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aboard the International Space Station*

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ZERO-Robotics: A Student Competition aboard the International Space Station

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Abstract—The designation of the International Space Station as a National Laboratory enhances the ability to use the facility for educational objectives. The MIT Space Systems Laboratory and Aurora Flight Sciences started the ZERO-Robotics program to enable High School students to participate directly in the science conducted aboard the ISS. The program, based on the successful history of the FIRST Robotics Competition, opens development of SPHERES software algorithms to high school students. For this purpose the team developed a simulation that allows students at many grade levels to program the satellites. The concept for the ZERO-Robotics competition consists of three phases: (1) software algorithm annual competition, (2) hardware enhancements to SPHERES, and (3) open announcement for participation in SPHERES. The first phase is already under implementation: a “pilot” program ran a competition in the MIT Flat Floor and aboard the ISS with two Idaho schools during the Fall of 2009.^{1,2}

The Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) program currently operates three nano-satellites aboard the ISS, pictured in Figure 1. The program is led by the MIT Space Systems Laboratory (SSL) and Aurora Flight Sciences, and supported by the DoD Defense Advanced Research Projects Agency (DARPA) and Space Test Program (STP) as well as NASA.

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1. INTRODUCTION

NASA and Congress have designated the ISS as a US National Laboratory [1]. This new status provides a framework that enables a wide range of research and development to be conducted onboard. It opens up multiple possibilities for outreach and educational opportunities for students.

Figure 1 - SPHERES operates 3 satellites aboard the ISS (astronaut and MIT alum Gregory Chamitoff)

The three satellites can be reprogrammed to conduct different tasks. In this way SPHERES has involved dozens of students in unprecedented levels of access to microgravity for experimentation and analysis at the undergraduate and graduate levels. The students use the satellites to demonstrate and validate control algorithms (software) that will be used in future distributed satellite systems which include a long list of missions, such as: formation flying space telescopes, in-orbit assembly of large space structures, re-supply and repair missions (docking and rendezvous), and other tasks where multiple autonomous satellites work together to complete robotic missions in a coordinated fashion. However, dozens of researchers is a very small number for a National Laboratory.

Using SPHERES, “ZERO-Robotics” is envisioned as a robotics competition that opens the world-class research facilities on the ISS to hundreds (potentially thousands) of students at multiple educational levels. A key objective is to

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² IEEEAC paper #11263, Version 2, Updated 2009:11:02

inspire future scientists and engineers by making the benefits and resources of the space program tangible to the students. In this way, students will view working in space as reachable objective that is not just reserved for astronauts, and will grow up pushing the limits of space exploration, engineering, and development. Further, ZERO-Robotics helps build critical engineering skills for students, such as problem solving, design thought process, operations training, team work, and presentation skills.

1.1 ISS as a National Laboratory for STEM

The NASA “International Space Station Education Concept Development Report” [1] states:

“Utilizing the International Space Station National Laboratory for education is an effort initiated in response to the 2005 NASA Authorization Act, which designated the U.S. segment of the ISS as a national laboratory and directed NASA to develop a plan to ‘increase the utilization of the ISS by other federal entities and the private sector...’”

The report shows a framework by which the goals are part of a pyramid: inspire a large number of students, engage a set of them, and educate a sub-set. This results in a highly motivated and educated workforce with strong skills. A revolutionary education program would inspire a large number of students, allowing many to learn by engaging them; the program would be attractive to all levels of students.

Since it began operations, the ISS has accommodated a number of education experiments. The report by Thomas et al [2] details activities such as demonstrations, classroom versions of experiments, and the launch of a small number of experiments built by high school students. In total the report identifies less than 15 programs which have allowed students to engage directly in space activities. While multiple programs have reached a substantial number of students via demonstrations and tele/video conferences with astronauts, these events do not allow students to become engaged in the research. The goal of the ISS as a National Laboratory is to educate them at a deeper level that keeps students interested in science, technology, engineering, and mathematics (STEM).

