NASA Robotic Mining Competition

Major Qualifying Project

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The Nonsense Factory

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Abstract

In conjunction with the NASA Robotic Mining Challenge, this MQP undertook the challenge of designing and constructing a robot capable of operation in a simulated Martian environment to remotely perform excavation operations. The team developed the robot with an ultimate goal of competing in the event hosted at the Kennedy Space Center in May of 2016.
# Table of Contents

Table of Figures ........................................................................................................................................... iii

Table of Equations ........................................................................................................................................... iii

Introduction ...................................................................................................................................................... 1

Background ...................................................................................................................................................... 3

  Competition .................................................................................................................................................. 3

Initial Research ................................................................................................................................................ 8

  Digging Mechanism .................................................................................................................................... 10

  Dumping Mechanism ................................................................................................................................. 13

  Drivetrain .................................................................................................................................................... 15

  Wheels ......................................................................................................................................................... 15

  Electrical ...................................................................................................................................................... 16

  Computers, Programing, and Sensors ....................................................................................................... 16

Methodology ................................................................................................................................................... 18

  Digging Mechanism .................................................................................................................................... 18

  Dumping Mechanism ................................................................................................................................. 21

  Drivetrain .................................................................................................................................................... 22

  Wheels ......................................................................................................................................................... 22

  Electrical ...................................................................................................................................................... 24

  Computers, Programing, and Sensors ....................................................................................................... 27

Outreach ......................................................................................................................................................... 31

Results and Conclusions ............................................................................................................................. 33

Future Work .................................................................................................................................................. 34

Table of References .................................................................................................................................... 35
Table of Figures

Figure 1: Competition Arena .................................................................................................................. 7
Figure 2: Design Chart ............................................................................................................................ 9
Figure 3: Diaphragm Wall Grabber ....................................................................................................... 13
Figure 4: Troy-Bilt 3-Stage Snow Blower ............................................................................................. 19
Figure 5: Analysis of the RS550 Motor .................................................................................................. 21
Figure 6: SolidWorks Model of Wheel .................................................................................................. 23
Figure 7: Wheel Wall Stress Simulation ............................................................................................... 24
Figure 8: Performance Graph of CIM Motor ........................................................................................ 26
Figure 9: Diagram of Electrical System .............................................................................................. 27

Table of Tables

Table 1: Dust-Tolerant Design Point Break Down .............................................................................. 6
Table 2: Dust-Free Operation Point Break Down .................................................................................. 6
Table 3: Autonomous Operation Point Break Down ........................................................................... 7

Table of Equations

Equation 1: Orientation Algorithm ..................................................................................................... 31
Introduction

Over the past 58 years NASA has pushed the envelope in scientific developments and innovations. Martian exploration and cultivation are among the largest challenges faced by the agency over recent years. Because of the magnitude of this problem, NASA has developed competitions to spur unique and imaginative innovations in the pursuit of improved extraterrestrial robotics. NASA introduced this type of initiative in 2007 with the Lunar Regolith Exploration Competition, where teams were tasked with excavating simulated lunar regolith. The Lunar Regolith Excavation Competition is in the same vein as the Martian Challenge. Since then, the competition has moved with NASA’s focus to remote operation of a robot on Mars. The NASA Robotic Mining Competition is designed to promote the creation of new robots for the purpose of operating on Mars and other extraterrestrial terrain. The team sought to design, build, program, and test a robot for use in this competition and beyond.

The three necessary aspects of robotics, mechanical, electrical, and software, each pose a unique challenge when designing a robot. The mechanical and electrical designs needed to take into account the challenges presented by the Martian environment. The robot required the capacity to navigate a field of basaltic regolith simulant and gravel to an excavation area where it would perform mining operations. Afterwards the robot would navigate to a collection zone where it would offload the payload of the mining operations into a collection bin to score points. The entirety of the system must be built to withstand the abrasive properties of the Martian regolith simulant in addition to maneuvering through deep and slick regolith simulant. The electrical system of the robot must be insulated from the regolith simulant in addition to efficiently providing the necessary power to all electrical actuators. Finally, the software of the
robot must be able to provide the operator with all the information necessary to remotely operate it without a direct line of sight to the arena.

This paper will discuss each of the three major areas of robotics used to solve the problems presented by the NASA Robotic Mining Competition as well as background research conducted by the team into the rules and potential solutions to the problem, potential future work on this project, and of course the problem this project is out to solve.
Background

Competition

The NASA Robotic Mining Competition is a university-level competition for students to design and build a robot that can travel a simulated Martian landscape for mining purposes. The robot must excavate basaltic regolith simulant (BP-1) and ice simulant (gravel) before returning the collected payload for deposit into a collector bin as a simulation of an extraterrestrial mining mission. All this must be accomplished while the robot is limited to autonomous and telerobotic operations with no line of sight from the operator to the robot.

