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FLIGHT MECHANICS EXPERIMENT ONBOARD NASA'S ZERO GRAVITY AIRCRAFT

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Abstract

This paper presents a method to promote STEM (Science, Technology, Engineering, and Mathematics) education through participation in a reduced gravity program with NASA (National Aeronautics and Space Administration). Microgravity programs with NASA provide students with a unique opportunity to conduct scientific research with innovative and creative solutions through hands-on experimental design and testing in reduced gravity conditions. A group of undergraduate students from California State Polytechnic University, Pomona, participated in the NASA's SEED (Systems Engineering Educational Discovery) Reduced Gravity Program, which focuses on addressing systems engineering challenges in microgravity. The team worked with a NASA Principal Investigator on a project to build and fly a prototype test article to demonstrate emergency atmospheric reentry with single-axis control. Through this experience, the team was able to gain hands-on experience with spacecraft instrumentation and learn valuable lessons in teamwork and systems engineering that can be applied to real-world situations. As part of the SEED program, the team shared its experience with local high schools in order to spark interest in STEM-related fields in the next generation of scientists and engineers.

Keywords - NASA Microgravity University, STEM, SEED, reduced gravity program, zero gravity.

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1 INTRODUCTION

The STEM (Science, Technology, Engineering, and Mathematics) education initiative is part of the NSF's (National Science Foundation) approach to incorporating technology, engineering, mathematics and science in the classroom in order to encourage excellence in these areas. Participants integrate college-level material into high school courses to provide hands-on learning at young ages (U.S. Department of Labour, 2007; Bybee, 2010). The overall goal of the program is to increase the number of workers in these fields and cultivate more successful members in society. The NSF estimates "that 80% of the jobs created in the next decade will require some form of math and science skills" (National Afterschool Association (NAA), 2011), and the U.S. President even commented that STEM education "is of the utmost importance to all students" and "critical to U.S. competitors" (The Opportunity Equation website, 2011). Women and minorities have especially been targeted by the initiative since there are relatively low percentages of these groups in STEM-related fields U.S. Department of Labour, 2007).

NASA has agreed to coordinate with NSF to promote STEM education and increase participation of underrepresented groups in those areas through “robust space exploration and aeronautics research programs.” Their mission is to motivate and inspire students through various programs in order to “build a well-educated and skilled workforce”. (Matthews, 2007; Marrett & Winterton, 2007).

Such programs that help spark interest in STEM careers include the Reduced Gravity Program operated by the NASA JSC (Johnson Space Center) in Houston, Texas. This program provides a unique environment of weightlessness (or “zero gravity”, also referred to as “zero-g”) onboard an especially modified aircraft for convenient testing and training purposes of flight hardware and astronaut crew prior to launch, and has been available to various researchers to develop new technological advances in science, engineering, and human space habitation (NASA Microgravity University, 2011).

High school, undergraduate, and graduate students seeking an academic experience involving cutting-edge scientific research and hands-on experiments in a microgravity environment can participate in the NASA’s Reduced Gravity Program through its SEED (Systems Engineering Educational Discovery) program. Within this program, students form teams and propose concepts to NASA that address various problems that can be tested in a reduced gravity environment. If selected, the teams then design and fabricate their proposed concept to eventually fly their experiment on one of the available flights. Post-flight analysis is then completed to evaluate the validity of the concept, which may be continued at the school and tested for future flights. Outreach activities and opportunities are typically supported by the program to exalt the wonders of weightlessness and build enthusiasm for participating in such a unique program (NASA Microgravity University, 2011).

A group of undergraduate students of Aerospace Engineering from California State Polytechnic University, Pomona participated in the 2011 SEED campaign. The team worked with a NASA Principal Investigator on a project to build and fly a prototype test article to demonstrate emergency atmospheric reentry with control in one axis. Through this experience, the team was able to gain hands-on experience with spacecraft instrumentation and learn valuable lessons in teamwork and systems engineering that can be applied to real-world situations.

