ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #17194

Using NASA's Robotic Mining Competition to Give Students a Quality Systems Engineering Experience

Dr. Jeremiah J. Neubert, University of North Dakota

Dr. Jeremiah Neubert is an assistant professor in the Department of Mechanical Engineering at the University of North Dakota. He conducted research and taught at Cambridge University. Prior to that, Dr. Neubert attended the University of Wisconsin and obtained a Ph.D. in Mechanical Engineering, and master's of science degrees in Computer Science and Mechanical Engineering. During his time at the University of Wisconsin, Dr. Neubert served as a National Science GK-12 fellow where he worked with a team of high school teachers and colleagues at the University of Wisconsin-Madison to develop modules for secondary school educators.

Using NASA's Robotic Mining Competition to give Student a Quality Systems Engineering Experience

Abstract

Today's engineers need to have a thorough understanding of systems engineering to be able to develop the complex systems used in a more connected world. NASA, motivated by its need for engineers with an understanding of systems engineering, developed the Robotic Mining Competition to provide a mechanism by which student can get a hands-on systems engineering experience. This paper discusses how the Robotic Mining Competition is used to provide students with a multidisciplinary, systems engineering learning experience. Specifically, it presents the general design process used by the University of North Dakota Robotic Mining Competition Team. The paper also contains a discussion of how the team evolved from year to year based on their successes and failures.

Introduction

As engineers develop more complex systems there is a need for every engineer to have at least a basic understanding of systems engineering. NASA defines systems engineering as "a robust approach to the design, creation, and operation of systems."[1] This process involves the establishment of a set of project objectives, creation of a set of design alternatives, conduction of trade studies, selection and implementation of the best design, verification of the design, and assessment of the design's ability to meet the project objectives. NASA scientists recognize the need for young engineers to have a background in systems engineering and for that reason have made it a significant part of their Robotic Mining competition[1]. As part of this competition each team is required to complete a systems engineering paper detailing their design and build process.

In addition to the systems paper, the process of creating a mining robot requires a diverse set of skills. The robot must have a mechanically sound digging system with a robust drive system to mine Black Point-1 (BP-1), which is Mars-like dirt, and move around the competition arena. The robot also requires a sound electrical system to sense the world around it and provide power to the actuators. The whole system is controlled by several microcontrollers and an onboard computer that must communicate via WiFi with a base station. Lastly, a thorough understanding of the regolith and its properties is required to make good design decision. This necessitates a multidisciplinary team and a systems engineering approach to be successful.

This paper will describe how the University of North Dakota has used this competition to bring students together from several departments and provide them with a hands-on systems engineering experience. It will detail the successes and failures of the team and provide tips for mentoring a successful team. In addition to providing information specific to the robotic mining competition, the paper will also provide more generic solutions to common problems that can be used in any multidisciplinary student competition.

Background

There is a belief that systems engineering is best taught by providing students with a hands-on experience[5,6]. Providing students with a multidisciplinary systems engineering experience can be difficult because it requires professors from multiple departments to work together with a relatively small group of students[4]. One of the easiest places to insert such an experience is the senior capstone course. Several institutions have used their capstone courses to teach their students about systems engineering[2,4,7,9]. One of the problems that is consistently mentioned in these works is finding an appropriate project for giving students a multidisciplinary systems engineering experience.

NASA's Robotic Mining Competition (RMC), originally called the Lunabotics Competition, was created to provide Universities with a project to aid in teaching systems engineering in their capstone design course. NASA, because of its current objective to send a manned mission to a near-Earth object, needs engineers with a strong understands of systems engineering. The idea of the RMC grew out of a course developed at Auburn to teach students about systems engineering. The course was based around the idea of regolith collection for oxygen production and lunar based emplacement[2]. Recently, NASA personnel evaluated the program and found that those groups that communicated a robust systems approach to their robot development and implementation were much more likely to be successful in the competition[2].

NASA's Robotic Mining Competition

The seventh annual Robotic Mining Competition will take place in the May of 2016. The Robotic Mining Competition askes students to design and construct a robot for mining lunar regolith simulant called BP-1, perform outreach with K-12 students, and communicate their design process to the judges through a systems report and presentation.

