Experiment Proposal
NASA Reduced Gravity Student Flight Opportunities Program 2004

GYRE 2: Evaluation of Visual Navigation Techniques for Autonomous Free-Flying Robots

in the field of
Free-Flying Robotic Navigation

submitted by

The GYRE Project
University of Washington
Seattle, Washington 98195

Contact:
David Bliss
+1 206 860 3514
dbliss@u.washington.edu

Faculty Supervisor:
Linda G. Bushnell
+1 206 221 6717
bushnell@ee.washington.edu

Team Members:

David Bliss, Flyer*
Junior, Chemistry
University of Washington
dbliss@u.washington.edu

Jennifer Lee Zeman, Flyer**
Freshman, Undeclared
Seattle Central Community College
leezee@dbsi.org

Amelia Lacenski, Flyer
Sophomore, Visual Communication
University of Washington
lacena@u.washington.edu

Matthew Dockrey, Flyer*
Freshman, Undeclared
Seattle Central Community College
gfish@cyphertext.net

Adam Bliss, Alternate Flyer*
Senior, Mathematics
Harvey Mudd College
abliss@hmc.edu

* Participated as Flight Crew for GYRE 1, July/August 2003.
** Participated as Ground Crew for GYRE 1, July/August 2003.

Linda G. Bushnell

I. Technical

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Note: this document is submitted electronically in RTF (Rich Text Format), as required by the NASA RGO. However, it is also available in Adobe’s Acrobat (PDF) format at `http://depts.washington.edu/gyre/04propfinal.pdf`. *Use the username ‘nasa’ and the password ‘rgo’ to access this document.*

2. Flight Week Preferences

The investigators would prefer the following flight weeks, most-preferred first:

1. Group 6, July 22 through July 31, 2004.
2. Group 5, July 8 through July 17, 2004.
3. Group 4, April 15 through April 24, 2004.

However, because the experiment is a free-float, the investigators emphasize their willingness to accept any flight week if necessary for scheduling reasons.

3. Advisor / Mentor Request

The investigators are not requesting the services of a NASA Advisor / Mentor.

4. Synopsis / Abstract

The proposed experiment, GYRE 2, is a follow-up to the original GYRE experiment, flown as part of the 2003 Reduced Gravity Student Flight Opportunities Program. GYRE 1 aimed to investigate the feasibility of visual servoing for navigation in microgravity, and good visual data was acquired from the onboard cameras during the course of the experiment. The current experiment, GYRE 2, will use analysis of the previous data to improve our motion estimation algorithms and evaluate the performance of closed-loop control with visual servoing for maneuvering in microgravity. Specifically, we will compare the performance of two closed-loop control methodologies in this unique environment. Closed-loop controllers adjust the behavior of a system based on the current output of the system in order to reach a desired output in the future. In this case, the input is motion estimated from onboard cameras and the desired goal is minimal motion in all six degrees of freedom. The output is the duty cycle to command to the onboard cold gas propulsion system. Several concerns govern the design of a feedback system for this application: the input, taken from motion estimation algorithms, is noisy and may have errors; the kinematics of the robot may be nonlinear; and the platform is compute-cycle-constrained. Also, the robot operates in a chaotic environment and may at any time strike a wall or be repositioned by a crewmember. To determine the best method for control, we will test two closed-loop controllers: PID and Lead-Lag. Our metrics for success are error and system response -- that is, the deviation of the final speed of the robot from zero and the time to reach a steady equilibrium. In determining success, error will be considered more important measure of success than system response, but system response will also be significant.

5. Test Objectives

The experiment is designed to select the most effective closed-loop controller for orientation and navigation in freefall based on motion estimation input from three orthogonal cameras and to demonstrate that automated orientation and navigation are possible via visual servoing and feedback controllers. We hypothesize that a Proportional-Integral-Derivative (PID) controller will provide the better closed-loop performance than a phase lag compensator, and that the robot will be able to orient itself and successfully adjust its rotation to bring itself to a standstill.

6. Test Description

Closed-loop controllers adjust the behavior of a system based on the current output of the system in order to reach a desired output in the future. In this case, the input is motion calculated from camera footage taken by the robot, and the goal is minimal motion in any direction. The output is a decision to fire certain thrusters at a certain duty cycle.

Closed-loop feedback lessens the likelihood of overshooting the goal or getting caught in an unstable oscillating rotation. Several concerns govern the design of a feedback system for this application. First, the input, taken from motion estimation algorithms designed and tested in a previous experiment, is erroneous at times. The interior of the Weightless Wonder is visually noisy, with many objects moving at independent speeds, resulting in “spikes” in the motion estimation data. Second, the input is discrete and digital. Many control systems designed for continuous data rely on second-order data. Any control algorithm used in the robot will of necessity assume that the rate of change is linear between each set of image pairs used in motion estimation, and the control loop must be flexible enough that this assumption will not invalidate it. Third, the control code must be efficient enough to run several times a second and adjust thrust levels. Last, there is a good possibility that the robot will be bumped, collide with a wall or be repositioned by a handler. A controller must be able to handle these outside forces.

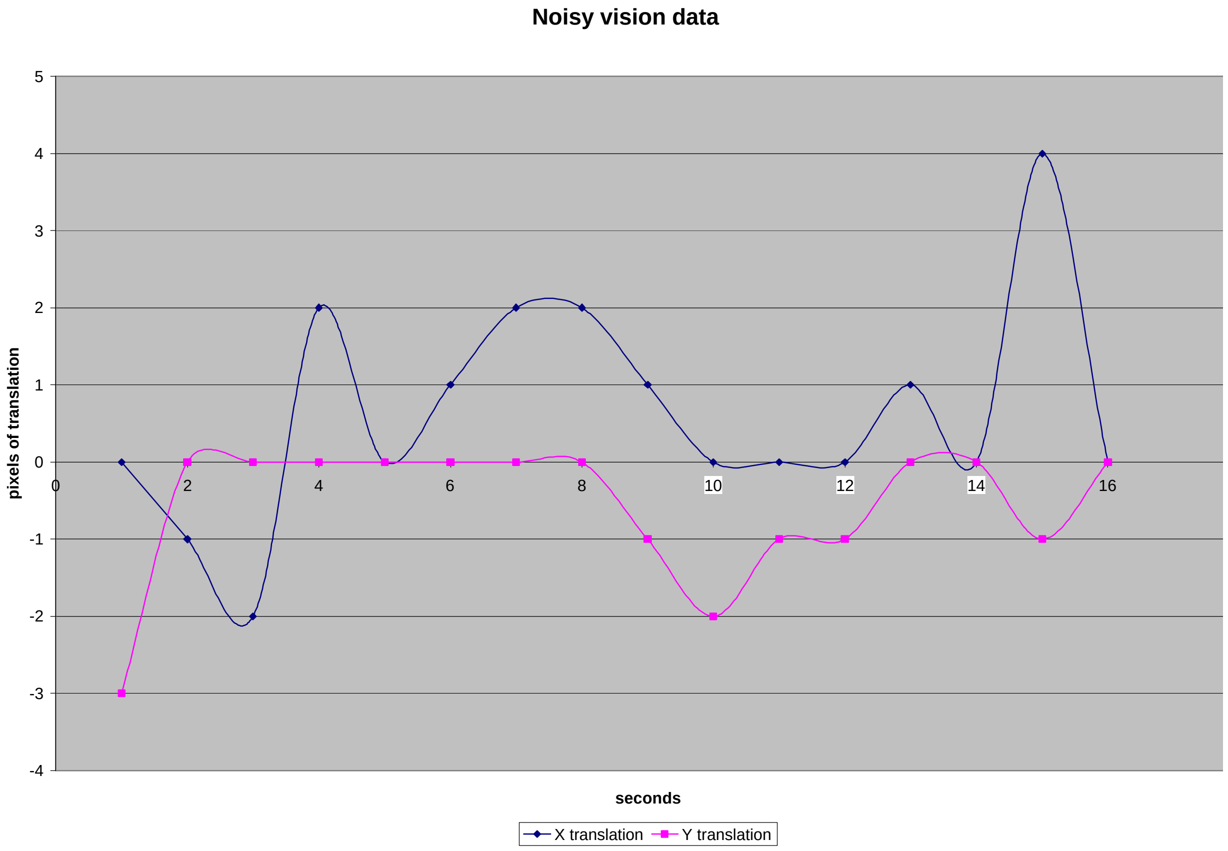

Figure 1: The robot's vision data as a team member grabs and jars it. An example of very noisy data a closed-loop control would have to compensate for.