2 SYSTEMS ENGINEERING EDUCATIONAL DISCOVERY PROGRAM

NASA’s Microgravity University hosts the Reduced Gravity Education Flight Program which consists of a number of educational reduced gravity flight programs that include self-created projects along with projects that are proposed by NASA mentors. The purpose of these programs is to provide students an opportunity to design and fabricate a reduced gravity experiment for actual flight in a simulated reduced gravity environment. These programs are funded by different organizations: NASA Exploration Science Mission Directorate, NASA Space Operations Mission Directorate, NASA Office of Education, JSC Teaching from Space Office, High Schools United with NASA to Create Hardware, the National Space Grant Consortium, the State Space Grant Consortium and specific Departments in the United States sponsoring particular flight teams.

The SEED program under the NASA’s Microgravity University aims to address “systems engineering challenges within a microgravity environment” (NASA Microgravity University, 2011). Students are expected to form an interdisciplinary team to manage complex systems through a formalized approach involving logistics, organization, and coordination of a project. A large component of systems engineering is safety and risk management —a topic encountered frequently in real-world engineering industry.

Projects are proposed by NASA mentors and posted as announcements on the Microgravity University website (http://microgravityuniversity.jsc.nasa.gov/); they include a wide variety of applications, such as fluid dynamics, materials science, and robotic science research. Interested students select the top three projects of their choice based on their previous experiences and expertise. If selected, these students work collaboratively with a faculty advisor from their university and their NASA mentor to meet the objectives of the proposed experiment by building and producing the system to be tested.

During the course of their hands-on experimental design, students prepare a TEDP (Test Equipment Data Package), a technical document that highlights the structural and electrical aspects of the system as well as safety hazards and possible risks of the experiment during flight. After a few months of design and fabrication, teams ship their experiments and fly to Houston, Texas in preparation for their flight. Teams and their faculty advisors are granted access to Ellington Field, a joint-civil-military airport 24 km southeast of downtown Houston, where they receive briefings and work on assembling or fixing their projects under NASA/JSC hangars.

They are also able to become acquainted with other students and learn about other research projects that are to be conducted during the flight week. Teams participate in a Test Readiness Review, where they brief NASA flight directors on their experiment and ensure that it is both ready and safe to fly. The flights then occur at the end of the week, and teams that are not flying on a certain day may be escorted around the Johnson Space Center for tours at different facilities.

Each experiment is tested in the course of two flights, which take place in different days. Only six members of each team, composed by the faculty advisor, the NASA Principal Investigator and four students, can participate in the flights, three at a time. Teams are allotted a section of the cabin space to place their experiment and carry out the research. Many flight crew personnel join the flights in order to ensure nobody is injured or ill and assist with any research activities if requested. Camera crews are also present in flights so that all experiments are well-documented for future publication and outreach. Students are encouraged to take advantage of the rare flight opportunity by having fun and performing outreach activities in addition to conducting research.

Upon their return to school, teams are encouraged to publicize their own work by creating videos, holding outreach events, and conducting interviews with the public media. Students are then required to complete post-flight analysis of their experiment and compose a final report that documents the results of the experiment: whether the objectives of the experiment were satisfied, lessons learned and recommendations, should a potential future zero gravity campaign the following year be required to complete the experiment.

3 ZERO GRAVITY AIRCRAFT OPERATIONS

The weightless, or zero gravity environment, is achieved onboard a specially modified Boeing 727-200 provided by the Zero G Corporation (2011), a privately held company acquired by Space Adventures, Ltd.

Weightlessness is achieved by doing aerobatic maneuvers known as parabolas (Fig. 1). A typical mission is 2 to 3 hours long and consists of 30 to 40 parabolas. These parabolas can be flown in succession or with short breaks between maneuvers to reconfigure test equipment. The aircraft flies in a Federal Aviation Administration designated airspace that is approximately 100 miles long and 10 miles wide.

Before starting a parabola, the aircraft flies level to the horizon at an altitude of 24,000 feet. The pilots then begin to pull up, gradually increasing the angle of the aircraft to about 45° to the horizon reaching an altitude of 34,000 feet. During this pull-up, passengers will feel the pull of 1.8 Gs (1.8 times the acceleration of gravity). Next, the plane is pushed over to create the zero gravity segment of the parabola. For the next 20-30 seconds everything in the plane is weightless. Then, a gentle pull-out is started which allows the flyers to stabilize on the aircraft floor. This maneuver is repeated 30 to 40 times, each taking about ten miles of airspace to perform.

