Advanced Space Surface Systems Operations

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The importance of advanced surface systems is becoming increasingly relevant in the modern age of space technology. Specifically, projects pursued by the Granular Mechanics and Regolith Operations (GMRO) Lab are unparalleled in the field of planetary resourcefulness. This internship opportunity involved projects that support properly utilizing natural resources from other celestial bodies. Beginning with the tele-robotic workstation, mechanical upgrades were necessary to consider for specific portions of the workstation consoles and successfully designed in concept. This would provide more means for innovation and creativity concerning advanced robotic operations. Project RASSOR is a regolith excavator robot whose primary objective is to mine, store, and dump regolith efficiently on other planetary surfaces. Mechanical adjustments were made to improve this robot's functionality, although there were some minor system changes left to perform before the opportunity ended. On the topic of excavator robots, the notes taken by the GMRO staff during the 2013 and 2014 Robotic Mining Competitions were effectively organized and analyzed for logistical purposes. Lessons learned from these annual competitions at Kennedy Space Center are greatly influential to the GMRO engineers and roboticists. Another project that GMRO staff support is Project Morpheus. Support for this project included successfully producing mathematical models of the eroded landing pad surface for the vertical testbed vehicle to predict a timeline for pad reparation. And finally, the last project this opportunity made contribution to was Project Neo, a project exterior to GMRO Lab projects, which focuses on rocket propulsion systems. Additions were successfully installed to the support structure of an original vertical testbed rocket engine, thus making progress towards futuristic test firings in which data will be analyzed by students affiliated with Rocket University. Each project will be explained in further detail, as well as the full scope of the contributions made during this opportunity.

Nomenclature

α_n	=	normal pressure angle (14.5°)
d_1	=	reference diameter of the worm (38.1 mm)
γ	=	worm lead angle
m	=	axial module
μ	=	coefficient of friction
n_1	=	rotational speed of the worm (revolutions per minute)
p_x	=	axial pitch between adjacent worm threads (6 mm)
q	=	worm diameter factor
V_s	=	sliding velocity
z_1	=	number of threads (starts) on the worm (5)
z(x)	=	position function defined in the Cartesian coordinate system

I. Introduction

Over the past few decades, research has been implemented into various forms of space technology at NASA's Kennedy Space Center. More specifically, an organization within Kennedy Space Center known as Swamp Works is an incredibly unique technology development group. This group is modeled after Lockheed Martin's Skunk Works which deals with advanced development projects.[1] Skunk Works is known for its unshakable sense of innovation and achievement in revolutionizing military aircraft along with supporting technology. A key to their success involves their approach to project development. Initially, ideation and designs are created to meet pre-set

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requirements. The next step would be to fabricate a chosen design after several design reviews. Once testing begins, expectations are generally in favor of failing. Failure, which is commonly seen as an unredeemable stamp on a project, is intended for just the opposite. It inspires learning from past mistakes and the application of gained knowledge to advance the project to successful operation. These characteristics of Skunk Works are the backbone for the Swamp Works approach to space technology. Swamp Works consists of four labs which includes the GMRO Lab, the Electrostatics and Surface Physics Lab, the Advanced Space Life Sciences Lab, and the Applied Chemistry Lab. However, the main focus will be towards GMRO Lab project involvement along with an additional project referred to as Project Neo, which specializes in rocket propulsion systems.

As a part of Swamp Works at Kennedy Space Center, the GMRO Lab develops various technologies designed to improve the efficiency of space exploration. In general, the GMRO Lab seeks to properly extract natural resources from the moon, mars, and other celestial beings within reach that contain certain elements which are essential for human survival. More specifically, regolith, the "dirt-like" material on the surface of other planets, contains desired substances such as dust, soil, and ice. A challenge which faces the GMRO Lab includes mining this regolith with the most efficient robotic technology possible in reduced gravity scenarios on the moon, mars, and even asteroids. Other projects involving the GMRO staff include rocket exhaust effects on regolith and landing pads as well as developing technologies to properly utilize mined regolith. Projects focusing on regolith resourcefulness are referred to as In-Situ Resource Utilization (ISRU) projects. ISRU mainly comprises using mined regolith for structure support material, producing energy through complex thermal processes, and extracting natural resources which combine to make both water and rocket fuel. This internship opportunity provided experience either with the design, fabrication, or post testing analysis phases of the aforementioned projects.

II. Tele-Robotic Workstation Consoles

One of the various workstations in the GMRO Lab is located next to the conference space, which is often referred to as the innovation space of the lab. This workstation is comprised of salvaged consoles from the Launch Control Center (LCC) at Kennedy Space Center, two monitors and one desktop tower per console, and recovered pilot seats from NASA Huey helicopters. The vision for such a workstation involves tele-robotic communication along with necessary engineering capabilities. For instance, one monitor on a console could be used to display real-time video feed while the other monitor displays the desired engineering data. Since it is not in full operation, the assigned task during this internship opportunity involved collaborating with other GMRO Lab interns to modify this workstation for engineering analysis and user convenience.