We will test two closed-loop controllers with different strengths and weaknesses to see which is more effective at bringing the robot to a stop. There are two primary metrics for success: error and system response. The error is the final speed of the robot – ideally, zero. System response is the amount of time it takes the closed-loop control to reach a steady equilibrium. We judge error to be a more important measure of success than system response; however, in the event that both algorithms succeed at canceling the spin of the robot, we will use system response as a measure of control effectiveness.

Each of the robot's three axes will have its own closed-loop controller, which will take input from the two cameras that point perpendicular to that axis (and are thus situated to detect motion around it). The controller will then decide whether to fire any thrusters on its axis, and if so, which ones and at what duty cycle.

A. PID Controller

Proportional-Integral-Derivative (PID) controllers are widely used in electronic appliances, and are frequently used to respond to visual input, such as aiming a robotic vehicle at a specific point on the road (Tsugawa). PID controllers are usually used to aim a closed-loop system at a specific goal.

PID controllers incorporate three separate controller “bands” to realize the benefits of all three. The proportional band fires the thrusters at a duty cycle proportional to the robot's current speed. This alters the speed accurately when the robot is rotating quickly, but can reach an inaccurate steady state at a speed too slow for it to take action, or an unstable oscillation between a positive and a negative rotation. The integral band fires the thrusters at a duty cycle proportional to the sum of the past several speeds, preventing steady-state errors. The derivative band fires the thrusters proportionately to the speed divided by the current acceleration. This prevents overshoot; the derivative bands slows down the robot when it approaches its goal.

We will be experimenting on the ground to determine the correct weights of the P, I, and D bands, using the Ziegler-Nichols frequency response tuning method (Ziegler). The weights will depend on thruster response times, drag, inertia, and camera accuracy. The robot will be hung from a rigid wooden test stand and freely rotating bearings such that it has one degree of freedom and we can configure the PID controller along that axis. A PID controller will be installed in the robot and limited to access only the Proportional band. We will increase or decrease the duty cycle a thruster is fired for each pixel of observed motion until the robot reaches a steady oscillation – it notices it is spinning clockwise, fires its thrusters counterclockwise, and is then spinning counterclockwise at the same rate. The thruster fire duty cycle is called 'ultimate gain' (G_u) and the period of the oscillation is the ultimate period (P_u).

According to Zieger and Nichol's method, the P, I, and D values can be calculated as:

$P = .6\ G_u$

I is integrated over $2/P_u$

and D is measured over $P_u/8$

We expect these experiments to validate large values of P and D and small values of I.

B. Phase Lead/Lag Compensator

Phase Lead/Lag compensators are most often used to shape the long-term behavior of a system into a desirable equilibrium. They are used in visual servoing to maintain a condition such as keeping a vehicle a certain distance from the road's centerline (Blasi). They adapt well to systems with a lot of sensor noise because they increase the margin of error and allow a closed loop to remain stable even in the event of poor decisions caused by bad data, incorrect modeling, or disproportionate system response.

Like the PID controller, Lead/Lag compensators calculate multiple terms in order to maximize the benefits and balance the negatives. Phase lead increases the system bandwidth, leading to a faster system response, but this term is very affected by data noise. Phase lag makes a system "slower" – more stable, less sensitive to noise, but slower to reach its goal.

We will be conducting ground tests with the robot in one axis to evaluate the best phase lead or lag for our Phase Compensator controller. We expect to adapt a phase lag in order to cancel out the spikes from the noisy vision algorithms, using the methods outlined in Xu's "Automatic Tuning of Phase-lead and Phase-lag Compensators."

C. Hardware Platform

We will evaluate these control algorithms using the GYRE Experimental Platform, a robot built for the 2003 RGSFOP flight and flown during July of 2003. While minor improvements to the hardware will be made, no major changes are anticipated. For specific details about the hardware design, please consult the GYRE 2003 documentation available on our website and the 'Experiment Safety' section of this document. A brief overview is included here.

The robot is composed of three main subsystems: the control system, the power system, and the propulsion system.

The control system

The robot is controlled from an external laptop. 802.11b wireless networking is used to communicate with a laptop on the robot itself. This link is bidirectional, allowing commands to be sent to the robot and data to be sent back. Software on the control laptop provides visualization of the output of the motion estimation as well as control over the operation of the robot. This allows us to easily change the feedback algorithm being used for a given parabola, as well as test thruster operation by using a manual control mode. The laptop on the robot is responsible for running the vision analysis and feedback control code. Video frames are acquired from three IEEE1394 cameras. A serial link to a National Instruments Fieldpoint module allows the laptop to fire thrusters as needed.

The power system

The control laptop is powered by commercial lithium-ion batteries. Two lithium-polymer battery packs manufactured by the GYRE Project provide power for all other onboard electronics.

The propulsion system:

The robot is maneuvered using 12 cold-gas thrusters. The propellant supply is two 1.4L tanks of air at 30.0 MPa, each regulated to 1.3MP with a pressure regulator. The supplies are tied together after the regulator to reduce asymmetrical thrusts from transient drop in pressure. Two manifolds then provide the propellant to 12 high-speed solenoid valves. For weight and routing reasons, Nylotube nylon tubing was chosen as the primary piping material. The thrusters are SS plugs with #59 holes for the throat. By choosing a target granularity in rotational control, we were able to define the target force of a thruster, and therefore the nozzle diameter for the chosen pressure range.

7. Justification for a Follow-Up Flight

The proposed experiment, GYRE 2, is a follow-up to the original GYRE experiment, flown as part of the Reduced Gravity Student Flight Opportunities Program 2003. The previous experiment, GYRE 1, flew during the week of July 24, 2003. GYRE 1 aimed to investigate the feasibility of visual servoing for navigation in microgravity. Due to a combination of hardware failures and insufficient integration testing of replacement hardware, no maneuvering was completed because the control bus to the thruster subsystem did not function in flight. However, good visual data was acquired from the onboard cameras. The current experiment, GYRE 2, will use the results from analyzing this data to improve our motion estimation algorithms, will use the time available this year to perform rigorous testing of the maneuvering system, and will test the performance of the maneuvering system and its associated control (servo) loops using data gathered by visual processing.

We do not anticipate making substantial changes to the hardware platform, but will make incremental improvements as needed to improve performance. For example, we intend to substitute a faster onboard computer for better performance. However, the onboard control software will be extensively rewritten for reliability, testability, and performance. Furthermore, extensive integration testing and an associated feature freeze will be carried out well before flight. Also, the electrical (ground loop) issues that led to hardware failure on the first flight will be corrected and extensive electrical burn-in testing performed.