The robot, constructed by the students, must cross an obstacle course containing rocks and craters, collect lunar simulant, return to the starting area, and deposit the regolith into an elevated collection bin. Students may control the robot from a remote location, but can earn a bonus by mining autonomously. Each team has two ten minutes runs to collect as much regolith as possible. The score a team earns is a composite based on the amount of regolith a team collected, the amount of icy regolith collected, the robot's weight, dust control, autonomy, and data usage. The use of the composite score requires teams to deal with conflicting requirements when making design decisions.

One of the unique parts of the competition is that it explicitly rewards teams for using a systems engineering approach for the design and implantation of their robots. Teams are required to document their design process and produce a report detailing the process. The report must demonstrate that the team generated a set of objectives for their design, used trade studies to make design decisions, followed a schedule, and tested systems to verify that they functioned as needed. In addition, a significant amount of points are devoted to an optional presentation on the team's design process. Thus, if a team wishes to compete for the Joe Cosmo Award for Excellence, the award given to team receiving the highest aggregate score, the presentation is required[3].

The Design Team

The University of North Dakota has participated in the RMC in each of the past six years. The exact composition of the team has varied, but the core has always consisted of senior design students—students enrolled in there senior capstone course—from the Departments of Electrical and Mechanical Engineering. Typically, there are two to four electrical engineering students and four to seven mechanical engineering students. In each department, students are required to take a two semester design experience. During this experience students are expected to design a product, produce a prototype, and test it. In addition, students of any level from various departments across campus have participated. This may include freshman that aid mainly in manufacturing and outreach to junior engineering students that take responsibility for an entire subsystem. In the past, these students have come from engineering, Computer Science, Space Studies, and Education.

The Design Process Used

In this project, we use a design process based on that described in NASA's Systems Engineering Handbook[1]. Throughout the whole process the team meets with their advisors from both electrical and mechanical engineering on a weekly or biweekly basis. The frequency of meeting is dictated by the team's ability to communicate outside of the meetings—a better communicating team requires less formal meetings. These meetings must contain at least one representative from both the mechanical and electrical teams, but typically most team members attend. The meetings are used to make high level design decisions and address integration issues. The electrical and mechanical teams also have weekly meetings separately with their respective advisor outside of this time. These meetings are used to evaluate the student's accomplishments over the past week and establish a new set of deliverables.

The design process begins with a basic high level timeline. The team starts working on a preliminary design on September 15th. They begin the process of designing the robot by generating a list of objectives. The objectives are based on what they feel will make it possible for them to be successful in the competition. This includes robot weight, amount of regolith to be collect, amount of automation, and data usage. These objectives are used to generate a general mining robot design. Typically, multiple general designs are generated and evaluated for complexity of manufacture, robustness, and likelihood of meeting the stated objectives. A trade study is done on the designs to make decisions such as whether or not to use tank-like tracks in place of wheels or a bucket ladder and hopper instead of one large scope. Based on the results of the trade studies, the students arrive at one general design.

This general design must be completed by October 15th and presented to their advisors in a preliminary design review (PDR). At the PDR the students present the designs they considered and how they arrived at their final design. In addition, they present a rough timeline for the completion of the robot. This timeline must include verifiable milestones. Often students will generate milestones such as "check on supplier for widget A" or "work on subsystem B". Such vague milestones are hard to verify and can lead to delays in the design and construction process. As an adviser, I require student to generate verifiable, specific objectives such as "Identify four suppliers for widget A and obtain two price quotes" or "complete the engineer drawings for subsystem B." The preliminary design review ends with students presenting potential problems and uncertainties they have identified in their design. After some discussion the initial design is approved by their advisors. This approval is often conditional, requiring the group to address some areas of concern.

The preliminary design is then broken up into a set of systems. Each subsystem is assigned to one student who is solely responsible for it. Other students may be involved with a subsystem, but assigning each subsystem to one student is important for enduring someone takes complete ownership of it and drives it to completion. Over a period of approximately one month a design is created for each of the subsystems. During this same period testing is conducted on components of the systems that could use further refinement or have been identified as an area of concern. At the end of this time, the goal is to have a complete design with a list of parts, suppliers, a manufacturing schedule with milestones, and testing schedule.

Student are expected to present their finalized design and schedules by November 15th and begin preparing for a critical design review (CDR) presentation. This presentation is part of senior design experience in both the Mechanical and Electrical engineering. It occurs during the first week in December with multiple faculty members attending. This is a great time for student to practice communicating complex ideas to others not involved with the design process and explaining the decisions that led to the final design. During this presentation students must convince the faculty that their design is ready for production so that they can begin the purchasing process. If faculty identify any problems with the design, the students must address this prior to beginning the purchasing process.