One major factor influencing the establishment of the competition is the issue of in-situ resource utilization (ISRU). ISRU is the practice of collecting resources within the exploration site. Making use of ISRU is paramount on deep-space missions where the travel time round trip to the destination and time there exceeds the amount of resources the ship can carry for the support of operations. In addition, resupply missions are not only expensive but also put the crew at risk when relied on as the sole provider of resources. NASA has attempted to focus efforts in this competition to encourage development of technologies to collect material containing consumables for human life-support systems, such as O₂, H₂O, N₂, He, etc. Additionally, the mined regolith might be utilized as radiation shielding or shelter for resources and infrastructure. A major material resource on Mars is the ice buried well beneath the surface. Martian regolith insulates the ice and must be excavated to procure the resource. NASA benefits from the development of innovative robotic concepts produced directly as a result of this competition.

The competition trials will be run using BP-1 in the official arena. The arena is filled with compacted BP-1, to simulate Martian regolith, to a depth of approximately 30cm. Beneath that
there will be approximately 30cm of quarter-sized gravel to simulate the icy regolith buried beneath the surface. Additionally, three obstacles and two craters will be distributed about the field. After each run the BP-1 and gravel will be returned to the arena and the obstacles and craters will be reset. The placement of the obstacles is randomly selected before the start of the competition. Each will have a diameter between 10 and 30 centimeters and an approximate mass between 3 and 10 kilograms. The two craters will have a varying depth and width, with a limit on diameter and depth of 30cm.

Teams compile points based on various aspects of operation. Upon passing inspection a team is awarded 1000 points. During each trial run a robot will earn 3 points for each kilogram over 10kg of BP-1 deposited in the collection bin. For example, if 50kg of BP-1 was deposited then the team has earned 120 points. Additionally, the team will earn 15 points for each kilogram of gravel deposited in the collection bin. This is measured separately from the BP-1.

A separate challenge of the competition addresses the difficulties of communicating with a robot operating on a different planet. During each run the team loses 1 point for each 50 kilobits/second of average data used by the robot in communicating with the command center. As an additional aid for controlling the robot, the team has the opportunity to use situational awareness cameras provided at the event. These cameras overlook the field and may be used by the team to aid in controlling the robot. During each run the team will lose 200 kilobits/second’s worth of data for each situational awareness camera used during the run. The robot has ten minutes for each run and the total score is the sum of the points from two runs.

Design challenges posed to the competitors include managing the weight and power consumption of the robot. In order to simulate the limitations of transporting a robot from Earth.
to Mars, the robot is limited to a mass of 80kg. To encourage lighter designs, the team will lose 8 points for each kilogram of the robot’s total mass. For example, a robot operating at the upper limit of the parameters, 80kg, will lose 640 points before the run starts. Additionally, a commercial off-the-shelf electronic data logger must be mounted on the output leads of the battery. The team will lose 1 point for each watt-hour of energy consumed during the run.

The robot must fit within a 1.5m length x 0.75m width x 0.75m height box during the outset of the trial run. The robot is permitted to expand beyond the 1.5 x .75m footprint after the start of the run but may not exceed a 1.5m height unless it is performing its dumping protocol. A permanent arrow must be placed on the robot establishing the forward direction of the robot.

The mining robot is prohibited from using any physical processes, gases, fluids, or consumables that would not work in the Martian environment. For example, GPS, pneumatic tires, and foam filled tires are not allowed. Any process that requires properties specific to Earth may be used if and only if the system using said process is designed to function in the Martian environment. Any resources necessary for this to happen must be provided by the robot itself. For example, pneumatic systems are only permitted if the gas is self contained on the robot from the start of the run. Additionally, the robot is not permitted to alter the physical or chemical properties of the BP-1 and gravel.

During each trial run the team will be awarded between 0 and 100 points for the robot containing dust tolerant design features as well as dust free operation. 30 of these points come from judgment on effort put into protecting the robot’s more vulnerable components from the abrasive BP-1. 70 of the points come from dust free operation; if the robot raises a substantial
amount of dust during operation then fewer points are awarded. The team is not penalized for airborne dust while unloading into the collection bin.