A timeline was initially set for the progress of this project. The first step was to present five conceptual solutions to each project need on June 6. By June 10, a recommended design was to be presented to Swamp Works Senior Technologist Robert Mueller. Once an agreement was reached on a chosen design, the critical design review for the workstation was scheduled for June 16, in which approval or disapproval for fabrication would be discussed. Fabrication of all modifications to the workstation was to be complete by June 30. However, due to complications with additional projects, this schedule was altered so that only a chosen design would be presented by the end of the opportunity using CAD software.

A. Needs and Requirements

While there are several alternatives to modification for this workstation, only the helicopter seats, monitor mounts, and additional spacing between consoles were considered. Beginning with the helicopter seats, there is instability becomes an issue once a user barely leans forward. This problem needs to be resolved with a structurally simple solution. Specifically, the front of the seat needs an additional feature for full stability. Constraints on this new addition include cost effectiveness along with keeping the seats safe, ergonomically adjustable, maintainable, and aesthetically appealing. It is easy to observe the missing mechanical structure at the front of each helicopter seat in Fig. 1.

Another aspect of the tele-robotic workstation that needs alteration concerns the computer monitor mounting. In their current state, the monitors are simply placed within the consoles with no special attachments. This situation is not the best for user convenience as the viewing angle is unnatural and not flush with the console. Some requirements that go along with fixing this issue are structurally secure monitors and flush interfacing with the console panels which may involve designing front covers to fit the monitor frames. Also, it is of interest to the Swamp Works staff to include operating system switching capabilities among both monitors of each console. This entails a special connection between monitors and towers which allows screen output to be switched from one monitor to another. Unfortunately, for the purposes of this opportunity, changing video feed between monitors was not included in the project. Figure 2 displays the consoles with their respective desktop computers and seats.

The final facet of modification includes the spacing between each console. The consoles are completely separate from each other with no mechanical attachments. A form of spacing is needed to create a more comfortable desk space. As one may observe in Fig. 2, the consoles are very close to each other, leaving little room for extra space that may be required once they are used for engineering purposes. Therefore, a spacing design that attaches between the panels of the consoles shall be efficient in utility and aesthetically appealing while not causing a violation of the fire marshal safety standards as the workstation should not block the nearby staircase.

Figure 1. Workstation Seats.

Figure 2. Current Workstation Setup.

B. Implementation and Analysis

Due to the lack of time and priority during the opportunity, the designs for the solutions have not been completed using CAD modeling software. However, the concepts for a chosen design were selected by both the interns and the Swamp Works staff. Starting with the workstation seats, a simple box was to be fabricated out of aluminum sheet metal and bolted onto the legs of the chair. Not only would this box be designed for preventing the chair from leaning forward, but a small, adjustable drawer would be installed for personal items to be stored as in a locker. This compartment would have a handle just below the actual seat, which opens down and away in the forward direction. An additional feature would include the Swamp Works logo water-jetted on the front side of the adjustable drawer, centered just beneath the handle. Figure 3 shows a concept drawing of this selected solution.

Concepts for the next requirement which involved properly mounting each console's monitors were also drawn in a simple schematic as seen in Fig. 4. Essentially, the monitors needed to be flush with the entire console panel structure. This would require additional panels to be installed around the monitor frame for support as well as aesthetic appeal. In this case, the interior of the console would be entirely covered by the monitor, which also provides more storage space if needed. The flush mating between the monitors and the console panels is both a simple yet cost effective design.

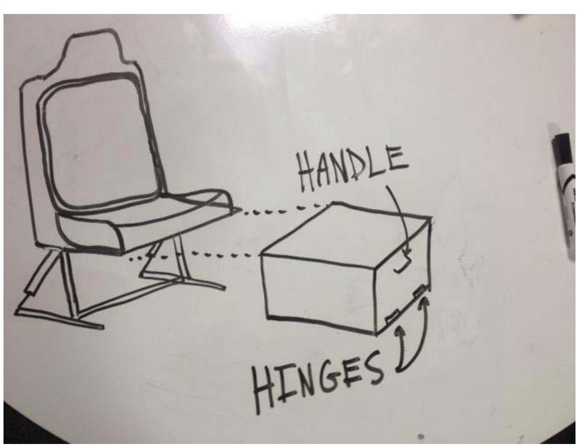

Figure 3. Workstation Seat Support.

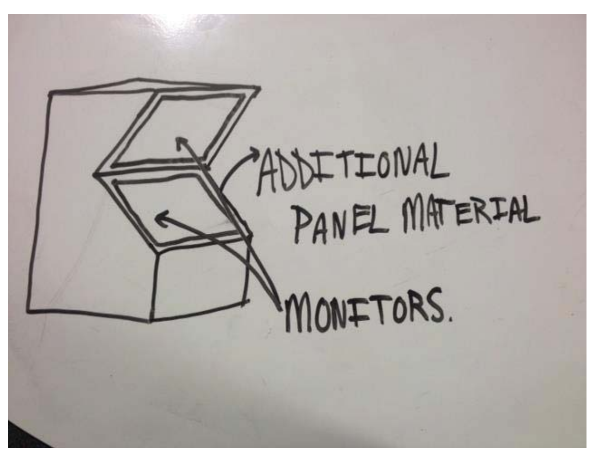

Figure 4. Monitor Mounting.