As part of the critical design review, the students are expected to set dates as to when each subsystem is to be completed. This must also include a testing schedule for each subsystem. System testing allows problems to be detected before they are integrated into the final product. Scheduling system tests increases the likelihood of the group being successful for several reasons. First, it provides an early warning to the group that they are behind schedule and need to make adjustments if they are to be successful. Second, problems with any subsystem are more easily diagnosed and fixed before it is integrated with the rest of the system. When the systems are integrated, a failure in one subsystem my generate issues in another area of the robot. Lastly, the mining robot requires software development. Working subsystems are helpful when developing complex control software.

After the CDR it is important that major design changes are discouraged. Any changes made need to be limited in scope and be required for the creation of a functional design. This is one of the times where adviser intervention may be needed. Without intervention many student groups will become trapped in a never ending process of redesign to address problems that are not fully understood. Frequent design changes are a recipe for disaster both in the academic and professional world[8]. The creation of a functional prototype will allow the students to better understand what is needed to be successful and lead to more thoughtful design modifications.

Students are encouraged to begin ordering components that have long lead times prior to the end of the fall semester, December 15th. Items ordered before December 15th typically arrive prior to the January 15th when students return from break. This allows construction to take place during the first weeks of the Spring semester when students have more free time to devote to the project. Ideally, the initial subsystem implementations and testing is finished by March 1st.

The month of March is used to integrate the subsystems. While the teams over the years have used various approaches to system integration, it is best if the subsystems are connected in a way that allows them to be easily removed. Using standard electrical connectors and bolts whenever possible. This makes the process of refining the design after testing much easier and also facilitates quick replacement of parts that fail.

The month of April is dedicated to a process of testing and refining the design. The testing is conducted in a small arena similar to that used in the competition. A reasonable lunar simulant was created using fly ash, sand, and gravel. The original test pit was roughly 15 feet long, 10 feet wide and covered with one foot of simulant. Recently, it was modified to have an area that is approximately three feet deep to allow testing of a system designed to dig icy regolith—regolith more than one foot below the surface. This area contains regolith with larger rocks to more accurately reflect the icy regolith used in NASA's competition arena. The pit dimensions are sufficient for the creation of a small obstacle course to test the drivability of the robot in the lunar regolith. In addition, the robot is able to dig enough regolith to test its mining and offloading mechanisms. The process of testing and refining the design continues until the team leaves for the competition.

After the competition the team is asked to write up a message for the next team. Typically the message is left on a white board in their design room. These messages have been very helpful. The messages contain some of the same tips each year such as "start early" and "make sure to pay attention to the details". In addition to these, the team will leave suggestions as to what issues need to be addressed in the following year, what components need to be replaced, or ideas for improving the existing robot. This message is important because much of the team will graduate and move into a career. Without it, the robotic mining team would not have a memory.

Successes and Failures

During the first year of the competition there was a lot of uncertainty as to what was needed to be successful. The team created a mining robot much like a combine. It had a bucket ladder to collect the regolith in a hopper and an auger to empty the hopper. The team tested them successfully using sand. The problem was that, unknown to the team, regolith resembles a mixture of flour, sand, and gravel. The gravel in the regolith jammed the auger during unloading causing the system to blow a fuse making it impossible to unload the hopper. This kept the team from qualifying and was our first learning moment. To prevent this issue, future teams have used self-resetting fuses.

While the team did not qualify, their robot had many quality systems. First, the software created for both the ground station and base stations was robust and easy to use. It was developed by a distance engineering student in electrical engineering. The student used C# to create the needed software and the .net framework to transmit video to the base station. It is important to note that during this first year, less than half the competitors were able to connect to their robot successfully. In addition, the drive system created during this year operated perfectly. It consisted of lightweight, cleated metal wheels each driven by an independent actuator. This system has been used in some form in each of the team's robots.

Figure 1: The robot created by the team in its second year.