**Table 1: Dust-Tolerant Design Point Break Down**

<table>
<thead>
<tr>
<th>Feature:</th>
<th>Points Available:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drivetrain components are protected</td>
<td>10 points</td>
</tr>
<tr>
<td>Custom dust sealing features</td>
<td>10 points</td>
</tr>
<tr>
<td>Active dust control (Electrostatics, etc.)</td>
<td>10 points</td>
</tr>
</tbody>
</table>

**Table 2: Dust-Free Operation Point Break Down**

<table>
<thead>
<tr>
<th>Feature:</th>
<th>Points Available:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving with minimal dust disturbance</td>
<td>20 points</td>
</tr>
<tr>
<td>Digging with minimal dust disturbance</td>
<td>30 points</td>
</tr>
<tr>
<td>Transferring material without dumping BP-1 on robot</td>
<td>30 points</td>
</tr>
</tbody>
</table>

Each run also presents the opportunity for teams to earn points for autonomous operation of the robot, based on several criteria. There are 500 possible points that will be awarded for completing certain tasks autonomously. The points are not cumulative; each level is achieved incrementally.
Table 3: Autonomous Operation Point Break Down

<table>
<thead>
<tr>
<th>Activity</th>
<th>Points Awarded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing obstacle field (Out and back)</td>
<td>50 points/pass (two times only)</td>
</tr>
<tr>
<td>Crossing obstacle field, excavate, return to collection bin</td>
<td>150 points</td>
</tr>
<tr>
<td>Crossing obstacle field, excavate, deposit payload (two times)</td>
<td>250 points</td>
</tr>
<tr>
<td>Fully autonomous run</td>
<td>500 points</td>
</tr>
</tbody>
</table>

During each run, the walls of the arena are not allowed to be sensed by the root to achieve autonomy. The team is required to explain to the judges how the autonomous systems function in order to prove the system does not use the walls for navigation.

Figure 1: Competition Arena

The mining robot is placed randomly in one of the starting positions; see Figure 1. The robot is only allowed to excavate BP-1 and gravel located in the area on the other end of the
arena from the starting area. The robot’s starting direction is randomly selected immediately before the trial run. Additionally, the robot is required to cross the obstacle area to the excavation zone then back to the starting area to deposit the BP-1 and gravel into the collection bin.

The top front edge of the collector bin will be placed behind the wall of the starting area as in Figure 1. The top edge is mounted approximately 0.55m +/- 0.05m from the top of the BP-1 surface. The collector bin has an opening of 1.575m by 0.457m to collect the BP-1 and gravel. The team is permitted to attach a target or beacon to the collector bin for navigation purposes. This piece must not exceed the length of the collector bin and must weigh less than 9kg. The mass of the navigational aid system is included in the total robot mass limit of 80kg and must not extend higher than 0.25m above the top of the collection bin.

The team must command and monitor the robot from a location outside the line of sight of the arena. To connect to the robot, the team must provide Wi-Fi equipment and any necessary power conversion devices. Teams are restricted to the USA IEEE 802.11b, 802.11g, or 802.11n standards for the wireless connection with the ability to switch between channel 1 and channel 11. This is because each trial run will consist of two teams operating on separate fields simultaneously. When not in the field or in a designated practice area, robots must manage communications through a wired Ethernet connection.

**Initial Research**

After performing basic research into previous robotic designs from previous competitions the team decided to pursue a unique approach to the challenge. This was a result of observing that many of the robots fielded in the 2013 competition [NASA Edge] followed the Conveyor-Scoop design popularized by the winner of the 2009 Lunar Mining Competition. The team
elected to pursue designing an excavation mechanism design that was untested in the competition thus far, hoping to inspire new innovations in a design pool that seemed to revolve around a very limited number of ideas.

The design phase of the project began with a massive brainstorming session generating numerous possible approaches to the challenge presented. Some ideas proposed but not pursued included: a vacuum cleaner-style system, a system inspired by the salmon cannon used to propel the fish up dams, as well as conveyor belts both within the robot and held outside. The Conveyor-Scoop system was also proposed as a reliable fallback design. Sorting through the competition point system, the team elected to pursue functional autonomy and the collection of both regolith and gravel as the primary goal.

![Design Chart](image)

*Figure 2: Design Chart*
**Digging Mechanism**

Designs, some of which are seen in Figure 2, such as rototillers, conveyer belts, scoops, hollow drum, and augers, were considered during the initial research and brainstorm phase of selecting a digging mechanism to design. The rototiller design, not seen in Figure 2, was a fantastic tool for mixing up the basalt and gravel to get the gravel higher up and more retrievable. A rototiller is a tool used in farming to mix up and aerate soil. It is a thin wheel made of slats of metal making a cross. The crosses push into the dirt and then rip it up and mix it around. It would, though, require another mechanism to bring the material to the storage unit in the robot and in order to reach the depth of the gravel would make the robot’s height dimension too large for the competition. A rototiller would be a great tool when in conjunction with another mechanism, but because of the size restrictions it was found to be not useful to the team.

