ESCUELA TECNICA SUPERIOR DE INGENIERIA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

PROYECTO FIN DE CARRERA

NASA Mining Robot (EN)

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Director: William Finch

Madrid
Julio 2018

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NASA MINING ROBOT

Autor: Atienza Lama, Gonzalo.
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Entidad Colaboradora: Colorado School of Mines.

RESUMEN DEL PROYECTO

INTRODUCCIÓN

En el año 2001, gracias a la exitosa misión ‘Mars Odyssey’ enviada por la NASA, se descubrió la existencia de hielo bajo la superficie de Marte. Este descubrimiento llevó a la NASA a pensar que dicho hielo podría ser utilizado como recurso para futuras expediciones. En 2009 la NASA creó una competición para universidades en la que cada universidad debía construir un robot cuya tarea sería recoger hielo en unas condiciones similares a las de la superficie de Marte. La universidad Colorado School of Mines, donde se realizó el proyecto, lleva participando 4 años en dicha competición.

Cada año, para hacer la competición más interesante, la NASA añade nuevas reglas para que los robots tengan que ser rediseñados. Una de las nuevas reglas añadidas este año a la competición establece que, durante la competición, la sustancia que simula al hielo (llamada de aquí en adelante “icy regolith”) que se ha de recoger no se encuentra en la superficie, sino que se encuentra enterrada 30 cm bajo la tierra (llamada también BP-1).

Este año, un equipo de 8 alumnos estaban encargados de construir el robot que iría a la competición. Para construir el nuevo robot se partió del robot del año pasado y se modificó para cumplir con las nuevas reglas impuestas por la NASA.

Para facilitar el trabajo en el robot, se dividió el proyecto en 3 subsistemas: el mecánico, el eléctrico y el de autonomía. El alumno fue nombrado líder del subsistema eléctrico, aunque también trabajó y ayudó en los otros subsistemas.

OBJETIVOS

Los objetivos de este proyecto son 3, uno para cada subsistema. El objetivo del subsistema mecánico era el de diseñar un nuevo sistema de excavación que fuese capaz de excavar 30 cm bajo tierra (BP-1) y conseguir recoger el “icy regolith”. El objetivo del subsistema eléctrico era el de diseñar un nuevo circuito de distribución de potencia y el de desarrollar el control manual del robot. El subsistema de autonomía tenía como objetivo desarrollar e implantar los algoritmos necesarios para que el robot fuese capaz de cumplir con los objetivos de la competición sin necesidad de utilizar el control manual en ningún momento.

METODOLOGÍA

Subsistema Mecánico

Debido a la nueva norma impuesta por la NASA, el diseño de un nuevo sistema de excavación adquirió mucha importancia desde el inicio del proyecto. Los primeros pasos del proceso de diseño fueron crear y testear 3 diferentes prototipos: el sistema utilizado el año anterior, un taladro y una draga de rosario.

El diseño del robot del año pasado incluía una única pieza que actuaba como sistema de excavación y como sistema de almacenamiento al mismo tiempo. Dicha pieza puede verse en la imagen 1.

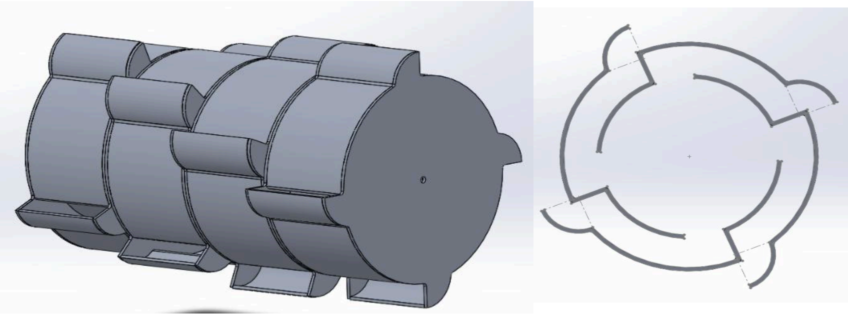
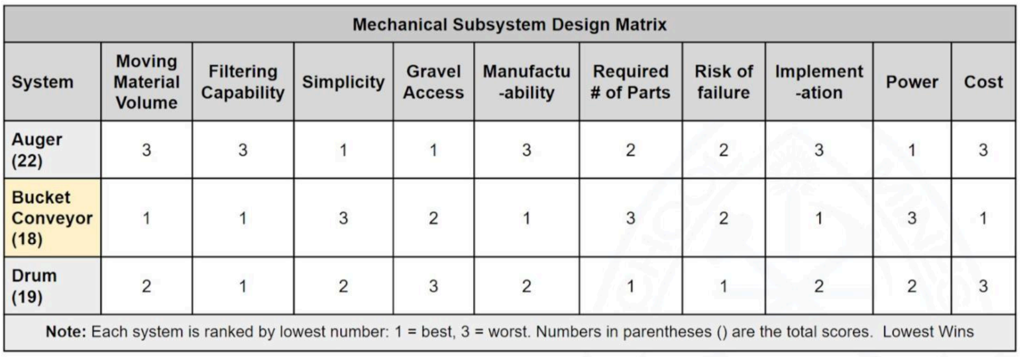


Imagen 1: Sistema de excavación diseñado para el robot del año 2016-2017

Una vez los 3 prototipos fueros testeados, una tabla de decisión (tabla 1) fue creada para decidir cuál era la mejor opción. El resultado mostró que el diseño más efectivo era la draga de rosario.



Mechanical Subsystem Design Matrix										
System	Moving Material Volume	Filtering Capability	Simplicity	Gravel Access	Manufactu-ability	Required # of Parts	Risk of failure	Implement-ation	Power	Cost
Auger (22)	3	3	1	1	3	2	2	3	1	3
Bucket Conveyor (18)	1	1	3	2	1	3	2	1	3	1
Drum (19)	2	1	2	3	2	1	1	2	2	3

Note: Each system is ranked by lowest number: 1 = best, 3 = worst. Numbers in parentheses () are the total scores. Lowest Wins

Tabla 1: Tabla de decisión para el sistema de excavación

Una vez el sistema de excavación fue decidido, el sistema de filtrado, el sistema de almacenamiento y el sistema de bajada tuvieron que ser diseñados. El sistema de filtrado acabó siendo una especia de tolva rodeado por una malla metálica, de tal manera que el “icy regolith” chocaba contra la malla y continuaba hasta el sistema de almacenamiento. El sistema de bajada estaba constituido por un gato de un coche que estaba unido por una pieza de aluminio a la draga de rosario. Finalmente, el sistema de almacenamiento constaba de 2 piezas, un cubo donde se depositaba el “icy regolith”, y una cinta transportadora (situada verticalmente) que conectaba el cubo con la salida de la tolva (sistema de filtrado). El diseño final con todos los sistemas mencionados anteriormente puede verse en la imagen 2.

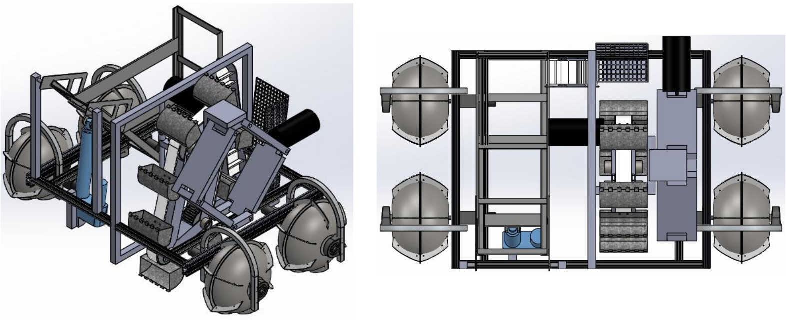


Imagen 2: Diseño final subsistema mecánico. Vista isométrica (izquierda) y vista superior (derecha)

Subsistema Eléctrico

Lo primero que se hizo en cuanto se comenzó el proyecto fue analizar el circuito que estaba implantado en el robot, observando algunas cosas que debían ser cambiadas de inmediato. El circuito utilizado el año anterior estaba muy desorganizado y no se sabía qué estaba conectado a qué, de manera que, si algún cable se desconectaba, sería muy difícil averiguar dónde debía estar conectado. Otra cosa que se observó fue que existían muchos puntos de soldadura que estaban empezando a deshacerse.

Debido a estas razones se decidió diseñar un nuevo circuito de distribución de potencia, haciendo los cambios que se consideren oportunos para el mejor funcionamiento del robot. El nuevo circuito puede verse en la imagen 3. En este nuevo circuito se han sustituido los 5 Arduinos que utilizaban el año anterior por un Intel NUN y una Raspberry Pi 3. Para el control de los motores, se han utilizado 4 Roboclaws; cada Roboclaw es capaz de controlar 2 motores, y todas las Roboclaws son controladas por la Raspberry Pi utilizando el protocolo de comunicación UART.

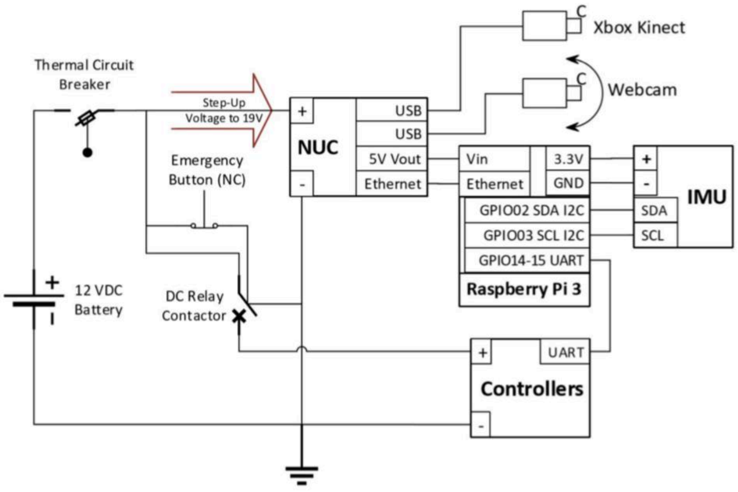


Imagen 3: Circuito de distribución de potencia

A la hora de implementar el circuito, algunos problemas aparecieron debido a la configuración de las Roboclaws, creando un retraso entre las ruedas del robot. Dicho problema se solucionó fácilmente reconfigurando las Roboclaws. El resto de la implementación del circuito se realizó sin que apareciera ningún problema más.

Subsistema de Autonomía

El trabajo del equipo del año anterior en la autonomía del robot fue muy bueno, pero no tuvieron suficiente tiempo como para terminarlo e implantarlo. Este año se continuó el trabajo heredado del equipo anterior, desarrollando el algoritmo de planificación de ruta (Algoritmo A*) y mejorando el cálculo de la posición relativa del robot (utilizando los algoritmos SLAM).

Este año la idea era la de utilizar una cámara Kinect para la detección de obstáculos y una cámara web y un IMU para la obtención de la posición del robot dentro de la arena de competición. Con la información obtenida a través de estos dispositivos, se utilizaría la librería

OpenCV para crear un mapa cuadriculado, en el cuál se mostrará dónde están los obstáculos. Dicho mapa seria después mandado al algoritmo de planificación de ruta que calcularía la ruta más rápida hasta el objetivo.

Con el trabajo de este año se ha conseguido que el robot funcione de manera autónoma cuando está conectado al ordenador, sin embargo al pasar todo el código al NUC y conectarlo al ordenador vía Wi-Fi, aparecieron algunos problemas de compatibilidad entre el OpenCV y el software del NUC, por lo que se decidió no implantar la autonomía en el robot.

CONCLUSIONES Y RESULTADOS

Una vez el robot fue completamente terminado fue enviado a la competición donde sería probado por primera vez y se verían los resultados finales. Tras la competición se observó que el robot funcionaba perfectamente con el control manual, pero desafortunadamente, el robot no fue capaz de recoger "icy regolith" durante la competición. En el primer intento, se quemó un motor por lo que el "icy regolith" que se excavaba era devuelto al suelo, y, en el segundo intento, se perdió la comunicación con el robot debido a que las Roboclaws se resetearon en mitad del intento.

BIBLIOGRAFÍA

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NASA MINING ROBOT

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Director: Finch, William.
Collaborating Institution: Colorado School of Mines.

PROJECT SUMMARY

INTRODUCTION

Thanks to the successful mission called 'Mars Odyssey' sent by NASA in 2001, the existence of ice beneath the surface of Mars was discovered. This discovery made NASA believe that such ice could be used as a resource for future expeditions sent to this planet. In 2009 NASA created a competition for universities in which each university had to build a robot which task would be to collect ice in conditions similar to those on the surface of Mars. Colorado School of Mines, where the project was carried out, has been participating in this competition for 4 consecutive years.

Each year, to make the competition more interesting, NASA adds new rules so that the robots have to be redesigned. One of the new rules added this year to the competition states that, during the competition, the substance that simulates the ice (hereinafter called "icy regolith") that has to be collected is not on the surface, instead, it is buried 30 cm underground.

This year, a team of 8 students were in charge of building the robot that would go to the competition. To build the new robot, last year's robot was recovered and modified to comply with the new rules imposed by NASA.

To facilitate the work in the robot, the project was divided into 3 subsystems: the mechanical, the electrical and the autonomy. The student was named leader of the electrical subsystem, although he also worked and helped in the other subsystems.

OBJECTIVES

The objectives of this project are 3, one for each subsystem. The objective of the mechanical subsystem was to design a new excavation system that would be able to excavate 30 cm underground and manage to collect the "icy regolith". The objective of the electric subsystem was to design a new power distribution circuit and to develop the manual control of the robot. The main objective of the autonomy subsystem was to develop and implement the necessary algorithms so that the robot would be able to meet the objectives of the competition without having to use manual control at any time.

METHODOLOGY

Mechanical subsystem

Due to the new rule imposed by NASA, the design of a new excavation system became very important from the beginning of the project. The first steps of the design process were to create and test 3 different prototypes: the system used the previous year, a drill and a bucket ladder.

The design of last year's robot included a single piece that acted as an excavation system and as a storage system at the same time. This piece can be seen in image 1.

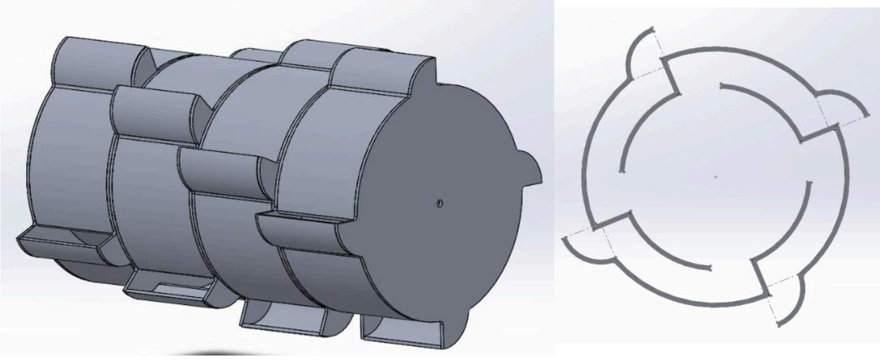
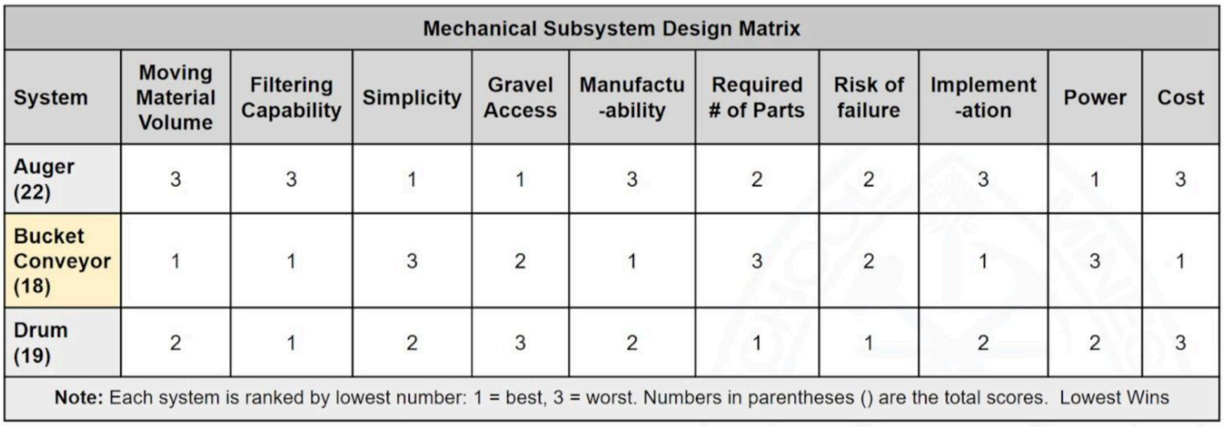


Image 1: excavation system used last year

Once the 3 prototypes were tested, a decision table (table 1) was created to decide which was the best option. The result showed that the most effective design was the rosary dredge.



Mechanical Subsystem Design Matrix

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Note: Each system is ranked by lowest number: 1 = best, 3 = worst. Numbers in parentheses () are the total scores. Lowest Wins

Table 1: Decision table for the excavation system

Once the excavation system was decided, the filtering, the storage and the lowering systems had to be designed and created. The filtering system ended up being a hopper surrounded by a metallic mesh, in such a way that the "icy regolith" would hit the mesh and continue to the storage system. The lowering system was a scissor jack united to the bucket ladder by a piece of aluminum. Finally, the storage system consisted of 2 pieces, a storage bin where the "icy regolith" was deposited, and a conveyor belt (located vertically) that connected the storage bin with the exit of the hopper (filtering system). The final design with all the systems mentioned above can be seen in image 2.