The second year was our most successful. During this year the objective was to make a simple, robust system that could mine approximately 200 kg in 20 minutes. The design that they settled on, shown in Fig. 1, was inspired by the common skid loader. The team relied heavily on a systems approach to create all the deliverables for the competition including the robot, outreach report, systems report, and presentation. The robot was also broken down into a system of systems with each of the electrical components connected using a standardized connector so they could easily be swapped out. The mechanical components were bolted together so they could also be easily removed for testing and modification. All the team's decisions were made using trade studies and sound engineering principles. In addition, the team made a schedule and worked hard to meet milestones on time. This provided plenty of time for testing and operator practice in the newly created pit with a simulant made from fly ash, gravel and course sand. This team finished second in the mining competition and placed in the top one or two spots in every other category of the competition. This resulted in the team getting the Joe Cosmo Award for Excellence, the prize awarded to the team with the highest overall score in the competition.

While this year resulted in our highest finish, this team had interpersonal issues throughout the year. One of the reasons for this was the systems approach used. For example, one member of the team focused on writing the reports and had limited participation in the build process. In the weekly meetings, I had to spend a great deal of time emphasizing what each member had accomplished. In addition, some members of the team struggled with accepting certain design decisions and repeatedly asked for significant changes. This was dealt with by asking the member to justify the change was required to meet the objectives set out by the team. Because the initial design was based on sound engineering principles, it was not possible to show the changes were required.

The competition rules changed in the third year to reward teams with a bonus point in the mining competition for autonomy, reduction in dust generation, and a lightweight design. While the skid loader design is robust and easy to implement, it is not ideal for automation. First, it requires a great deal of skill to operate. The approach angle must be constantly adjusted to get the bucket to enter to regolith. Second, the short wheel base made to robot unstable and difficult to drive. This led the third year team to pursue a robot that mined with a drum in the center of the robot frame. This would make for a more stable design with simpler operation that could be automated.

This team worked hard to redesign the robot, but due to a variety of factors including some poor design decisions, failure to follow a schedule and a lack of attention to detail, the robot did not meet the team's objectives. First, the team's design had major issues that were not identified at the design reviews because of a lack of complete mechanical drawings. This generated a need for major design changes during the build. The design changes generated a second problem, an inability to stay on schedule. Delays in the build eliminated any chance for testing. Thirdly, the robot suffered from some significant design flaws. The most significant one was lengthening the wheel base to accommodate the mining system. The longer wheel base made skid-steer turning nearly impossible and led to the robot getting stuck. Lastly, due to very limited time to test and refine the robot, refinements did not involve trade studies. This resulted in poor design decisions such as replacing lightweight aluminum plate with quarter inch steel plate when a small change in geometry would have solved the problem.

Figure 2: The robot used in the fourth year of the competition. This robot featured a spinning bucket with a baffle system.

In the fourth year, the team decided to focus on simplicity and lessen the weight of autonomy in making design decisions. Their goal was to mine 100 kg in each of their 10 minute runs—the competition was changed from one twenty minute run to two ten minute runs. They returned to the skid-steer loader design, but replaced the bucket with a bucket wheel which can be seen in

Fig. 2. The bucket wheel design was based on the results of testing and was one of the most innovative designs at the competition. It even incorporated baffles to allow the drum to be completely filled. In addition, they made changes to their digging strategy to reduce the time it takes to collect the regolith and deposit it in the collection bin. They succeeded in meeting their objectives and mined more regolith than any other team that year.

While the year four team did mine more regolith than any other team, they placed third in the mining competition and placed relatively low in the overall competition. The problem was that the team did not align their goals with that of the customer (NASA). First, their robot was heavier than it needed to be. This cost them a significant number of points in the mining competition. Second, they were penalized for data usage and dust control in the mining portion of the competition. Thirdly, they did not invest much time into preparing the systems and outreach reports. Lastly, the team chose not to submit a presentation. The presentation is worth nearly as much as winning the mining competition so, despite their mining performance, the team did not score well in the overall competition.

The fifth year team chose to refine the robot from the previous year. The focus of their design changes were aimed at reducing weight, stabilizing the robot, and increasing autonomy. Two of the objectives were in direct conflict. Reducing the weight of the robot increased its instability when the bucket was full. To address this the team modified the rear wheel to fill with regolith and constructed a mechanism that moved the battery away from the center of gravity in an attempt to offset the effect of the loaded bucket. The hope was that these changes would offset the problem caused by reducing the robot's weight by 30%.

While the fifth year's robot design was sound, the team did not allow enough time for testing. There were some complex electrical issues that could not be identified. The team was able to modify the design to allow the microcontrollers to be reset remotely, but this was not enough to overcome the issues. The robot was never able to successfully complete a run.