The second digging mechanism in Figure 2 is a conveyer belt shaped like a candy cane and has small long scoops every few inches along its length. This conveyer belt spins so that the scooping action happens towards the inside of the cane. This allows the dirt to be dumped into a bucket under the hook of the cane with minimal dust dispersion. This design was looked into for a brief amount of time because it is one of the most commonly used diggers in the competition and has therefore most likely been brought to its peak of efficiency. In the time that this design was looked into the team looked at moving the mechanism vertically, straight at a forty-five degree angle, and rotating it. The most efficient seemed to be to rotate it, so that it could move out of the way of the actuation of the dumping mechanism on the robot.

The third mechanism, the straight conveyer belt was a suggestion that was not quickly discarded. This is because a traditional conveyer belt system can have many issues with a dusty/sandy environment. The chains can be run off their tracks or make the chain snag. If not
for the problems of this system this mechanism would have the potential to be both the digging and dumping mechanism if rotated about the end. It is then able to both move material into a holding bin as well as deposit it into the collection bin.

Next the team looked at miniaturizing a backhoe. A backhoe is a bucket then goes out from the robot and scoops towards the robot then can move up to dump the load. Though the backhoe design allowed for easy and large scoops, it did not allow for functional maneuverability to a containment bucket in the robot. The weight of the backhoe, in order to have it pivot on this small robot, would cause problems with tipping over and height restrictions. Overall, this design was determined to be too heavy and have too many maneuverability problems to account for its good points.

The hollow drum is a very limiting device. It is a drum that spins in one direction, in line with the openings in the drum’s wall, to collect material inside the center of the drum itself. It then spins in the opposite direction to dump out the material through the same holes it collected with. The holes are small so that none of the material escapes, but that also means that the filling and dumping processes are slow. The hollow drum is usually large and takes up a large amount of space. To use this mechanism means having it be the only mechanism on the robot or having an entirely separate digging and dumping system, so the hollow drum can not be changed or manipulated much. These restrictions meant that the team discarded this mechanism.

There are many kinds of augers using both in construction and in the competition. Most of these are a single long auger in a tube to move the material up and out of the small hole made in the ground. This design is susceptible to clogging and has a single point of attachment. Having a single point of attachment makes the component the weak point of the robot especially when it
is assumed that the auger must be driven into the ground moving up and down. This design would also be restricted with the height limitation of the robot. Because of these reasons this design was only looked at briefly, then discarded.

The initial concept promising the most potential was a diaphragm wall grabber. This concept was based on an excavation machine utilized in quarries. The initial proposal was to manufacture a diaphragm wall grabber as the primary digging mechanism, Figure 3. The grabber was selected for its highly efficient method of grabbing a large amount of material and protruding deep enough into the regolith in order to gather the ice simulant. For this design, the collection mechanism included a moving bucket that travelled underneath the diaphragm wall grabber during the unloading process at the apex of its throw. This design demonstrated the potential to retrieve gravel after three scoops of the claws, reaching deeper on its initial grab than most designs were capable of reaching during a full run, even while factoring in the regolith moving back into the newly created hole. The potential for collecting a high quantity of gravel was a major factor in support for the design and justified the amount of time it spent in development. The Achilles heel of the design was the height limitations placed on the robot. The team developed a plan for the range of motion necessary for success, but the quantity of material proved too massive and pushed the weight of the robot over the limit. Therefore, the mechanism was deemed too complex and a new design began development.
There were many initial concepts for the dumping mechanism for the robot after the initial brainstorming session. One set of designs utilized a conveyor belt system. One was the straight conveyor belt that could move material out of a storage area into the collection bin. This could be used either with a digging mechanism or as both the digging and the dumping mechanism as explained in the digging section above.

The other conveyor belt system considered by the team was to span the length of the field. This would be attached to the robot and at the beginning of the round the robot would

**Dumping Mechanism**

*Figure 3: Diaphragm Wall Grabber*
attack it to the collection bin. As the robot moved the length of the field the belt would lengthen and shorten. As the robot mined it would send the material constantly over the conveyor belt to the collection bin. This was quickly determined to be against many of the competition rules as it would have mining and dumping happening at the same time and the robot is required to go back and forth across the terrain every time it dumps. It also posed the interesting problem of how to make the conveyor belt not slump to the ground in between the robot and the collection bin. Finally, this system would allow for either a classic conveyor belt or a bucket line system where the buckets will be filled with material, as seen in Figure 2.

Another design was based on the salmon cannon, used to relocate salmon up dams that have been built in their migratory path, and would have capsules, instead of fish, used to load the cannon which would then use differential air pressure to shoot the regolith and gravel to the collection bin. While this was possibly the most entertaining option, it, like many of the initial concepts, ended up violating competition regulations.