Another factor of this project that was neglected due to time constraints consisted of the spacing panels which would increase work space between consoles. Although this would have been a convenient feature to design, only the other two requirements were pursued for further consideration. This therefore concludes the implementation and analysis section of this project.

C. Project Accomplishments and Applications

The importance of the tele-robotic workstation can be clearly observed in its flexibility of operation. An original intent for the workstation setup was to encourage tele-robotic communication in the GMRO regolith bin. Such activity could utilize both console monitors for video feed as well as engineering data in real time transmission. But as the workstation needed mechanical upgrades for aesthetic appeal and user convenience, solutions were successfully designed for the helicopter seats as well as the desktop monitor mounts.

III. Project R.A.S.S.O.R.

With the uprising generation of space technology, more focus has been placed on the usefulness of regolith from the planetary surface. Various needs such as producing water, electrical power, and even rocket fuel, can be solved by only using regolith as a natural resource. As research continues to perfect the requirements of this technology type, one need for these advanced surface systems includes mechanical input of the regolith itself. The current solution to this problem is a robotic excavator that not only mines regolith but deposits it into a designed port for further use. This excavator prototype, known as the Regolith Advanced Surface Systems Operations Robot (RASSOR), was designed and fabricated by Swamp Works' to function in reduced gravity. Hence, the mechanical design and maneuvers of the robot are tailored to reduced gravity situations that would be common on an asteroid, the moon, or Mars.

In recent months, several flaws have been discovered in RASSOR's mechanical systems. Specifically, the excavation arms that support the bucket drums experience backlash when rotating about their fixed axis. Possible explanations as well as solutions to this will be discussed further in technical analysis. Another issue which sidelined RASSOR from further testing was found in the tracks of the mobility system. Thin spring steel, which attaches several metal plates to form the tracks, ripped during operation. Thus, efforts during the opportunity were focused on improving the robot by reducing the effects of these known problems.

A. Needs and Requirements

Properly identifying the needs in RASSOR's mechanical system was important for setting up the correct requirements. The torn spring steel in the tracks was the first issue attended to. Each track needed two new strips of spring steel that was twice as thick as the previous version. In this case, doubling the spring steel thickness would prevent further tearing while still allowing a decent amount of flexibility in the track. To correctly renovate these tracks, each riveted plate had to be detached from the old set of spring steel, and then re-riveted to the new strips of spring steel. Figure 5 displays a CAD illustration of the track system, in which the arrow points out the location of where the rivets attach the plate to the spring steel.

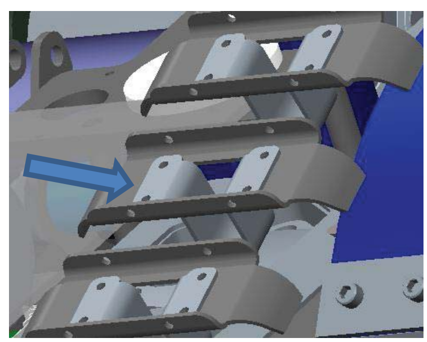

Figure 5. RASSOR Tracks.

Another necessity for improvement in the RASSOR mobility system involved replacing the 3D printed wheels with delrin wheels. Figure 6 is a Pro/ENGINEER CAD drawing that shows all wheel assemblies which were upgraded. One may observe that on each track, there are five wheel assemblies, each originally composed of two 3D printed wheels. Hence, those wheels were to be removed, primer and Loctite needed to be applied to each screw, and the screws could then tighten the new wheels onto the robot.

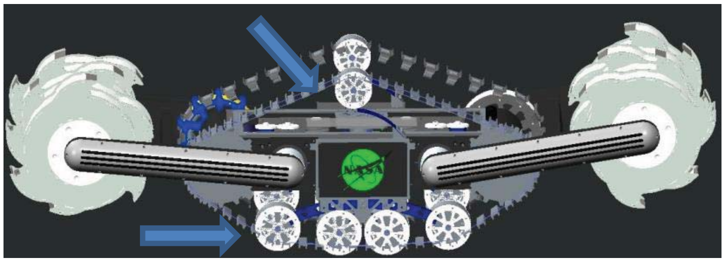

Figure 6. RASSOR Track Wheels in Pro/ENGINEER CAD Model.

Backlash in the bucket drum support arms was also an obvious problem that needed to be resolved. In short, backlash occurs in a gear system as a result of extra space between the mechanical parts. It could either be due to spacing between the threads and teeth of the worm gear, or the lack of proper tooth contact with the driving chain which connects the motor and the gear assembly. Therefore, the entire worm and planetary gear systems assembly had to be disassembled from the chassis for full maintenance. Again, Loctite needed to be applied to the screws in the worm gear assembly, while re-tightening the system back in place. An additional necessity involved increasing tooth-chain contact beneath the planetary gear system. Initially, the system only consisted of one sprocket for tension under the planetary gear system. More sprockets along with an updated plate design would need to be added to the chassis attachment. The arrow in Figure 7 points to the plate which needed adjustment for additional sprockets to increase the tooth-chain contact.