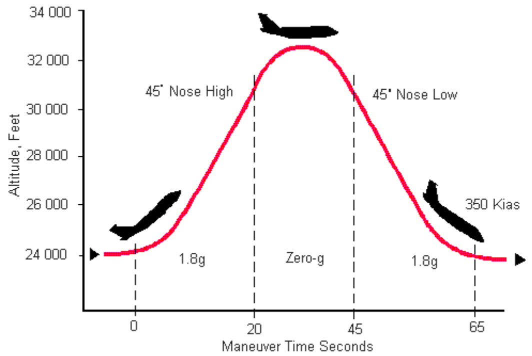

Fig. 1. Typical zero gravity maneuver

The aircraft is also able to provide during the flight periods of lunar gravity (1/6 of Earth's gravity) for approximately 30 seconds, and Martian gravity (1/3 of Earth's gravity) for approximately 40 seconds (NASA/JSC Aircraft Operations, 2011). These gravity forces are created by flying a larger arc over the top of the parabola.

4 FLIGHT MECHANICS EXPERIMENT

A group of undergraduate students from California State Polytechnic University, Pomona, worked in collaboration with their NASA Principal Investigator (the third author of this paper) on a project entitled "Emergency Atmospheric Entry with Control in One Axis" (AECOX), (Matthews et al., 2011). The goal of the experiment was to prove an innovative control method, primarily conceived as an emergency backup system, which addresses the problem of a capsule-type spacecraft in space that needs to execute a safe atmospheric entry in an emergency situation in the absence of nominal control capability and where the spacecraft is at an arbitrary initial orientation (also referred to as "attitude") and angular rate.

To prove this control method, the students designed and built two test apparatus. They chose, integrated and tested the instrumentation they deemed was required to fly the experiment, and designed, developed and tested the internal flight software. They also carried out, together with the NASA Principal Investigator and Faculty Advisor, the experiment onboard the NASA's zero gravity aircraft.

4.1 Background of the Experiment

The location and orientation of the reaction control system (RCS) jets in a manned space capsule is arranged to provide control in three axes: torques on pitch, yaw, and roll (Fig. 2). Upon completion of the mission, after separation from the service module (SM), the RCS maneuvers the capsule to the entry attitude and, during nominal atmospheric flight, manages the orientation of the capsule's lift vector to control crossrange and downrange. In the absence of backup systems, a major malfunction in the nominal RCS after the separation from the SM would prevent the capsule from actively recovering from either a possible tumbling or an adverse attitude that could result in a non-heat-shield forward entry that could jeopardize the safety of the crew.

In case a software or hardware failure makes it impossible to fly a guided atmospheric entry, the emergency entry system mode is invoked to fly a ballistic entry. A ballistic entry is solely focused on crew survival. To achieve a safe ballistic entry, two control phases need to be executed sequentially: First, the spacecraft must be oriented such that the heat shield faces the incoming airflow (i.e., in a heat-shield-forward attitude) to counteract the heat rate buildup, and second, the spacecraft must attain a ballistic roll rate during entry to prevent a lift-vector-down situation that would result in excessive loads on the crew.

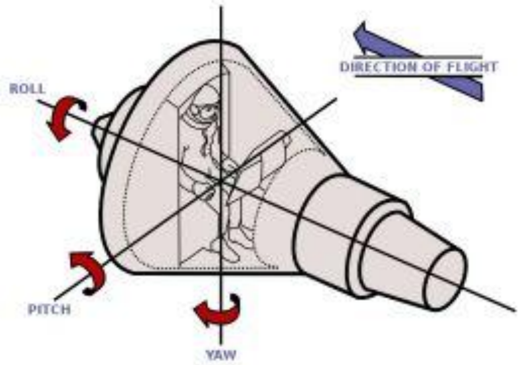

Fig. 2. Pitch, yaw and roll angles in a capsule-type spacecraft

García-Llama and Senent (2008) developed a method, primarily conceived as an emergency backup control system, which enables a space capsule to execute a safe atmospheric entry from an arbitrary initial attitude and angular rate in the absence of nominal control capability. Specifically, this method permits the arrest of a tumbling motion, orientation to the heat shield forward position and the attainment of a ballistic roll rate of a rigid capsule with the use of control in one axis only.