Finally, there were many ideas proposed that involved a bucket. An example of this included having the bucket go to the ground to be part of the digging mechanism. A separate proposal was to manipulate the bucket to pass underneath the collection unit at a position that allowed the collection mechanism to empty its contents; this would allow the robot to perform multiple cycles of the excavation protocol within the mining area. There was also the option to have a stationary bucket. Each of these bucket designs would have the ability to rotate to dump into the collection bin. The dumping option selected for the robot will be covered in the Methodology section bellow.
Drivetrain

Caterpillar treads and wheel drivetrains were investigated. Treads worked well, as observed in past robots, but could be clogged with basalt in a manner similar to the conveyor belts. They are also a bit restricted in motion and weight. The team then looked into wheels and looked at the advantages of having four or six and having all or some driven. Four wheels would allow for less weight, and though unlikely, the robot could during this competition get stuck in a whole or land on a large rock where no wheels could touch the ground. Six wheels would help to mitigate this, but would make the robot significantly heavier and more cluttered. The option of having the back wheels driven would mean that the direct torque of the motor and gearbox could be placed directly on the wheel instead of having a transfer system between them. Having all the wheels driven means there needs to be chains connecting motors and wheel shafts, but the robot can turn fast and sharp.

Wheels

The wheels went through many concept iterations. Beginning with wide scale research of commercial options, it was quickly discovered that the market was unlikely to provide an option that was the correct size and weight, all while economical and within the competition’s regulations. The rules state that wheels can not have air or foam in them. Commercially the other option is to have solid rubber or plastic tires which are too heavy to work for this competition.

With the inability to locate an off-the-shelf option that fit all criteria, the team moved to designing a customized set of wheels. Inspiration from the wheels of Curiosity and other Martian
robots, influenced the team to design a skeletal structure that could be either 3D printed or laser cut out of acrylic then assembled manually. After looking into the 3D printing of the wheels it was found out that each wheel would cost between $70-$120. That was too much for the team to spend on the project, so 3D printing was not considered henceforth.

**Electrical**

The electrical components of the robot underwent minimal evolution over the life of the project. This was due to the timing between the final rendition of the mechanical design and the decision process of the electrical requirements. Since the team designed the mechanical constraints before fully examining what would be needed electrically, the team was able to streamline the decision and design process for the electrical features of the robot.

In original designs, the components were to be manipulated by a winch system. These motors would originally move the diaphragm grabber and bucket into position while collecting material. While powerful, the current necessary to use the winches was calculated to be about 24amp constant draw and in the shifting of designs, the need for moving the bucket became unnecessary.

**Computers, Programming, and Sensors**

The software design began with a few simple flowcharts of how the robot needed to operate. These yielded the requirements for both the hardware and software. From this, the basics of the code were formed for movement, digging, and orientation.

The team considered the Beaglebone Black for its strong processing power as compared to the original Raspberry Pi. The Beaglebone has more than enough GPIO pins to manage basic
sensors, along with 512MB of RAM and 2GB of storage; the Beaglebone had far greater processing power and would have greater capability to do image processing and other high intensity programs. However, with the release of the Raspberry Pi 2, the Beaglebone falls behind in processing power. The Beaglebone also only contains one USB port as compared to four on the Pi 2, which would limit our sensor options.

An Arduino was considered for use in addition to a primary computer. The Arduino Uno has the capability outputting PWM signals to multiple devices. While the Uno was not the most powerful in terms of processing, it would have functioned well as a PWM controller but was not selected in favor of utilizing the CAN busing available on the RoboRIO. Using CAN meant less wiring had to be done and that there was greater control over the speed of the motors.

When determining sensors for use in the robot, an accelerometer was considered as it would allow the team to know the orientation of the robot. By zeroing the sensor at the start of the match, the team would be able to determine their changes in direction and know if the robot was thrown off balance. While the information would have been useful to understanding the position of the robot, the team decided that an orientation algorithm based on image processing and odometry would have been more effective as they would give more accurate and direct data.
Methodology

Digging Mechanism

Auger designs were considered very early on the brainstorming process. However, research indicated them to be too heavy for successful implementation. Additionally, concerns were raised about the limitations placed on the robot’s carrying capacity with such a design. This design analysis was based on the concept of using a one-tooth auger that pushed material up a single tube. However, a Troy-Bilt snow blower, see Figure 4, was discovered that utilized a three stage auger allowing for greater excavation capabilities in addition to a hopper system that provided a simple method of redistributing material to a collection bucket. This design was taken and pursued as a feasible method of excavating regolith, with modifications made to allow for operation within the parameters of the competition.
After reaching out to Troy-Bilt, the team received a donation of a snow blower to integrate into the robot. The front auger and enclosure were removed from the snow blower and the combustion engine. Next, the snow blower’s combustion engine needed to be replaced by an extraterrestrial-feasible solution. An electric motor system capable of similar RPM and torque provided by the combination of a Banebots motor and gearbox were selected for their ability to operate at the necessary speeds and torques at peak efficiency. They were mounted on the casing of the auger. This allowed the auger itself to be the support system for holding the motor and
when the auger moves on its suspension, the drive belt always stays taut between the auger and the motor.