The effort also includes the goal to involve many other institutions, both government and non-government, in the use of the International Space Station. In August 2009 NASA published its “Opportunity for the use of the ISS” [3]. This open-ended call for proposals seeks to create relationships “to support national laboratory activities”. SPHERES seeks to bring together NASA (including Space Grant), DARPA, MIT, and Aurora. Further, the potential exists to involve other private companies, individuals, and especially other universities as mentors who will help support ZERO Robotics participants.

1.2 SPHERES

The SPHERES program began in 1999 as the first MIT Aero/Astro “CDIO” capstone class [4]. The CDIO program stands for “Conceive Design Implement Operate”, where over the course of three semesters undergraduate students conceive a solution to a complex problem, design it, build it, and operate it. SPHERES began by instructing the students to “build a satellite that flies inside the Space Shuttle” (later changed to the ISS). In 2000 the students flew two weeks of reduced gravity aircraft campaigns to validate their designs. After a few modifications to meet NASA safety requirements, the SPHERES satellites were delivered to NASA in 2003, and launched to the ISS in 2006 (after a delay due to the Columbia accident). SPHERES became one of the first educational programs that launched student-designed hardware to the ISS.

SPHERES consists of a set of tools and hardware developed for use aboard the ISS and in ground-based tests: three nano-satellites, a custom metrology system (based on ultrasound time-of-flight measurements), communications hardware, consumables (tanks and batteries), and an astronaut interface. Figure 2 shows the three SPHERES satellites in formation aboard the ISS. After the crew starts a test, the satellites operate autonomously within a volume defined by the position of the metrology system. The ground-based setup consists of a set of hardware analogous to what is in Station: three nano-satellites, a metrology system with the same geometry as that on the ISS, a research oriented GUI, and replenishable consumables.

Figure 2 - The SPHERES satellites in Formation aboard the ISS

The SPHERES satellites were designed to provide the best traceability to future formation flight missions by implementing all the features of a standard thruster-based satellite bus. The satellites have fully functional propulsion, guidance, communications, and power sub-systems. These enable the satellites to maneuver in 6-DOF, communicate with each other and with the laptop control station, and identify their position with respect to each other and to the

reference frame. The laptop control station (an ISS supplied standard laptop) is used to collect and store data and to upload new algorithms. SPHERES uploads new algorithms (ahead of time) and downloads data (after the session) using the ISS communications system. Figure 3 shows a picture of a SPHERES satellite and identifies its main features. Physical properties of the satellites are listed in Table 1.

Figure 3. SPHERES Satellite.

Table 1. SPHERES Satellite Properties.

Diameter	0.22 m
Mass (w/tank & batteries)	4.3 kg
Max linear acceleration	0.17 m/s ²
Max angular acceleration	3.5 rad/s ²
Power consumption	13 W
Battery lifetime (replaceable)	2 hours

SPHERES was designed to be a *facility* aboard the ISS, not just a single experiment, by following a set of design principles learned from previous MIT SSL experience [5]. These principles include the ability to involve multiple scientists in an easy manner. For that purpose, a SPHERES “Guest Scientist Program” (GSP) was created [6]. This program supports the efforts of geographically distributed researchers in the development of algorithms. It consists of a test development framework, a robust and flexible interface to the SPHERES flight software, a portable high-fidelity simulation, two laboratory testbeds, and data analysis utilities. The ZERO-Robotics program expands the GSP with a simplified interface so that students at many different levels (including High School) can program the satellites.

1.3 FIRST Robotics Competition

While MIT and Aurora strive to innovate, as demonstrated by the development of SPHERES as an undergraduate class, the team also strongly encourages learning from successful programs. One such program is the FIRST Robotics Competition, which helped inspire the name for ZERO-Robotics.

FIRST was founded in 1989 to inspire young people's interest and participation in science and technology. FIRST consists of five innovative programs that motivate young people to pursue career opportunities in science, technology, engineering, and math. Over 85,000 volunteers (students and mentors) participate in the programs every year. Of the five programs, the Robotics Competition is a prime model for ZERO-Robotics.

The FIRST Robotics Competition is an annual event with more than 1600 high school teams participating (over 30,000 students and mentors). It “challenges teams of students and their mentors to solve a common problem in a six-week timeframe using a standard “kit of parts” and a common set of rules.” [7] It is important to note that the teams must raise funds to pay \$5k to \$7k for initial kits/registration. Those that advance to the finals pay \$5k more for the final competition entry fee and/or \$4k more for regional competitions.