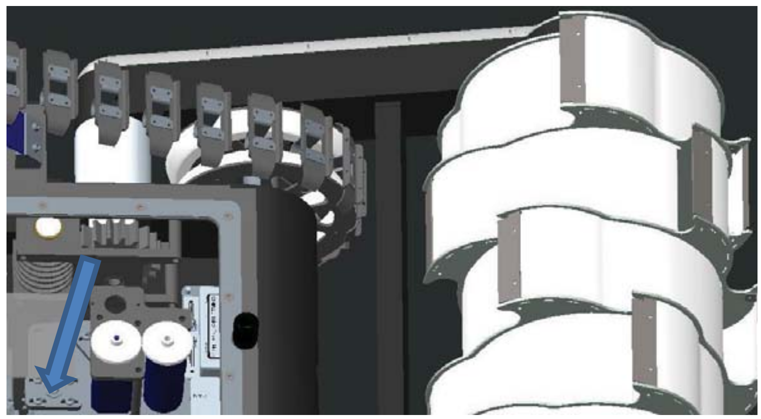

Figure 7. Arm Gear System Assembly in Chassis.

B. Implementation, Testing, and Analysis

First, the track systems were completely disassembled by drilling out the rivets in each plate. Once the old spring steel was finally removed, each plate was re-riveted to the new spring steel strips. Figure 8 shows an example of the new spring steel riveted to the track plate. Once this was completed, the 3D printed wheels were replaced with the new wheels made of delrin. Primer and Loctite was applied to each screw and then tightened back onto the wheel assembly to ensure proper operation. The complete assembly of these new wheels can be seen in Figure 9 below.

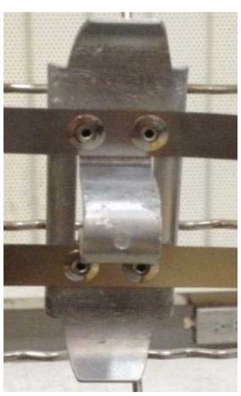

Figure 8. Riveted Plate and Spring Steel.

Figure 9. Delrin Wheels on RASSOR.

The next task to perform was to disassemble the worm and planetary gear systems connected to the arms. An attempted solution to the backlash problem was to simply re-tighten the worm gear and arm attachments. Also, the chain was to be in contact with more sprockets to avoid slipping while supporting an applied load. The solution to chain contact involved producing a different assembly plate between the planetary gear system and the chain. Figure 10 below shows the design for the new plate drawn in Pro/ENGINEER. This design complements the ability to add three new sprockets to the bottom of the chassis for increased tooth-chain contact.

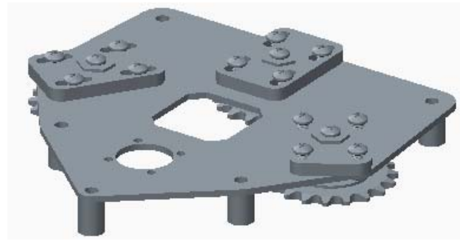

Figure 10. Plate and Sprocket Assembly.

With the attempted solutions in place for increased arm operation efficiency, it is important to know the theoretical efficiencies of which the worm gear is capable. The calculation process for theoretical efficiencies of each worm gear can be seen below. Note that two different efficiencies will be calculated to specify a desired efficiency range given two differing torque inputs. These will range from the motor functioning at 500 rpm and 4000 rpm. In observing Eq. (1) below, it is evident that values for the coefficient of friction, μ, and the worm lead angle, γ, need to be calculated in order to find the efficiency, η.[2]

$$\eta = \frac{\cos(\alpha_n) - (\mu)\tan(\gamma)}{\cos(\alpha_n) + (\mu)\cot(\gamma)} \tag{1}$$

First, the worm lead angle can be easily calculated as displayed in Eq. (2), Eq. (3), and Eq. (4) below. Specified values for the known variables can be found in the nomenclature section of this report.

$$m = \frac{p_x}{\pi} = 1.9098\ mm \tag{2}$$

$$q = \frac{d_1}{m} = 19.949 \tag{3}$$

$$\gamma = \frac{180}{\pi} \times \arctan\left(\frac{z_1}{q}\right) = 14.0706° \tag{4}$$

Now that the worm lead angle has been found, the coefficient of friction must be calculated. In order to determine an approximate value for μ, the sliding velocity must be calculated in order to attain the corresponding coefficient value from Table I. The sliding velocity equation, Eq. (5), as well as Table I can be observed below.

$$V_s = \frac{\pi}{60000}(d_1 n_1)\sec(\gamma) \tag{5}$$

Table I. Relation between V_s and μ.

Sliding Speed (m/s)	Friction Coefficient (μ)
0	0.145
0.001	0.12
0.01	0.11
0.05	0.09
0.1	0.08
0.2	0.07
0.5	0.055
1	0.044
1.5	0.038
2	0.033
5	0.023
8	0.02
10	0.018
15	0.017
20	0.016
30	0.016

For the motor speed of 500 rpm, the worm rotational speed (n_1) is 3 rpm. This gives a sliding velocity of approximately 0.0060 m/s. For the motor speed of 4000 rpm, the rotational speed of the worm is about 202 rpm. This yields a sliding velocity of 0.4154 m/s. Using these velocity values to interpolate from the table above, the friction coefficients for the 500 rpm and 4000 rpm motor speeds are approximately 0.1145 and 0.0592 respectively. These values were plugged into the efficiency equation, Eq. (1), to generate corresponding efficiencies for the 500 rpm and 4000 rpm motor speed situations, which are 49.45% and 79.35% respectively.