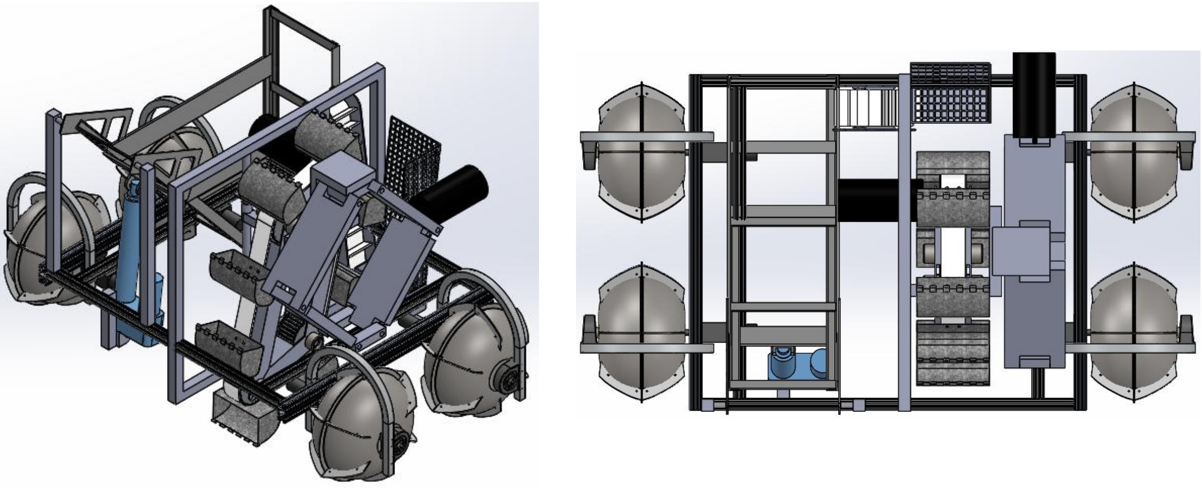

Image 2: Final design mechanical subsystem. Isometric view (left) and top view (right)

Electrical subsystem

The first thing that was done as soon as the project started was to analyze the circuit that was implanted in the robot, observing some things that had to be changed immediately. The circuit used the previous year was very disorganized and it was not known what was connected to what, so that, if a cable was disconnected, it would be very difficult to find out where it had to be connected. Another thing that was observed was that there were some soldering points that were starting to disasseble.

Due to these reasons, it was decided to design a new power distribution circuit, making some changes in order to make the robot work the best way possible. The new circuit can be seen in image 3. In this new circuit the 5 Arduinos that were used the previous year were replaced by an Intel NUN and a Raspberry Pi 3. The motor controllers were 4 Roboclaws; each Roboclaw is capable of controlling 2 motors, and all Roboclaws are controlled by the Raspberry Pi using the UART communication protocol.

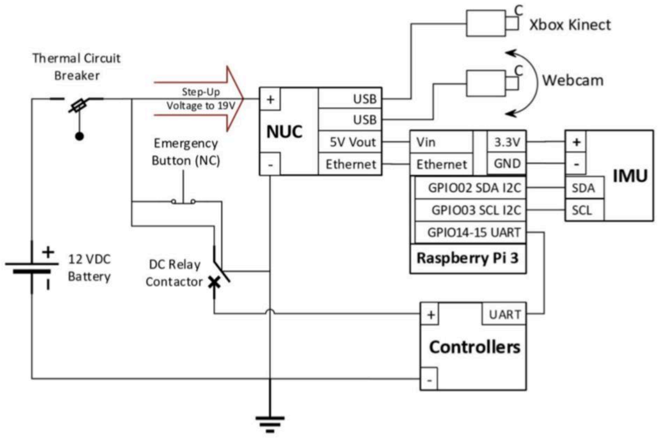

Image 3: Power distribution circuit

During the implementation of the new circuit, some problems appeared due to the configuration of the Roboclaws, creating a delay between the wheels of the robot. This problem was easily solved by reconfiguring the Roboclaws. The rest of the circuit implementation was carried out without any further problems.

Autonomy subsystem

The work of the previous year´s teams in the autonomy of the robot was very good, but they did not have enough time to finish and implement it. This year the work inherited from the previous team was continued, developing the path planning algorithm (A* algorithm) and improving the calculation of the relative position of the robot (SLAM algorithms).

This year the idea was to use a Kinect camera to detect obstacles and a webcam along with an IMU to obtain the position of the robot in the competition arena. With the information obtained through these devices, the OpenCV library would be used to create a grid map, which will show where the obstacles are. This map would then be sent to the path planning algorithm that would calculate the fastest path to the target.

With this year's work it has been possible for the robot to work autonomously when connected to the computer, however, when passing all the code to the NUC and connecting it to the computer via Wi-Fi, some compatibility issues appeared between the OpenCV and the software of the NUC. Due to this problem, it was decided to stop working on the autonomy of the robot and focus all the efforts in finishing the excavation system and the power distribution circuit.

CONCLUSION AND RESULTS

Once the robot was completely finished it was sent to the competition where it would be tested for the first time and the final results would be seen. After the competition it was observed that the robot worked perfectly with the manual control, but unfortunately, the robot was not able to collect "icy regolith" during the competition. In the first attempt, an engine was burned so that the "icy regolith" that was excavated was returned to the ground, and, in the second attempt, the communication with the robot was lost because the Roboclaws reset themselves in the middle of the attempt.

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1 INTRODUCTION

Since the end of the year 1957, a rivalry appeared between the United States of America and the Soviet Union. This rivalry, that took part during the Cold War, is also known as the “Space Race”, and lasted until 1975. During this period of time both countries invested a lot of money in space research, sending a huge amount of missions to space, to the moon and to other planets in the solar system.

During the years in which the “Space Race” was developed (1957-1975), great progress was made in space technology, eventually designing and building spacecraft capable of transporting living beings out of the Earth’s atmosphere. This was not the only achievement that was made, another important goal that was accomplished was to be able to send ships capable of landing on the surface of other planets.

At the time when the rivalry between the US and the USSR was beginning to lose importance, great interest was acquired on planet Mars. Such was the interest that both countries had in the exploration of Mars, that between the year 1960 and today more than 40 missions have been sent to Mars. Of all the missions sent to the red planet, approximately 53% have failed, either at take-off or during the trip. On the other hand, successful missions have been very useful and have been key in the important discoveries made on the Martian surface. Some of these missions are the following:

- 'Mariner 4' (1964): First successful mission sent by the USA
- 'Mariner 9' (1971): helped making the first map of the surface of Mars
- 'Viking 1' (1975): First American spaceship that successfully lands on Mars
- 'Mars Odyssey' (2001): Thanks to this mission, the existence of ice under the Martian surface is discovered
- ‘Curiosity’ (2011): discovers the existence of organic molecules on the surface of Mars

Due to this latest discovery, in 2009 NASA decided to create a competition for American universities in which each university had to create a robot capable of collecting ice under conditions similar to those of the Martian surface. The university Colorado School of Mines, where the project is being carried out, has been participating in this competition for at least 4 years, assigning the project to design and assemble the robot to a group of 8 students.

The student will be part of the team assigned to the competition that takes place between May 14 and 18, 2018. This document presents the work done by the student in this project throughout the academic year, briefly explaining the work of their colleagues when necessary to facilitate the understanding of the project.

2 STATE OF THE ART

As mentioned in the previous section, more than 40 missions have been sent to Mars. Unfortunately, more than half of those missions failed during take-off or during the journey from Earth to Mars. However, thanks to the missions that were successful, incredible discoveries have been made on the Martian surface. Some of the most important missions sent by NASA are mentioned below.

The 'Mariner 4' mission was the first successful mission sent by NASA. This spaceship was sent in 1964, getting to be located at 9,800 km from the surface of Mars and sending 21 black and white photos of the red planet.

The first American mission that managed to orbit around Mars was the spaceship 'Mariner 9', sent in 1971. The first map of Mars could be made thanks to the almost 7,500 photos it took of the Martian surface.

In 1975 NASA successfully landed a spacecraft on the surface of Mars, this spaceship is the 'Viking 1' probe. This probe was in operation for just over 6 years before it broke down and communication was lost.

In 1997 the rover 'Sejouner' was sent aboard the 'Mars Pathfinder'. In this mission, the first self-propelled rover was successfully sent to Mars. This rover was able to send around 17,000 photos of the Martian surface in addition to performing chemical analyzes on rocks.

In 2001 NASA discovers the existence of ice beneath the surface of Mars. This discovery is made thanks to the 'Mars Odyssey', which was sent with the goal of making a map showing the distribution of minerals on Mars´s surface.

The 'Curiosity' rover, sent in 2011, confirms the existence of ice under the Martian surface in addition to finding evidence of the existence of organic molecules on Mars.

Concerning the competition, the university where the project is being carried out has been participating for 4 years. Every year the robot designed the previous year is recovered and modified to satisfy the new rules imposed by NASA. In the 4 years that the university has been competing, no team has been able to excavate and collect the ice simulant.

3 COMPETITION RULES

In this Section some of the most important rules will be shown. All these rules suppose limitations when designing the robot. Each year NASA adds some new challenges, making the competition harder, so the new teams in charge of the robot have to redesign the robot.

Before saying the rules and challenges it is important to clarify 2 terms that will be used throughout the whole document. We have to distinguish between BP-1 (or regolith) and gravel (or icy regolith). The BP-1 (Black Point-1) is the substance that will be used in the competition for simulating the surface of Mars; on the other hand, the gravel is the substance that will be used in the competition for simulating the ice.

The most important challenge that was added for this year's competition was that the icy regolith (gravel) that has to be collected is placed 30 cm beneath the surface. Another new rule was that, while last year both the BP-1 and gravel counted in order to score, this year the amount of BP-1 collected is worth 0 points.

Although the rest of the rules are the same as in the previous years, it is important to remember them, as most of them will affect the design of the robot. The most important rules for the competition are the following:

- Each competition team will be required to perform two official attempts of 10 minutes
- The mining area consists on 30 cm of BP-1 placed on top of 30 cm of gravel
- In order to score, a minimum of 1Kg of gravel must be deposited on the collector bin
- Only the gravel deposited on the collector bin will be weighted
- The robot weight must not exceed 80 Kg
- The mining robot must be contained within 1.5 m length x 0.75 m width x 0.75 m height

The arena where the competition attempts will take place is divided in 3 different zones or areas, the starting area, the obstacles area and finally the mining area. At the start of each attempt the robot will be paced in a random position inside the start zone and will have to go to dig on the mining area avoiding the obstacles that are placed on the second zone. An image of the competition arena can be seen in image 1. The robot is only allowed to dig on the third zone (mining area) and will have to go back to the starting zone in order to deposit the gravel in the collector bin.

Also we can see the distribution of the BP-1 and the icy regolith in image 2 in the next page.

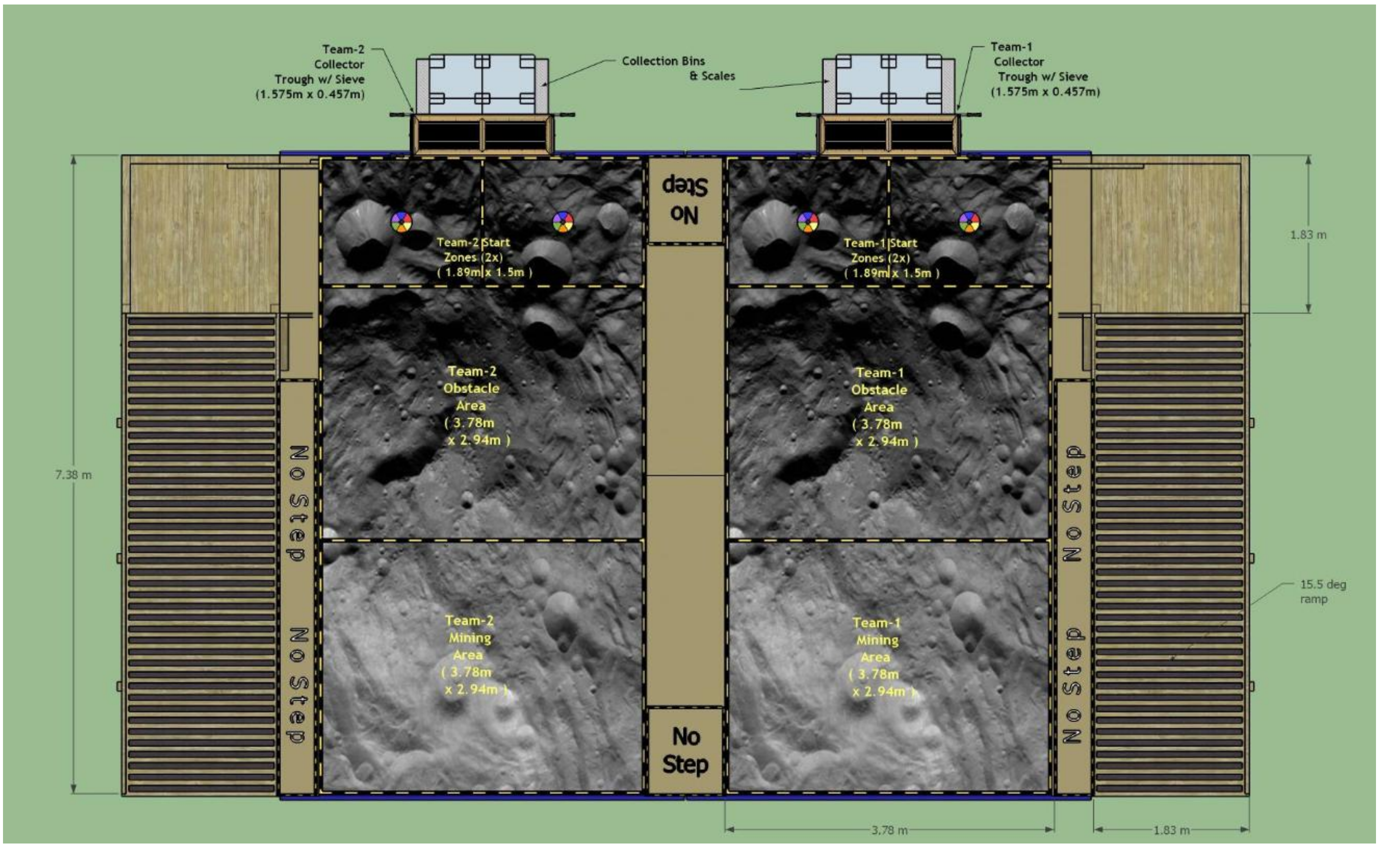


Image 1: Competition Arena

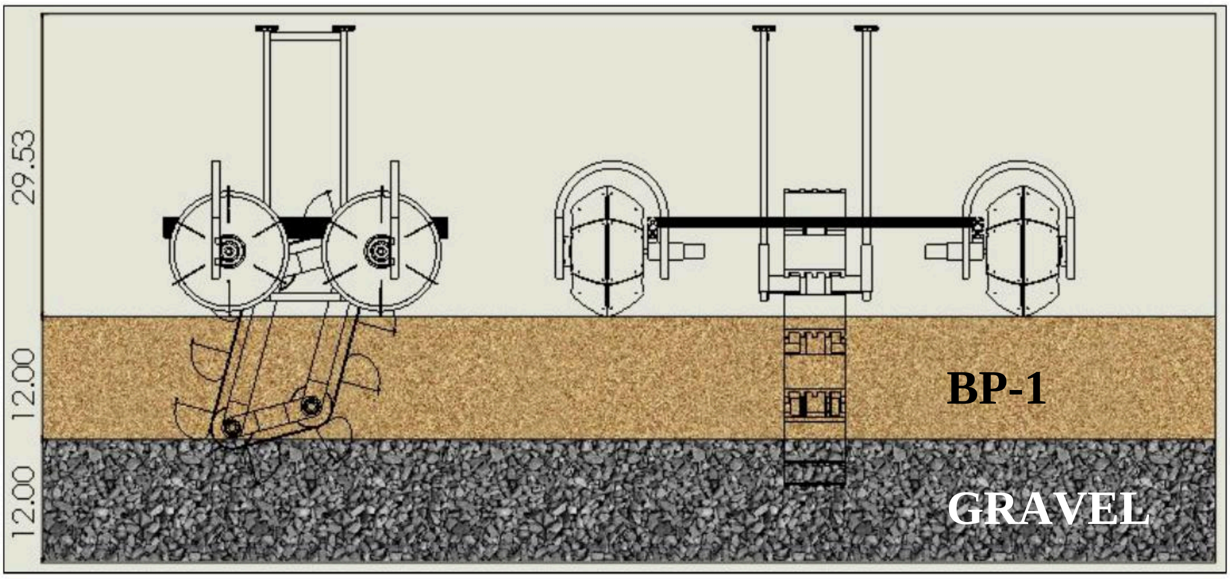


Image 2: Distribution of the BP-1 and the gravel in the Competition Arena (dimensions in inches)

4 OBJECTIVES

As stated on the previous section, the major challenge this year is that the icy regolith is buried 30 cm beneath the surface, in order to be able to collect this icy regolith almost the entire robot will be redesign. From the design used last year, only the main frame and the wheels will be reused, the rest of the parts will be redesign from scratch. The main objectives for this project are the following:

1. *Design and implement a new excavation system able to collect the icy regolith.*

   With the new challenge that was added, the excavation system will be redesign and it will include a lowering system so the robot can collect the icy regolith which is located beneath the surface. Before building and implementing a new excavation system, the system used last year will be analyzed very carefully in case some parts of it can be reused. Besides the lowering system, a filtering system will also be design and implemented into the excavation system.

2. *Design and implement a new power distribution circuit.*

   The first impression when seeing the robot from last year was that the circuit that was being used was not in very good conditions; There were some connections that were starting to fail as well as some soldering points that were starting to disassemble. Also, last year´s design used 5 Arduinos for controlling the movement of the robot. The main objective is to disassemble the whole circuit and redesign everything again. Some changes to make in the circuit are the following:

   - Substitute the Arduinos with a Raspberry Pi and a NUC
   - Change all the wires with new ones
   - Redesign and build a new electrical box
   - Redesign the emergency stop button circuit avoiding soldering points

3. *Develop the autonomy of the robot as much as possible and try to implement it.*

   This is the most difficult objective to achieve, last year´s team did a very good work developing the autonomy, but, unfortunately, it did not work the way it was supposed to work. In order to complete this objective, the code from last year´s team will be revised and modified. If necessary, new algorithms for path planning and obstacle detection will be coded. However, if the deadlines for this objective are not met, both the student and the team will stop working on this objective and focus more on the other objectives.

5 PREVIOUS DESIGNS

In this section I will briefly show and discuss the robot built 2 years ago and the robot built last year.

The robot used 2 years ago can be seen in image 3. As we can see in the image it consists on 3 moving parts apart from the wheels. These three parts are the bucket ladder, the conveyor belt and the storage bin. 2 years ago they only had to collect regolith, so they did not need a lowering system. This robot collects the regolith that is on the surface with the bucket ladder and drops it on the conveyor belt, then the conveyor belt moves the regolith and throws it into the storage bin. In this robot the electrical box with all the electronic components is located underneath the conveyor belt. Lastly, we can see that this robot was already using the salad bowl wheels that we will use this year.