Because GYRE 1 did not successfully demonstrate closed-loop control and maneuvering, it is necessary to fly GYRE 2 to determine whether this can be achieved and to compare the performance of two closed-loop control methodologies in the unique environment of microgravity. Data and experience gathered during GYRE 1 will be used to enhance the viability of GYRE 2.

The results from GYRE 1 indicate that reasonable performance in motion estimation can be attained using COTS hardware in real time. The conclusion is that visual servoing may be an adequate technique for free-fall operations, but the remainder of the control loop must be validated by further research.

8. References / Bibliography

Abramamovici, Aand Chapsky, J. *Feedback Control Systems: A Fast-track Guide for Scientists and Engineers.* Boston: Kluwer Academic Publishers, 2000.

Blasi, R, et al. "Vision-based Lateral Control of Vehicles." *IEEE Conference on Intelligent Vehicles* (1997)

Morris, Kristen. *Introduction to Feedback Control.* London: Harcourt Academic Press, 2001.

Stefani, Raymond, et al. *Design of Feedback Control Systems.* New York: Oxford, 2002.

Tsugawa, S., et al. "A Lateral Control Algorithm for Vision-Basised Vehicles with a Moving Target in the FIeld of View." *IEEE Conference on Intelligent Vehicles* (1998): page numbers.

Xu, Y. “Automatic Tuning of Phase-lead and Phase-lag Compensators,” *International Journal of Control*, 60.4 (1994)

Xu, Y. "Robust Control of Free-Floating Space Robot Systems," *International Journal of Control* 61.2, (1995)

Ziegler, J. G. and Nichols, N. B. "Optimum settings for Automatic Controllers," ASME Transactions 65 (1942).

II. Experiment Safety Evaluation

1. Introduction

Because the experiment hardware is substantially unchanged from the GYRE 1 (2003) flight, and in the interests of providing the most current, complete and accurate technical information available, the final (i.e., used for TRR) TEDP from GYRE 1 is reproduced verbatim here – that is, *in the interests of maximum safety this section, unlike the rest of this proposal, contains non-original content. This content is purely factual and technical. This content was produced by, and all rights therein are held by, the GYRE Project, and is reused by permission.* Specific names, dates and details have been corrected for the current proposal, but the technical content is unchanged. The TEDP for GYRE 2 will be created by making revisions to the GYRE 1 TEDP in order to account for any (minor) hardware changes made.

2. Quick Reference

Principal Investigator:	Linda G. Bushnell
Contact Information:	David Bliss +1 206 860 3514 dbliss@u.washington.edu

Experiment Title:

GYRE 2: Evaluation of Visual Navigation Techniques for Autonomous Free-Flying Robots

Flight Date(s):	TBD
Overall Assembly Weight (lbs.):	50 pounds
Assembly Dimensions (L x W x H):	18" x 18" x 18"
Equipment Orientation Requests:	None

Proposed Floor mounting system:

None (we will require the use of two crash crates during TOAL).

Gas Cylinder Requests(Type and Quantity):

None (onboard high-pressure air cylinders are provided by the investigators)

Overboard Vent Requests(Yes or No): No

Power Requirements (Type and Amps Required):

None required (operates from onboard batteries)

Flyer Names for Each Proposed Flight:

Flight 1:	David Bliss*, Amelia Lacenski
Flight 2:	Matthew Dockrey*, J. Lee Zeman**

* Participated as Flight Crew for GYRE 1, July/August 2003.
** Participated as Ground Crew for GYRE 1, July/August 2003.

Camera Pole and/or Video Support: 1 camera pole

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(elided)

4. Flight Manifest

Flight 1:

David Bliss (GYRE 1, 2003, Flight Crew)

Amelia Lacenski (no prior experience)

Flight 2:

Matthew Dockrey (GYRE 1, 2003, Flight Crew)

J. Lee Zeman (GYRE 1, 2003, Ground Crew)

5. Experiment Background

Motion calculations based on visual input offer greater precision and flexibility than motion data derived from accelerometers. However, there are many factors complicating implementation of visual servoing for this application. Many previous autonomous robots have relied upon a pre-generated model of their area or a "base image" taken while the robot was at rest, which is not possible in this case. The interior of the KC-135 or a space station is visually "noisy" in unpredictable ways - objects of several sizes, rigid and non-rigid, moving at various speeds in three dimensions, require very adaptable processing. In addition, the algorithm must be efficient enough to process 30 images of 640 x 480 pixels in a second.

We would like to determine which of several motion detection algorithms is best suited to this application, and will test three separate algorithms. The first algorithm is designed to be as simple and naive as possible. This method will group pixels of similar colors together and ignore areas with a high degree of color variation. The second method is slightly more sophisticated. It will choose and analyze eight to ten key points: intersections of edges, boundaries between regions. Unfortunately it is much slower than the simple method and may not be executed the full 30 times a second. The third method will be a hybrid of the above two.

Our robot will use the algorithms described above to determine its velocity relative to the aircraft visually, and act using its compressed air thrusters to counteract that motion, to come to a stop relative to the aircraft and maintain that attitude.

This experiment is a follow-up to GYRE 1, which flew aboard the Weightless Wonder V in July, 2003. It is not a preliminary step to a future experiment nor related to a space flight experiment.

6. Experiment Description

We will position the robot in various attitudes and rotations and compare the time it takes to bring itself to a stop using different control algorithms. During each microgravity interval, a control algorithm will be chosen, the robot will be positioned by investigators in the approximate center of the available cabin space, and a rotational moment will be imparted by a team member. The robot will then attempt to cancel that moment and perform station-keeping. For each microgravity period we will measure the time taken for the robot to come to a relative stop, assess its effectiveness at station-keeping, and observe and document errors made by the system. This information will be used to determine the most suitable visual control algorithms for this application. In addition to our own observations, we plan to use a digital video camera mounted to the plane to record the movements of the robot for additional accuracy and later analysis.

7. Equipment Description

The equipment consists of off the shelf commercial laptop computers, commercial 802.11b wireless networking cards, off the shelf digital cameras, and a fabricated robot. The robot has the form of a cube 45cm in side length and massing about 20kg. Each edge is a section of 1"x1"x0.125" 6061-T6 structural aluminum angle stock, covered with padding. Cameras protrude slightly from the centers of three faces of the cube and thrusters emerge from the center of each edge. All edges and corners are well padded for protection. The robot frame contains two lithium polymer batteries in 12 volt 2 amp hour packs; a Sony commercial laptop computer with attached lithium-ion battery; a National Instruments Fieldpoint interface system; two high pressure air tanks with attached pressure regulator, gauges, shutoff valves and relief (safety) valves; two pressure manifolds; twelve electronic solenoid valves; and twelve thrusters.

8. Structural Analysis

Per email of May 2003 from Mrs. Deanna Wilmore, structural analysis of the experiment is not required because the experiment will not be mounted to the aircraft in flight and will be stowed in NASA-provided crash crates during TOAL.

9. Electrical Analysis

Load Table:

Power Source Details		Load Analysis	
Name	System Battery	IEEE 1394 Firewire Hub	.5A
Voltage	29.6VDC Nominal	FieldPoint Network Interface and PWM Modules	<.1A
	33.8VDC Max	12 Thruster Solenoids	4A
Wire Gauge	12 Gauge for Loads >1A		
	24 Gauge for Loads <1A		
Max Battery Current	7.5A (Fused)	Total Current Draw	4.6 A

Electrical Schematic:

Stored Energy

The experiment uses no high-charge stored energy devices.