A study by Brandeis on the impact of FIRST Robotics [7] shows that these competitions have an important effect on students and their involvement in STEM activities. The report findings include: more than half the students are from *minority* groups; 37% come from families where the parents do not have higher education degrees; the approval rating of FIRST Robotics by the students is above 95%; a similar number responded that it helps improve their attitude towards teamwork and mentoring their younger peers; 89% of FIRST alumni went to college (compared to 65% national average). The successes of FIRST are clear, and ZERO-Robotics seeks to leverage these successes in creating a *complementary* program to FIRST.

FIRST Robotics concentrates heavily on the development of hardware. However, it is not yet possible to send new hardware to the ISS on an annual basis as part of a high school level competition. Since SPHERES concentrates on the development of software, ZERO-Robotics complements FIRST Robotics by providing students an avenue to develop innovative software, with the incentive that it will be tested by robots and astronauts in space.

2. ZERO-ROBOTICS

The long-term objectives of the ZERO-Robotics program is to engage high school, undergraduate, and graduate students, with age appropriate tasks. There are three main phases of ZERO-Robotics. Phase 1 is a software design competition that allows students to have their algorithms run in the microgravity environment on SPHERES aboard the ISS. Phase 2 is a hardware design competition that enables students the opportunity to design enhancements that use or add to the SPHERES satellites to accomplish complex tasks not possible with the current hardware. By operating inside the ISS, with SPHERES, the design of this hardware requires substantial engineering skills but is low

risk. Phase 3 opens up the SPHERES program by creating an open solicitation for unique ideas on an ongoing basis. All phases expose students to the challenges faced in the aerospace field, in a fun and safe learning environment. Phase 1 completed its pilot program in 2009 and is described in detail below. Phase 2 & 3 are presented in the future phases section.

2.1 Phase 1

The first phase kick-starts the ZERO-Robotics program by providing high school students the opportunity to develop algorithms for SPHERES in the near future. This first phase requires little lead time because the SPHERES testbed is already operating successfully aboard the ISS. Four steps are planned for the annual Phase 1 competitions (not all steps took place during the pilot program, described below), the corresponding schedule is illustrated in Table 2:

1. Proposal Submission: students submit a proposal that indicates their intent to participate in the competition, describes their team organization, and completes some initial tasks that demonstrate they understand the competition. This phase is intended to teach students the basics of writing a proposal and help them organize their team. Also, this step serves as a registration step. Teams are not eliminated at this step.
2. Simulation: students implement all of the tasks via simulation. This step verifies successful algorithm implementation, prior to hardware testing, and allows for a baseline performance expectation. If the number of teams participating is greater than can be accommodated in flight, this step can be used as an elimination round.
3. Ground testing: teams convert their algorithms from simulation to hardware, accounting for computation and communications bandwidth limitations. Teams that demonstrate their simulations operate correctly (or which pass the first round of elimination if that is necessary) are invited to test their algorithms in a flat floor facility on actual SPHERES satellites. Based on the performance of hardware tests, teams are downselected to approximately 15-20 teams.
4. Flight testing: The winning teams finalize their algorithms for implementation in space. Tests are

integrated and packaged to be run on ISS. This step includes at least one ISS test session, with live feed of the crew executing the tests. Students will have the opportunity to view their test runs in real-time. Data and telemetry will be downlinked to them a few days after the event so that they can perform data analysis and submit a final report.

The proposed calendar is designed to complement FIRST Robotics. Their competition is based on six weeks during the Spring term; therefore ZERO-Robotics has been designed to take place during the Fall term. The ZERO-Robotics kick-off would take place at or shortly after the finals of FIRST Robotics, allowing the teams to have the summer to plan for their participation. This is important since there is a wide range of programming skills at the high school level, and the summer period would allow students to become experienced with the software. By the end of October, the students will go through the simulation competition, so that teams that go to the next round can participate in flat floor hardware tests. The competition aboard the ISS would take place during December, before Winter break, so that it does not conflict with the FIRST Robotics kickoff in January.