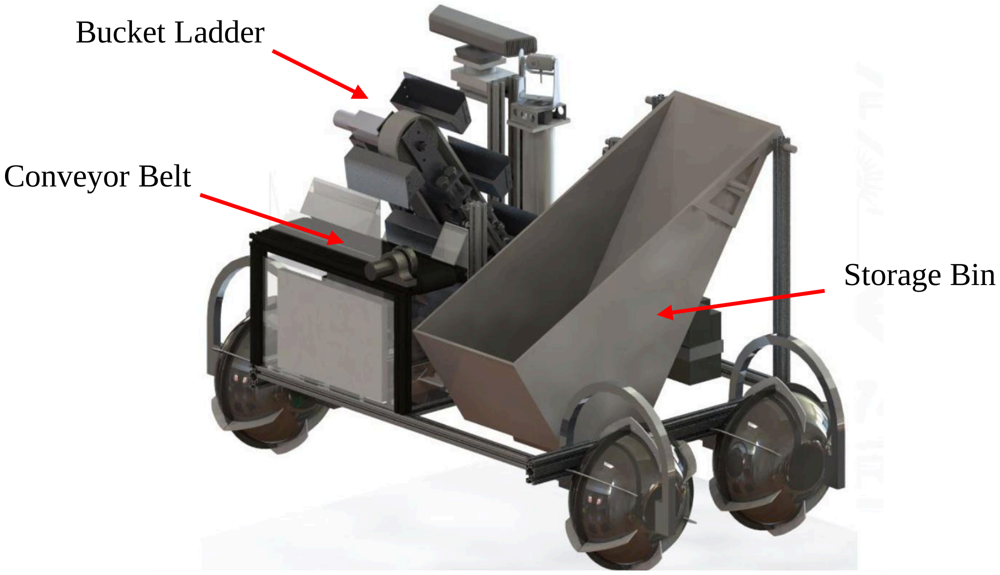


Image 3 : Robot from 2015-2016

The Robot from last year´s team reused the main frame and the salad bowl wheels from the robot shown in image 3. The robot designed and built for the 2017 competition is shown in image 4. For the 2017 competition both the gravel and the BP-1 were mixed on the surface and they both were worth points. Last year´s team decided to build only 1 moving part that would work both as the excavation system and as the storage bin. This system is shown in image 5 in the next page.

The excavation system used last year work in such a way that if it turns clockwise, this system will collect the gravel and the regolith, whilst, if it turns counterclockwise, it will empty the bucket drum depositing the gravel and regolith that was inside into the official collector bin. This robot also uses the salad bowl wheels. Also, the electrical box is now placed on top on the wheels.

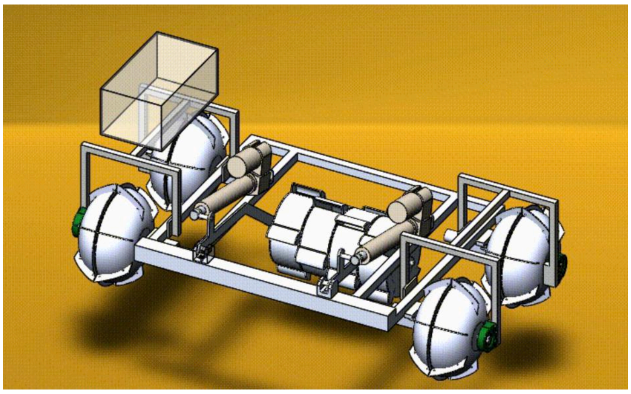


Image 4: Robot from 2016-2017

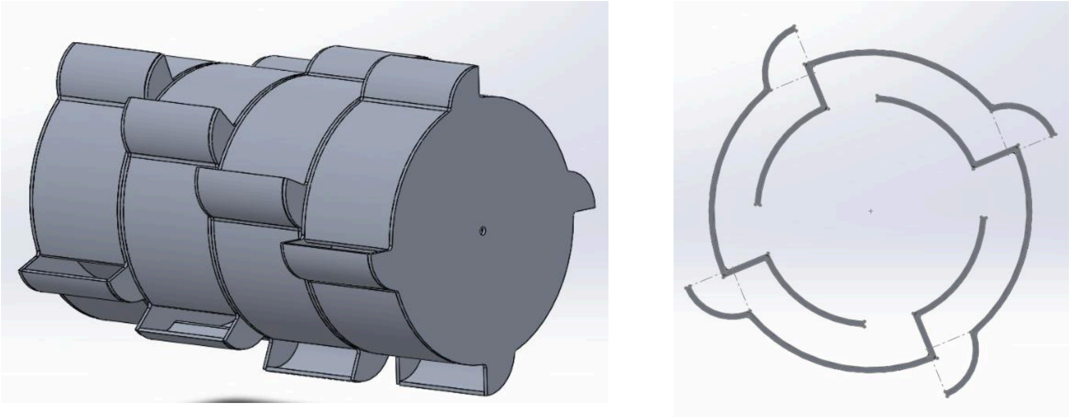


Image 5: Bucket Drum design

6 PROJECT DEVELOPMENT

This section describes all the work done by the student during the whole academic year. In order to make it easier to explain and to comprehend, the project has been divided into 3 different subsystems: Mechanical, Electrical and Autonomy. Almost all the work the student has done has been in the mechanical and electrical subsystem, however, the autonomy is probably the most important subsystem considering how difficult it is to create an autonomous robot.

6.1 MECHANICAL SUBSYSTEM

Like almost every other designing process, a series of steps were followed in order to achieve the respective objectives assigned to this subsystem. This subsystem was in charge of designing and building 4 different parts: the excavation system, the filtering system, the lowering system and the storage bin.

6.1.1 EXCAVATION SYSTEM: FIRST DESIGNS AND PROTOTYPES

The first design that was considered to be used as the excavation system was the bucket drum that was used the previous year, this system was chosen for many reasons, some of this reasons were: it could be used as the excavation system and as the storage bin at the same time, it was already assembled in the robot and it is a very simple system.

Image 6: Bucket Drum prototype

The second prototype that was made for testing was a bucket ladder, this system had some advantages: it is very effective excavation system, there was already a bucket ladder that was used 2 years ago and it is easy to add a filtering system to the bucket ladder.

Image 7: Bucket Ladder prototype

Finally, the last excavation system chosen was an auger. For the testing of this excavation system, a gardening auger was used, using a PVC pipe as a sheath. The advantages this system had were: it is the simplest excavation system of all three chosen, it is easy to dig to deep zones with it and it is the least power consuming option.

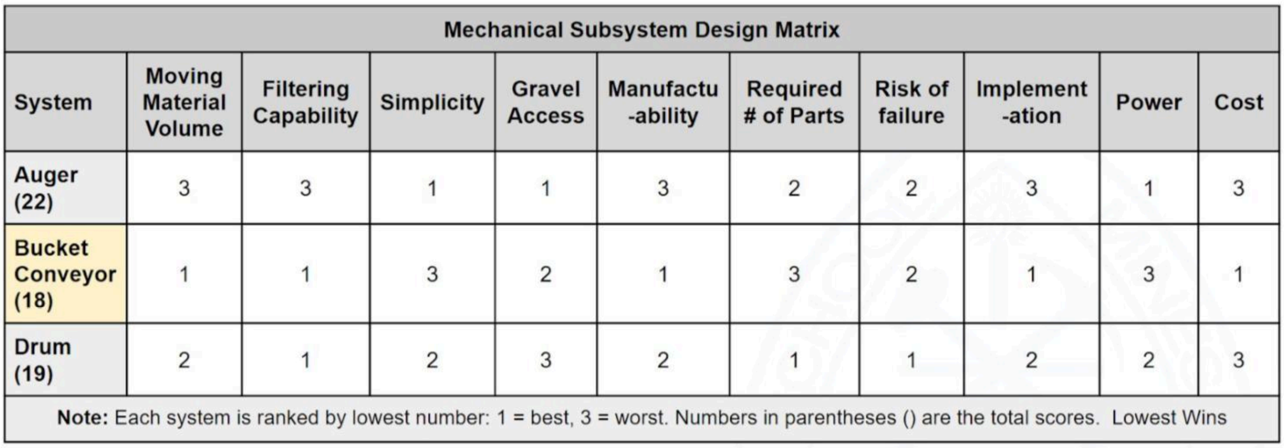
Image 8: Auger prototype

6.1.2 EXCAVATION SYSTEM: TEST AND RESULTS

Once the prototypes of the 3 chosen excavation system were built, intensive testing was done to all 3 of them in sand and gravel. The results from the testing are the following:

- Bucket drum: Despite having the final design used last year, the performance of this system was very disappointing. It had some difficulties when trying to collect the gravel as well as being unable to dig the 30 cm to reach the gravel during the competition.
- Bucket ladder: Overall, the performance of this prototype was the best one. Sometimes it got stalled due to the force required to keep moving, this may have been a result of a bad angle of approach or a bad bucket design. Apart from that, it was capable to collect the gravel and it is easy to customize it.
- Auger: During the testing of this prototype it was seen that, although it was capable of reaching 30 cm of depth without much difficulties, it was not the best option when it came to collect the gravel, as it was prone to jamming against the gravel.

After testing the 3 prototypes multiple times, a decision matrix was done comparing different aspects between the 3 prototypes and their performance during testing. All the aspects were scored deciding which prototype was the best one and which one was the worst one. The scores used were 1, 2 or 3 points, being 1 the best and 3 the worst. Finally, all the scores were added and the prototype with the lowest score was chosen for this year´s excavation system.



Mechanical Subsystem Design Matrix

System	Moving Material Volume	Filtering Capability	Simplicity	Gravel Access	Manufactu-ability	Required # of Parts	Risk of failure	Implement-ation	Power	Cost
Auger (22)	3	3	1	1	3	2	2	3	1	3
Bucket Conveyor (18)	1	1	3	2	1	3	2	1	3	1
Drum (19)	2	1	2	3	2	1	1	2	2	3

Note: Each system is ranked by lowest number: 1 = best, 3 = worst. Numbers in parentheses () are the total scores. Lowest Wins

Table 1: Excavation System Decision Matrix

As it can be seen in table 1, the best option for the excavation system was the bucket ladder. The next steps after deciding the excavation system was to design the filtering system, the lowering system, and then, build the whole excavation system.

6.1.3 FILTERING SYSTEM

The filtering system has now become a very important part of the excavation system as a result of the new rules added to the competition. From this year forward, the BP-1 collected is worth 0 points, so it is important to find a way to separate the gravel from the regolith. In order to do so it is crucial to know the average dimensions of the substances we want to separate, this information can be found in the documents released by the NASA about the competition.

According to the information provided by NASA "BP-1 behaves like a silty powder soil and most particles are under 100 microns in diameter". The gravel has a diameter of approximately 2 cm. After knowing the dimensions, the next decision that had to be made was either to have the filtering system included in the bucket conveyor, or to build it as a different part of the robot.

Both options were considered, for the first option, a bucket like the one shown in image 9 was made, while the second option consisted on a small cube structure, called a hopper, made of 13 mm chicken wire.

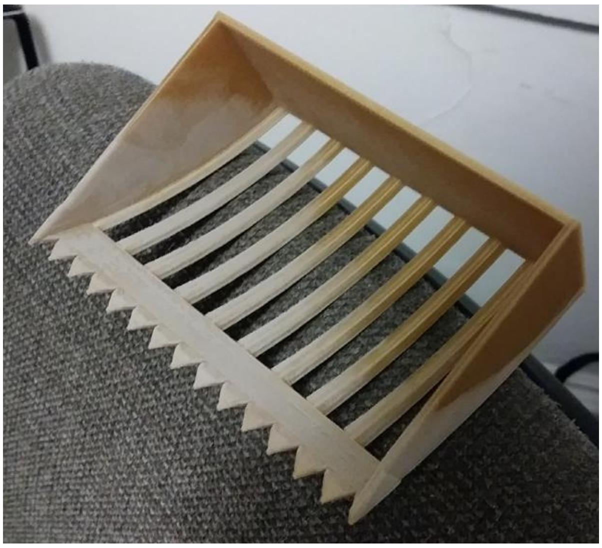


Image 9: Bucket with filtering system included

After testing the bucket conveyor with this new bucket, the first option was abandoned and the hopper was chosen. This was because the 3d printed buckets did not have much resistance and could be broken very easily, and carving those holes in a metallic bucket was not an easy task. An image of the hopper along with the dumping system can be seen in image 13.

6.1.4 LOWERING SYSTEM

From the very beginning, 2 options were considered for the lowering system. The first option consisted on 4 acme lead screws that would connect to the side of the bucket ladder and vertically translate it. the second option was to use a scissor lift and connect it to one side of the bucker ladder.

The first option utilized 4 screws that would be connected one to each other via a chain. This chain would be connected to a DC motor and would make the 4 screws to move simultaneously, lowering the excavation system.

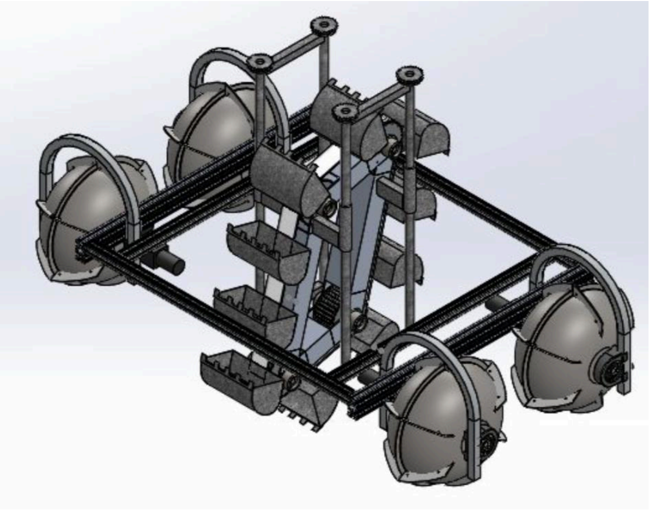


Image 10: early draft of the robot with Acme Lead Screws

The second option was the simplest one, it consisted on a car jack or scissor lift with only one screw and a 90° flat plate corner connecting the bucket ladder to the scissor jack. Image 12 shows the excavation system attached to the scissor lift. After making a computer simulation, the results showed that the maximum depth the buckets can reach is of 50.87 cm.

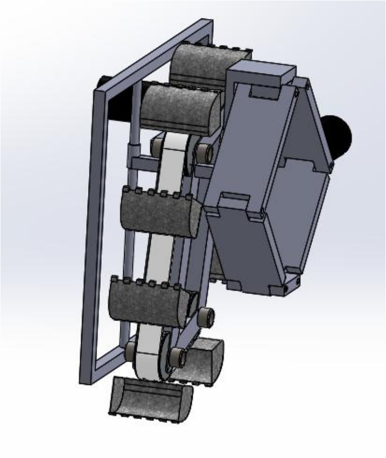


Image 11: Scissor Lift design

To determine the best option, a decision matrix was made to compare these 2 lowering systems. This decision matrix compares 5 different aspects: simplicity, Dust maintenance, Strength, Weight, Spacing. The scores in this decision matrix work the same way as in the decision matrix shown in table 1; the score can be either a 1 or a 2, 1 being the best option and 2 the worst one. All the scores are then summed up and the option with the lowest score wins.

System	Simplicity	Dust Maintenance	Strength	Weight	Spacing
Acme Screws (10)	2	2	2	1	1
Scissor Lift (7)	1	1	1	2	1

Table 2: Lowering System Decision Matrix

After analyzing the decision matrix, it showed that the scissor lift was the best option, so the option of using Acme screws was immediately discarded.

At this point, the excavation system, the filtering system and the lowering system were already chosen. The only thing that was left was to build a new storage bin and to build the final excavation system for testing.

6.1.5 FINAL DESIGN

The final design of the mechanical subsystem includes 5 different components: the bucket ladder, the scissor lift, the hopper, the storage bin and a stationary conveyor.

This last part, the stationary conveyor, is the component that connects the hopper and the storage bin. This conveyor is used for collecting the gravel that comes out of the hopper and depositing it into the storage bin.

The storage bin is very similar to the one used 2 years ago, with the main difference that the new bucket only needs 1 linear actuator instead of 2. Also the dump bucket has a trapezoidal form and the top part in this new design is all at the same height instead of being inclined like in the bin from 2 years ago. Image 13 shows the hopper, the stationary conveyor and the storage bin.

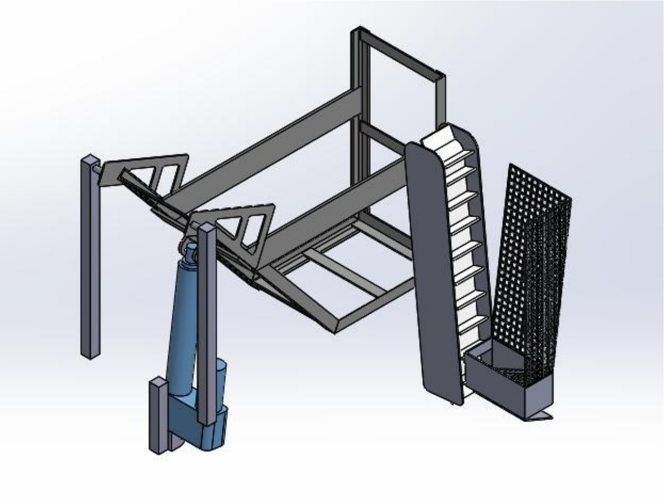


Image 12: Filtering and Dumping Systems

The bucket ladder designed this year also includes some changes when compared to the one used 2 years ago. This year´s design can be seen in image 14. As we can see in that image, the new design is a quadrangle. One of the reasons this was done this way is that the scissor lift requires a wider area to be attached to the bucket ladder than the one offered by the design from 2 years ago.

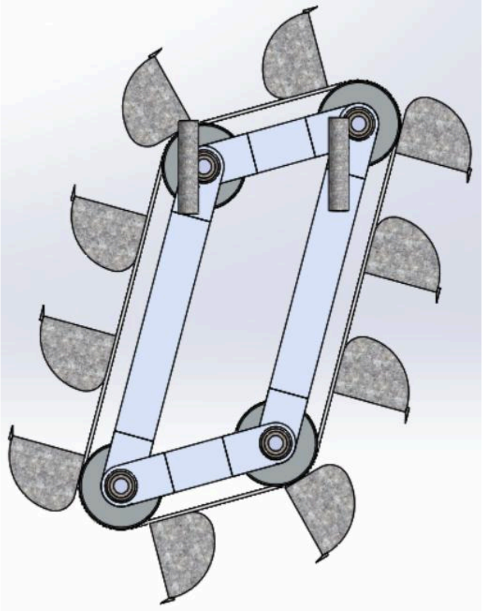


Image 13: Bucket Ladder design

At this point all the parts of the mechanical subsystem were designed, when putting all of them together the robot looked like it looks in image 14. With the final design of all the parts, the next step was to build everything and assemble everything together. While the teammates of the students were in charge of fabricating and building everything that was needed, the student focused his efforts in the electrical subsystem and in choosing the appropriate motors for each component.