Electrical Kill Switch & Loss of Electrical Power

Two large non-momentary emergency stop buttons are permanently mounted on the robot, in locations easily reached during both free-fall and normal gravity portions of the flight. Tripping the switch immediately cuts off all current from the onboard batteries. All thruster solenoids are of a “usually closed” type and will fail to the closed position. The onboard host laptop is not hooked into the emergency stop circuit, as it has its own battery power; however, the operations of the laptop should pose no conceivable hazard. The laptop can be shut down relatively rapidly (within ten seconds) by means of its standard power switch.

10. Pressure Vessel Certification

Our experiment involves two identical cross-connected Category B pressure systems. The OCCP request follows.

OCCP Request

1. Statement of purpose.

This OCCP is being requested for an operational test of a microgravity research experiment to be conducted by the University of Washington under the auspices of the Reduced Gravity Student Flight Opportunities Program.

2. Test location.

The system tanks (with attached regulators) will be filled offsite to 4500psi with air and brought to Ellington Field. At Ellington they will be mated to the rest of the pressure system via Foster 12MP quick-disconnects and structurally mounted to the experiment. The remainder of the system will be pressurized in-flight aboard the KC-135 by opening the regulator valve. In the event that the air reserves are not depleted in flight, the regulator valve will be closed and the remainder of the system drained prior to stowage for landing. Once on the ground, the tanks will be dismounted from the remainder of the experiment and taken offsite for refilling.

3. System description.

Is the system flight or flight-like?

This is a flight-like system.

What is the system designed to do?

The system is designed to provide cold gas maneuvering for our experimental package within the confines of the KC-135 aircraft.

When and where was the hardware first assembled?

The hardware has undergone an iterative design/build/test process at the University of Washington's Reduced Gravity Robotics Laboratory. The current design was assembled at the UW RGRL during April of 2003.

Has the hardware been modified since its original build?

The current iteration of the hardware has not been modified since the original build. Many components were shared with previous design iterations.

4. Pressure history.

What historical documentation exists for the system, or for parts of the system?

Is a pressure or service history available?

No pressure or service history is available for any components of the system. The tanks underwent DOT hydro at manufacture in July of 2000. The tanks were hydrostatically tested per DOT spec by a DOT-authorized inspector (Compressed Gas Western, Seattle, Washington) in June of 2003 and tagged accordingly. This hydro is valid through June of 2008.

5. Description of system fluid(s).

The system fluid is standard compressed air, which is not toxic.

Nominal temperature is room temperature, 20C. Worst case temperature depends on the KC135 environment. The tanks are rated to a maximum temperature of 140F. The batteries powering the system should not generate significantly more heat than ambient temperature and have relatively little thermal mass; however, the maximum temperature the batteries can reach before being shut down by thermal cutoff is 60 degrees Celsius. As an additional precaution, the batteries are well separated from all pressure components.

6. Schematic diagram:

Notes:

1. The experiment contains two identical pressure systems conforming to this diagram. They are cross-connected from manifold to manifold. In the event flight conditions warrant, it may be necessary to operate the system with one tank removed. This would be accomplished by connecting a blank plugged QD in place of that tank. This plugged QD is described below in the event it is required.

2. Normal lines are Nylotube Nylon-11 .375 inch semi-rigid grade tubing.

3. Bold lines are SS304 1/4" nominal schedule 80 2" nipples.

4. Dashed lines are brass 1/8" nominal schedule 40 close nipples.

5. All joints are NPT thread with mil-spec Teflon tape.

7. Detailed drawings.

Thrusters and solenoids.

There are 12 thrusters. Rotation of solenoid and thruster vary.

Tanks.

Tanks are kept in a hard-shell plastic case in fitted foam to prevent possible damage when not mounted to the robot, and padding is placed between the tanks and the tank-tie downs during tank mounting.

8. Maximum Design Pressure (MDP).

What is the system's MDP?

1000 psi. Please note that the regulators are adjustable over a range of 0-1000psi. We are currently operating at 200psi; however, we will have to determine the appropriate operating pressure closer to flight date. Therefore, we wish to certify those portions of the system downstream of the regulator to 1000 psi, even though we will operate at an unknown pressure less than that. This will also involve replacing the low-side relief device with one rated appropriately for the working pressure to be used.

How was the MDP established?

1000 psi is the maximum output of our regulator in normal operation. As this system is not scheduled for Space Shuttle flight, a two-fault scenario is not necessary.

9. Component matrix.

In some cases, exact specifications of off-the-shelf components are not available. In all such cases, we are using components according to manufacturer's specifications. Design burst pressure is listed for all components fabricated by the team or for which we were able to determine by measurement and analysis in accordance with ASME B31.3, section 302.3.6. MAWP (maximum allowable working pressure) according to the manufacturer is listed for all components we were unable to determine a design burst pressure on.

Part	Description	Fluid	Operating Pressure	Manufact Rating (when known) or design burst press.	MDP	Safety Factor	Material	Attach-ment
Tank	Carleton Technologies Part #6196, 88ci (11.65" long, 4.10" OD) 4500psi DOT-CFFC/TC/HSE tank, DOT Exemption #11194	Air	4500 psi	>18000 psi	4500 psi	>4	Carbon fiber	MS33649 -07 (5/8"-18 O-ring)
Regulator	Max Flow 4500 PSI regulator	Air	Input 4500 psi; Output 1000 psi.	>18000 psi	4500 psi	>4	Aluminum	MS-07 input, 1/8 NPT 27 female threaded port output
Burst disc (high side relief,		Air	4500 psi	7500 psi	4500 psi	1.66	Steel	1/8 NPT 27 threaded joint

7500 psi)								
High Side Pressure Gauge	0-5000psi	Air	4500 psi		4500 psi	[5]	Various	1/8 NPT 27 threaded joint
Fill port	Foster QD ID=0.137”	Air	4500 psi		4500 psi	[5]	Steel	1/8 NPT 27 threaded joint
Low Side Pressure Relief Device (240psi)	Generant VRVH-125B-V-240	Air	1000 psi		1000 psi	[5]	Brass	1/8 NPT 27 threaded joint
Low Side Pressure Gauge	Ashcroft 9072-01 0 to 1200 psi gauge	Air	1000 psi		1000 psi	[5]	Various	1/8 NPT 27 threaded joint
Elbow Fitting	Ninety degree elbow, ID = .186 OD = .405	Air	1000 psi		1000 psi	[5]	Brass	1/8 NPT 27 threaded joint
Small quick disconnect	Foster 12MP OD = .405, ID = .170	Air	1000 psi	2500 psi	1000 psi	[5]	Brass	1/8 NPT 27 threaded joint
Elbow Fitting	Ninety degree elbow, ID = .186 OD = .405	Air	1000 psi		1000 psi	[5]	Brass	1/8 NPT 27 threaded joint
Newloc male adaptor	Newloc 6200369	Air	1000 psi	5800 psi	1000 psi	5.8	Brass	High-pressure push connection
Supply pipe	Nylotube semi-rigid nylon11 tubing, OD = .375, ID = .225	Air	1000 psi	5800 psi [1]	1000 psi	5.8	Nylon-11	High-pressure push connection
Newloc male adaptor	Newloc 6200369	Air	1000 psi	5800 psi	1000 psi	5.8	Brass	High-pressure push connection
Reducing	1/8” to 1/4 McMaster-Carr	Air	1000 psi	Manufacturer certified to	1000 psi	>3 [5]	ASTM A312	1/8 NPT 27