3. PHASE 1 PILOT PROGRAM

The ZERO-Robotics team was privileged to receive seed funding to create a Pilot program during the Fall of 2009. The pilot program consisted of two schools in the Idaho area: Bonners Ferry High School and Coeur d'Alene School District, both from the northern Idaho area (where our funding originated). The pilot program did not require the teams to create proposals, and there was no "elimination" rounds. However, they did compete against each other in simulation, on the flat floor, and aboard the ISS. Scores were kept for all phases to study the strategy for elimination in future competitions.

The pilot program schedule followed closely the one desired for the long term Phase 1 competitions:

- September 2009 - Kick off
- October 2009 - Simulation development
- Early November 2009 - Simulation competitions
- Mid November 2009 - Flat Floor Testing
- Early December 2009 - Flight algorithms delivered

Table 2 - ZERO-Robotics Phase I proposed competition schedule

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Competition Pre-Planning
Competition Announcement
Step 1: Proposals
Step 2: Simulation coding
Step 3: Ground testing "regionals"
Step 4: Flight code preparation
Step 4: ISS Competition

- Mid December 2009 - Competition aboard the ISS

In order to run the pilot program the MIT ZERO-Robotics team had to do the following:

1. Define the competition
2. Create a scoring system
3. Provide the teams with a simulation
4. Create methods for the teams to interface with us
5. Prepare hardware testing at MIT and the ISS

These tasks are described below.

3.1 The Competition

Like FIRST Robotics, ZERO-Robotics revolves around a competition between the teams. It is important to relate the competition to a real-life objective, so that the teams realize their work can have an effect beyond the competition. For the pilot program the motivation was inspired by the idea of inspection satellites. The following was presented to the teams during the kickoff of the competition:

An exciting research area in the field of human-robotic interaction is the concept of a flying inspector or assistant satellite. These robots could be deployed alongside astronauts both inside and outside space stations. They could help during space walks to provide another set of eyes or retrieve tools. In this game the students will program the control system for a robotic assistant that is transporting a tool from its starting location to a waiting astronaut. At the same time, you must avoid a second satellite that is observing the spacewalk but has an unfortunate habit of getting in the way. During all maneuvers the robots must conserve fuel so that they can reach the target before running out.

Players - The competition requires each team to program two players:

- **Helper** - This player tries to reach a goal region at the opposite end of the test volume.
- **Blocker** - This player attempts to disrupt the other player by moving to block the motion.

For the Pilot program, the SPHERES team assigned one MIT freshman student to be a third “competitor”. The pilot program teams regularly sent their code to the MIT team, allowing the SPHERES team to know how the teams progressed. The MIT student then tried to beat the high school student teams, in order to provide a “standard player” that both teams could compete against. The teams prepared for multiple rounds aboard the ISS: helper 1 vs MIT blocker, helper 2 vs MIT blocker, MIT helper vs Blocker 1, MIT helper vs Blocker 2, helper 1 vs. blocker 2, and helper 2 vs. blocker 1. Therefore, the teams had to think of strategies for both satellites and against more than one team.

Gameplay - An algorithm developed by MIT graduate students caused the Helper satellite to be repelled by the Blocker satellite. In this way the Blocker disrupted the path of the Helper. When programming the Blocker satellite the teams had to experiment via simulation in order to determine how to best use this ability.

To allow the Helper satellite to reach the goal region, the Blocker satellite was repelled by the goal region in the same way that the Helper satellite was repelled by the Blocker.

End Conditions - The game terminated when any of the following conditions were met:

- The Helper satellite was within 8cm of the goal, located at (0.3, 0.3, 0.3), and its velocity was less than 1.5cm/s
- The Helper satellite ran out of its allocated fuel
- The time for the round expired. The maximum time to reach the goal was 360 seconds

Scoring - During the game only the Helper satellite was scored. The Blocker satellite affected the Helper satellite's score by blocking it. There were four factors that affected the score:

- *Percentage of Time Blocked (100 Points)* During the game, the Helper satellite kept track of each second that it was blocked by the Blocker satellite and divided this by the total elapsed time. The percent of time that it was blocked was subtracted from the score. For instance, if the satellite was blocked for 30 seconds out of 100 seconds, 30 points were subtracted from the score. A maximum of 100 points could be lost, corresponding to being blocked the entire time.