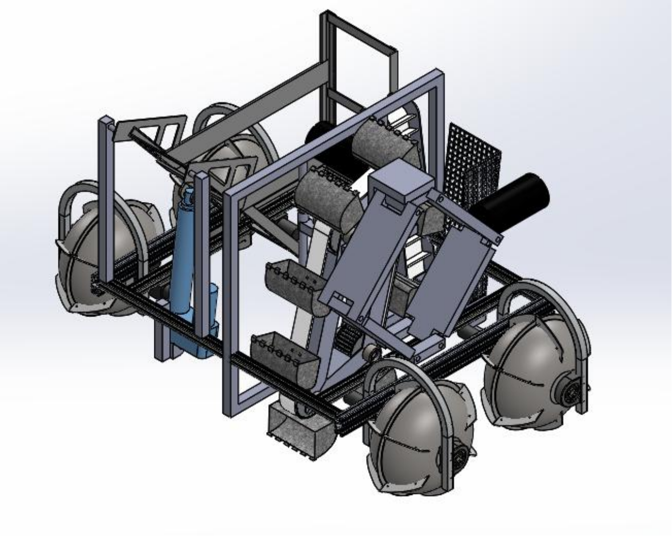


Image 14: Robot Final Design

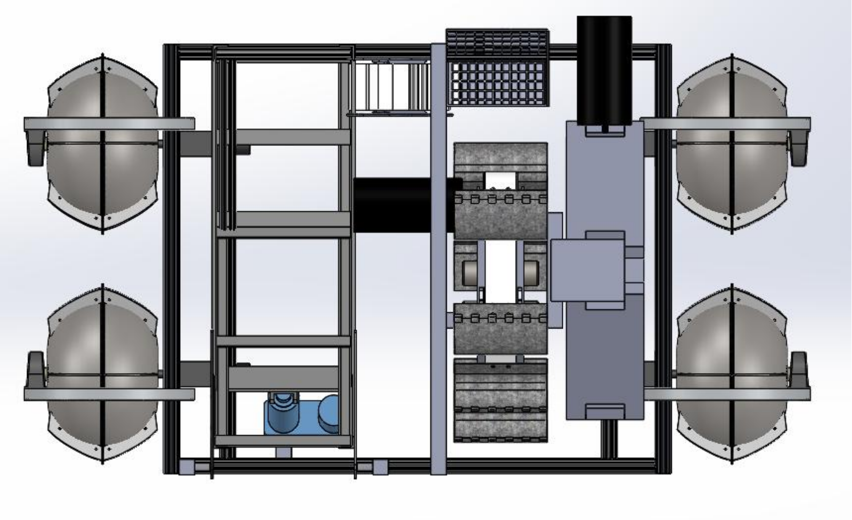


Image 15: Top View of Robot Final Prototype

6.1.6 ELECTION OF THE MOTORS

The election of the motors is something very important, a motor powerful enough to supply the torque required is needed in every component. If a motor not powerful enough is connected to the bucket ladder or any other part, this motor will end up burning at some point during the competition.

Searching through the boxes left by previous teams, 2 different type motors were found:

- Torquemaster expert 540 55t
- Midwest Motion Product (MMP) D22-376D-24V

The first one can support a maximum of 10V, while the second one can support up to 24V. This two type of motors have been inherited from previous teams and some of them were not in very good conditions; in some motors the connections were starting to fail, some cables were broken and some gearboxes were also broken.

Unfortunately, there was not enough time to characterize the motors and make the proper calculations in order to know which motor to use, so the procedure that was followed was to connect the Torquemaster DC motor to each component and see if it worked, in case it did not work, the MMP DC motor would be connected.

Information retrieved from previous years showed that the bucket ladder need to use the MMP motor because the Torquemaster can´t supply enough torque to move the ladder. In case of the scissor lift, the MMP motor was also needed as the Torquemaster was not able to move the screw. When trying the Torquemaster on the stationary conveyor it was seen that it was working perfectly.

For the wheels, the same motors that were used last year were kept, in this case 4 Torquemaster motors. The only thing that was changed here was the cables of 1 motor that were completely broken and needed to be soldered.

Lastly, the storage bin used one of the two linear actuators that were used for the bucket drum las year. This actuator is a Duff-Norton TAC05-1D20-8 that can support as much as 12V.

Component	Motor used
Bucket ladder	Midwest Motion Product D22-376D-24V
Scissor lift	Midwest Motion Product D22-376D-24V
Stationary conveyor	Torquemaster expert 540 55t
Wheels	Torquemaster expert 540 55t
Storage bin	(Linear actuator) Duff-Norton TAC05-1D20-8

Table 3: Chosen Motors

6.2 ELECTRICAL SUBSYSTEM

In this subsystem the student has worked more than in the other two subsystems, being the only electrical engineer of the team and being the leader of this subsystem.

This subsystem is in charge of: deciding all the electronic components that will be used, designing a new power distribution circuit, designing and building a new electrical box, designing a new emergency stop button circuit and making all the connections.

Like in the mechanical subsystem, in order to create and assemble a new circuit, some steps were followed. The first step was to analyze and disassemble the previous circuit and keep the parts that could be reused. Following this, a new circuit was designed and all the components that were going to be used were tested to ensure they worked. Finally, the electrical box was fabricated and the circuit was assembled.

6.2.1 PREVIOUS CIRCUIT ANALYSIS

Before designing a new circuit, the current one needs to be analyzed. Unfortunately, no wiring diagrams could be retrieved for the circuit used last year, however, when the robot was given to this year´s team, the circuit was still assembled and everything was still connected.

This circuit worked really good during the competitions that took place 1 and 2 years ago, however, some parts of this circuit were starting to fail. The first thing that was noticed in this circuit is that the emergency stop button circuit was not very safe and it had to be changed right away.

The emergency stop button is the one shown in image 16, as we can see it has 3 different slots to connect the signal. What was done in the circuit is that the main signal that came from the battery was divided into 3 different cables, and after going through the emergency stop button, was reconnected into only 1 cable. This was done through soldering points, soldering the 4 cables together. This was not very safe as these soldering points had the risk to disassemble or to catch fire if too much current went through that soldering point.

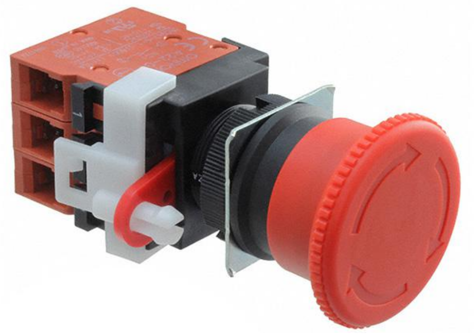


Image 16: Emergency Stop Button

The second thing that was noticed is that this circuit was using way too many components, they were using 4 Arduinos Nano, 3 Roboclaws 2x60A, 2 other motor controllers, 1 Arduino Mega, 1 emergency stop button, 1 thermal breaker, 1 fuse box, 1 onboard computer, 1 Kinect Camera, 1 IMU and 1 Webcam.

The movement of the robot and the bucket drum was controlled using a Master – Slave communication. During the competition, the onboard computer was controlled remotely through a Wi-Fi connection, the computer then executed a program where the Arduino

Mega was the Master and the 4 Arduino Nano where the Slaves. These Arduinos Nano where in charge of controlling the Roboclaws and the motor controllers that controlled the linear actuators.

One of the 3 Roboclaws was connected to the motor that made the bucket drum rotate, the other two Roboclaws were connected to the motors on the wheels, one controlled the right side wheels and the other one controlled the left side wheels. The other 2 motor controllers where connected to the 2 linear actuators that raised and lowered the bucket drum.

The fuse box that can be seen in image 22 was used to divide the main signal that came from the battery into the different signals that went to the rest of the devices in order to power them up. In between the battery and the fuse box, the signal first went through the emergency stop button and then through the thermal breaker, that was already inside the electrical box.

From all these different components, only a few will be reused. For the new circuit only the 3 Roboclaws, the thermal breaker, the emergency stop button, the Kinect Camera, the IMU, the Webcam and the fuse box will be reused, the rest of the devices will be substituted for other ones. Apart from the electronic components, some cables gauge 6, 10 and 12 will be reused as well as some wire connectors.

The main idea of designing a new power distribution circuit was to minimize the amount of components and to organize them in the most efficient way to use as less cables as possible. One of the big ideas here is to substitute the onboard computer with another device with the same capabilities and smaller, and also to replace the 5 Arduinos with only 1 Raspberry Pi 3.

6.2.2 NEW CIRCUIT DESIGN

In the new circuit design that can be seen in image 17, apart from all the reused components mentioned in the previous subsection, some new components were needed. These new components were the NUC, the Raspberry Pi 3, new cables of gauge 6, 10 and 12, 1 more Roboclaw and new connectors and fuses.

In the new circuit the main brain of the robot is the NUC. The NUC is in charge of executing the main program and communicate with the Raspberry Pi through an SSH communication protocol using an Ethernet cable. The main task of the NUC is to process all the data received from the Webcam, the Kinect Camera and the Raspberry Pi in order to make the robot work autonomously. This data processing includes executing different algorithms for obstacle detection and path planning.

The next most important device is the Raspberry Pi 3; this device is in constant communication with the NUC through an SSH communication protocol using an Ethernet cable. The Raspberry Pi will be in charge of making all the calculations needed in order to run autonomously. Another task the Raspberry Pi will have is to collect the data from the IMU and to control all the motors and linear actuators through the Roboclaws.

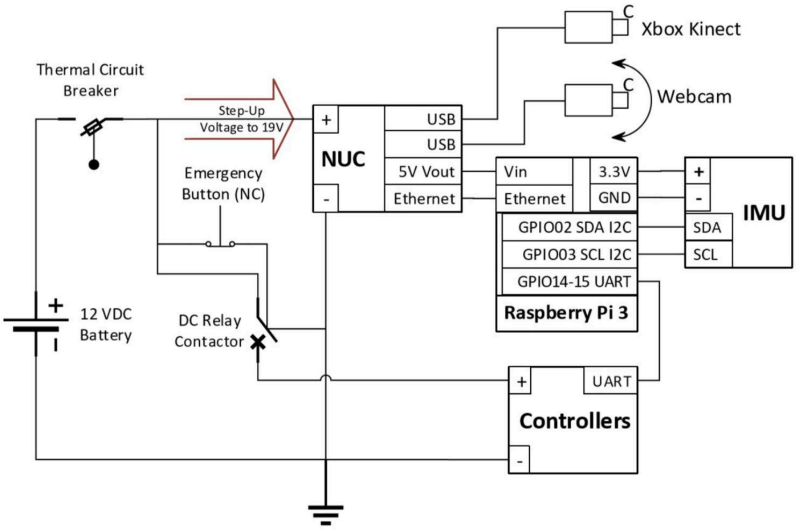
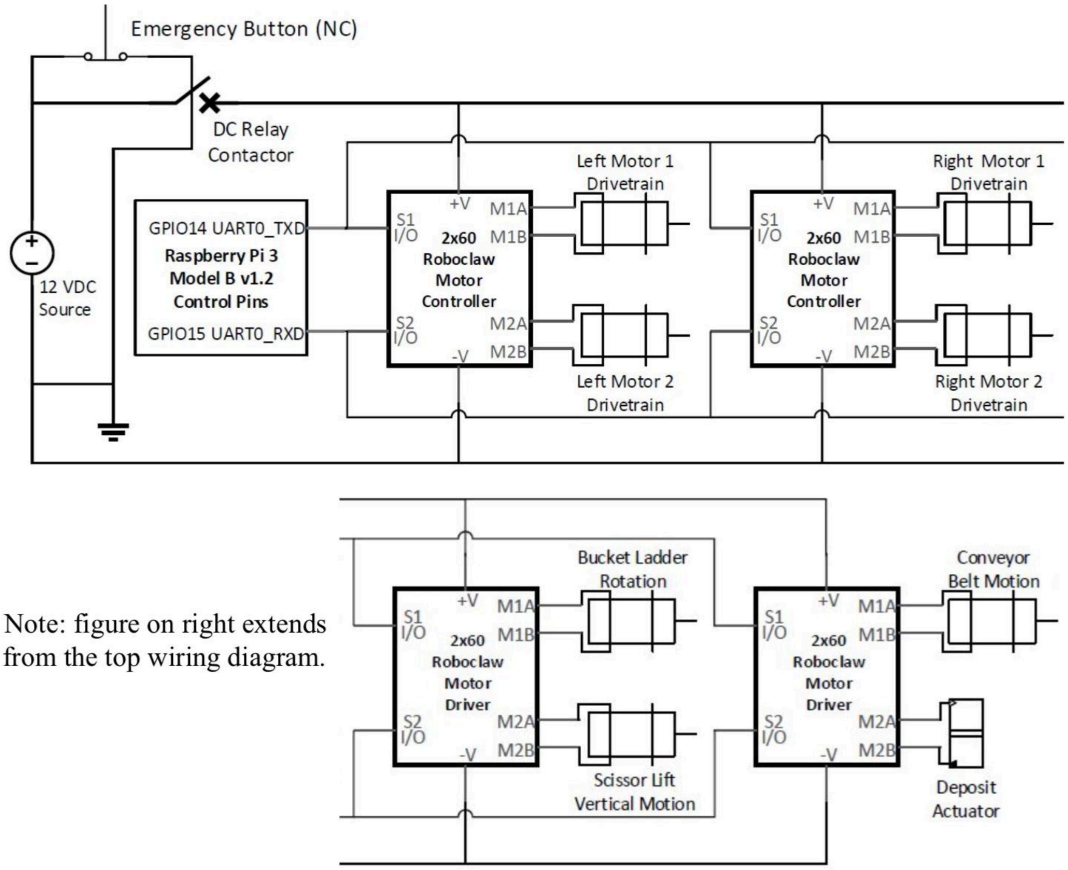


Image 17: Wiring Diagram

The Roboclaws are all connected to the Raspberry Pi using the UART protocol. They were configured to work on the multiunit mode, each one with a different address. The connection of the Roboclaws can be seen in image 18 and is represented by the box that says controllers in image 17. As mentioned before, in the new circuit there are 4 Roboclaws, each one of them controlling two different motors. 1 of the Roboclaws controls the left side wheels and another one controls the right side wheels, the two Roboclaws that are left are in charge of controlling the 3 motors and the linear actuator that are used in the excavation system and the dumping system; one of them is in charge of controlling the bucket ladder and the stationary conveyor while the other one controls the scissor lift and the linear actuator of the storage bin.

All the Roboclaws are connected to the 12 V signal that comes out of the DC relay connector, so in case someone presses the emergency stop button, only these 4 Roboclaws will be turned off.



Note: figure on right extends from the top wiring diagram.

Image 18: Controllers Wiring Diagram

One new thing to take into account in this new circuit is that the emergency stop button circuit has been redesign and relocated. In the previous design if the emergency stop button was pressed, the whole systems, computer and Arduinos included, turned off, in this new circuit, when the button is pressed, only the Roboclaws shut down. This new emergency stop button includes a DC relay Contactor that is controlled by a 12V signal that comes directly from the battery. This signal that comes from the battery is the signal that goes through the emergency stop button, this way if the button is on, the DC relay is on, and if the button is off, the DC relay is off.

As it can be seen in image 17, a step up voltage circuit is also needed in order to power up the NUC. At first this step up voltage circuit was going to be designed and built according to the diagram shown in image 19, however, a simpler solution was found when doing some research, and instead of designing this circuit, a DC converter from 12V to 19V was bought. This solution made things much easier as the diagram shown in image 19 was taken from the internet and no one knew how it was going to work. Also another of the concerns was the current supplied by the circuit to the NUC; the NUC needed to be powered with 19V and 3.42A. The step up device can be seen in image XX and converts 12 V into 19 V and 3A, which is more than enough to power up the NUC.

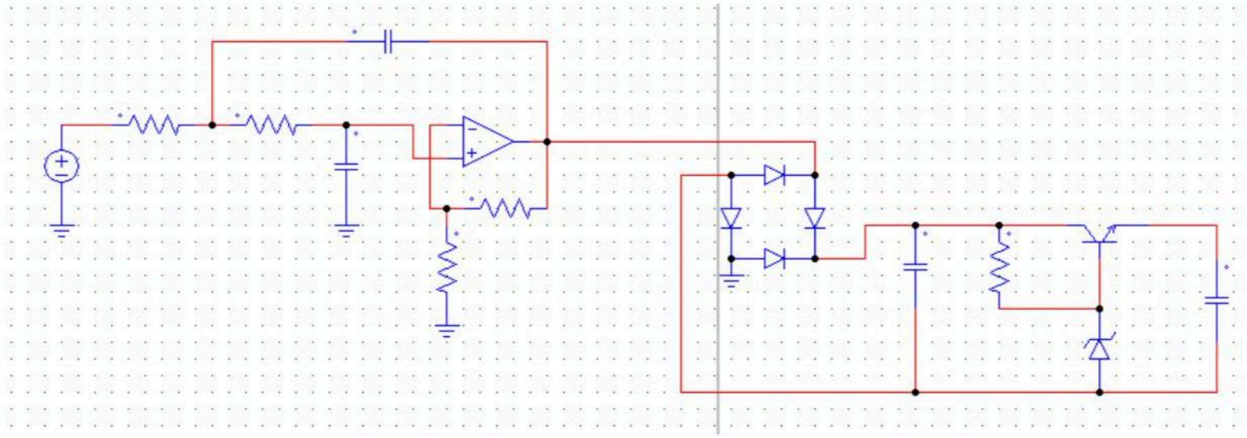


Image 19: First Design of the Step-Up Voltage Circuit

For the assembly of this power distribution circuit, cables of gauge 6 were used for the signal that goes from the battery to the fuse box; cables of gauge 10 and 12 were used for powering up all the devices from the fuse box; and finally, some jumper wires (gauge 22) were used for connecting the IMU to the Raspberry Pi. Apart from all these wires, an Ethernet cable was also used for the connection between the NUC and the Raspberry Pi, and lastly, 2 USB cables were used to power up the Kinect Camera and the Webcam from the NUC.

6.2.3 COMPONENTS

In this subsection all the electronic devices and all the components that had been used during the assembly of the circuit will be briefly described. As it has been said several times during this document, the most important devices are the NUC and the Raspberry Pi, but, knowing the function and how all the components work can be useful.

NUC

Image 20: Intel NUC7i3BNH

The NUC is the most important device of the robot. The NUC (Next Unit of Computing) is a product released by Intel and it is basically a powerful mini PC. The NUC that is used for this year´s robot is the NUC7i3BNH, which possesses an Intel Core i3 processor. This device needs 19V to be powered up, so a step-up voltage circuit is used to increase the voltage from 12V to 19V. All the specifications of this device can be seen in Appendix A.