Figure 3: The robot created by the sixth year team. This robot had a bucket ladder to mine regolith and a cleated belt for depositing it into the hopper.

In the six year, the team chose to completely redesign the robot. The objective was to further reduce the weight of the robot, increase the ease of driving, increase the robustness of the electrical system, and create a robot that could collect icy regolith autonomously. The icy regolith focus was the result of a change to the competition to reward teams that collect the regolith six inches below the surface. The team adopted the design shown in Fig. 3, which collected regolith with an extendable bucket ladder. The regolith is then stored in a central hopper and deposited in the collection bin using a cleated belt. In addition, they implemented a traction control system the delivered more power to the wheels that have the most traction.

The robot failed during the competition due to a lack of testing. This was caused by long lead times on some of their material. The biggest contributor was creating their parts with a lightweight magnesium alloy which had a lead time of six weeks. In addition, the alloy needed to be sent out to be coated after it was machined because of its reactivity. While the system did work initially, the lack of testing meant that the team did not catch robustness issues. Broken electrical connections and a faulty Arduino board prevented the robot from delivering regolith. Despite this, the robot was able to demonstrate its traction control system and was the only team to mine the icy regolith.

While the year six team was not successful in the mining competition, they were very dedicated to the systems approach. They identified that the mining portion of the competition was just one of their customer's needs. By recognizing this, they were able to place fourth in the overall competition and placed first in the outreach portion of the competition. This demonstrated how important understanding the customer is to success. By understanding the rubric supplied by NASA, the team was able to succeed despite the robot's failure to mine any regolith.

Conclusions/Recommendations

NASA's RMC offers is a great mechanism for providing students with a hands-on systems engineering learning opportunity. It is nearly impossible to create a mining robot without a group of students with a diverse skill set. To be successful, the team needs members to help with outreach, report writing, budgeting, and logistics that correctly follow the systems design process. For example, failing to identify all the costumer's needs can result in teams meeting their objectives and not achieving the desired outcome in the competition. The lessons learned during this experience will serve the students throughout their career.

Having advised a robotic mining team for each of the past six years I have learned that one of the most import and difficult things to do is allowing the student to make the important decisions. Good or bad, the students must be allowed to make the design decisions. As an advisor, I feel it is my role to point out potential issues and get students to think about the decisions they are making, but in the end it is the team's decision. People often learn the most from their mistakes. For example, I am guessing that the year four team members are more mindful of the customer's needs after their experience on this project.

References

1. *NASA Systems Engineering Handbook*. SP-2007-6105 Rev 1, December 2007.

2. L. Guerra, G. Murphy, and L. May. "Applying Engineering to the Lunabotics Mining Competition Capstone Design Challenge." Proc. of the ASEE Annual Conference and Exposition, June 2013.

3. *Robotics Mining Competition: Rules and Rubrics*, http://www.nasa.gov/sites/default/files/atoms/files/rmc_rules_and_rubrics_for_2016_rev_2.0_-_01.08.2016_.pdf, 2015

4. M. Ardis, C. Carmen, M. DeLorme, and E. Hole. “Using a Marketplace to Form Multidisciplinary Systems Engineering Capstone Project Teams.” Proc. of the ASEE Annual Conference, June 2014.

5. K. Shimazu, and Y. Ohkami. “Systems engineering education for inexperienced students by providing hand-on practices.” IEEE Systems Conference (SysCon), 2011, pp. 367-370.

6. W. Bauer, W. Biedermann, B. Helms and M. Maurer, “A student laboratory for Systems Engineering: Teaching Systems Engineering to students without previous SE-knowledeg based on an industry-oriented example,” IEEE Systems Conference (SysCon), 2012, pp. 1-6.

7. J. Valasek, and K. Shryock, “Enhancing Systems Engineering Content in Aerospace Courses: Capstone Design and Senior Technical Electives.” Proc. of ASEE Annual Conference, June 2015.

8. Y. Bar-Yam. “When systems engineering fails-toward complex systems engineering," Proc. of Systems, Man and Cybernetics, 2003, pp. 2021-2028.

9. E. McGrath, S. Lowes, C. Jurado, and A. Squires, “SE Capstone: A Pilot Study of 14 Universities to Explore Systems Engineering Learning and Career Interest through Department of Defense.” Proc. of ASEE Annual Conference, June 2011.