control the system adequately.

**Challenges:** The chief challenge in estimation area have been caused by both ultrasound impingement in certain areas within the volume. Due to the present inability to feedforward the EM force to the estimator, it is not currently propagated in the dynamics. As a result, the EKF will begin to trust its sensor measurements less over time as they diverge from the
on-board dynamics model because the model does not represent the EM force caused by the coils. Ground testing should be completed to determine the length of time that the EM coils can be operated before the estimates diverge from reality. That knowledge will define the maximum test time until a method for EM dynamics model reduction is achieved.

**Testing:** Estimation verification can mostly occur on the ground testbed, but should be verified on flight as well during the checkout session.

**Thruster Controller**

**Result:** Demonstrate that a position and attitude controller can use the thrusters to correctly position the satellites prior to electromagnetically actuated maneuvers.

**Challenges:** The primary challenge with the thruster controllers will be controlling in the degrees of freedom that utilize the impinged thrusters. Another challenge will come when trying to integrate the thruster controller with the EM controller. Ideally, the electromagnetic force and torque would be fed forward to the thruster controller so that it could adjust its control input appropriately. Another possibility would be to increase the frequency of the thruster attitude control relative to the electromagnetic controller so that it could reject the disturbances.

**Testing:** Though these tests should be verified as much as possible in a 3-DOF ground environment, they will require the full 6-DOF microgravity environment to become fully validated.

**EM Controller**

**Result:** Demonstrate that an EM controller, combined with supplemental attitude control, can maneuver in the 6-DOF environment.

**Challenges:** This step has many challenges that will depend on the way in which the previous steps are accomplished. One clear challenge that needs to be overcome is model reduction for the EM dynamics model that enables the real-time determination of commanded current from the desired controller force. If the model reduction decreases the accuracy, as in the case of the far-field equations, then the controller will need to be designed to account for this. This will also affect the attitude controller’s ability to reject EM disturbance torques because the attitude control law will not have knowledge of the EM torque until it is picked up by the sensors resulting in a delay. To accommodate this, the EM controller can be designed...
to act at a lower frequency than that thruster controller so that the delay is mitigated. It
is important to emphasis that this task should be attacked in incremental steps. The test
should begin using 6-DOF thruster control to achieve a stable position and attitude hold in
the axial configuration. Then, with the state error very close to zero, the EM controller can
be activated in the 1-DOF along the axis connecting the two satellites. Though it seems triv-
ial because 1-DOF tests can be tested on the ground, it is important to verify that the EM
controller can maintain 1-DOF in the axial configuration while the attitude controller rejects
disturbances in all three rotational 3-DOF. Then, a small step input can be commanded to
bring the satellites closer or separate them. Then the other can be tested. After the team is
comfortable in controlling with the electromagnets in the axial configuration, they can begin
using the thrusters to ‘steer’ the system by rotating and then adjusting the commanded
current to achieve a desired EM force and torque that results in a new commanded state.

Testing: Though these tests should be verified as much as possible in a 3-DOF ground
environment, they will require the full 6-DOF microgravity environment to become fully
validated.

Figure 6-4 shows how these tasks might be broken into test sessions. The tasks listed
under ground testing can be fully validated in the ground environment. However, since the
flight units are already on the ISS, it is suggested that the functionality be quickly verified
in the checkout session as well. In the same way, tasks listed under the Checkout session
and Science 4 need to be validated in a microgravity environment, but they should still be
exhaustively tested on the ground hardware, under flight-like conditions, prior to flight. As
mentioned above, the task of validating an EM Controller is much more involved than the
other tasks and therefore will warrant its own science session. After that, multiple sessions
will be needed to learn from previous control architectures and designs and improve the
technology.
6.3 Summary

This chapter uses the Performance-Driven Experiment Framework in order to develop an experiment campaign plan for further EMFF research with the RINGS testbed. The objective is formulated to focus on achieving stability and relative control in 6-DOF within the capabilities of the SPHERES satellites using electromagnetic actuation supplemented with thrusters. The current state is summarized based on the knowledge of the first experiment campaign with RINGS discussed in Chapters 2 and 3. Using the two endpoints, a Work Breakdown Structure was used to break down the objective into the individual tasks that need to be addressed in thruster control, EM control, and estimation. These tasks were sequenced to form a schedule for the campaign. Each task was defined in terms of the results that need to be achieved to progress through the plan, while also highlighting the expected challenges that will be faced based on experience from the first RINGS campaign.
Chapter 7