This device is the brain of the robot, processing all the data received from the Kinect Camera, the Webcam and the Raspberry Pi. This device receives the data from these three devices and its function is to find the possible obstacles and to find the most optimal path avoiding those obstacles. Once this is done, the results obtained are sent to the Raspberry Pi. Also, during the competition, this device will be remotely controlled from a laptop through a Wi-Fi connection, and at the same time the NUC will have access to the Raspberry Pi, controlling it and running the proper programs.

This device was chosen for many reasons:

- Produces minimal heat without needing fan cooling.
- Includes Wi-Fi compatibility for remote access.
- Allows Ethernet and USB access for external devices.
- Has a large storage space for coding, noting a smaller physical size.
- Has sufficient memory to intake and process the Kinect and Webcam data for navigation

Raspberry Pi 3

Image 21: Raspberry Pi 3 Model B

The Raspberry Pi is the second most important device, this device is in charge of receiving all the data from the IMU, making all the calculations required in order to run autonomously and controlling all the moving parts of the robot.

The Raspberry Pi was chosen to replace all the Arduinos and to control all the Roboclaws and all the moving parts. The Raspberry Pi used is the Raspberry Pi 3 model B, using the Ubuntu Operating System for an easier software implementation within the Linux-Based device.

This device uses the UART and the I2C protocols to communicate with the IMU and with the Roboclaws. All the coding that was done in this device for activating these two protocols was done either on python or on C++. Apart from these two protocols, an SSH communication was stablished between the NUC and the Raspberry Pi using an Ethernet cable.

Fuse Box

Image 22: Fuse Box

This device was inherited from previous teams, and its main function is to divide the signal that comes from the battery into the different signals that go to the devices. The fuses used for the Fuse Box could withstand currents from 1 A to 45 A.

Roboclaws

Image 23: Roboclaws 2x60A

The actual design of the robot includes 8 different motors, so 4 Roboclaws are used in order to control all the motors. The Roboclaws used are the Roboclaws 2x60 A, this type of Roboclaw is able to control 2 motors at the same time, supplying a maximum continuous current of 60 A per channel. This type of Roboclaw requires a minimum power supply voltage of 6 V, and a maximum of 34 V.

The Raspberry Pi is the device controlling the 4 Roboclaws using the UART communication protocol. In order to control the Roboclaws correctly from the Raspberry Pi, the multiunit unit mode has to be activated in all the Roboclaws, assigning a different address to each one of them.

Emergency Stop Button

One of the requirement of the competition is that a red Emergency Stop Button, like the one that can be seen in image 16, has to be included in the robot. This button has to be placed in a part of the robot which allows an easy and a safe access to it.

According to what the rules of the competition say: “The emergency stop button must stop the mining robot’s motion and disable all power to the mining robot with one push motion on the button.”. In the circuit designed this year, the Emergency Stop Button controls the signal that activates and deactivates the DC Relay Contactor.

IMU

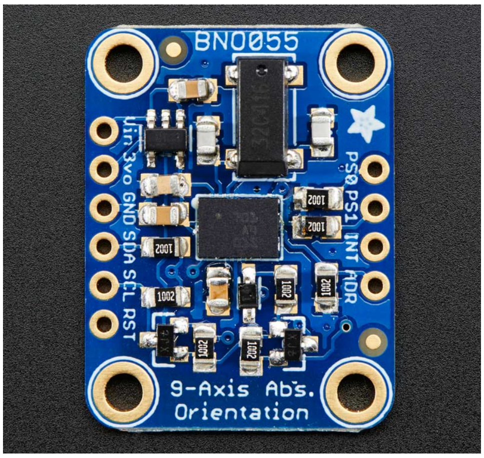


Image 24: Inertial Measurement Unit (IMU)

The IMU is connected to the Raspberry Pi 3 and uses the I2C communication protocol to send the data collected to the Raspberry Pi. This IMU is a 9 axis sensor, with a 3 axis accelerometer, 3 axis gyroscope and 3 axis magnetometer. This IMU helps the robot know its relative position and orientation in relation with the collector bin during the competition. the IMU also helps the robot know if it is stuck in the sand; if the robot is moving the wheels but the IMU measures the same position as before it means that the robot is not moving at all and that it is stuck in the BP-1.

Thermal Breaker

Image 25: Thermal Breaker

The Thermal Breaker is placed inside the electrical enclosure and is in charge of killing the signal coming from the battery in case it measures too much heat. The maximum current rating for this device is 120 A and the maximum voltage rating is 48 V.

Wattmeter

Image 26: Wattmeter

Another requirement of the competition is that all robots must have a wattmeter that measures the energy consumed during the competition attempts. This is related to another rule that says that during the competition attempts, teams will lose points depending on the Watts-hour consumed by the robot.

DC Relay Contactor

Image 27: DC Relay Contactor

This year´s circuit includes a DC Relay that acts like a switch between the battery and the Roboclaws. This DC Relay can support a maximum of 30 A and 30 V DC, which is more than enough for this robot.

DC-DC Voltage Converter

Image 28: DC-DC Voltage Converter

As mentioned earlier, the NUC needs to be powered by approximately 65W and 19V, which is the same as 19V and 3.42A. The battery used in the robot is a 12 V battery, so a DC-DC converter is needed to step-up the voltage from 12V to 19V. This converter also has an output current limit of 3 A, giving a total of 57W.

Kinect Camera

Image 29: XBOX Kinect Camera

This year, the robot has 2 cameras, one of them is the XBOX Kinect Camera, connected directly to the NUC through a USB connection. This camera is used to analyze the surroundings of the robot and detect possible obstacles.

Webcam

Image 30: Webcam

Apart from the Kinect Camera, The NUC also has a Webcam connected to it. The Webcam is used to find the collector bin during the competition attempts; a LED beacon will be placed where the collector bin is, this way the robot only has to find the light using the Webcam and then calculate its position and orientation.

Battery

Image 31: 12V Battery

The battery used is a SHORAI LFX36L3-BS12. It is a 12V, 36A·h battery with a maximum output current of 540A. In subsection 6.2.4 are some calculations that were made in order to decide how many batteries the robot needed.

Other components

Image 32: LED beacon (left) and wire connectors (right)

There are a lot of components that were used in addition to the ones already described. One of them is the LED beacon, which will be used to locate the collector bin during the competition. Other component that were used are wire connectors for cables of gauge 6, 10 and 12. There were different types of connectors that were used: ring connectors, spade connectors and male and female connectors. Another connector that was used was the XT90 type which can be seen in image 33.

Image 33: XT90 type connector

Another two components that were used during the development of the autonomy and will also be used in the competition were the laptop and the Wi-Fi router that were inherited from previous years.

Finally, many different tool were also used during the assembly of the circuit: electrical tape, many different types of screwdrivers and screws, scissors, knives, crimping tool, wire stripper, soldering gun, multimeter, drill, computer monitors and many others.

6.2.4 CALCULATIONS

One of the decisions that had to be made when starting to assemble the power distribution circuit was either to use only 1 battery or to use 2 batteries. In order to decide, some calculations needed to be done to know if only one battery was able to supply enough power to the rest of the devices.

Table 4 shows the electrical specification of all the devices that were used in our robot. With the electrical specifications the power that each device consumes can be easily calculated, and knowing the total power consumption the decision of using 1 or 2 batteries can be done.

Sensors	Voltage (V)	Current (A)	#
NUC7i3BNH	19	3	1
Raspberry Pi 3	5	1	1
IMU BNO055	2.4-3.6	0.0123	1
Kinect Camera	12	1	1
Roboclaw 2x60A	12	3	4
Motors	Voltage(V)	Current (A)	#
Wheels (Torquemaster Expert 540 55t)	12	Max 540	4
Bucket (Linear Actuator)	12	4	1
Digging (Midwest Motion Products D22-376D-24V)	12	24.2	1
Conveyor Belt (Torquemaster Expert 540 35t)	12	Max 540	2
Battery	Voltage (V)	Capacity (Ah)	#
Shorai LFX36L3-BS12	12	36	1

Table 4: electrical specifications

For knowing the power consumed by the devices the electrical power (P) equation using voltage (V) and current (I) is used:

$$P = V \cdot I$$

SENSORS

$P_{\text{NUC}} = 19 \cdot 3 = 57\text{W}$

$P_{\text{RPi}} = 5 \cdot 1 = 5\text{W}$

$P_{\text{IMU}} = 3.6 \cdot 0.0123 = 0.044\text{W}$

$P_{\text{Kinect}} = 12 \cdot 1 = 12\text{W}$

$P_{\text{Roboclaw}} = 12 \cdot 3 = 36\text{W}$

$P_{\text{Total-sensors}} = P_{\text{NUC}} + P_{\text{RPi}} + P_{\text{IMU}} + P_{\text{Kinect}} + 4 \cdot P_{\text{Roboclaw}} = 218.044\text{ W}$

MOTORS

$P_{\text{bucket}} = 12 \cdot 4 = 48\text{W}$

$P_{\text{digging}} = 12 \cdot 24.2 = 290.4\text{W}$

For knowing the power consumed by the motors on the wheels and the conveyor belt, we need to know first how much current they need, this current depends on the torque and on some constants from the motor. These calculations were made by some teammates with the result of the motors consuming 18. 358A in both the wheels and the conveyor belt.

$\mathrm{I}_{\mathrm{motor\_wheels}} = 18.358\ \mathrm{A}$

$\mathrm{I}_{\mathrm{motor\_belt}} = 18.358\ \mathrm{A}$

$\mathrm{P}_{\mathrm{wheel}} = 10 \cdot 18.358 = 183.58\mathrm{W}$

$\mathrm{P}_{\mathrm{belt}} = 10 \cdot 18.358 = 183.58\mathrm{W}$

$\mathrm{P}_{\mathrm{Total-motors}} = \mathrm{P}_{\mathrm{bucket}} + \mathrm{P}_{\mathrm{digging}} + 4 * \mathrm{P}_{\mathrm{wheels}} + \mathrm{P}_{\mathrm{belt}} = 1256.3\ \mathrm{W}$

TOTAL POWER

$P_{Total} = P_{Total-motors} + P_{Total-sensors} = 1{,}474.344\ \mathrm{W}$

Know that the total power is known, a comparison between the total power consumed and the power supplied need to be done. Here a comparison will also be made between using 1 battery or 2 batteries.

1 Battery

BATTERY POWER

$P_{Battery-max} = 12 \cdot 540 = 6{,}480W$

FACTOR OF SAFETY

$FoS_{Battery} = \frac{P_{Battery-max}}{P_{Total}} = 4.39$

BATTERY RUNTIME

$Capacity_{Battery} = 36\ A \cdot h = 129{,}600\ \mathrm{A{\cdot}s}$

$E_{Battery} = Capacity_{Battery} \cdot V_{Battery} = 129{,}600 \cdot 12 = 1{,}555{,}200\ \mathrm{J}$

$$runtime_{Battery} = \frac{E_{Battery}}{P_{Total}} = 1{,}054.84\ s = 17.58\ min$$

2 Batteries

BATTERY POWER

$P_{Battery-max} = 2 \cdot 12 \cdot 540 = 12{,}960W$

FACTOR OF SAFETY

$FoS_{Battery} = \frac{P_{Battery-max}}{P_{Total}} = 8.78$

BATTERY RUNTIME

$Capacity_{Battery} = 36\ A \cdot h$ = 129,600 A·s

$E_{Battery} = Capacity_{Battery} \cdot V_{Battery} = 129{,}600 \cdot 12 \cdot 2$ = 3,110,400 J

$$runtime_{Battery} = \frac{E_{Battery}}{P_{Total}} = 2{,}109.68\ s = 35.16\ min$$

If we look at the calculations, there is a factor of safety of 4.39 when using 1 battery, this means that the battery can supply 4 times more power than the power that it is going to be consumed. Also, taking a look to the battery runtime we can see that the battery runtime of 1 battery is approximately 17 minutes and it is more than enough for the 10-minute run. The final decision was to use only one battery as it was able to provide enough power to the rest of the circuit.

6.2.5 INDIVIDUAL TEST OF COMPONENTS

In this subsection the results of the individual tests performed to each component will be shown. These tests were done to make sure every component worked as it was expected and to see which components needed a replacement.

The first components that was checked were the Battery, the Thermal Breaker and the Fuse Box; the signal that came from the Battery was connected to the Thermal Breaker and then to the Fuse Box. A multimeter was connected to the positive and negative terminals of the Fuse Box, measuring the voltage of the Battery. Once the multimeter was connected the Thermal Breaker was opened and closed to see if the measurement of the multimeter changed.

The results of these tests were that the multimeter measured a voltage of 13.68V when the Thermal Breaker was closed and a voltage of 0V when it was opened.

Image 34: Battery, Fuse Box and Thermal Breaker test

The next test was to add some fuses to the Fuse Box and make sure the signal travelled through these fuses to the terminals were the connections were going to be made. This test had a satisfactory result as every fuse and every terminal worked correctly.

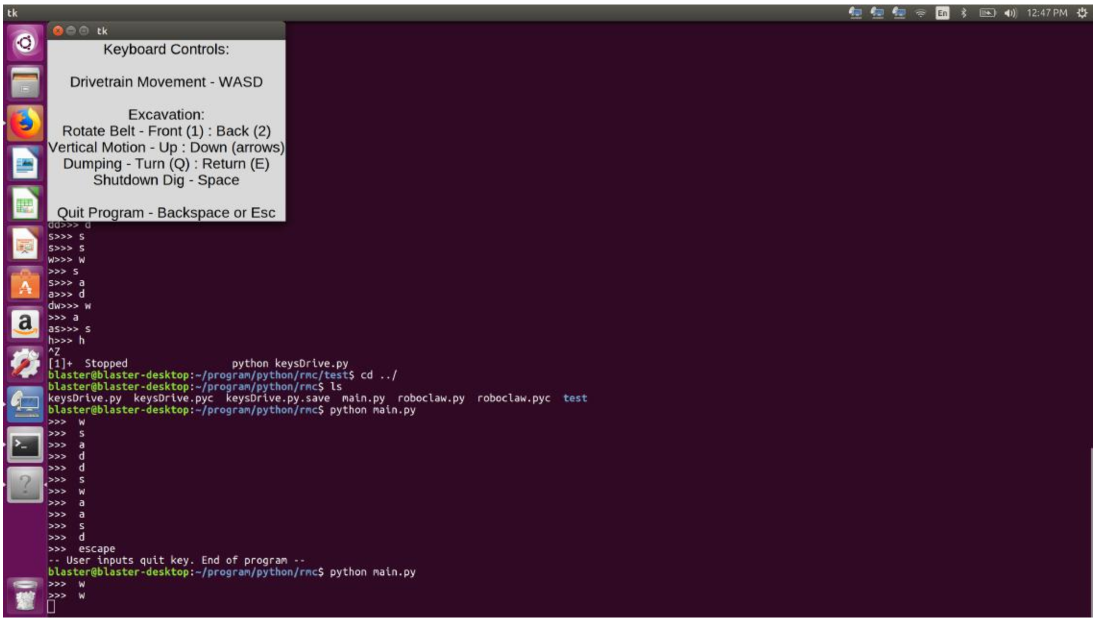
The next test was made to the Emergency Stop Button circuit, as it was going to be implemented in the rest of tests in case something went wrong. The signal that went to the DC Relay came from the Fuse Box, and the output signal of this DC Relay was connected to the multimeter to measure the voltage. The signal that controls the Relay came from a 5V pin of the Raspberry Pi that, at the same time, went through the Emergency Stop Button. The result of this test was that when the Emergency Stop Button was unpressed, the Relay was on and the multimeter measured 13.68V, but, when the Emergency Stop Button was pressed, the DC Relay was off and the multimeter measured 0V.

At this point, the basic components of the circuit were already connected, the next step was to test the Roboclaws and the motors. In order to test the Roboclaws, a test code was written in the Raspberry Pi. The Roboclaws were connected one by one to the Raspberry Pi and a motor was connected to the Roboclaws.

The results of this test was that the three Roboclaws that were tested worked perfectly, but the fourth Roboclaw that was needed in the circuit did not arrived until the whole circuit was already assembled. Most of the motors that were tested with the Roboclaws worked, but some of them were burned and had to be discarded. The motors attached to the wheels worked well, however, when testing one wheel it was noticed that there were some missing screws.

The next test was to make the three Roboclaws work at the same time with 6 motors attached to them. For doing so, a new test code had to be written in the Raspberry Pi. The result of this test was that the 6 motors worked but there was some delay between the motors. This resulted to be a problem of the configuration of the Roboclaws and it was solved immediately.

The following step was to test the connection between the NUC and the Raspberry Pi, for this an Ethernet cable and a monitor was used. Inside the NUC a program was used in order to control the Raspberry Pi through the SSH connection. The result was that the terminal of the Raspberry Pi appeared on the screen of the NUC allowing the NUC to control the Raspberry Pi through the terminal.



Keyboard Controls:

Drivetrain Movement - WASD

Excavation:
Rotate Belt - Front (1) : Back (2)
Vertical Motion - Up : Down (arrows)
Dumping - Turn (Q) : Return (E)
Shutdown Dig - Space

Quit Program - Backspace or Esc

```
dd>>> d
s>>> s
s>>> s
w>>> w
>>> s
s>>> a
a>>> d
dw>>> w
>>> a
as>>> s
h>>> h
^Z
[1]+  Stopped                 python keysDrive.py
blaster@blaster-desktop:~/program/python/rmc/test$ cd ../
blaster@blaster-desktop:~/program/python/rmc$ ls
keysDrive.py  keysDrive.pyc  keysDrive.py.save  main.py  roboclaw.py  roboclaw.pyc  test
blaster@blaster-desktop:~/program/python/rmc$ python main.py
>>>  w
>>>  s
>>>  a
>>>  d
>>>  d
>>>  s
>>>  w
>>>  a
>>>  a
>>>  s
>>>  d
>>>  escape
-- User inputs quit key. End of program --
blaster@blaster-desktop:~/program/python/rmc$ python main.py
>>>  w
>>>  w
```

Image 35: NUC and Raspberry Pi test

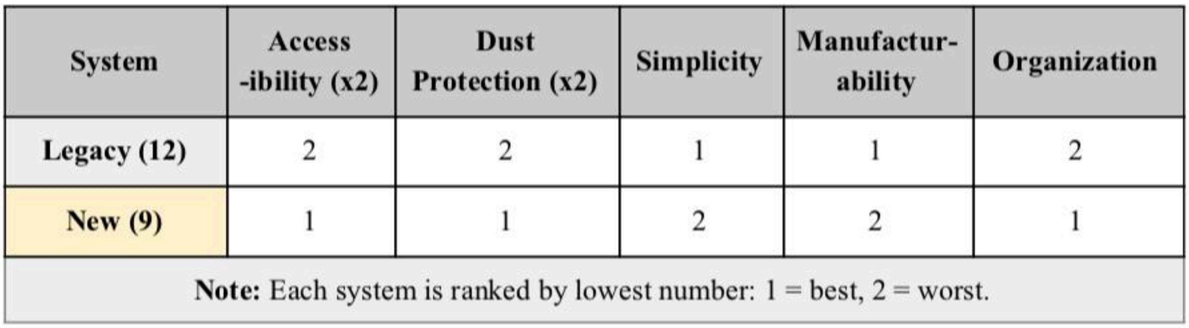
Now that the NUC and the Raspberry Pi worked, the Wi-Fi connection between the NUC and the computer had to be tested. Here, a router that was inherited from last year´s team was used. At first, some troubles were found trying to connect the NUC and the computer via Wi-Fi, but finally the connection was stablished. Once the connection worked, the computer used a program that allowed it to show the desktop of the NUC and navigate through the it.