$$p = -100 \times \frac{t_{\text{blocked}}}{t_{\text{total}}}$$

- *Fuel (30 Points)* If the Helper satellite ran out of its allocated fuel, 30 points were subtracted from the score, and the game ended. If the Blocker satellite ran out of fuel, the game continued, but the Blocker was no longer able to fire thrusters. The Helper satellite received a 30 point bonus if the Blocker ran out of fuel.

$$f_{\text{helper}} = \begin{cases} -30 & \text{if fuel exhausted} \\ 0 & \text{otherwise} \end{cases}$$

$$f_{\text{blocker}} = \begin{cases} +30 & \text{if fuel exhausted} \\ 0 & \text{otherwise} \end{cases}$$

- *Goal Bonus (100 Points)* The Helper satellite received up to 100 points for reaching the goal zone before time expired. The bonus was the percentage of the total time that still remained available once the goal was reached.

$$g = 100 \times \left(1 - \frac{t_{goal}}{t_{total}} \right)$$

- *Other Penalties* During the ISS competition, the astronauts played the role of referee. They kept track of qualitative penalties such as wall collisions. The list of penalties included:

- Crashing into a wall: 10 points per collision
- Exiting and re-entering the test volume: 5 points per exit
- Terminating test due to user algorithm: DSQ
- Uncontrolled exiting of the test volume: DSQ

The final score was tallied by summing up the points for each section:

$$S = g + p + f_{helper} + f_{blocker} - penalties$$

3.2 Simulation

The SPHERES team has worked with a simulation since the beginning of the program. However, the basic simulation is geared towards graduate students and professionals who have substantial experience with C programming and MATLAB®. This simulation is not appropriate for ZERO-Robotics, since high school students usually do not have access to MATLAB. At the same time, the program does seek to encourage students to learn more about programming.

The ZERO-Robotics simulation (show in Figure 4) is a compromise between the use of special tools (ie, MATLAB) and students learning how to program. The simulation combines all of the original SPHERES MATLAB simulation into a single executable. The students run the simulation just like any other computer program. In addition, students are required to install the free “Microsoft Visual C++ Express” program and program their algorithms in C. They are provided with a “wizard” to create a DLL which is called by the simulation executable.

The SPHERES simulation was enhanced by embedding the competition game in the program. As the students run their code, they can see the progress in the simulated game. The students can see, in real time, their current score, the fuel of the satellites, and the limits of the test volume.

The simulation allows students to quickly swap the code that controls the satellites by replacing the DLLs called by the simulation. In this way the students could compete against their own players or the MIT standard players. The first time the two schools competed against each other was during MIT Flat Floor testing (see below), rather than simulation.

Figure 4 - ZERO-Robotics simulation: red (left) is “helper”, blue (center) is “blocker”, S=score, F=Fuel

3.3 Flat Floor Testing

Testing on flight-identical hardware is a mandatory step of all SPHERES experiments that operate aboard the ISS. Therefore, the pilot program has established a schedule that allows for one week of testing at the MIT SSL Flat Floor facility. While in future competitions teams are expected to be present at the Flat Floor facility, during the pilot program the SPHERES team students ran all the tests at MIT. The high schools participated via video conference, so that they could see their algorithms operate live.

The objectives of the flat floor testing during the pilot program were to ensure that the software was integrated into the SPHERES hardware and to provide students with an idea of the differences between testing in simulation and on actual hardware.

Flat floor testing poses several important challenges: it must be in 2D while the simulation and the ISS tests are in 3D; the 2D motion is occasionally disrupted by friction or scratches in the floor; and the SPHERES dynamics are augmented by the air carriages that support the satellites on the floor. Typically, SPHERES researchers devote a significant portion of ISS algorithm development time to flat floor testing and frequently implement a separate 2D version of the flight code. During the Flat Floor segment of the Pilot program the pilot teams were not required to program separate algorithms for 2D and 3D tests, so the MIT SPHERES team had to determine how to best demonstrate the performance of the 3D algorithms on the flat floor facility. To demonstrate the effect of the blocker and show the general motion of the satellites, the goal position was moved to be in the same plane as the two satellites, and the vertical thrusters were disabled.