The goal of the experiment was to prove the proposed control concept using two test articles; each one with a different inertia matrix configuration. For the sake of simplicity for this experiment, a reaction wheel was used to simulate the torque that would be provided by the jets in an actual spacecraft.

4.2 Test Apparatus

Two test apparatus structures made with aluminum with dimensions 22.9 cm x 22.9 cm x 15.2 cm were created for the free floating experiment (Fig. 3). One structure was built to test an axis symmetrical inertia matrix design while the second structure was built to test a diagonal non-axis symmetric inertia matrix design. Both structures were the same in design with the structure and components; however, the diagonal non-axis symmetric design used weights to offset the moments of inertia.

The internal parts of the test apparatus consisted of a brushless motor, motor flywheel, batteries, avionics, electronic speed controller, and two project boxes, which enclosed the avionics and the speed controller. All the internal components were enclosed within the test structure through the means of Lexan sheets, which were fastened to the exterior of the structure to form the walls of the structural test apparatus. An acrylic sheet was attached to the center of the test apparatus to create a shelf-like surface for placement of internal components. All internal components, covers, and structures were fastened to each other through the use of machine screws and lock washers, thus preventing parts from coming loose due to vibrations emanating from the motor and flywheel during testing. Foam corners were also utilized in the structure by placing them on the corner beams to ensure safe handling for the structure itself and any passengers on the flight, if the free floating test apparatus were to become a projectile.

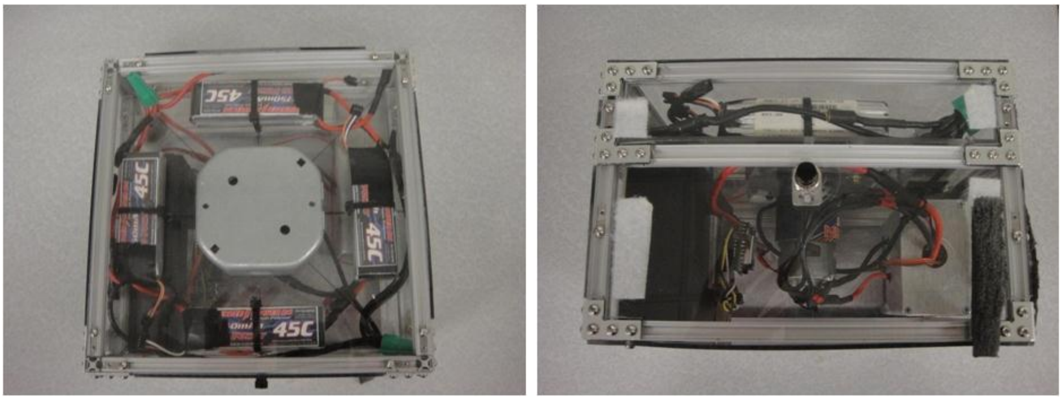

Fig. 3. Complete assembly of the test apparatus with all internal components

4.3 Experiment Description

Before flight on board the Reduced Gravity Aircraft, the aircraft was loaded with the two test articles, a camera, a notebook computer, and the outreach items. Velcro and duct tape were used to secure the notebook computer to the floor of the aircraft.

Four foot straps (Fig. 4) were obtained and mounted to the floor of the aircraft to ensure physical security and mobility during the microgravity portion of the flight. Once the apparatus was fully prepared for flight, the computer, test articles and the camera were stored in the available storage containers provided by the Reduced Gravity Office.

Fig. 4. Installation of foot straps

Once the plane was airborne and it was safe to maneuver inside the cabin, the team set up the needed instrumentation for the experiment. This included mounting the notebook computer to the aircraft, turning on the computer, and opening all of the needed software programs and user interfaces for commanding the electronics. Three initial tests were conducted to verify operational ability of electronic components and to confirm the functional use of the reaction wheel.