Lastly, before assembling the whole circuit, the step-up voltage circuit was tested to ensure that the NUC received enough power. This was an easy test as it only required 2 connections; the input of the circuit was connected to the Fuse Box and the output to the multimeter. The result was that output voltage was 18.7V. After this, the NUC was connected to step-up voltage circuit turning on when connected.

After this, the whole circuit is assembled and tested. When testing the final circuit, some troubles were found. In first place, the delay on the wheels appeared again due to some cables that were loose, also the connection between the Raspberry and the Pi was interrupted sometimes, this problem was solved using a new Ethernet cable. Another problem that appeared was that the motors did not stop when they were supposed to stop, this was a problem of the code and was solved right away.

6.2.6 ELECTRICAL ENCLOSURE DESIGN

For the Enclosure Design there were two options, keep the enclosure that was already on the robot or build a new one. For making the best decision, a decision matrix was done with 5 different fields. This matrix can be seen in table 5.



System	Access -ibility (x2)	Dust Protection (x2)	Simplicity	Manufactur-ability	Organization
Legacy (12)	2	2	1	1	2
New (9)	1	1	2	2	1
Note: Each system is ranked by lowest number: 1 = best, 2 = worst.					

Table 5: Decision Matrix for the Electrical Enclosure

The electrical enclosure was designed and build before the whole circuit was assembled. It was designed with the idea of having enough space for the components that are used and some more space in case more components are needed. Another concern when designing the enclosure was the heat, it has to be big enough so that the heat could dissipate without creating any problems.

The main idea was to build a box that had a front door and that had 4 different shelves, one shelf for the Thermal Breaker and the Fuse Box, another for the NUC, the Step-Up Circuit and the Raspberry Pi, another one for the Roboclaws and the last one for spare components.

This design had 3 different holes carved into the walls, 1 on the right wall and another 2 on the left wall. The cables went through these 3 holes in order to connect the components inside the electrical box with the different motors that were placed outside of it. The whole in the right was used for the signal coming from the battery, and the other 2 holes werw used for the Roboclaws and the motors.

This year, the electrical enclosure was placed on the same spot as last year. It is placed on the left side of the robot on top of the wheels.

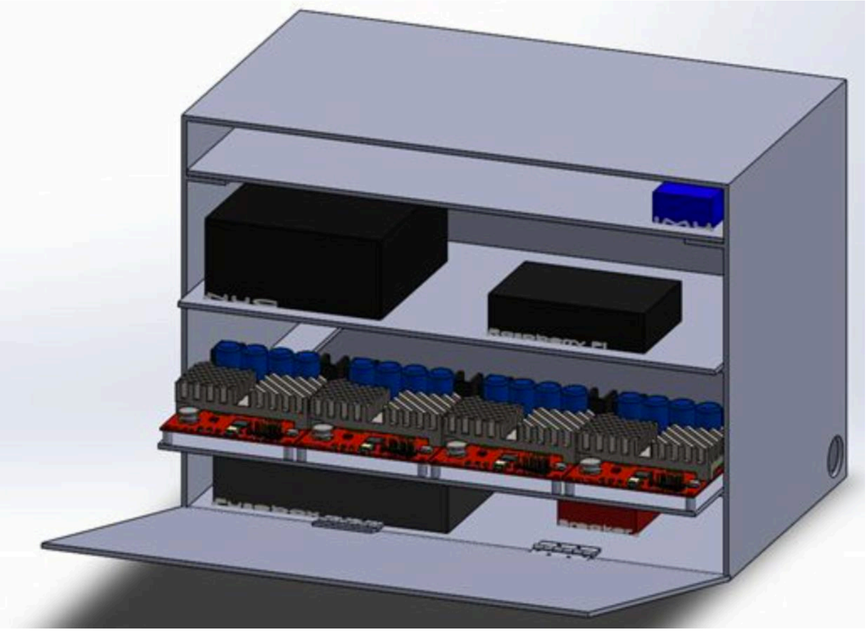


Image 36: Electrical Enclosure Design

Apart from the electrical box shown in image 36, another little box was design for the Emergency Stop Button circuit. This box was placed on the right side of the electrical enclosure and it contained the DC Relay and the Emergency Stop Button. This box is connected to the Electrical Enclosure Through some tiny holes to make the connections between the Raspberry Pi and the Emergency Stop Button.

The final design of this electrical enclosure was designed by the teammates of the student, also building the enclosure using Plexiglas.

6.3 AUTONOMY SUBSYSTEM

This subsystem, as its own name says, was in charge of working on the autonomy of the robot. The objective was to use the Kinect Camera and the Webcam along with the Inertial Measurement Unit (IMU) to navigate through the competition arena and mine on the mining area, all without any human intervention. The Webcam was in charge of looking for the LED Beacon that was placed on top of the Collector Bin, this Webcam is mounted on a two-axis gimbal which allows the Webcam to move along the vertical and horizontal axes.

Image 37 shows the software flow, using squares to denote hardware and ovals to denote software processes.

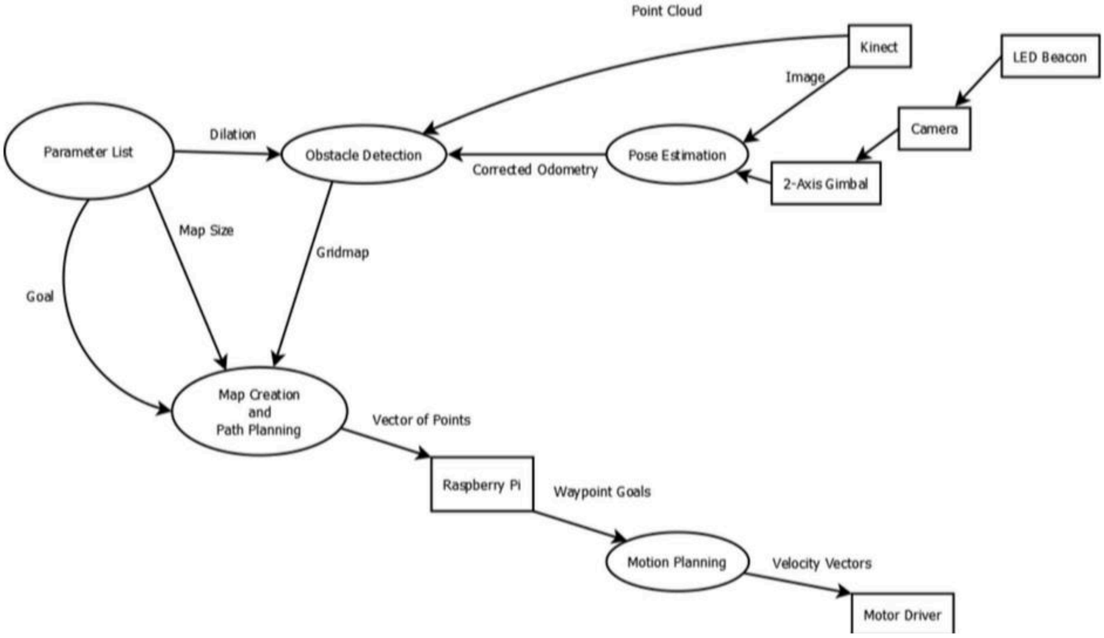


Image 37: Software flow

The software architecture will be built upon Robot Operating System (ROS) to act as a message-passing interface for the various pieces of code and hardware. ROS offers many tools that ensure timing, data type conversion, and standardization layout of code.

6.3.1 SYSTEM HIERARCHY

This year´s team has continued the work from last year´s team, using both Simultaneous Mapping and Localization (SLAM) and OpenCV along with A* Path Planner.

The NUC uses the Point Cloud created thanks to the Kinect Camera to determine obstacles. Obstacles shall be defined as any obstruction that is above or below the plane defined by contact made by all four wheels. Additionally, the obstacle avoidance has a gap-finding feature. Any obstacle greater in height than the base of the robot, or in contact with the top of the robot from an overhang, shall be treated as an object to be avoided. Should an obstacle be determined to not make contact with the robot, within a degree of error, it shall be considered passable and treated as non-existent.

The Point Cloud and the obstacles detected are also used to create a map and to calculate the optimal path. This path planning is done via the A* Path Planning Algorithm. In A*, the world is broken down into a 2D grid squares (like a chessboard). This year the squares of the grid were defined to be half of the size of the robot, this is because the testing area was not very big and, otherwise, the robot would not be able to find an optimal path to the objective. Using the obstacle avoidance algorithm, each square of the grid is assigned a different value. The greater the value the greater immediate impediment to forward motion that obstacle is. Once the grid is completely defined with all the values, the A* algorithm is executed to find the most optimal path. One thing to consider is that the competition rules do not allow the autonomy to use the walls to travel through the arena. To avoid using the walls, the A* path planner only plans the path for the next 5 feet and updates the grid until it reaches the objective.

One possible risk of updating the grid so often is that the robot can start to make circles around an object. To avoid this, the Webcam with the gimbal system is used in a way that it does not let the robot turn around unless it has completed the digging task.

Throughout all the process, the NUC and the Raspberry Pi are in constant communication through a serial line. As it has been said earlier in the document, the NUC receives the data from the Kinect Camera and is in charge of creating the Point Cloud and the grid map using SLAM. On the other hand, the Raspberry Pi is in charge of controlling the motion of the robot and receiving the data from the IMU.

For all these operations the Raspberry Pi uses Ubuntu Mate OS and ROS Kinetic, both the NUC and the laptop use Ubuntu 16.04. Apart from these operating systems, OpenCV 3.2 is also used. OpenCV is a computer vision software that runs through ROS Kinetic. Concerning the communications protocols, I2C is used between the Raspberry Pi and the IMU, UART is used between the Raspberry Pi and the Roboclaws and SSH protocol is used between the NUC and the Raspberry Pi using an Ethernet cable.

6.3.2 SIMULTANEOUS LOCALIZATION AND MAPPING (SLAM)

SLAM is used to detect the possible obstacles or obstructions that can interfere between the robot and its predetermined objective. Apart from obstacle detection, SLAM is also used to build the map used to determine the path followed by the robot. Since regulations dictate walls impractical, a local window has been created to ensure all data outside of its range is disregarded. Grid maps are a 2D array that can include multiple layers of data within one cell. They can also have a specified width and length, as well as resolution of each cell. For this application, data in each cell includes elevation and surface normal axes. The data used for the elevation layer is obtained from the Kinect. If the camera detects values beyond thresholds (which are predetermined) safe for the robot to traverse, then these locations will be marked as invalid in the global map. This technique can also account for holes or craters, which may be too difficult for the robot to navigate. This grid map is put into a Kalman filter to ensure the map is followed correctly by the robot as it moves.

With the local window that has been created, walls are considered as very large obstacles and the robot will have to turn around and go towards the middle of the arena.

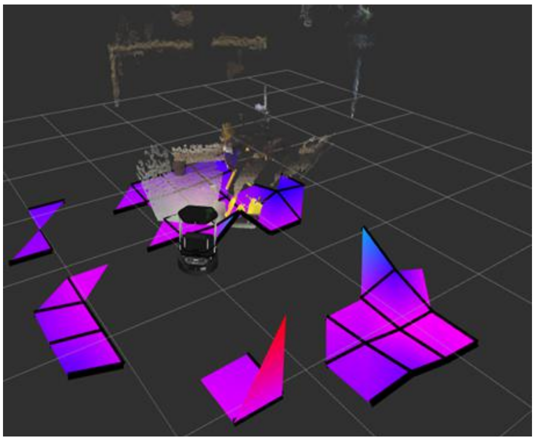


Image 38: Simultaneous Localization and Mapping (SLAM)

6.3.3 MOTION PLANNING

Thanks to the information obtained through the IMU and pose estimation, the robot has a strong estimate of its location within the competition arena. The grid map obtained using SLAM is a 2D grid, where cells are designated as go or no-go zones based on the mapping data. This 2D grid is then fed into the path planning algorithm (A*) to calculate the most optimal path to reach the mining area.

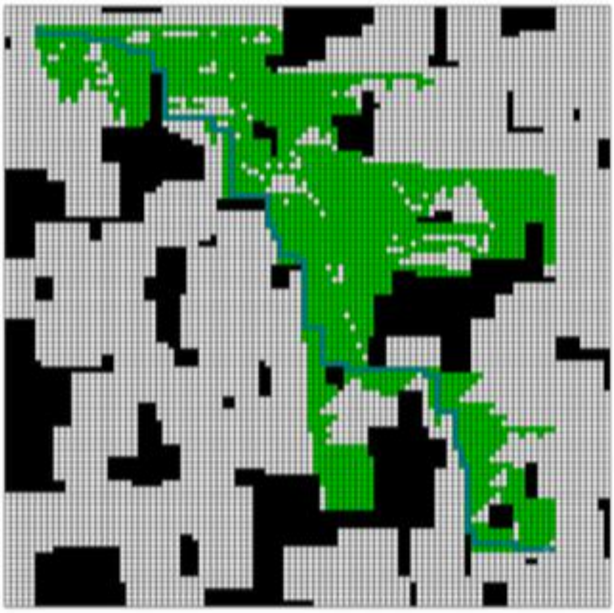


Image 39: A random map with blue computed path*

Image 39 shows a 100 by 100 grip map with a random path calculated by the A* path planner. The blue line in the image is the path calculated.

6.3.4 DEVELOPMENT OF THE AUTONOMY

This year the autonomy subsystem was mostly focused on developing the code for the A* Path Planning. The SLAM code was inherited from previous teams and seemed to work perfectly. Another task the autonomy subsystem had was to create, using ROS, the nodes needed to connect the different codes and tasks.

Last year´s team used the IMU and 4 encoders, one in each wheel, to calculate the relative position of the robot. The encoders of the wheels were used to calculate the distance travelled by the robot and the IMU utilized the accelerometer to see if the robot was moving or if it was stuck. However, based on the results from last year´s test, this method was not very reliable as the IMU indicated a massive leap forward by the robot when it was bumped. In addition to that, almost everyone recommended not to use encoders. Encouraged by these recommendations, this year the encoders were removed from the robot and only the IMU and the Webcam were used.

During the whole year the autonomy team has been working on developing the A* path planning and updating the SLAM code to work with the updated predetermined values for the new size of the robot and the size of the cells of the grid map. Also the team worked on creating a new code using python for the manual control. The most difficult task was to make openCV use the point cloud library to detect the obstacles and communicate the results to the NUC through ROS in order to create the grid map.

Due to the difficulty of this three tasks, the team decided that each member of the subsystem should work only on one of three tasks. The student was asked to develop the code for the manual control along with another teammate.

The code created for the manual control used the keyboard as an input and the output are the signals sent to the Roboclaws. The main keys used for manual control are the following:

- W, A, S, D: used for controlling the drivetrain motion.
- 1, 2: used for controlling the conveyor belt and the bucket ladder. 1 make both conveyor increase their speed and 2 makes them decrease it.
- Up, Down Arrows: used for controlling the lowering mechanism.
- Q, E: used for controlling the dumping system.
- Space: Shutdown the program and the digging system.

The manual control code has been written in python inside the Raspberry Pi. This code has to be accessed from the laptop, using the Wi-Fi communication and accessing the Raspberry Pi through the NUC.

6.3.5 TEST AND RESULTS

In this section the results obtained from testing the autonomy and the manual control will be explained.

In order to test the manual control, the Raspberry Pi was connected to the Roboclaws and the motors were connected to the Roboclaws. For this test the Raspberry Pi was powered using the official wall adaptor for this device. Also a USB was connected to the Raspberry Pi that allowed the navigation using a mouse and a keyboard. Once everything was connected, the code was executed and all the commands were tested to see the behavior of the robot.

The result of this test showed that the excavation system worked without any difficulty, but when trying the drivetrain motion, the delay that appeared when testing the Roboclaws appeared again, so a change in the settings of the Roboclaws was needed in order to make the code work flawlessly.

Other test were done for the manual control to ensure it worked in the same conditions as in the competition.

The following tests were controlling the Raspberry Pi via the NUC using an SSH communication protocol. The following one was, with this same SSH connection, but this time controlling the NUC with the laptop via Wi-Fi. The last test was like this last one but adjusting the router to the specifications of the competition.

All these test showed that the code worked without any major difficulty. At first the Wi-Fi communication did not work very well, but once that communication worked, the code did not give any problems.

For the autonomy the SLAM and the A* path planning codes were tested using a turtlebot like the one shown in image 40. The laptop with the code was placed on top of the turtlebot with the Kinect camera and the turtlebot was placed in a room with chairs and tables and some random obstacles. The result of this test was impressive as the turtlebot was able to navigate through the room avoiding all the obstacles.

Image 40: Autonomy testing

Unfortunately, when trying to put everything together there were some compatibility issues with the software used and the OpenCV. At this point, the autonomy subsystem was not complying with the schedule shown in appendix C, so it was decided to stop working on the autonomy of the robot and focused all the efforts on the other 2 subsystems.

7 FINAL IMPLEMENTATION

At this point, all the decisions about the robot design were already made, the only thing left was to build everything and connect the different components to make the robot work. The teammates of the student were in charge of building the bucket ladder, the storage bin, the conveyor belt and the pieces for the lowering system. Meanwhile, the student focused on finishing the power distribution system and to implement the excavation components once they were built.

When implementing the scissor lift and testing it with the motors, some problems appeared as some motors did not work correctly and they up burning; luckily, there were some spare motors that could be used. These problems appeared because that weight of the bucket ladder was higher than the calculated and this resulted in the necessity of a more powerful motor than the one tested the first time.