Despite attempts to provide a realistic environment for ground testing, feedback from the high school teams suggests that it was very difficult to use the results from 2D testing to extrapolate the 3D behavior of the satellites. The satellites were occasionally disrupted by friction effects and collisions between air carriages, and the 3D trajectories programmed by the satellites were only followed approximately. The flat floor testing was beneficial in that it gave the students a realistic idea of downtime associated with changing consumables, delay due to video link, as well as a partial idea of how environment disturbances affect the motion of the satellites. To better utilize the flat floor as an intermediate elimination round, it may be necessary to structure the initial phase of the competition in the same pattern as SPHERES research with a separate 2D implementation in simulation and hardware.

Following flat floor testing, the MIT SPHERES team then took the student algorithms and integrated them into the same deliverable package normally sent to NASA prior to any SPHERES Test Session.

3.4 ISS Testing

The ISS game scenario was revealed October 16, and the teams were allowed one month to submit their draft test code to MIT. After testing on the flat floor, teams had one week to update their algorithms to the final ISS version. The teams had two deliverables: (1) their algorithms programmed in C code and (2) descriptions of their algorithms and the expected motions of the satellites during the competition. The code from both high school teams was integrated by the MIT team into the correct file format for delivery to NASA. The algorithm descriptions were inserted into the test descriptions that the astronauts read before starting a test aboard the ISS.

The ZERO Robotics Competition (SPHERES Test Session 21) was conducted on December 9th, 2009 by crew member Jeff Williams. This test session accomplished a first in space: the first time algorithms written by high school students were directly run as an experiment in space and aboard the International Space Station. From the perspective of NASA and their operations team, the competition was just like a regular SPHERES test session: the crew set up the metrology system, loaded the satellites with the software, and then ran a set of tests. On the ground, the MIT SPHERES team received live video and audio feeds from the ISS and provided narration to fill the teams in with information about details of the session as it took place. Both teams were present at MIT for the test session and were able to see their algorithms run in real-time.

The test session lasted for approximately 4 hours. A total of 30 tests were run during the session, with real-time scores calculated by the satellites and called down by the crew. The tests consisted of each head-to-head competition

scenario of the two teams, as well as a team developed by MIT to serve as the baseline player.

An important part of the ISS session was evaluating the ability to keep real-time scores for each competition scenario. In general the scoring system performed well in awarding points to Helper satellites that reached the goal quickly with minimal interference from the blocker. Helpers that reached the goal obtained between 169 and 208 points. A lower score represented a slower approach to the goal or some blocking. Helpers that did not reach the goal typically received a much lower score around 100 points, depending on how much they were blocked. In all but one test, Helpers that did not make it to the goal ran out of fuel. In future competitions, real-time scoring calculated by the satellite will be a feasible method for scoring and could open up the possibility of one or more down-selection final rounds aboard the ISS.

The MIT team found it particularly difficult to track the number of qualitative penalties such as wall collisions as they occurred in real time. In future competitions, the penalties should either be simplified into a single large point deduction or not counted. Relying on the crew to simultaneously track the number and type of penalties should not be expected, but the test session showed that the crew can provide sufficient narration to signal that penalty events have occurred.

Though the student algorithms executed as expected, two coding bugs on the MIT side of the SPHERES software had an effect on the competition. The first, a bug in the virtual fuel indicator, caused one team's Helper satellite to disable its thrusters at the beginning of the game. After a few seconds of drifting, it reactivated and moved toward the goal. The second, an incorrect parameter in the initialization of the SPHERES estimation system, resulted in lower positioning accuracy of the satellites and increased fuel consumption. While the software errors caused several failed tests and some scoring uncertainty, they did not prevent the demonstration of the student algorithms. To prevent this type of mistake in future competitions, it will be important to increase the time allocated for MIT to integrate student code, especially when there are significantly more schools participating.

The success of the test session shows that it is possible to conduct a competition at the high school level, conducted aboard the International Space Station. Overall, the pilot program was very well received by the students, and the ISS test session, in particular, was viewed as a momentous and exciting learning experience.