As stated above, two test articles simulating two spacecraft with different inertia configurations were tested in the experiment, each on different flight days (Fig. 5). One test article simulating a spacecraft with an axisymmetric inertia matrix was tested on the first flight day whereas the other, simulating a spacecraft with a diagonal non-axisymmetric inertia matrix, was tested on the second flight day. Each had a reaction wheel mounted at the center of gravity that provided torque along the longitudinal axis. On each flight day, before each parabola, the corresponding test article was placed in an arbitrary orientation simulating the heat shield forward position with the longitudinal axis aligned with the simulated velocity vector. Once in that orientation, the attitude on board was reset to zero in all axes. That became the reference attitude for the remaining of the experiment during that parabola. After this operation took place, the test article was manually induced with a tumbling motion during the zero-g periods. Following the commands from the control law, the reaction wheel generated torques aimed at stabilizing the test article at a selected total angle of attack (angular distance between the longitudinal axis and the direction of the simulated velocity vector) simulating the heat shield forward position, at the same time that an angular rate was generated about the longitudinal axis of the test article, simulating a ballistic roll rate.

Fig. 5. Release of the test apparatus inside the cabin during a zero-g period

5 RESULTS AND LESSONS LEARNED

Some aspects of the concept of the project were relatively similar to previous experiments the team had conducted in a prior experience. Thus, the conceptual approach in terms of building the test articles was familiar, and the team had studied related aspects in their course learning as well. However, the team still lacked the amount of expertise needed for such a complex project; as a result, the team encountered many difficulties especially interfacing the electronic hardware and yielding the desired outputs from their avionics system (Matthews et al., 2011).

5.1 Results

Upon reviewing the data from both test flights, it was determined that the obtained data could not be used to reach a conclusion that could validate or invalidate the hypothesis of the experiment. Although, during flight, some of the experiments visually seemed to be successful (the spacecraft would tumble and then precess and stabilize about one axis), the data obtained did not display any similar patterns in comparison to the theoretical results, which were generated through a dynamical model developed in the MATLAB and Simulink software engineering tools. Also, during the second flight day, while testing the test article with the diagonal non-axisymmetric inertia matrix, the signals were not being transferred correctly inside the apparatus. During the first four tests of the second day, after the article was released, there was no motor rotation. At that time, it was concluded that this behavior was due to a program flow error. Once it was determined that this test article was not compliant, the test articles were quickly switched and the one with the axisymmetric inertia matrix was tested again.

5.2 Lessons Learned and Recommendations

A huge component that hindered the outcome and success of the project was the lack of experience on the team. The electrical team in particular had only previously started operating with electronics (microcontrollers, sensors, etc.) and had not yet fully developed the knowledge required to interface these electronics together into a complete system. The team heavily relied on peers from the Electrical and Computer Engineering department for help or advice. Improvements can be made by having a more interdisciplinary team that has the proper training and background to sufficiently accomplish the goals of the project. A future microgravity team will be accommodating more Electrical/Computer Engineers for this purpose.

Physical application of the control torque was performed via a brushed R/C car motor in conjunction with an aluminum flywheel. Many of the difficulties arose due to the unrepeatability performance of the motors. The original (first choice) motor was brushless and it was anticipated that the velocity of the output of the motor would be a linear function of the applied voltage. However, after extensive testing, it was found that the motor was operating on a step output of velocity and was not feasible for adaptation for the project. This led to the decision to switch to a brushed motor setup, which ultimately provided the expected relative linear nature of velocity output with voltage, but most importantly, more accurate and repeatable results. For future projects, the team plans to look into stepper motors, as they may provide for an even more accurate rotation.

Another problem was correcting for gyroscopic drift. For the future, greater expertise in this area is required, because the sensor plays a vital role in the overall objective and scope of the project. Monetary constraints prevented the purchase of higher quality sensors. For future projects, the team plans to invest in better sensors providing the funding is available.

A general unfamiliarity of integrating gyroscopes into a system compounded the previously mentioned problem, resulting in a position error of up to ±10 degrees. Also, during the actual test, the gyroscopes did not initialize correctly and thus the angular rates and angles were incorrect. The angular rates are key inputs for the control law and error in the angular rates caused an error in the output of the control law. From this, the team learned that integrating components to yield a fully functioning system is much more difficult than expected and there are many factors that need to be accounted for when attempting to correct for gyro drift.