Other problem that appeared was that the conveyor belt was prone to getting stuck and stop moving. The only solution that was found was to modify the code for the manual control and make the conveyor belt move at constant speed.

Another problem appeared as the schedule planned at the beginning of the year could not be followed and some parts of the mechanical subsystem were built later than planned, leaving no time for the team to test the robot before the competition.

Although the complete robot could not be tested, some parts of it were tested with great results. The bucket ladder. The drivetrain and the storage bin were tested showing that they worked without any major difficulties.

In the following page there can be seen 2 images, the first one of the robot almost finished and the second one of the first test of the bucket ladder with the robot completely built. When this test was finished the robot was disassembled for shipping it to the competition.

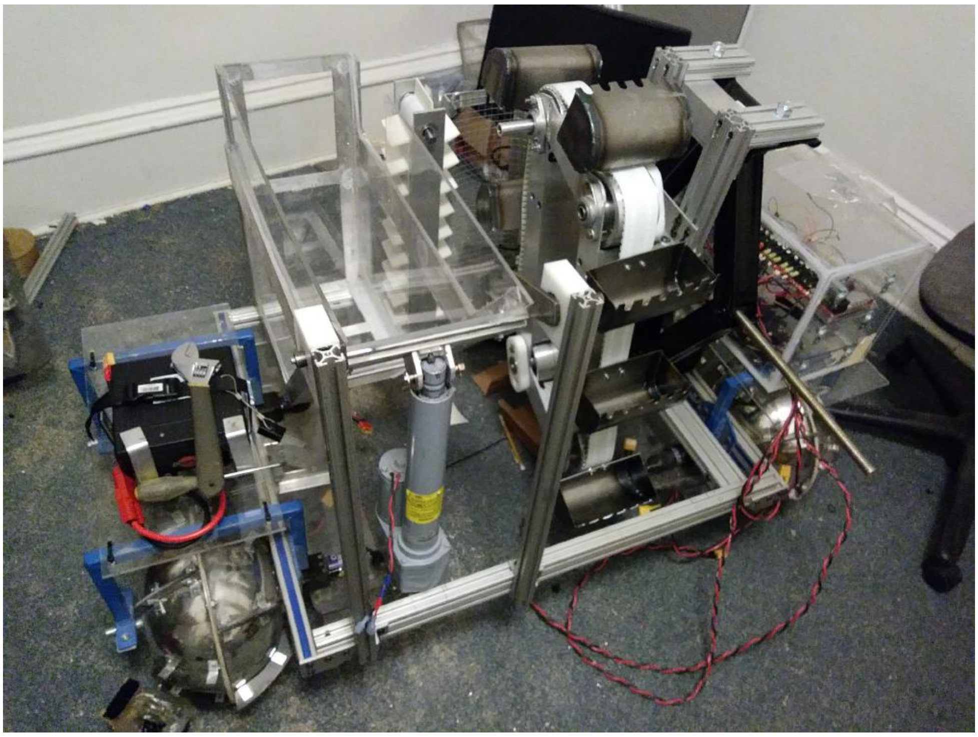


Image 41: completely assembled robot

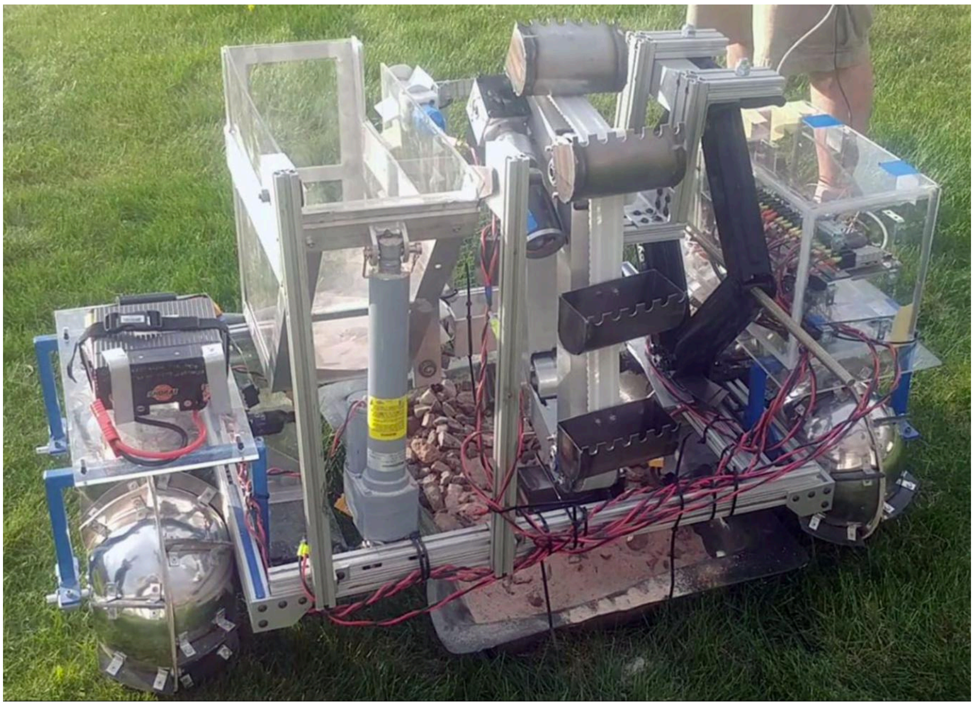


Image 42: Bucket ladder final test

8 COMPETITION

The competition took place in the Kennedy Space Center, Florida, U.S. between the 14th and the 18th of May. There were a total of 44 different teams during the competition. Each team was assigned a working area called Robopit in which the team worked in their robot and made the proper modifications in order to perform as good as possible during the competition.

The competition consisted on 2 different attempts of 10 minutes each. During each attempt the robot has to go to the mining area avoiding the obstacles placed randomly in the obstacles zone and dig. When the robot finished the mining task, it has to go back to the starting area and dump the icy regolith into the collector bin.

The competition arena was a big tent placed outside the building where the Robopit were, so the robot had to be transported from one place to another, but, before taking the robot to the competition arena, some inspections regarding the weight and the dimensions of the robot had to be done. Image 43 shows the robot being transported to the competition arena.

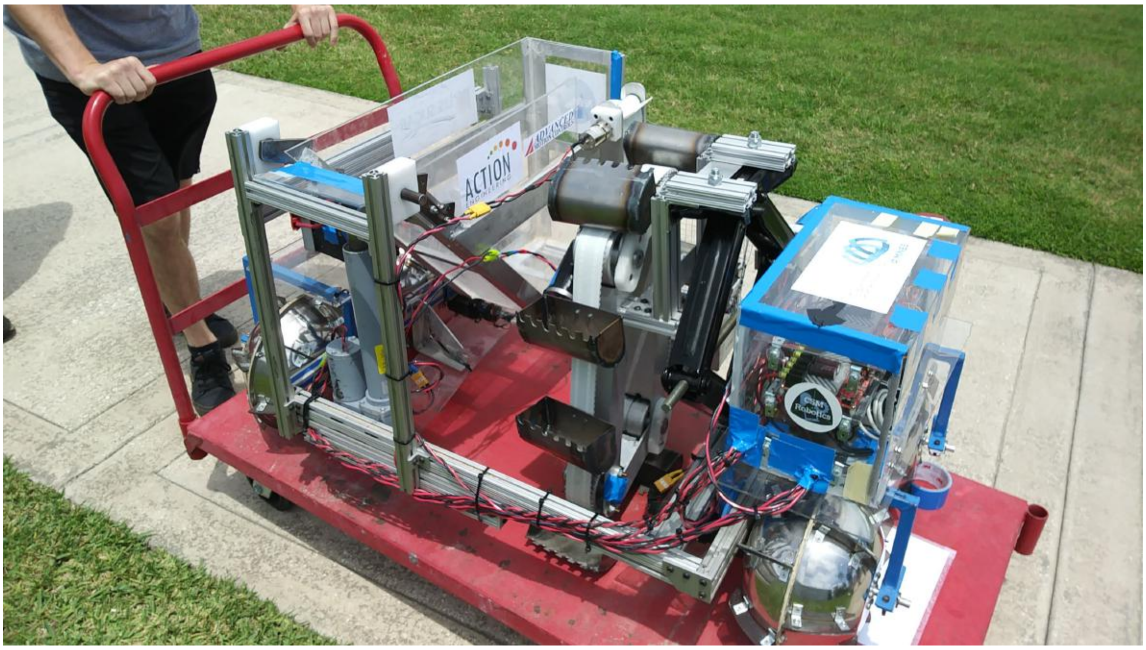
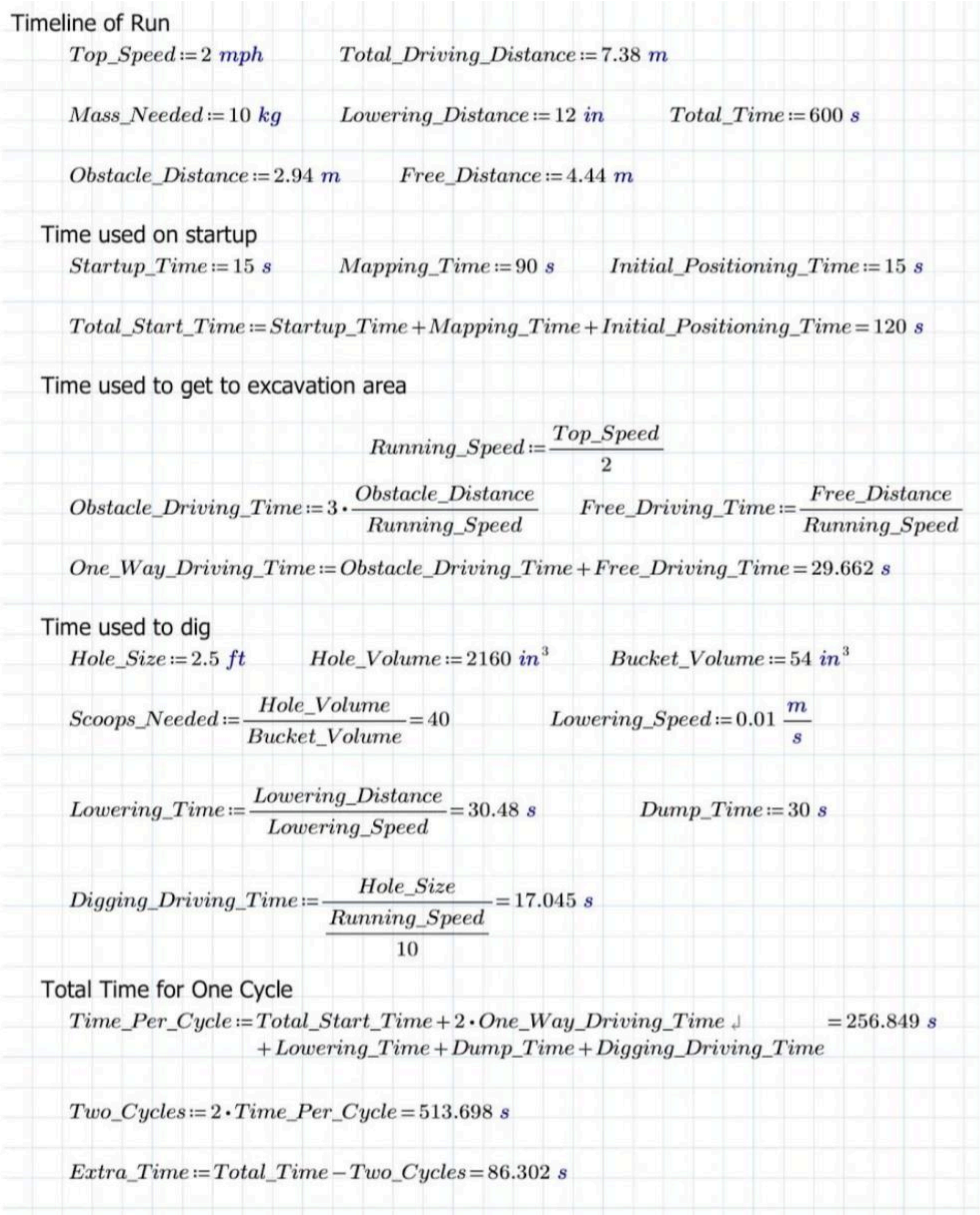


Image 43: Robot being transported to the competition arena

8.1 TIME CALCULATIONS

In order to know how many cycles the robot was able to do during the 10-minute attempt, time calculations were done, calculating the time delegated to each task during the competition. The result of the calculations showed the robot was capable of completing 2 cycles and it still had 86 seconds more in case something went wrong.



Timeline of Run

$Top\_Speed := 2\ mph$ $Total\_Driving\_Distance := 7.38\ m$

$Mass\_Needed := 10\ kg$ $Lowering\_Distance := 12\ in$ $Total\_Time := 600\ s$

$Obstacle\_Distance := 2.94\ m$ $Free\_Distance := 4.44\ m$

Time used on startup

$Startup\_Time := 15\ s$ $Mapping\_Time := 90\ s$ $Initial\_Positioning\_Time := 15\ s$

$Total\_Start\_Time := Startup\_Time + Mapping\_Time + Initial\_Positioning\_Time = 120\ s$

Time used to get to excavation area

$$Running\_Speed := \frac{Top\_Speed}{2}$$

$$Obstacle\_Driving\_Time := 3 \cdot \frac{Obstacle\_Distance}{Running\_Speed} \qquad Free\_Driving\_Time := \frac{Free\_Distance}{Running\_Speed}$$

$One\_Way\_Driving\_Time := Obstacle\_Driving\_Time + Free\_Driving\_Time = 29.662\ s$

Time used to dig

$Hole\_Size := 2.5\ ft$ $Hole\_Volume := 2160\ in^3$ $Bucket\_Volume := 54\ in^3$

$$Scoops\_Needed := \frac{Hole\_Volume}{Bucket\_Volume} = 40 \qquad Lowering\_Speed := 0.01\ \frac{m}{s}$$

$$Lowering\_Time := \frac{Lowering\_Distance}{Lowering\_Speed} = 30.48\ s \qquad Dump\_Time := 30\ s$$

$$Digging\_Driving\_Time := \frac{Hole\_Size}{\frac{Running\_Speed}{10}} = 17.045\ s$$

Total Time for One Cycle

$$Time\_Per\_Cycle := Total\_Start\_Time + 2 \cdot One\_Way\_Driving\_Time + Lowering\_Time + Dump\_Time + Digging\_Driving\_Time = 256.849\ s$$

$Two\_Cycles := 2 \cdot Time\_Per\_Cycle = 513.698\ s$

$Extra\_Time := Total\_Time - Two\_Cycles = 86.302\ s$

Image 44: time calculations for the competition

8.2 PERFORMANCE AND RESULTS

During the competition, the first two days were used for assembling the robot and going to the security inspection, once the security inspection was done, the robot was ready for competing and the weight and dimensions inspection was done. The results of these inspections were that the robot weighted almost 79 Kg and the dimensions were all pretty close to the maximum dimensions allowed by the competition; the actual dimensions of the robot were: 1.40 m length x 0.71 m width x 0.75 m height.

In order to achieve these dimensions some modifications had to be done during the competition. The most important modification was that the screw of the scissor jack had to be cut as it was too long, these meant that the bucket ladder could not be lowered as much as before.

The performance of the robot was not the best one as it was not able to dump any gravel in the collector bin. During the first attempt the conveyor belt that connected the filtering system and the storage bin got stuck due to some rocks and this ended up in the Roboclaw giving too much power to the motor and burning it. In the second attempt, everything was working perfectly and the robot was dumping gravel into the storage bin, but, when the robot was going back to the dumping station, it got stuck because the bucket ladder was too low and this resulted in the reboot of the Roboclaws, losing all communication with them.

Even though the score on the mining section was 0, the team managed to get the 14th place in the competition. The official scores of the competition can be seen in Appendix D.

9 CONCLUSION

This was not an easy project, building a robot is not something everyone can do. The effort of all the team members during the whole year has been has been the key to the good performance of the robot during the competition. The performance could have been better if the deadlines stablished at the beginning of the year were followed, that would have let the team some time to test the robot and see the possible problems it could have during the competition. However, creating a robot almost from scratch and being able to compete passing the security inspection is something to be proud of.

All the decisions of the project were done creating the proper decision matrices and asking for the advice of students and professors. Overall, the team and the student think they have made the best decisions for the project. The only thing that may not be considered a success was that, unfortunately, the autonomy of the robot could not be finished and implemented in the robot, only leaving the manual control for the competition.

Overall, it can be said that this project was a great success. It is not easy to make a fully functional robot, and it is more difficult for undergraduate students who had never worked on a project this big. All the members of the team have been working really hard during the whole year in order to achieve the internal objectives of the team.

The success of the project is reflected in the position obtained in the competition. This year´s team was 14 out of 44 different teams. This is a great result if we take into account that other teams had much more members and their budget was higher.