The auger was connected by a small slide and spring system to the robot, allowing for a suspension system. The auger is kept at a stationary height and the mining is based on the movement direction of the robot. To mine, the robot drives in reverse with the auger running, and to go to the excavation area and back to the collection bin, the robot maneuvers with the dumping bucket forward.

The last modification was to remove the spout. The new electric motor did not have as much speed as the original motor, so the mining material does not fly into the bucket. The material does still fly out of the opening far enough to be caught in a smaller transfer bucket. This bucket is shaped so that when it rotates to dump into the main bucket of the robot, the material falls out only into the bucket and not onto the robot, even though most of the transfer bucket is out of the main bucket.

To drive the auger, the necessary speeds and torques had to be found. While the actual speeds and torques of the snow blower motor were never found, by utilizing a variety of readily available resources for other types of snow blower motors and comparing them to the type of motor in the original snow blower donated by Troy-Bilt, it was determined that the motor to be used would need a torque of around 14.4 ft-lbs while running at 3600 RPM. An electric motor replacement, the RS550, was found, using Figure 5, to have sufficient torque and speed when used in conjunction with a 64:1 gearbox. This combination was able to output 14.1 ft-lbs of torque while running at 7720 RPM and 18.8 ft-lbs at 3860 RPM. The motor’s small size also made it ideal for mounting on the snow blower.
The motor calculations of the snow blower are included in Figure 5. The figure shows the effectiveness of the motor when driven through a 64:1 gearbox. The speed, torque, current, power, and efficiency can all be seen in relation to the torque of the motor. The graph shows that, at good efficiency where the dotted vertical line is, the motor can drive at 230 RPM to dig fast enough to gather material while maintaining enough torque, approximately 19 ft-lbs, to rotate the auger and dig into the material.

![Graph showing the effectiveness of the RS550 Motor](image)

*Figure 5: Analysis of the RS550 Motor*

**Dumping Mechanism**

A collection bucket was selected as it allowed the robot to collect a large amount of material while maintaining a sizable area for motors, computers, and other necessary components underneath it. A bucket moved by a linear actuator proved most reliable as it required fewer
moving components and provided the robot with the ability to position the bucket directly above the collection bin while unloading its contents into the collection trough. The center of mass was monitored closely during this portion of the design process to minimize the risk of the robot tipping during the actuation of the bucket. A linear actuator was chosen to manipulate the bucket as it is the most efficient mechanism, with regard to force/power limitations, for the task.

**Drivetrain**

The chosen drivetrain for this robot consisted of four driven wheels. There are two Banebots FIRST CIM motors mounted to Banebots P80 16:1 gearbox with two sprockets on each motor-gearbox system to run one chain to each wheel. This makes four separate chains to allow for maximum tooth to chain contact.

**Wheels**

The final design of the wheels consisted of two ten inch diameter laser cut circular acrylic disks, with a keyed hole for the axle, connected by a series of eight acrylic paddles as shown in Figure 6. The wheels are four inches wide each and they were held together using Epoxy. This design allowed the robot to travel over compact surfaces, such as concrete or grass, using the wheel walls as well as in loose surfaces, such as sand or snow utilizing the paddles.
The wheel design that was chosen for the robot was simulated in SolidWorks to determine a single side of a wheel would undergo a maximum von Mises stress of $3.549 \times 10^7$ (N/m$^2$), if the mass of the fully loaded robot, including collected regolith, (over-estimated to be 200kg) were to be set on that one wheel. The yield strength of acrylic is calculated to be $4.5 \times 10^7$ (N/m$^2$). This created a safety factor of ~5 when using four wheels. As a result of these simulations, the robot was then fitted with four of these customized wheels. The simulation results can be viewed in Figure 7 and the simulation report can be found in the archived folder.
Figure 7: Wheel Wall Stress Simulation

Electrical

The final design for the robot consisted of a battery, five motors, a linear actuator, six Talon motor controllers with encoders, emergency cutoff switch, and the required data logger. The battery is connected to a power distribution panel to allow for the current to be safely distributed to all of the components. The wheel motors were selected by determining the amount of torque required for moving a robot at the maximum weight of 80 kg with a maximum load of 100 kg for an overestimation of 200 kg. With this mass and a wheel diameter of 10 inches, it was approximated that a motor would need to be able to output a constant torque of 110 in-lbs. Using this, the Banebots For Inspiration and Recognition of Science and Technology (FIRST)
Controlled Industrial Motor (CIM) motors were selected as they had the necessary power while using a 16:1 gearbox to drive the robot while operating at the motor’s optimal power draw. The linear actuator and motors for operating and lifting the auger were chosen in similar manners, utilizing the maximum load they would need to apply.