Typically, when the program is initialized, the onboard gyroscopes record an initial reading for calibration in case any background noise is present. However, during tests, the gyros had issues initializing and were reporting movement when the test article was not in motion. This was observed when the angular rates were streamed to the laptop prior to the actual test. This resulted in inaccurate angular readings that adversely affected the remainder of the data calculated using the angular rates.

Due to an algorithm error, the angular position was not reset after each test, causing the angular positions to accumulate after each conducted test. To remedy this issue, the test article was reset after each test using the kill switch installed onboard. Typically, this would not be an issue except for the aforementioned initialization error. This error indicated that the gyros could be initialized incorrectly each time the system was reset, which dramatically increased the likelihood of error in the system.

In addition, for future research the team plans to integrate a gyro filter that will help rid the system gyroscope signal noise. This was attempted during the time span the team had to work on the project, but because of time constraints, the team was unable to complete the filter and integrate it into the system. This task will be one of the most important for the new and upcoming team.

Another improvement the team plans to make is the addition of a sensor that will read the actual angular velocity of the reaction wheel. The system, as it is now, is commanding the reaction wheel to rotate at a certain velocity without measuring the actual rotational velocity, accepting the theoretical value. Time constraints prevented the team from implementing a speed sensor. The addition of the sensor would allow for the team to perform more precise data analysis. The more known factors of the system the easier it is to troubleshoot. This will also show the team if the signal commanded by the control law was being implemented and sent successfully to the motor.

While analyzing the data, it was noticed that some of the calculated angles were diverging. It was determined that using Euler angles resulted in singularities for certain values. These singularities resulted in dramatic changes to the system. This error can be alleviated, but it requires changing the orientation system from Euler angles to quaternions or direct cosine matrices (any system that does not suffer from singularities). This will be looked at in future projects.

Finally, while analyzing why the non-axisymmetric code failed to produce any results, there was no solid conclusion. There does not appear to be any significant differences between how the two codes handle the control law, however, the microcontroller appears to fail while calculating the required acceleration. It was concluded that if the needed mathematical calculations are too complex, the microcontroller is unable to process further calculations, becoming “stuck” on a certain number. It is not fully understood why this happens, but it is recommended for future projects to acquire better microcontrollers for complex algorithms (such as a PIC microcontroller). Despite choosing the Ariduno microcontroller for this project (because of it is ease-of-use), it did not seem to be designed for heavy calculations, such as the ones involved in this project.

The last and probably most prominent obstacle the team encountered was simply the lack of time needed to complete the project. The lack of experience required greater time for research and ground testing of the final fully assembled test articles prior to flight. Such a complex system requires more than ten weeks to fully complete, considering the class requirements and work load each student had while working on the project. Many projects that are tested in microgravity are continuations of projects worked previously by other students, while this project had very little references from which it could build a solid foundation. Had the program provided a few more months, more would have been accomplished.

6 CONCLUSION

NASA’s Microgravity Program provides students with the opportunity to engage in STEM-related activities to learn valuable lessons in teamwork and gain real hands-on experience with challenging projects. These unique and thrilling activities can be used to motivate younger students and stir interest in science and engineering in the classroom. The SEED program in particular allowed for a complete systems engineering approach to gain a holistic perspective of a complex system and encouraged the employment of management, organization, and communication skills with an interdisciplinary team to design and fabricate a project. Students at the California State Polytechnic University, Pomona, were able to extract valuable lessons in teamwork and systems engineering through the SEED program that will prepare them for real-world applications and help inspire others to pursue similar careers in STEM fields.

Upon the completion of this experiment, the team gained experience not only in the technical realm but also in communications, innovation, time management and leadership areas. Each of the students that worked on this project also gained valuable experience in space flight mechanics that will be very useful both in school and future career opportunities. Starting from scratch, learning the mechanics, and being able to develop a prototype spacecraft allowed for the perfect blend of innovation and teamwork: qualities that are very important for the development of young engineers. The opportunity to work with a NASA mentor provided an excellent opportunity to develop the communication skills that will eventually be needed while working with a customer or other teammates in industry.

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