Conclusion

7.1 Thesis Summary

Space systems are inherently difficult to verify prior to launch due to the difficulty of replicating the space environment on the ground. The SPHERES testbed on the International Space Station has responded to this challenge over the past decade by providing a dynamically authentic test environment for spacecraft control algorithms and new mission architectures. The operational aspect of the SPHERES facility also parallels many of the challenges faced in the operations of space projects by NASA, the Air Force, and commercial organizations. Due to its low-risk nature, best practices can be learned from the lessons of past SPHERES projects and applied to future SPHERES projects to assess their effectiveness.

This thesis reviewed the RINGS operational campaign in pursuit of its objective to demonstrate Electromagnetic Formation Flight capability for the first time in a 6-DOF environment. Due to the incompleteness of the Checkout Session, errors in the testbed were not detected long into the science campaign resulting in multiple schedule delays as the team became stuck trying to match simulation data to flight data that was ‘unmatchable’. The Science 1 Session revealed that the RINGS coils are designed such that one translational and one rotational degree of freedom are left uncontrollable due to thruster impingement. Trying to push through the science campaign to Science 2 without fully completing the necessary prior steps resulted in a difficult setback in Science 2 when none of the closed-loop control tests were able to demonstrate system stability. To close the initial campaign, the Science 3
session proved to be a disappointment as infrared noise from the upgraded lighting assemblies aboard ISS disrupted the performance of the state estimator resulting in a significant reduction in microgravity testing time that prevented any attempt at a closed-loop control test. Thankfully, the team was able to execute their suite of open-loop control tests whose data ultimately led to the validation of the Electromagnetic Formation Flight dynamics simulation which can be used to develop future control algorithms for the RINGS testbed.

There were many valuable lessons that the team was able to take away from the RINGS operations campaign that have already been helpful to future SPHERES projects and will likely be helpful to many other spaceflight projects. One of the early mistakes that propagated through the campaign was the general approach to student turnover. Though it is clear that 100% graduate student turnover should be avoided in the future, it is also important to understand that the overestimation of the students’ experiences on the project resulted in level of management oversight that was too little to transfer all of the required knowledge to complete the tasks. The pace of the campaign caused the deadlines and schedules to take center stage placing a much higher emphasis on test session execution rather than on achieving (or even defining) the desired results. Thorough results analysis and reconciliation between differences in the expected and actual behavior of the system were sidelined in favor of the development of whatever test session was next. The operations team needs to shift their emphasis more toward results completion and let that drive scheduling, while the research team needs to design their tests and post-session analysis procedures to give the operations team results confirmation as quickly as possible so that they have enough lead time to plan around other activities. The Science 3 Session also revealed the importance in considering the external environment that the testbed will operate in and not simple focus on verification of the testbed itself. In addition to the lessons learned about flight operations, the RINGS project showed time and time again that all ground testing done to prepare for flight needs to test all modes expected on flight under conditions that are as flight-like as possible in order to increase the chances for success.

Using many of the lessons learned from the RINGS project, an experiment framework is presented that focuses on the development of space technology through iterative experimentation on the International Space Station. Though iterative research on ISS has been
emphasized within the SPHERES program throughout the past decade, this thesis focuses on specifically defining how each increment builds off of the results of the previous increment so that the experiment campaign is driven more by the required results and less by the estimated deadlines that drive the schedule. The framework starts using a clear definition of the campaign objective and an assessment of the current state of the project infrastructure and personnel knowledge so that the two endpoints can be defined. A Work Breakdown Structure is used to filter the objective into individual tasks that are then sequenced according to their logical dependencies on other tasks. Each task is linked to a desired result that enables all successive tasks towards the completion of the project objective. Finally, these tasks are broken into test sessions based on their success confidence and test plan is designed efficiently to achieve the desired results of every task assigned to the session. The session is kept flexible by using back-up tests that can accomplish the necessary results in the event of various operational challenges. Each test is designed to gather data necessary to confirm the expected behavior and/or update the working theory/model in the event of unexpected behavior. The tests also include result indicators that help the research team confirm results or identify unexpected behavior rapidly so that the operations team can be flexible in scheduling the following test session.