It was calculated that, using a gearbox with a 16:1 gearing ratio, the amount of torque the motor would need to produce was reduced to 110 oz-in. The CIM motors were selected as they had a torque output of 173 oz-in at maximum power and a stall torque of 347 oz-in, as seen in Figure 8, keeping well within safe operation. The use of a gearbox made for this type of motor also ensured that the motor would be able to effectively operate under the given conditions. Beyond torque and speed, the motors were also light enough for use in the robot while also being heavy enough to act as counterweights to maintain the robot’s center of mass.

The use of a twelve volt lithium iron phosphate, or LiFePO4, battery allowed for a reduction in weight while maintaining a high current, while being safer than the standard lithium phosphate battery. Twelve volts also meant that the team could use more commonly available components, as the vast majority of commercially available motors and linear actuators utilize twelve volts for operation. The battery itself was purchased from BatterySpace as it had 60 amp-hours of energy storage and was tested for up to 100A.
The motors for driving were found to pull the most current of all the components, pulling a total of 60 Amperes while driving with maximum weight. Using this, a 12 volt, lithium iron phosphate battery was found with a current capability of up to 100 Amps and 60 amp hours, which would be enough to drive the robot for at least two full runs. The battery is fed through the emergency stop button so that power can immediately be cut if necessary. Before the distribution panel, the data logger will also be in place to record all the power used during operation, as seen in Figure 9.

Figure 8: Performance Graph of CIM Motor
The robot also has a small computer consisting of a Raspberry Pi and its sensors. This will include the strain gauge used to determine the amount of material in the bucket and the infrared sensor to determine the proximity to the bucket while dumping. These components will all be powered together. An emergency stop button, attached to the top of the robot, is set to cut all power to the robot when compressed.

Computers, Programing, and Sensors

After considerable lobbying on the part of the Graphically Represented Image Processing engine (GRIP) MQP team and their pledged support throughout the project’s software development, the team elected to include the National Instruments RoboRIIO in the list of computing devices. It was also determined that the Raspberry Pi would be utilized for computing
and Talon motor controllers due to their ease of use with the RoboRIO and encoders. Software tools included the Java programming language, the Python programming language, the GIT source control program, GRIP Imaging software for computer vision, and the Eclipse IDE for its numerous plugins to speed up programming of the RoboRIO.

The team decided to use the Java programming language for development on the RoboRIO for several reasons. First, the language is platform independent and should be able to run on any OS with the Java Runtime Environment installed. Second, Java allowed for software development on any platform. This was found to be immediately useful when Microsoft Windows was required to image the RoboRIO but the RoboRIO itself was a Linux board. Third, the RoboRIO supported Java and, most importantly, the GRIP software was written in Java.

The team elected to utilize GIT for source code control. This was mainly due to GIT being the source control software that the team had the most experience with. It was also noted how useful GIThub would be in allowing different team members to program on multiple platforms together and to upload the code to the RoboRIO and Raspberry Pi.

The decision to use Python was due to the massive support provided by the Raspberry Pi community. Given that the Pi would be the device doing most of the image interpretation for the robot’s navigation, it was determined that it would be beneficial to use a heavily supported language on the device.

In addition to the Raspberry Pi assisting with navigation, it was also decided that it could be used for interpreting other sensor readings and communication back to the driver station. The sensors included a strain gauge, a camera, encoders, and potentiometers. The strain gauge was designated to determine the amount of material collected by sensing the change in bending of the
bottom of the bucket. The encoders and potentiometers were for determining the position of the wheels, bucket, and auger by measuring the change in position from rest.

The combination of a RoboRIO and Raspberry Pi is designed to allow for simultaneous control of actuation and sensor reading. The robot determines its position based on two color designated bars to be placed behind the bucket. This information is pulled from an on-board camera into the Raspberry Pi. With the GRIP software, the Raspberry Pi determines the robot’s relative position in the field by observing the apparent change in height of the bars and comparing the observed heights to their known height. The exact formula for this, as seen in Equation 1, utilizes the constants of camera focal length, image size, sensor size, and actual object size to determine the relative change in size of an object. This comparison gives an approximation of distance from each bar. Using the distance from the bars and knowing the distance between them, the robot can use simple trigonometry to get an approximate planar coordinate on the field and send that information to the operators at mission control.