Coupling	#45525K641			3000 psi MAWP			Type 304 Stainless steel	threaded joint to 1/4 NPT 18 threaded joint
Supply Nipple	1/4" Schedule 80 nipple (Wall thickness .119; OD .540; ID .302) McMaster-Carr #46755K22	Air	1000 psi	5184 psi design burst pressure [2]	1000 psi	5.18	ASTM A312 Type 304 Stainless steel	1/4 NPT 18 threaded joint
Manifold	McMaster-Carr #5469K171	Air	1000 psi	Manufacturer certified to 1000 psi MAWP	1000 psi	[5]	6061-T6 Aluminum	8 1/8 NPT 27 threaded joints, 2 1/4 NPT 18 threaded joints
1 Newloc male adaptor	Newloc 6200369	Air	1000 psi	5800 psi	1000 psi	5.8	Brass	High-pressure push connection
1 Cross-connect pipe	Nylotube semi-rigid nylon11 tubing, OD = .375, ID = .225	Air	1000 psi	5800 psi [1]	1000 psi	5.8	Nylon-11	High-pressure push connection
1 1/8” plug	1/8 NPT 27 MCM 4464K321	Air	1000 psi	3000 psi	1000 psi	3	steel	
1/4" plug	1/8 NPT 18 steel plug McMaster-Carr #50925K381	Air	1000psi	6000 psi MAWP	1000 psi	> 6	Steel	1/4 NPT 18 threaded joint
6 Newloc male adaptors	Newloc 6200369	Air	1000 psi	5800 psi	1000 psi	5.8	Brass	High-pressure push connection
6 Thruster pipes	Nylotube semi-rigid nylon11 tubing, OD = .375, ID = .225	Air	1000 psi	5800 psi [1]	1000 psi	5.8	Nylon-11	High-pressure push connection
6 Newloc male adapt	Newloc 6200369	Air	1000 psi	5800 psi	1000 psi	5.8	Brass	High-pressure push connection

ors								
6 Solenoid Valve	McMaster-Carr #7892 K999; 24 VDC, with 24” leads 1/8” fpt, .023” CV, 1000 Max Operating Press Diff	Air	1000 psi	1000 psi MAWP	1000 psi	[5]	Brass	1/8 NPT 27 threaded joint
6 Close nipples	ID = .240 od = .405	Air	1000 psi	15786 design burst pressure [3]	1000 psi	15.78	Brass	1/8 NPT 27 threaded joint
3 Thruster street elbows	90-degree street elbow ID = .240 OD = .405	Air	1000 psi	15786 design burst pressure [3]	1000 psi	15.78	Brass	1/8 NPT 27 threaded joint
6 Thrusters	See attached drawing	Air	1000 psi	9524 psi design burst pressure [4]	1000 psi	9.524	ASTM A312 Type 304 Stainless steel	1/8 NPT 27 threaded joint

Table Notes:

[1] Value calculated in accordance with ASME B31.3. – t = .075, d = .375, s = 8700

[2] Values calculated with tm = .119, c = .04444, d = .540, E = 1, y = .4, s = 16700

[3] Values calculated with tm = .165m c = .02963, d = .405, E = 1, y = .4, s = 17300

[4] Values with d = .4084, tm = .094825, c = 0, t = tm, E = 1, y = .4, s = 16700

[5] Within manufacturer’s guidelines

10. Test procedures.

Include any written procedures available that describe the pressurization/operation activities planned for the system.

The system tanks (with attached regulators) will be filled offsite to 4500psi with air and brought to Ellington Field. At Ellington they will be mated to the rest of the pressure system via Foster 12MP quick-disconnects and structurally mounted to the experiment. The remainder of the system will be pressurized in-flight aboard the KC-135 by opening the regulator valve. In the event that the air reserves are not depleted in flight, the regulator valve will be closed and the remainder of the system drained prior to stowage for landing. Once on the ground the tanks will be dismounted from the remainder of the experiment and taken offsite for refilling.

Detailed written procedures are not yet available but will be prepared.

11. Fracture/stress analyses.

No fracture/stress analysis has been completed for this system at this time.

12. Date required.

When is the OCCP needed?

Prior to our assigned flight week.

13. Pressure System Managers Office (PSMO) involvement.

The PSMO has been contacted regarding this pressure system.

Has the PSMO (Paul Torrance, 281-483-1883) been contacted regarding this pressure system?

The system has been discussed with Glenn Ecord.

Has PSMO inspected any pressurized ground support equipment or other facility pressure systems that might interface with this system?

No.

Is there any pressure equipment planned for use that is not either covered by PSMO or covered within the planned OCCP?

No.

14. Personnel involvement.

Who, besides PSMO, must be included on distribution of this OCCP (i.e. project managers, project and safety engineers, etc.)?

Deanna Wilmore, deanna.c.wilmore1@jsc.nasa.gov

Reduced Gravity Office, donn.g.sickorez1@jsc.nasa.gov

15. Safety review panel involvement.

This system has not been assessed by either the Payload Safety Review Panel or the Space Station Review Panel; neither is relevant.

16. Special considerations.

There are no unusual components that require special consideration. There are no brazes or welds in any component of this system.

11. Laser Certification

This experiment does not involve lasers.

12. Parabola Details and Crew Assistance

No special parabola requirements or crew assistance are needed.

13. Free Float Requirements

Our experiment is free-floating, weighs fifty pounds, and is a cube approximately eighteen inches on a side. All edges and corners of the cube are thickly padded to prevent damage to crew or equipment.

14. Institutional Review Board (IRB)

This experiment does not use living test subjects and is therefore not subject to IRB approval.

15. Hazard Analysis (Hazard Source Checklist)

Enumerate or mark N/A

_N/A_Flammable / combustible material, fluid (liquid, vapor, or gas)
_1__ Toxic/noxious/corrosive/hot/cold material, fluid (liquid, vapor, or gas)

_2__ High pressure system (static or dynamic)
_N/A Evacuated container (implosion)
_N/A Frangible material
_N/A Stress corrosion susceptible material
_N/A Inadequate structural design (i.e., low safety factor)
_N/A High intensity light source (including laser)
_3__ Ionizing/electromagnetic radiation
_4__ Rotating device
_5__ Extendible/deployable/articulating experiment element (collision)
_N/A Stowage restraint failure
_N/A Stored energy device (i.e.,mechanical spring under compression)
_N/A Vacuum vent failure (i.e., loss of pressure/atmosphere)
_N/A Heat transfer (habitable area over-temperature)
_6__ Over-temperature explosive rupture (including electrical battery)
_N/A High/Low touch temperature
_7__ Hardware cooling/heating loss (i.e., loss of thermal control)
_N/A Pyrotechnic/explosive device
_8__ Propulsion system (pressurized gas or liquid/solid propellant)
_N/A High acoustic noise level
_9__ Toxic off-gassing material
_N/A Mercury/mercury compound
_N/A Other JSC 11123,Section 3.8 hazardous material
_N/A Organic/microbiological (pathogenic)contamination source
_10_ Sharp corner/edge/protrusion/protuberance
_N/A Flammable/combustible material, fluid ignition source (i.e., short circuit; under-sized wiring/fuse/circuit breaker)
_N/A High voltage (electrical shock)
_N/A High static electrical discharge producer
_11_ Software error
_N/A Carcinogenic material

DETAILED HAZARD DESCRIPTION

Hazard Number: 1
Title: Battery rupture and subsequent chemical contamination

Hazard Description: The robot uses eight lithium-polymer gel electrolyte batteries. If the batteries were to rupture, the gelled acid electrolyte they contain could react with the metal of the robot and cause acid burns on flight crew, or over pressurization of the battery case could result in explosive rupture and release of hydrogen fluoride gas .