The next step in this process was to test the reassembled worm gear system. This could easily be performed by applying a load at the end of the arm while using a torque wrench to estimate the torque required to turn the worm gear. After several weights, the most consistent data showed that the newly assembled worm improved its required torque by approximately 6.4% compared to the pre-disassembled worm gears. Further information reveals that the former worm gear setup achieved the highest efficiency at about 32%. Therefore, the actual efficiency of the new worm gear assemblies is approximately 38.4%. This value of course may vary depending on the speed of the worm once the motor torque is applied, but overall the worm gear assemblies are closer to the theoretical efficiencies as desired.

C. Project Accomplishments and Applications

Excavator robotics is a major factor in ISRU technology, and RASSOR serves as a stepping stone for the desired prototype that will eventually be flown to another planetary surface, namely the Moon, Mars, or an asteroid. At this point in RASSOR's prototype stages, a few mechanical upgrades were certainly required in order to continue testing. The mobility systems and the excavator arm systems were disassembled and carefully put back in their proper locations. Up to this point in the opportunity, the excavator arm assemblies require more assembling, as they are very complex in nature. Overall, the requirements for Project RASSOR were accomplished in producing a better functioning prototype for regolith excavation.

IV. Robotic Mining Competition Reports

Having similar objectives to Project RASSOR, the NASA Robotic Mining Competition (RMC) is a nationwide competition for college engineering students. As many students enter this competition for either a club project or a senior design course, the main goal is to develop solutions to mining planetary regolith in reduced gravity using excavator robots. The competition consists of practice runs as well as two official, timed competition performances. Overall performances of each robot are judged by the Swamp Works staff along with additional, voluntary staff. Not only does this competition encourage space robotics at the college level, but lessons learned by successes and failures of each robot are considered invaluable to the Swamp Works staff. During each official performance, mining judges record robot specifications and detailed descriptions on the robot's operations for future reference. An important task of this internship opportunity included transferring these written notes from the 2013 and 2014 competitions into organized electronic documents. This contributes progress towards producing the official RMC reports for those years, which Swamp Works seeks to complete in the near future.

A. Needs and Requirements

Since the Swamp Works staff needs to convert these documents of notes from the 2013 and 2014 mining competitions into official reports, information organization is crucial. The required formatting consists of a robot picture, robot specifications, and performance descriptions. Including a picture of each robot is certainly important for analysis sake. A reader can easily visualize what parts of the robot each description references. The robot specifications section breaks down key elements of each robot's design, explaining in detail how various subsystems are supposed to function. These are followed by performance descriptions which communicate how each robot operated during the timed runs. Once all the necessary material for each robot is entered for each robot, a method of sorting robots based on physical features for logistical purposes is needed. This method of categorizing each university's robot requires a practical approach that may lead to further implications about future excavator designs.

B. Implementation, Analysis

According to the previously mentioned formatting, the notes taken for each competitor's robot were documented. Each robot specification described subsystems such as mobility, excavation, storage, and dumping. Excavators where mainly characterized by wheels or tracks, drive motors with various setups, several different mining assemblies, a hopper for regolith storage, and linear actuators for dumping. Performance descriptions included how the mobility system operated in the regolith, how efficiently the mining assembly attained soil, and how well regolith was transferred from the hopper to the arena bin.

It was then necessary to categorize each robot according to specific design features. In detail, these robots are sorted based on their mobility, excavation, and dumping systems. Table II, Table III, and Table IV display these comparisons respectively for the 2013 competition. Overall, 49 teams competed although there are three robots whose subsystems are not fully described. For instance, the excavation and dumping systems of one robot were not included in the original collection of notes, and are therefore not accounted for in Table III or Table IV. Also, the other two competing robots are not described in any subsystem category and thus were not included in any of the following tables.

Table II. 2013 Mobility System Breakdown.

Mobility Type	**Number of Robots**
4 Wheels	36
2 Tracks	8
2 Augers	0
6 Wheels	3

Table III. 2013 Excavation System Breakdown.

Excavation Type	**Number of Robots**
Load, Haul, Dump	13
Bucket Chain	4
Bucket Wheel	3
Bucket Ladder/Conveyer Belt	16
Bucket Drum	5
Scraper	4
Snow Blower	1

Table IV. 2013 Dumping System Breakdown.

Dumping Type	Number of Robots
Load, Haul, Dump	13
Bucket Ladder/Conveyor Belt	8
Bucket Drum	3
Actuated Hopper	21
Hopper with Auger	1

Similar to the previous year, the 2014 Robotic Mining Competition consisted of 37 competitors with two robots whose subsystems were not fully described. One of these robots was never mentioned concerning any subsystem category whereas the other was not described in only the excavation subsystem. The subsystem organization for the 2014 competition can be observed in Table V, Table VI, and Table VII below.