4. NATIONWIDE PROGRAM

The conclusion of the pilot program marks the start of the preparations for the first year of a national program. The pilot program supplied the basic tools to run Phase 1 of ZERO-Robotics (simulation, scoring method, logistics of flat floor testing, etc). However, there will be substantial organizational changes in order to support the program on a national scope. This section discusses the main differences expected between the pilot program and future national competitions.

4.1 Organization

Several organizations form part of the ZERO-Robotics efforts: MIT SSL, Aurora Flight Sciences, the Space Grant Program, DARPA, and NASA.

The MIT SPHERES team leads the academic and software development efforts (tutorials, simulations, competition scenarios, etc). Further, MIT provides flat floor facilities for testing during Part 3 of Phase 1. Aurora Flight Sciences ensures the continued operation of SPHERES aboard the ISS by manufacturing and providing SPHERES supplies.

The Space Grant program has been approached to become the general administration and to provide public relations and human resources. Their presence in almost all the states of the Union will enable them to serve as a robust local contact with schools. They are also an important interface with NASA.

The NASA Education Office is expected to have at least one person be a full time liaison to the program, working with crews and public relations teams.

DARPA, the original sponsor of SPHERES, will participate by providing further public relations and being a source of ideas for the competitions; there is the potential of DoD sponsored scholarships for participants/winners.

4.2 Elimination Process

A national competition will require elimination rounds, since the ISS test sessions will always be limited to a few hours of operations. This means that only a few teams will be able to run their algorithms in the ISS session. However, because ZERO-Robotics wants to involve a large number of students, the intent is to develop a system by which the elimination rounds are as large as possible. Three elimination steps are envisioned:

1. The proposal phase will be a first filter, as it will identify teams that have true interest in participating.
2. The requirement that tests have to run properly in simulation is another “automatic” elimination round. Teams will be required to have their algorithms

working in simulation before they can compete in hardware testing. Initially this step will require no formal competition, and several teams will likely not get their algorithms working in time. In the future, a threshold might be established (such as “beat the MIT algorithm”) in order to advance to hardware testing.

3. The last elimination round takes place at the Flat Floor. These rounds are envisioned as one or more days of testing in a facility that can welcome the competitors and where the actual SPHERES hardware is used. The goal of this round is to select between 12 to 20 (TBD) teams that will be part of the ISS finals.

4.3 Regional Competitions

Flat Floor elimination rounds are an ambitious effort for ZERO-Robotics. It is not physically possible to welcome teams from all over the country to the MIT SSL Flat Floor both because of the size of the MIT facilities and the logistics of high school teams having to fly to MIT for a competition other than the “final”. Therefore the ZERO-Robotics team intends to learn from the successful FIRST Robotics competitions and create “regional” finals.

The goal of the ZERO-Robotics team is to recruit a large number of government, industry, and educational partners who have flat floor facilities around the nation. During the “ZERO-Robotics Regional Finals week” the three SPHERES ground satellites would travel across the country to these facilities, so that the teams can compete and the finalists are determined. Flat floor facilities exist at many locations: Marshall Space Flight Center, Johnson Space Center, Lockheed Martin in Denver and San Francisco, and Boeing in Washington. The team is working to identify even more locations. These competitions also open up the possibility to engage students even more by having astronauts and other highly regarded engineers participate as official representatives of ZERO-Robotics at the competitions.

If a regional competition Flat Floor facility is not found for a certain region of the nation, the team will help organize an elimination round based on simulation testing and/or via video conferences.

These regional finals have multiple positive effects. They:

- lower the costs to high schools to participate in ZERO-Robotics.
- encourage high schools in the same geographic locations to interface with each other.
- bring in multiple industry, government, and educational institutions to support ZERO-Robotics.

4.4 ISS Finals

Once ZERO-Robotics is established as a national competition, the ISS Finals are expected to be a major

event. Current plans will request NASA to provide live *two way* communications with the ISS, so that the crew can interact with the high school finalists. Further, it will be requested for the finals be transmitted live on NASA TV. The national competition will have a winning team, as well as different winning categories beyond the “champion”.