Hazard Cause(s):

- Batteries used outside their rated conditions.
- Manufacturing defect in battery.
- Overcharging or undercharging batteries, causing gas buildup.
- Drawing too much current from batteries.
- Overheating causes gas buildup.

Hazard Control(s):

- All batteries will be used in accordance with the manufacturer's specifications.
- All batteries will have a 48 hour 'burn in' prior to flight.
- Battery ratings will be compared to predicted flight conditions and such
- Ratings and conditions will be documented in the electrical analysis of this document.
- Components will be tagged upon burn-in and tag verified on final assembly checklist.
- Installed battery circuit board prevents overcharging, undercharging, and overcurrent.
- Self-resetting thermal cutoff fuse prevents rupture due to overheating.
- Batteries will be charged only on ground.
- Entire electrical bus is protected by hard fuse to prevent any overcurrent conditions.
- Battery cells encased in rigid plastic to prevent impact damage.

Hazard Number: 2
Title: High Pressure Air System Explosion

Hazard Description: The robot uses two high pressure air tanks. If these tanks were to rupture they could release their contents in an uncontrolled manner.

Hazard Cause(s):

- Tank inadvertently designed to less than that required.
- Tank fabrication defective.
- Pressure relief valve failed to open at the correct pressure.
- Tank pressure gauge reading incorrectly.
- Tank failure due to incorrect filling.
- Heat from batteries raises pressure in tanks.

Hazard Control(s):

- Tanks are designed and manufactured in an audited process in conformance with a DOT certificate of exemption, preventing underdesign.
- Tank manufacture in an audited process in conformance with a DOT certificate of exemption prevents manufacturing defects.
- Pressure relief devices are certified to operate before an unsafe pressure develops.
- Tank pressure gauges will be calibrated before flight.
- Tanks will be filled only by qualified personnel and off JSC property.
- Tanks were hydrostatically tested in June 2003 by a DOT-certified technician.
- Batteries and tanks are not mounted in close proximity, and batteries have been wired with thermal cutoff switch.

Hazard Number: 3
Title: RF Interference

Hazard Description: Aircraft instrumentation, other experiments or crew medical devices could fail due to RF interference.

Hazard Causes:

- Failure of RF devices to conform with FCC regulations.
- Unforeseen interactions between conforming devices.

Hazard Controls:

- All devices are commercially manufactured in accordance with FCC regulations and are inspected for proper operation by a radio operator trained in interference resolution (David Bliss, FCC call sign KF4MWN).
- In the event of any unforeseen interaction, RF devices will be shut down for the remainder of the flight.

Hazard Number: 4
Title: Rotating Devices

Hazard Description: Personnel or equipment could be caught in or struck by the rotating robot, causing damage or injury.

Hazard Causes:

- Personnel failure to observe safe distance requirements.
- Software error results in unpredictable sudden acceleration of the robot.

Hazard Controls:

- All personnel will maintain minimum safe distances from the robot at all times.
- Validity of software will be verified prior to flight; software and hardware kill switches can halt acceleration immediately if a problem develops in flight.
- Thrust system can only provide low acceleration, thus giving operators time to respond to control problems.

Hazard Number: 5

Title: Collision of Robot

Hazard Description: Free-floating robot collides with personnel or equipment, causing injury or damage.

Hazard Causes:

- Thruster misfire or software error sends the robot out of control.
- Personnel fail to maintain safe distances.

Hazard Controls:

- All edges of the robot are padded with 3/8” polyurethane pipe insulation to prevent damage or injury to equipment or personnel.
- The robot conforms to free-floating experimental guidelines and has a mass of only 50 pounds and a maximum thrust of only 1.2N in any axis. Only low levels of acceleration are possible, thus limiting the amount of available energy in a collision.
- Hardware kill switch allows for complete shutdown of the robot at any time.

Hazard Number: 6

Hazard Title: Explosive Rupture of Electric Battery

Hazard Description: Gelled-electrolyte lithium-polymer battery heats up and ruptures.

Hazard Causes:

- Manufacturing defect in battery
- Heat generated by some other portion of the robot may overheat battery.
- Batteries reach threshold of thermal runaway.

Hazard Controls:

- Batteries will be fused to prevent excessive load.
- Batteries will be tested with a 48 hour ‘burn-in’ prior to flight.
- No other portion of the robot can generate significant amounts of heat in flight.

- Self-resetting thermal cutoff fuse mounted in center of battery array will shut down batteries before they overheat, even if the heat is from an external source.
- Batteries will be charged only on ground.
- Entire electrical bus protected by hard fuse to prevent any overcurrent conditions.

Hazard Number: 7
Hazard Title: Loss of thermal control

Hazard Description: Abrupt pressure drop in tank leads to rapid heat loss

Hazard Causes:

- Rapid depressurization of tank due to leak in plumbing.

Hazard Controls:

- Plumbing system is designed with a proper safety factors to preserve pressure integrity.
- Piping is rated to a temperature of minus ninety degrees Fahrenheit. Fittings are rated to a temperature of minus ten Fahrenheit.

Hazard Number: 8
Hazard Title: Propulsion System

Hazard Causes:

- Danger from thruster exhaust.
- Loss of control of propulsion system leads to erratic movement.

Hazard Controls:

- Propellant is cold and is not a thermal hazard.
- Propellant is standard compressed air and is not a toxic hazard.
- Electronic kill switches can be actuated locally or remotely.
- Maximum thrust for the propulsion system is less than 1.2 N.

Hazard Number: 9
Title: Toxic outgassing from batteries

Hazard Description: The robot uses eight lithium-polymer gel-electrolyte batteries. Gaseous buildup inside batteries could lead to rupture and toxic outgassing.

Hazard Cause(s):

- Batteries used outside their rated conditions.
- Manufacturing defect in battery.
- Overcharging or undercharging batteries.
- Drawing too much current from batteries.
- Overheating causes gas buildup.
- Electrical short.

Hazard Control(s):

- All batteries will be used in accordance with the manufacturer’s specifications.
- All batteries will have a 48 hour ‘burn in’ prior to flight to verify correct operation and lack of electrical shorts.
- Battery ratings will be compared to predicted flight conditions and such ratings and conditions will be documented in the electrical analysis of this document.
- Components will be tagged upon burn-in and tag verified on final assembly checklist.
- Installed battery circuit board prevents overcharging, undercharging, and overcurrent draw.
- Self-resetting thermal cutoff fuse prevents rupture due to overheating.
- Batteries will be charged only on ground.
- Entire electrical bus protected by hard fuse to prevent any overcurrent conditions.

Hazard Number: 10
Hazard Title: Sharp Edges of Frame

Hazard Description: Jagged or sharp edges on outside aluminum frame

Hazard Causes:

- Padding is detached from frame.
- Portion of frame breaks, exposing sharp edges.

Hazard Controls:

- 3/8" of pipe insulation covers all edges and aluminum struts.
- All edges have been deburred to remove sharpness.
- Capscrews securing frame have no exposed sharp edges.

Hazard Number: 11

Hazard Title: Software Error

Hazard Description: A software error leads to miscalculated thruster activation, causing the robot to move in an uncontrolled fashion.