Table V. 2014 Mobility System Breakdown.

Mobility Type	Number of Robots
4 Wheels	27
2 Tracks	7
2 Augers	1
6 Wheels	1

Table VI. 2014 Excavation System Breakdown.

Excavation Type	Number of Robots
Load, Haul, Dump	6
Bucket Chain	5
Bucket Wheel	8
Bucket Ladder/Conveyer Belt	12
Bucket Drum	3
Load Scoop	1

Table VII. 2014 Dumping System Breakdown.

Dumping Type	Number of Robots
Load, Haul, Dump	6
Bucket Ladder/Conveyor Belt	6
Bucket Drum	3
Actuated Hopper	20
Hopper with Auger	1

C. Project Accomplishments and Applications

Over the past few years in which the Robotic Mining Competition has been hosted by Kennedy Space Center, the Swamp Works staff have learned a great deal of information concerning excavator robotics. By analyzing the past two years of competing robots, it is useful to see the trends in different subsystems as many schools implement various new designs. The particular set of data analyzed from the previous two years revealed certain trends in each subsystem. For mobility, the general preference of most competing teams is a four wheel design. The excavation subsystem has a trend leaning from “Load, Haul, Dump” and “Bucket Ladder/Conveyor Belt” towards all the other listed possibilities. And finally, the dumping systems tend to gravitate more towards actuated hoppers but the use of a conveyor belt is beginning to grow. Not only has the structure for the 2013 and 2014 competition reports been solidified, but analysis on the various design types was successful as anticipated.

V. Morpheus Landing Pad Erosion

Another project included in this opportunity experience involved support analysis for Project Morpheus. Morpheus acts as a vertical testbed (VTB) in which advanced spacecraft technologies can be evaluated with a lower end budget. It is capable of vertical launch, and autonomous landing in hazardous terrain through the Autonomous Landing and Hazard Avoidance Technology (ALHAT). Thus far, there have been fourteen free flights, or test flights, and all of them have been performed near the Shuttle Landing Facility (SLF). Over the period of several flights, the landing pad for Morpheus has experienced erosion as a result of the rocket exhaust plume. A glimpse of this process at work during flight can be seen in Fig. 11 below. The goal of the support analysis was to provide valuable estimates for the volume of eroded concrete as well as conclusive implications for the use of stress relief lines in the pad.

Figure 11. Pad Erosion Process during Free Flight 13.

A. Needs and Requirements

In the early stages of analysis, laser scanned images were taken directly over the stress relief lines which intersect near the middle of the pad. This data had to be imported into a program known as Geomagic Studio, which served as image processing software used to create virtual models. Each scanned image of the pad was carefully stitched together in Geomagic Studio to produce a partial 3D surface of the landing pad. Figure 12 shows the scanned cross section of the Morpheus landing pad. With this 3D surface properly centered at the origin, a probe feature in Geomagic Studio could trace a 2D curve along a specific point on the defined y-axis. For the interest of the analysis, the curve produced by this probe shall generate a volume for the eroded concrete through simple methods of calculus. The goal of this data analysis is to recommend a certain time period for whence the landing pad should be repaired.

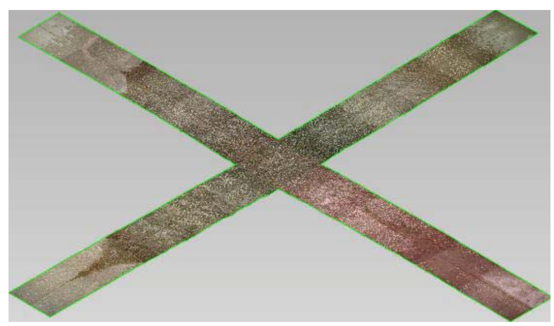

Figure 12. Scanned Section of Landing Pad.

B. Implementation, Testing, and Analysis

Beginning with the probing feature, data points were collected along the east and west section of the pad. Figure 13 shows the probing process where red dots mark the point chosen by the user along with the corresponding X, Y, and Z coordinates. These points were then exported into Microsoft Excel for plotting and calculation purposes. However, since the curve produced by the probing feature is only characteristic for one small portion of the pad, it was necessary to estimate an elliptical shape of erosion which more accurately accounts for the roughness of the entire eroded region. The dimensions of the ellipse were determined based on rough estimations for the average depth of the erosion. Both of these curves can be seen in Fig. 14. By using a

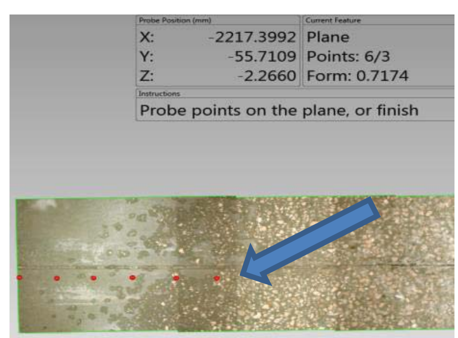

Figure 13. Probing Feature in Geomagic Studio.

simple calculus technique of curve revolution, an approximate volume of eroded concrete could be produced. This technique also assumes perfect symmetry of the curve and the eroded portion of the landing pad. Essentially, the technique treats one side of the symmetrical curve as a radius. As the square of the function is integrated over a set of points and multiplied by π, the curve produces a numeric value for enclosed volume. The process can be seen beginning with Eq. (6). Note that the bounds of integration take into account the minimum point being (-4.0, -1.94).