5. FUTURE PHASES

Phase 1 of ZERO-Robotics will accomplish many of the educational objectives for the ISS. It will engage a large number of students in a way that will allow them to learn about space software and encourage them to pursue higher education and a STEM career. However, the first phase is geared only towards high school students and software development. ZERO-Robotics plans to establish two more phases of the program, to increase its exposure to the college level.

5.1 Phase 2: Development of a hardware kit

The goal of the second phase is to immerse students, including high school and college undergraduates, in the complexities of developing space hardware. The concept of Phase 2 involves students developing new hardware to enhance the capabilities of SPHERES every four years. Knowing that launching hardware to the ISS is a complex endeavor, the team selected a four-year period to launch new hardware as one that would enable any college student to be part of a group that would ultimately launch the hardware.

To tie together Phase 1 and 2, the Phase 2 hardware will be designed such that future Phase 1 software competitions can use the new hardware. Therefore, every four years the Phase 1 competition will be enhanced with new capabilities, ensuring that the software competitions evolve in time and present new challenges to the students.

Hardware development for the ISS includes several substantial tasks. The projects will be challenged with the same safety requirements as any other project for the ISS. There will be limitations on funding and strict deadlines. Students will have to write procedures for the crew to use the new hardware; and interface documents for others to be able to use their new tools.

This phase still remains in the planning stages. Developing space hardware by undergraduates is not a typical project, and no standard procedure has been established. Therefore, some key questions must be addressed:

- How will the hardware for Phase 2 be launched to station?
- Is it possible to develop a “kit” that can be reconfigured every year, with the crew receiving instructions?
- What are the integration & safety challenges?

While Phase 2 has many challenges ahead of it, past lessons show that students are highly motivated by working with hardware. Therefore, a successful Phase 2 will be essential for the long-term viability of the ZERO-Robotics program.

5.2 Phase 3: Ongoing collegiate competition

Once the ZERO-Robotics program infrastructure (Phase 1) is well established, the next goal will be to create an ongoing “open solicitation” for ideas to investigate unique robotics problems aboard the International Space Station. This outreach would be primarily aimed at undergraduate and graduate collegiate teams who wish to demonstrate their own robotics research using SPHERES. On regular intervals (multiple times per year), the team will evaluate the submitted proposals and choose a winner to demonstrate their unique research aboard the ISS. This creates a continuous outreach to students, utilizing the ISS as a National resource for education and space-robotics research.

5.3 Ground-SPHERE simulator

Another objective of the ZERO-Robotics team is to create a “SPHERES satellite simulator” which would operate on any generic flat surface (not on a special “Flat Floor”). Such a vehicle would be able to run with the programs created by the software simulator, and use advanced control techniques to simulate the motion as if it were on a frictionless 2D surface. One requirement for this simulator would be for its cost to remain as low as possible, so that many high schools could purchase the kits and use them as part of their participation in the competition. The simulator would not necessarily replace the use of SPHERES during regional finals, since part of the learning process is to use incrementally higher fidelity testing facilities.

6. CONCLUSIONS

ZERO-Robotics looks forward to leveraging three existing highly successful programs: the International Space Station National Laboratory, SPHERES, and FIRST Robotics, to create a unique opportunity to expose students to space flight experience very early in their educational career. By exposing students to the challenges of the space program, these students will be better trained to solve complex problems as they enter the workforce. By making this a fun learning experience, these students are more likely to continue to pursue math, science, and engineering as a career. A pilot program has been successfully completed, which exposed two high school teams to operating SPHERES aboard the ISS during the Fall of 2009. With a successful pilot completed, the ZERO-Robotics team looks forward to the kick off of the nationwide program in 2010.

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9. BIOGRAPHY

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Gregory Chamitoff is an active member of the NASA Astronaut Corps. He was a member of the ISS Expedition 17-18, living aboard the ISS for 179 days during 2008. Dr. Chamitoff has a PhD in Aeronautics and Astronautics from MIT (1992) as well as MS degrees in Aeronautical Engineering (CalTech) and Space Science (University of Houston Clearlake). While a visiting professor at the University of Sydney Dr. Chamitoff

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