The experiment framework was then applied to an upcoming SPHERES project, the Universal Docking Port, so that the concepts discussed can be shown in a more specific and concrete way. The objective was determined using a number of different resources and becomes focused on the demonstration of a docking mission that includes autonomous rendezvous, docking, manipulation, and undocking of a collaborative target satellite. The WBS method was used to break down the objective into its component parts and tasks were sequenced and broken into two test sessions. The test plan for the Checkout Session was presented and an overview of each test was given to show how the test will achieve its assigned objective(s) and which result indicators will be available to the research team during the test session or shortly following it.

The framework was also used to draw up an experiment campaign plan for potential RINGS operations in the future. Since the specific details of a future operational campaign were unknown, the plan was kept general so that the test session definition and individual test
design could be created to meet the requirements and constraints of that future campaign. Due to the time between test campaigns and the change of personnel that will occur over time, it is important that the system re-complete a checkout both on the ground hardware and the flight hardware. The steps were defined in terms of their desired result and were accompanied by a description of expected challenges that each step will face based on experience from the first experiment campaign.

7.2 Recommendations for Future Work

7.2.1 RINGS

In the event that the RINGS project is funded for more test sessions to continue EMFF research, the experiment plan described in Chapter 6 will provide a good starting point for planning operations. Though there are only three test sessions discussed in the plan, each one will require significant development time and ground testing in order to adequately prepare. As lessons are learned from each of these test sessions, knowledge will be gained that will enable the research team to plan future sessions using the principles discussed in the Performance-Driven Experiment Framework. For the sessions discussed in the current experiment plan, the rest of the framework will need to be used to design the tests in each session more specifically, so that they address the test session objectives defined by the tasks in the experiment plan.

7.2.2 Tools that Support Framework Automation

Though the framework presented is useful in organizing ideas to develop an experiment campaign plan and test designs, there are many improvements that can be made to improve the way that the process can be linked to provide better traceability from the project objectives down to the test design. This transition is analogous to the development of Model-Based Systems Engineering to improve the way requirements, designs, and analysis are all linked together to improve organization and reduce errors. Similar modeling tools would be useful in capturing different system views that are relevant for the experiment campaign, using
those views to generate a WBS, arrow diagram, and design tests that maintain links through- out the process so that the information is organized in a way that provides quicker access. Uncertainty Quantification techniques could also be incorporated into the tools so that the framework could leverage quantitative analysis for decisions to support the qualitative judgement currently used.

7.2.3 Framework for Ground Verification

An extension of the framework presented here for experiment planning and design would be a framework that focuses on the ground verification of the flight software for each test session. Though it is mentioned in this work that ground verification needs to test all operational modes used in flight in conditions that are as close to flight-like as possible, it would be useful to have a framework for determining the most efficient way of achieving that verification so that this part of the test session development process could be reduced. It is often the case that the engineers on a flight project wish they could have done more ground testing prior to flight but had to reduce their testing due to time constraints. Having a framework for making decisions on which forms of verification are sufficient and which forms to cut or modify if necessary would also surely benefit future flight projects.

7.2.4 InSPIRE-II

In the near-term, the UDP project will execute its Checkout Session on ISS and complete the data analysis to determine which results match the expected behavior and which results require more attention before moving onto the next test session. In the second session, Science 1, the focus will move towards more advanced, complex algorithms for relative navigation, docking, and manipulation that will require longer development times per task. In the long-term, the possibility of the Halo payload joining the facility after Science 1 creates a higher degree of opportunity for testing architectures of further complexity using the basic fundamentals for docking and manipulation that were hammered out using the first two UDP sessions. It is suggested that this framework be revisited often as new information becomes available so that the next tasks in the following sessions can be planned in more
detail than was presented here. The development of the INSPECT system, which adds a thermographic sensor, optical sensor, and CMGs to the Halo, also presents an opportunity to support technologies that focus on intra-vehicular inspection capability to support future extra-vehicular inspection. Finally, development of a robotic arm that can attach to the Halo will enable a large new suite of testable applications that further support Robotic Servicing and Assembly.
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