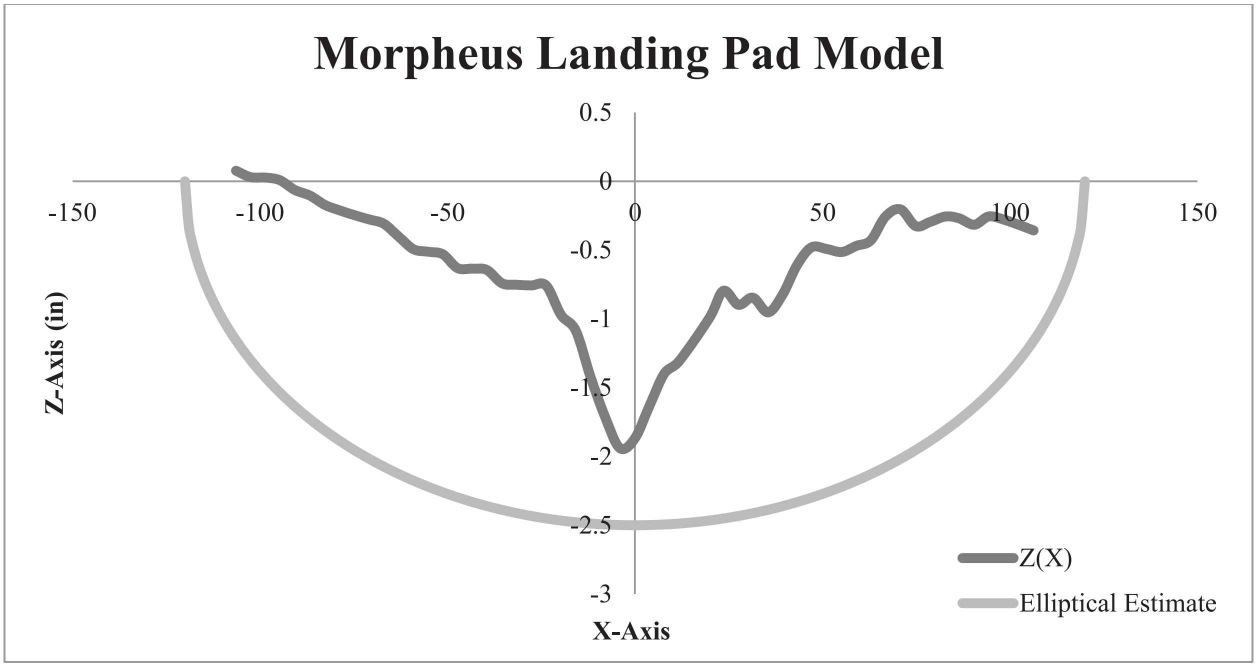

Figure 14. X-Z Pad Curves with Fixed Y position.

$$V \approx \pi \int_{-4}^{106} [z(x)]^2 dx \approx \text{ 5 gal eroded concrete} \tag{6}$$

When the ellipse is revolved, the eroded portion basically becomes an oblate sphere. By using the definition of an ellipse, it is easy to see that the estimated volume can be found using Eq. (7) below.

$$V \approx \pi \int_{0}^{120} 2.5^2 \times \left(1 - \frac{x^2}{120^2}\right) dx \approx \text{ 6.8 gal eroded concrete} \tag{7}$$

Although this value is relatively different from the volume attained from the probed curve, it is probable that this is closer to the actual volume of eroded concrete due to the roughness of the pad surface. In order to physically test this approximation, a technique was performed in which known volumes of water should be poured into the eroded portion of the pad. Once the entire eroded surface was covered, that was to be the approximate volume of eroded concrete. Buckets of 5 gallon capacity were filled with water and taken out to the Morpheus landing pad. A total of six buckets was required to cover the eroded region, which is about thirty gallons. Figure 15 shows this whole amount of water poured over the pad. This number is far different than the approximated estimates for missing concrete by a large factor. However, it was determined that external conditions such as concrete roughness and evaporative environmental conditions can be held

Figure 15. Morpheus Landing Pad with Water.

responsible for this seemingly large approximation. Therefore, this method was deemed inaccurate and the estimated volume of erosion obtained during this process can be ignored.

C. Project Accomplishments and Applications

From the curve estimates produced through the Geomagic Studio probing feature and the elliptical curve approximation, relatively accurate volumes were calculated. It appears, nevertheless, that the oblate spherical volume is the closest to the actual amount of eroded concrete given the rough surface and asymmetric properties of the pad. A major implication from the attained data analysis involves the time period in which the landing pad should be repaired. Given that this pad has been used during fourteen previous free flights, it is recommended that pad repair should take place after a maximum of two more free flights. Hence, landing pads for the Morpheus can withstand up to about sixteen free flights before repair is needed. Since the eroded landing pad consists of rough concrete edges, further erosion during free flight might free up more jagged pieces of concrete to impact the vehicle during descent, causing damage to the vehicle. Overall, the results of this analysis contribute towards Morpheus support in the future.