Hazard Causes:

- Software calculations return erroneous results, causing robot to mistake its direction and speed and fire thrusters incorrectly.
- Software locks up, leading to anomalous outputs.
- Interface between software and hardware malfunctions.

Hazard Controls

- All control software will be tested extensively on the ground and will be debugged as extensively as possible.
- Thrust system can only provide low acceleration, thus giving operators time to respond to control problems.

16. Tool Requirements

Tools borrowed from RGO:

We do not plan to borrow any tools from the RGO program.

Tools that will be used aboard the KC-135:

Tools brought aboard the KC-135 will be used only between parabolas and kept in a plastic hardshell box in precut form-fitting foam. The tool box will be locked, latched, and inside one of the provided crash crates during parabolas. A printout of the complete inventory of the tool box will be attached to the inside of the lid so that flight crew can quickly double-check that all tools have been returned to the box and crash crate before each parabola begins.

In addition, flight crew members will keep items such as multipurpose folding tools, small flashlights, and PDAs in the pockets of their flight suits, but these will be used only between parabolas.

The control laptop and small digital cameras will be used by the crew during parabolas and will not be allowed to freefloat within the cabin.

17. Photo requirements

Our experiment calls for a commercial 8mm video camcorder at rest with regards to the frame of reference of the plane to provide independent data on the movements of the robot for later analysis. We will need a “hands-free” camera pole to mount this camera to.

18. Aircraft Loading

Hardware consists of a fifty pound cubical robot fitted with two handles each along the top and bottom faces. It can be easily manipulated on the ground or in the aircraft by two people with a load of twenty-five pounds each. The robot will be stowed in a JSC-provided crash crate for takeoff and landing, and loaded with a forklift and lifting pallet. Since our experiment is free-floating, base plate area is not needed.

19. Ground Support Requirements

We do not anticipate requiring ground support.

20. Hazardous material

No hazardous materials are used in this experiment.

21. Material Safety Data Sheets (MSDS)

MSDS are attached for the following components:

Fluids:

Air, compressed

Toxic:

Lithium-polymer gel battery

22. Procedures

Shipment

Equipment will be shipped to Ellington Field by Federal Express and will arrive the day prior to the beginning of the flight week at the latest. No special storage conditions are required.

Ground Operations

To demonstrate equipment for TRR tanks will need to be filled with air and batteries charged off-site. No on-site support requirements are anticipated.

Loading

No special procedures are required for loading. The robot and tool box will be crated and either carried onto the plane or loaded by forklift and secured appropriately.

Pre-Flight

We will set up our camera pole and attach, align and focus our camera before flight.

We will also visually inspect the robot, paying special attention to any possible damage to the pressure system. Both tanks will be unmounted and checked separately.

Take-off/Landing

We plan to utilize two of RGSFOP's cargo boxes to store the robot and toolbox during takeoff and landing. No other special procedures are needed.

In-flight

Before Parabolas Begin:
- Uncrate robot.

- Calibrate camera and double-check camera mounting

Immediately before a parabola:

- Team members verbally confirm roles and readiness with each other
- Team member A takes charge of control laptop
- Team member B holds the robot
- B turns the robot so that each of its three cameras points away from the ground or himself
- B uses the control laptop to instruct the robot to run its camera configuration routine. The configuration routine should take around thirty seconds.
- B checks the image output of the configuration routine to make sure nothing is wrong

During parabola:

- B moves the robot to the center of the team's assigned experimental area
  - B visually confirms that the release area is clear
  - A and B confirm verbally readiness to release the robot
  - B lets go of the robot, using the mounted handles to impart a slight spin to the robot.
  - A transmits the signal to the robot to begin its station-keeping program

At the end of a parabola:

- A transmits the signal to end station-keeping
- B grabs the robot by its handles

If the robot is drifting out of our experimental area or into a wall or other obstacle:

- A transmits the signal to stop the station-keeping program
- B grabs the robot

In case of a serious malfunction:

- A transmits ths signal to stop the station-keeping program
- B presses the emergency stop button on the robot to cut off power to the main bus.
- B grabs the robot.

If in-flight mechanical repairs are needed:

- B grabs robot
- A and B wait until current parabola is over.

- A uncrates toolbox.
- A and B perform necessary repairs.
- A and B verbally confirm agreement that the robot is repaired
- A uses the inventory attached to toolbox to make sure all tools have been returned to the toolbox.
- The toolbox is returned to its crate. At the start of the next parabola, experimentation resumes.

After last parabola:

- B captures robot.
- A shuts down robot from control laptop.
- B cuts off power to main bus with emergency stop switch.
- A opens crate, and robot is returned to crate.

Post-flight

- Upon landing, detach camera from camera pole.
- Refill tanks before next flight, if applicable.

23. References

Micci, Michael M. and Andrew D. Ketsdever, Ed. Micropropulsion for Small Spacecraft. Reston, Virginia: American Institute of Aeronautics and Astronautics, Inc, 2000.

Carignan, Craig R and David L. Atkin. “Tracking and Station-keeping for Free-Flying Robots Using Sliding Surfaces.” Robotics and Automation, 1988. Proceedings., 1988 IEEE International Conference on , 1988. 2: 969-974.

Lots, J.-F, et al. “A 2-D visual servoing for underwater vehicle station keeping”. Proceedings of the 2001 IEEE International Conference on Robotics & Automation. 2767-72..

Choset, Howie, et al. “Path Planning an Control for AERCam, a Free-flying Inspection Robot in Space”. Proceedings of the 1999 IEEE International Conference on Robotics & Automation 1396-1403.

Zhang, Hon and James P. Ostrowski. “Visual Servoing with Dynamics: Control of an Unmanned Blimp.” Proceedings of the 1999 IEEE International Conference on Robotics & Automation. 618- 23.

Borst, Cristoph W. and Richard A. Volz, “Telerobotic Ground Control of a Space Free-Flyer”. Proceedings of the 1998 IEEE/RSJ Int. Conference on Intelligent Robots and Systems. 1183.

Kortenkamp, David, et al. “Applying a layered control architecture to a free-flying space camera”. Intelligence and Systems, 1998. Proceedings., IEEE International Joint Symposia on, 998. 188-94.

Marks, Richard L., et al. “Automatic Visual Station Keeping of an Underwater Robot”. OCEANS '94. Oceans Engineering for Today's Technology and Tomorrow's Preservation. Proceedings.2:137-42

Chapeau, Bertrand and Eduoard Francois. “Motion-based segmentation for object-based video coding and indexing.” Image and video communications and processing 2000; Proceedings of the Conference. Vol 3794 853-60

III. Outreach Plan

1. Team's Objective in Outreach Activities

Our objective for outreach programs is to promote and publicize the RGSFOP as an opportunity for students to perform science and engineering research. Our outreach activities educate both engineering students and the general public about the value of student research. Finally, we have planned special programs and activities to interest underrepresented student groups in our research and in science and engineering technology.

2. Team Website

The GYRE Project maintains a website for all research conducted under its auspices at `http://depts.washington.edu/gyre`. This website contains information about the GYRE 1 flight in 2003, as well as other work performed by the group. The website is will be updated to contain information about the 2004 GYRE 2 flight throughout the course of the program. Outreach information will be updated as activities are planned and completed.

3. Description of Outreach Audience

We plan outreach events for several different audiences, and every event is customized for the specific time, circumstance and audience. Material presented to educational institutions is designed to be scientifically accurate, age-appropriate, and grade-level appropriate. For example, where elementary students receive a simple discussion and demonstration of visual tracking, more advanced students are shown the actual algorithms in greater detail.