The system will use the information provided by a strain gauge mounted on the bottom of the bucket to extrapolate the current mass of our payload. This will be accomplished by taking near constant measurements from the strain gauge and averaging this data to determine when the payload is nearing its maximum weight capacity. The data are averaged to ensure that the large impulses in strain due to the impact of material against the bucket do not alter the behavior of the autonomous system. The auger will stop digging when the information from the strain gauge indicates that bucket has reached maximum capacity. The robot will then move into position for unloading the contents into the collector bin, using an infrared sensor to determine the distance between the robot and its target. The linear actuator will maneuver the bucket into its dumping position while a potentiometer monitors the position of the bucket. Another potentiometer is used
on a servo attached to the camera used for the orientation algorithm seen in Equation 1. While the camera allows for the robot to find itself in a coordinate system, the potentiometer gives the robot an angle to add to the output sent to the operators. The orientation algorithm uses a red and a green marker on the back of the collection bin to orient the robot. By using Equation 1 and the GRIP software, the robot can determine the distance it is from the two distinctly colored markers, see Figure 10. By using those distances and the known distance between the markers, the robot can create a coordinate location of its position in the field. By using the angle data from the servo, the robot can also determine the orientation of the robot on the field. This data will then be sent back to the operators.

Figure 10: Orientation Algorithm Diagrams
A wireless router was used to manage communication between the driver station and the on-board computers. This would allow both the Raspberry Pi and the RoboRIO to communicate to each other and be reached separately. As both systems have Ethernet ports, there were no issues in connecting them to the router. The RoboRIO is programmed with a standard IP address and the Pi was given one itself to allow for easy connections.

To achieve partial autonomy, the team implemented three automated programs to simplify the operation of the robot. The dumping and mining operations need only a single button press to trigger the beginning or end of the respective cycles. The other autonomous function was the parallel operation of the intermediary system, which autonomously ran during the digging operation to transfer material into the main bucket from the snow blower auger.

Outreach

As a part of the requirements for competing in the Robotic Mining Competition, the team has organized an outreach event with Needham High School and its robotics program. The school has recently created a robotics curriculum to educate students in the ever growing field of robotics. The team intends to visit the high school on May 12th to talk about the various opportunities available in the field of robotics by discussing current projects in the world, particularly focusing on past and ongoing projects by NASA. The team also intends to bring example projects from WPI to display the types of projects they have worked on and to demonstrate the experiences one might find at a university level. The school has also recently

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L_x (\text{mm}) = \frac{\text{constant focal length (mm) \cdot constant real height (mm) \cdot pixel height of image (px)}}{h_x (\text{px}) \cdot \text{constant sensor height on robot (mm)}}
\]
created a FIRST Robotics team. The MQP team hopes to assist the high school robotics team by giving advice and guidance in design and programming aspects with the hope of promoting engineering ideas and concepts.
Results and Conclusions

At the conclusion of this project the team has demonstrated the capabilities of the fully assembled robot. The wheels successfully supported the fully loaded robot through operation on both compact and malleable surfaces. However, the coefficient of friction was low enough between the acrylic and surfaces such as concrete that a more adhesive substance will need to be added for locomotion. The CIM motors easily powered the robot through sand via the customized wheels. The snow blower successfully collected sand and rocks which was then successfully transferred into the on-board bucket powered by the linear actuator. All of the on-board processes were managed from the driver station software running on an external computer. The operator utilized an XBox360 controller to dictate commands to the driver station software. In conclusion, the team accomplished their goals of designing a robot unprecedented by the competition, minimizing bandwidth usage during operation, and instilling partial autonomy to manage operations aboard the robot.
Future Work

The team hopes that the robot can be used and improved upon for future competitions. The first idea the team would like to see improved upon would be an improved auger system. The current design of the auger directly uses the entire piece from the Troy-Bilt system. In future designs, the team would hope to see a more maneuverable system capable of digging for the ice simulant. This would improve the robot’s ability to mine and gain far more points in the competition. This would also reduce the weight of the robot, provided the auger could be held together without the use of its surrounding components.

Another feature for future improvement would be to expand the robot’s abilities to full autonomy. Currently, the robot utilizes partial autonomy to control its dumping and digging actions. In future iterations, the robot should be able to run more autonomously, utilizing the orientation algorithm and odometry to navigate the field without input from the operators. This could be done to many levels, such as functioning autonomously for the full time, or simply moving from the starting area to the digging area and begin digging.

The team hopes to involve community work in future iterations of the project. The team will be heading to Needham High School to promote interest in the field of robotics, in particular NASA’s current programs and projects in robotics. The team will also present students with examples of WPI robotics projects so as to give them a sense of what college level robotics programs. The high school has also recently created a FIRST robotics team. The MQP team plans to advise the team in the building and programming of their own robot.
Table of References