VI. Project Neo

Although this project is exterior to Swamp Works, Project Neo entails creating a rocket propulsion testing unit for application in the Rocket University training program. Mainly, the system consists of an injector 71 engine that combusts liquid oxygen and liquid methane, both of which are in a super-cooled state. The engine itself is rated to produce approximately 2400 lbs. of thrust, while the entire propulsion unit is being manufactured to withstand up to 6000 lbs. of thrust. Various subsystems are currently being implemented to support future static firing tests which will be conducted once the entire test unit is complete in assembly. This internship opportunity also provided experience in the manufacturing phase of the support unit which houses the rocket engine.

A. Needs and Requirements

Broadly, the support unit, referred to as the test skid, is manufactured to withstand a rated amount of thrust from the injector 71 engine. In an effort to produce valuable data from a static firing of the engine, the test skid must remain in its place. One of the most important features of the skid includes the support feet located underneath the structure on each side. Figure 16 points this out in a CAD model of the engine mounted to the test skid using Pro/ENGINEER software. However, additional support needed to be installed on each foot for increased structural integrity, thus creating a more stable testbed. While there were certainly other aspects of the skid that needed maintenance, such as the electrical box and the fuel piping, this was the only aspect of Project Neo which this opportunity was involved with.

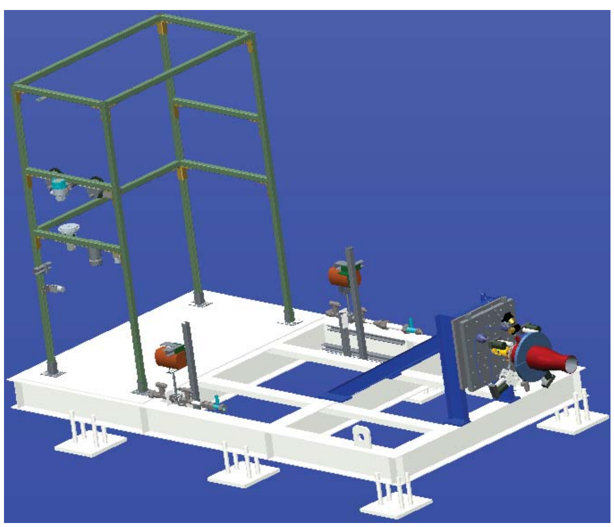

Figure 16. Project NEO Skid Model.

B. Implementation and Analysis

As a requirement for producing a more stable support system, the test skid for the injector 71 engine needed additional plates to be attached to each foot. The solution to this problem involved drilling 4 holes into 1 inch thick plates of aluminum. Twelve total aluminum plates were used, tightening 2 plates onto each foot, as each side has 3 support feet. These plates were successfully installed, as seen in Fig. 17, making the skid flush with the ground. More work on the skid is definitely required before test firing can begin, but limited time during the opportunity inhibited further work on this project.

Figure 17. Aluminum Plates beneath Skid.

C. Project Accomplishments and Applications

The purpose of the test skid being constructed in Project Neo is to encourage students affiliated with Rocket University to explore the more difficult challenges of rocket science. The injector 71 engine used in this project is a salvaged remnant to the first vertical testbed, or the predecessor to Morpheus, that NASA developed a few years ago. Contributing towards the overall structural stability of the engine support skid is certainly a success given that this opportunity does not necessarily specialize in this area. Though not its primary intent, Project Neo could even possibly produce experimental data that assists the GMRO staff concerning the topic of rocket plume effects on planetary regolith. Nevertheless, much can be learned from this project given its various applications to the rocket science field.

VII. Conclusion

Over time, the need for advanced surface systems technology is becoming paramount in NASA's future. Not only does this research in ISRU related topics benefit the space agency in cost and efficiency, but it will someday prove beneficial to mankind on a large scale. The purpose of this opportunity was to contribute to this shift in space technology in the most effective ways possible. The tele-robotic workstation serves as a place within the GMRO Lab from which innovative ideas are inspired for robotic operations on different planetary surfaces. Project RASSOR is also a stimulating project, as it symbolizes the next giant leap for mankind to properly utilize planetary resources for human benefit. Excavator robotics is a vital aspect of future deep space missions that involve processing planetary regolith for life support systems which will be capable of producing water, rocket fuel, and even human housing. Relative to excavators, the annual Robotic Mining Competition encourages this part of ISRU technology development among college engineering students. The data analysis concerning robot design trends from the past two years revealed some change in subsystem preferences, yet overall both years were consistent. However, system designs may become more similar as autonomous operation takes priority over other system design goals. An additional project that the GMRO Lab supports is Project Morpheus. The landing pad data analysis proved to be helpful in suggesting a time period for repair, while also providing new insights into landing pad design. And finally, as a project exterior to the GMRO Lab, support for Project Neo during this opportunity contributed to the education of several students involved with Rocket University who are interested in rocket propulsion systems. The requirements of each project, with exception to those hindered by time constraints, were accomplished, hence deeming the overall contribution of this opportunity successful.

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