In our outreach, we particularly emphasize work with elementary and secondary school audiences. In addition to discussing and demonstrating our work, we also distribute materials from Washington Space Grant designed by NASA to promote careers in science, mathematics, engineering and technology. We talk about the potential space applications of our research, and also discuss other NASA enterprises, missions, programs and projects. In cooperation with the Washington Space Grant, we encourage participation in other NASA educational programs.

We maintain an ongoing relationship with the students and teachers of Lawton Elementary School in Bellingham, Washington in order to strengthen their K-12 math and science education efforts by showing them the progress of our work and other NASA projects. We first visited Lawton Elementary in the Spring of 2002 and plan future visits for this year's project. Many letters the GYRE team have received from the students of Lawton are posted on our website, `http://depts.washington.edu/gyre`.

We are in negotiations with Nova High School in Seattle to demonstrate our work to high-school students. Nova has a substantial population of minority students. In this way, we plan to enrich their science program and interest minority students in the fields of engineering and robotics.

We will document our efforts in outreach using the NASA NEEIS evaluation system.

One audience we will make a particular effort to reach is school-age females, who are another underrepresented population in engineering, to interest them in science, math, engineering and technology. The two female team members will make a particular effort to show that women can, and do, make great contributions to research and society.

We plan to present the GYRE project to these audiences because they represent the next generation of scientists, researchers, and engineers. For this reason, lectures and presentations targeted at older audiences discuss the technology in considerable detail. In addition to educating students (and potential future researchers) about the technologies used in the GYRE project, the project serves to generate public interest in the program and in space robotics research in general.

4. Specific Plans for Activities

Each activity is tailored to the particular audience and circumstances, but many share common features. Typically these include a lecture and presentation, a hands-on demonstration, a question-and-answer or discussion session, and handouts regarding our work and that of others.

Each lecture is written specifically for the audience at hand and is designed to deliver scientifically accurate, age-appropriate, grade-appropriate content about our work and other NASA missions and enterprises. The lectures typically include a PowerPoint™ presentation and a lecture delivered by one of the investigators. We discuss the uses for microgravity robotics, possible applications to NASA missions, hardware design and fabrication, visual processing techniques, control algorithms, and reliability. Obviously these topics are not covered in great depth for elementary students, but are covered in considerable detail for college students. Audience participation is encouraged during the lectures and questions are welcomed. Audience participation activities are used to demonstrate points whenever possible – for example, students are asked to rotate their heads and then translate them to demonstrate the difference in visual appearance of these maneuvers. These activities encourage interest, particularly in the younger audiences. PowerPoint™ is used to deliver both text and visual aids to the lectures, including actual images and video captured from the robot and the results of image processing. Images of the robot are used to aid discussion of the hardware design. Audience questions and discussions are welcomed.

Hands-on demonstrations are usually given next. These involve setting up the robot on its test stand (which allows one-dimensional rotational maneuvering using the onboard thrusters) and the control laptop is set up with a projector. Live video, processed images, and telemetry from the robot is transmitted over an 802.11b wireless network to the control laptop and displayed to the audience. The robot is then commanded to maneuver and perform stationkeeping (within the constraints of the test stand) and its workings are explained. Students are allowed to command the robot from the control stand, and feel the cold gas thruster exhaust stream (a great opportunity to explain Newton's laws of action and reaction). Any questions and discussion are welcomed and answered.

A group discussion follows and any further questions are answered. In a classroom setting, this is an opportunity for the teacher to tie what the kids have just learned back into their everyday curricula. Often we find that kids want to tell us about their own robotics projects (invariably Lego™-based).

5. Specific Planned Events

The GYRE team will be presenting our research work, including the work for the RGSFOP 2004 flight, at the Seattle Robotics Society's annual Robothon event (`http://www.seattlerobotics.org/robothon`). The Robothon is one of the oldest and largest amateur robotics events held in the U.S. This year's event will be held in the Center House at the Seattle Center on October 25th and 26th. The Seattle Robotics Society anticipates over 5,000 people coming through the Center House that weekend and receiving extensive media coverage for the event. The GYRE team will be demonstrating and discussing our work in conjunction with Dr. Linda Bushnell's Autonomous Robotic Control Systems (ARCS) lab.

Our work will also be presented to the ARCS Lab in a meeting on November 5th, 2003.

The investigators are in negotiations with Bryant Elementary School in Seattle, Washington, to present our work to students there during their annual Science Fair event. We will be demonstrating the robot and discussing robotics in general and ours in particular.

As discussed above, we maintain an ongoing relationship with the students and teachers of Lawton Elementary School in Bellingham, Washington, and we plan to visit them again to discuss the 2003 flight, its results, and the 2004 work.

Many further events will be planned and executed, but specific details are not available at this time.

6. Creative / Innovative Approaches for Delivering Activities

One of our investigators, Amelia Lacenski, works at Scientific Explorer, a Seattle company that produces science and engineering education kits. Ms. Lacenski will negotiate with Scientific Explorer to gain their corporate sponsorship and include educational materials about physics, aerodynamics, and cold-gas rocket propulsion – complete with science demonstrations – for elementary and middle school audiences.

7. Press Plan

The GYRE team is seeking publicity for our research work and the RGSFOP in a variety of media.

In print, we are in negotiations with the *Cincinnati Pulse-Journal* and *The Onion* to publicize our work. We have made arrangements with Christina Siderius, the Features editor at the UW Daily, to print a feature article about GYRE during the Autumn 2003 academic quarter. Print publicity will take the form of general-audience articles discussing the goals of GYRE, possible future implications of our work, the NASA RGO, and the RGSFOP and the opportunity it presents.

In television, we are discussing coverage with Nippon TV and UWTV. Possibilities here include news coverage, documentary coverage and videotaped lectures.

In online media, we have published an extensive project website (`http://depts.washington.edu/gyre`) and are in negotiations with *The Onion* and technology news sites Kuro5hin and Slashdot for further news coverage.

We also plan to contact other outlets, including the Seattle public radio station (KUOW), other Seattle local media, Los Angeles local media, and national media, in television, radio, print and nontraditional formats.

IV. Administrative Requirements

1. Institution's Letter of Endorsement

A letter of endorsement from Bruce Darling, Acting Chair, Department of Electrical Engineering, University of Washington, is attached.

2. Statement of Supervising Faculty

A statement of support from Linda Bushnell, Ph.D., Research Assistant Professor, Department of Electrical Engineering, University of Washington, is attached.

3. Funding / Budget Statement

Category	Expected Expenditure	Potential Source
Equipment (parts, supplies, shipping)	$800	Corporate Sponsorship (Online Metals, Active-Robots.com, others)
Transportation to / from Houston	$2000 (5 @ $400)	Washington State Space Grant, Mary Gates Endowment Research Training Grant, Corporate Sponsorship (Southwest Airlines)
Accommodations in Houston	$1969 (11 nights @ $179)	Department of Electrical Engineering Undergraduate Research Fund
Transportation in Houston (Car Rental)	$869 (11 days @ $79, contract rate)	Department of Electrical Engineering Undergraduate Research Fund
Total	$5638	

4. Institutional Animal Care and Use Committee (IACUC)

Not applicable to the proposed experiment because no animal test subjects are used in the experiment.

5. Parental Consent Forms

Not applicable to the proposed experiment because no team members are under the age of 18.