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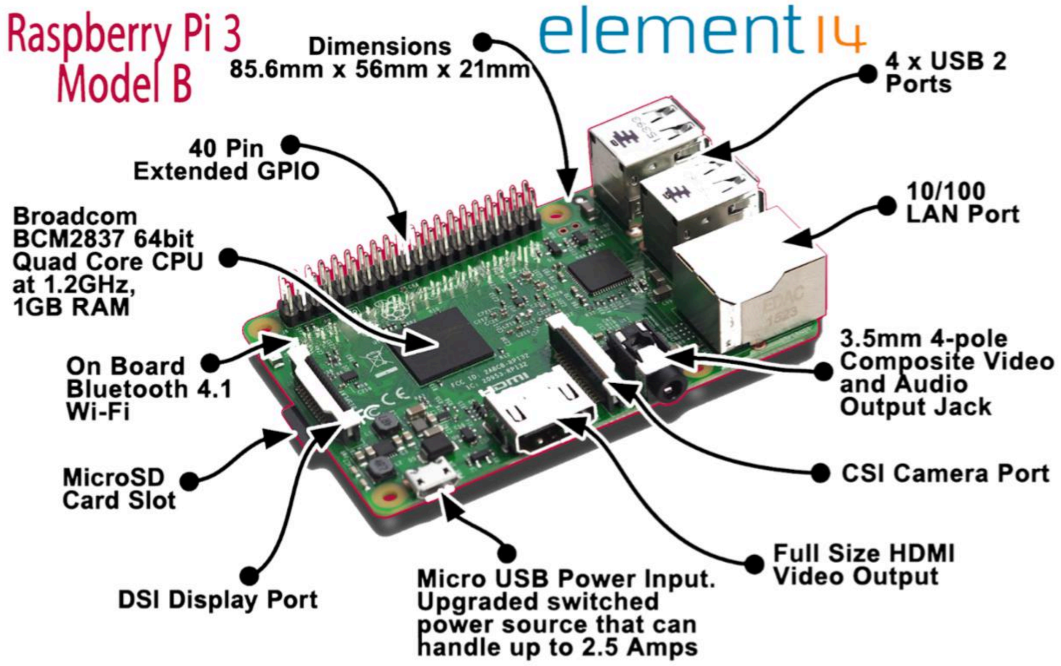
APPENDIX A: NUC SPECIFICATIONS

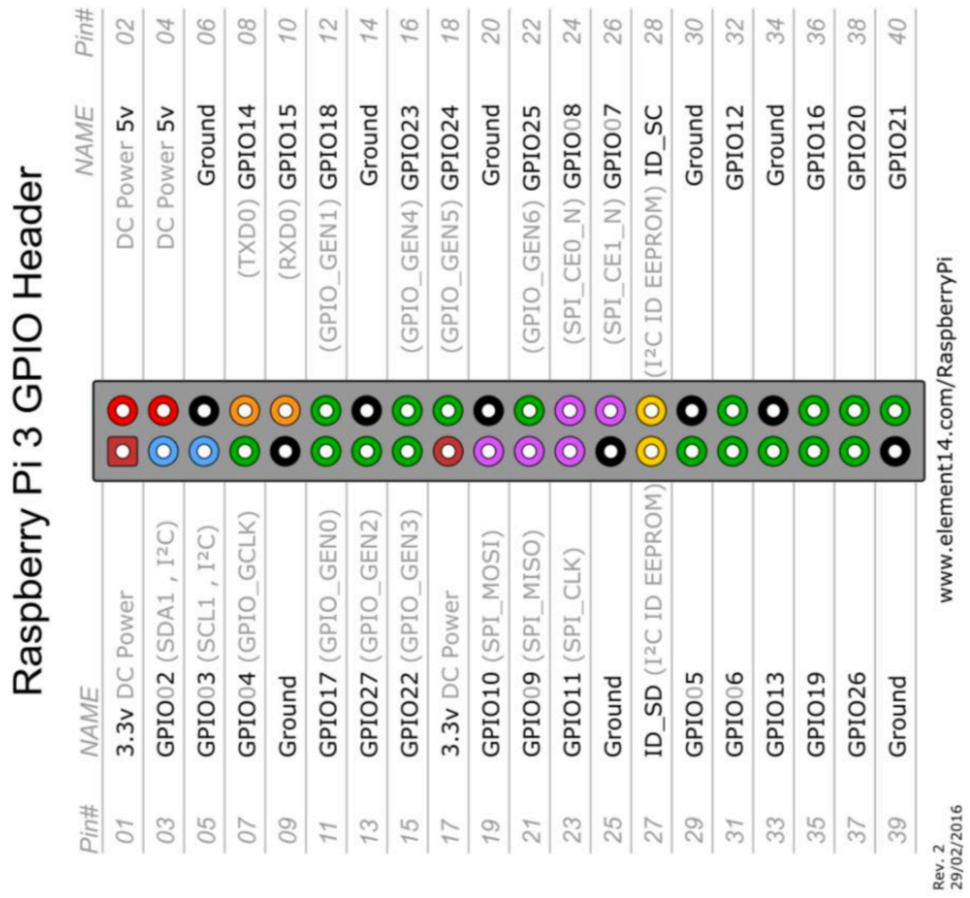
POWER, CAPABILITIES, AND PERFORMANCE IN FOUR INCHES SQUARE

Highlighted Features

1 7th generation Intel® Core™ i7-7567U processor
2 Intel® Iris™ Plus Graphics 650
3 Two DDR4 SO-DIMM sockets (up to 32 GB, 2133 MHz)
4 1x SATA3 port for connection to 2.5" HDD or SSD
5 M.2 slot with flexible support for a 42 or 80 mm M.2 SSD
6 Intel® Optane™ Memory ready
7 Intel® Dual Band Wireless-AC 8265 and Bluetooth* 4.2
8 Back panel DC power connector (12–19V)
9 One full-size HDMI* 2.0 display port supporting 8 channel audio (7.1 surround sound)
10 Intel® Gigabit LAN
11 Two USB 3.0 ports on the back panel
12 Thunderbolt™ 3 port with support for USB* 3.1 gen 2, DisplayPort* 1.2 and 40 Gb/s Thunderbolt
13 Kensington lock support
14 Support for user-replaceable third-party lids
15 Micro SD card slot
16 Consumer infrared sensor
17 Two USB 3.0 ports (including one charging port) on the front panel
18 Front panel headphone/microphone jack
19 Front panel power button
20 Dual-array front microphones
21 Multi-color front panel LED ring

APPENDIX B: RASPBERRY PI 3 SPECIFICATIONS





Raspberry Pi 3 GPIO Header

Pin#	NAME	NAME	Pin#
01	3.3v DC Power	DC Power 5v	02
03	GPIO02 (SDA1 , I^{2}C)	DC Power 5v	04
05	GPIO03 (SCL1 , I^{2}C)	Ground	06
07	GPIO04 (GPIO_GCLK)	(TXD0) GPIO14	08
09	Ground	(RXD0) GPIO15	10
11	GPIO17 (GPIO_GEN0)	(GPIO_GEN1) GPIO18	12
13	GPIO27 (GPIO_GEN2)	Ground	14
15	GPIO22 (GPIO_GEN3)	(GPIO_GEN4) GPIO23	16
17	3.3v DC Power	(GPIO_GEN5) GPIO24	18
19	GPIO10 (SPI_MOSI)	Ground	20
21	GPIO09 (SPI_MISO)	(GPIO_GEN6) GPIO25	22
23	GPIO11 (SPI_CLK)	(SPI_CE0_N) GPIO08	24
25	Ground	(SPI_CE1_N) GPIO07	26
27	ID_SD (I^{2}C ID EEPROM)	(I^{2}C ID EEPROM) ID_SC	28
29	GPIO05	Ground	30
31	GPIO06	GPIO12	32
33	GPIO13	Ground	34
35	GPIO19	GPIO16	36
37	GPIO26	GPIO20	38
39	Ground	GPIO21	40

www.element14.com/RaspberryPi

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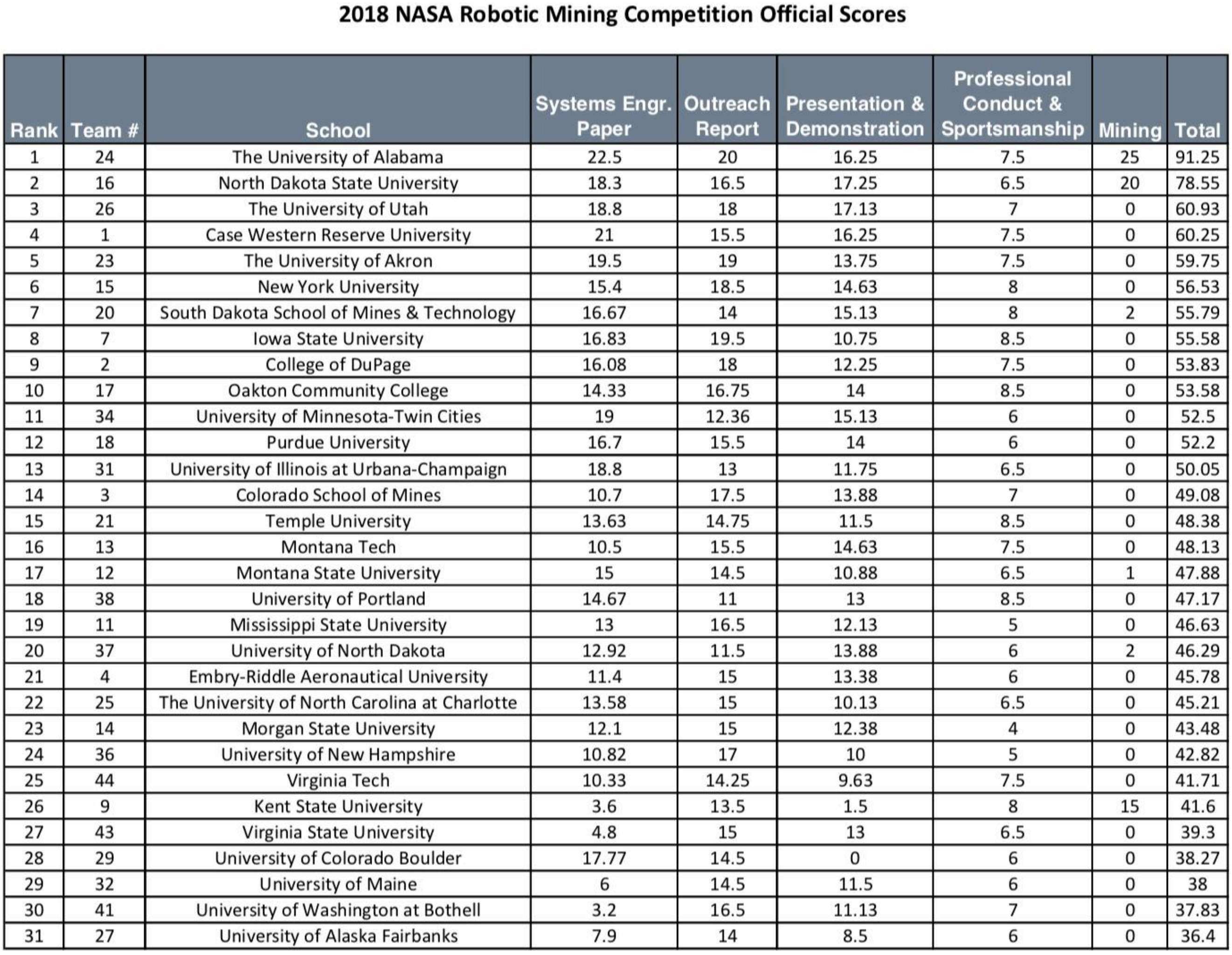
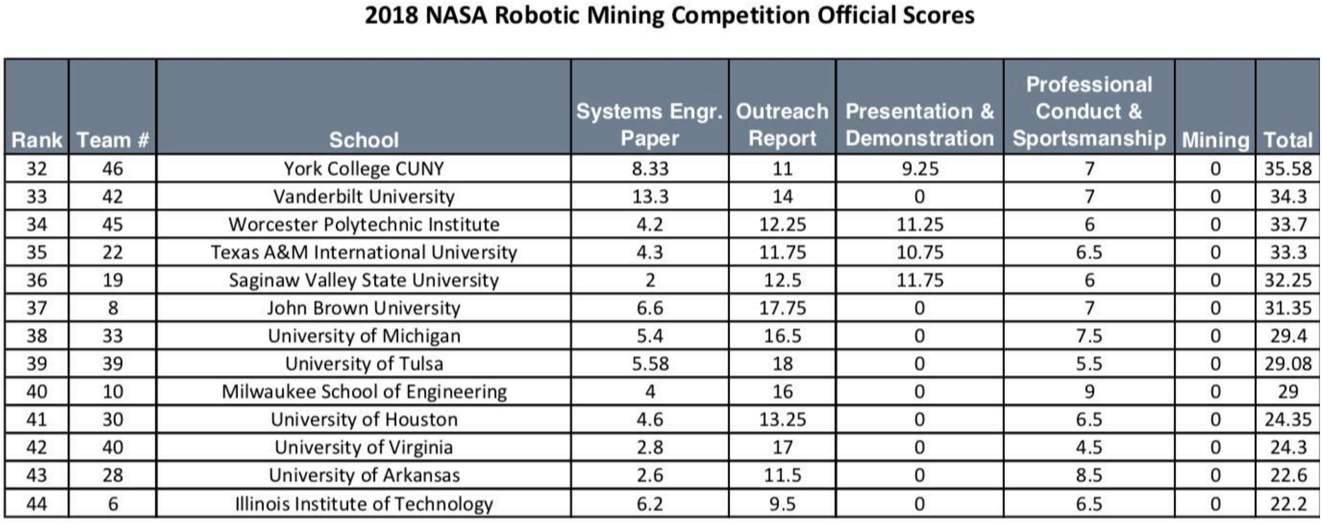
APPENDIX C: SCHEDULE

APPENDIX D: OFFICIAL SCORES



2018 NASA Robotic Mining Competition Official Scores

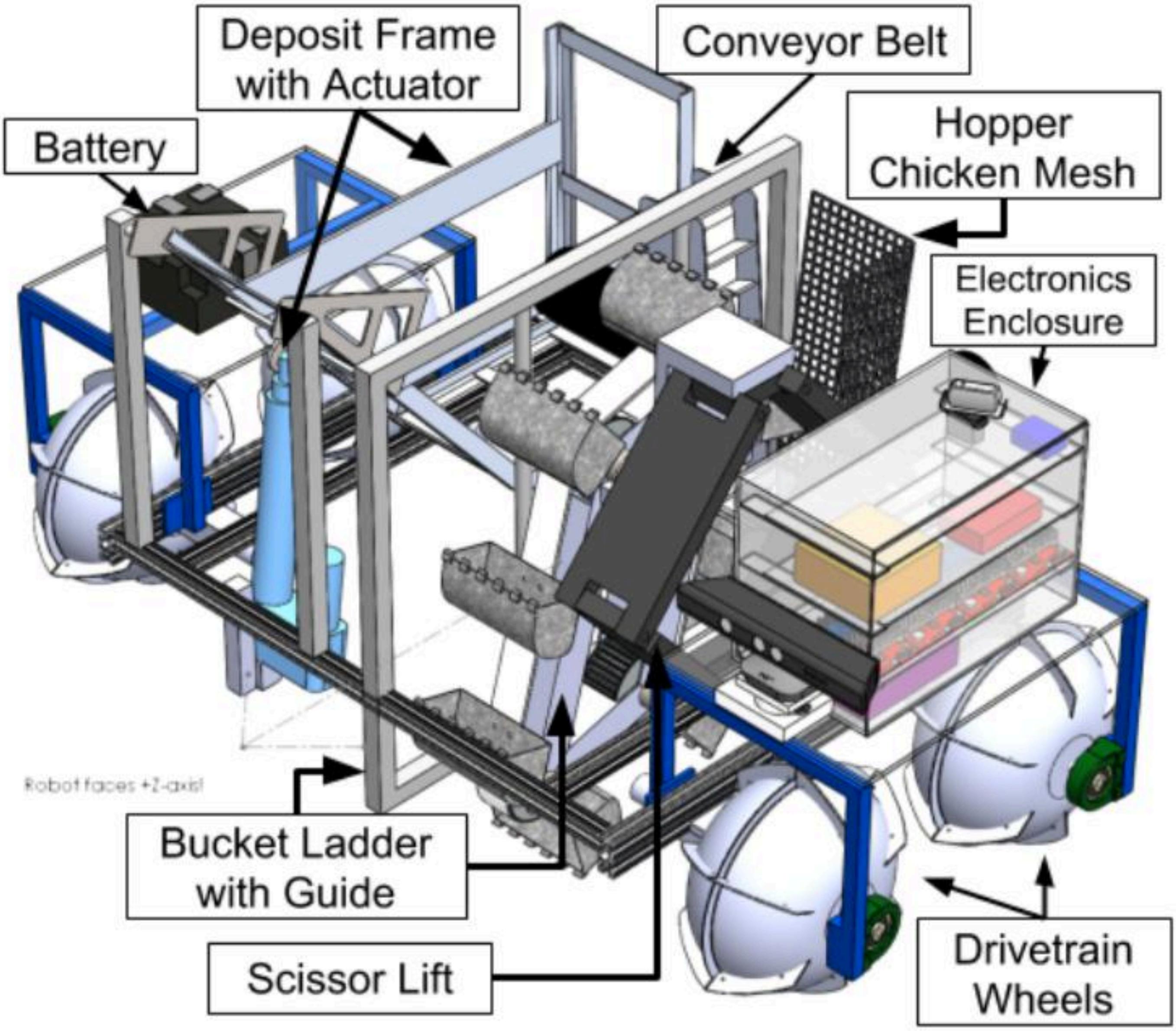
Rank	Team #	School	Systems Engr. Paper	Outreach Report	Presentation & Demonstration	Professional Conduct & Sportsmanship	Mining	Total
1	24	The University of Alabama	22.5	20	16.25	7.5	25	91.25
2	16	North Dakota State University	18.3	16.5	17.25	6.5	20	78.55
3	26	The University of Utah	18.8	18	17.13	7	0	60.93
4	1	Case Western Reserve University	21	15.5	16.25	7.5	0	60.25
5	23	The University of Akron	19.5	19	13.75	7.5	0	59.75
6	15	New York University	15.4	18.5	14.63	8	0	56.53
7	20	South Dakota School of Mines & Technology	16.67	14	15.13	8	2	55.79
8	7	Iowa State University	16.83	19.5	10.75	8.5	0	55.58
9	2	College of DuPage	16.08	18	12.25	7.5	0	53.83
10	17	Oakton Community College	14.33	16.75	14	8.5	0	53.58
11	34	University of Minnesota-Twin Cities	19	12.36	15.13	6	0	52.5
12	18	Purdue University	16.7	15.5	14	6	0	52.2
13	31	University of Illinois at Urbana-Champaign	18.8	13	11.75	6.5	0	50.05
14	3	Colorado School of Mines	10.7	17.5	13.88	7	0	49.08
15	21	Temple University	13.63	14.75	11.5	8.5	0	48.38
16	13	Montana Tech	10.5	15.5	14.63	7.5	0	48.13
17	12	Montana State University	15	14.5	10.88	6.5	1	47.88
18	38	University of Portland	14.67	11	13	8.5	0	47.17
19	11	Mississippi State University	13	16.5	12.13	5	0	46.63
20	37	University of North Dakota	12.92	11.5	13.88	6	2	46.29
21	4	Embry-Riddle Aeronautical University	11.4	15	13.38	6	0	45.78
22	25	The University of North Carolina at Charlotte	13.58	15	10.13	6.5	0	45.21
23	14	Morgan State University	12.1	15	12.38	4	0	43.48
24	36	University of New Hampshire	10.82	17	10	5	0	42.82
25	44	Virginia Tech	10.33	14.25	9.63	7.5	0	41.71
26	9	Kent State University	3.6	13.5	1.5	8	15	41.6
27	43	Virginia State University	4.8	15	13	6.5	0	39.3
28	29	University of Colorado Boulder	17.77	14.5	0	6	0	38.27
29	32	University of Maine	6	14.5	11.5	6	0	38
30	41	University of Washington at Bothell	3.2	16.5	11.13	7	0	37.83
31	27	University of Alaska Fairbanks	7.9	14	8.5	6	0	36.4



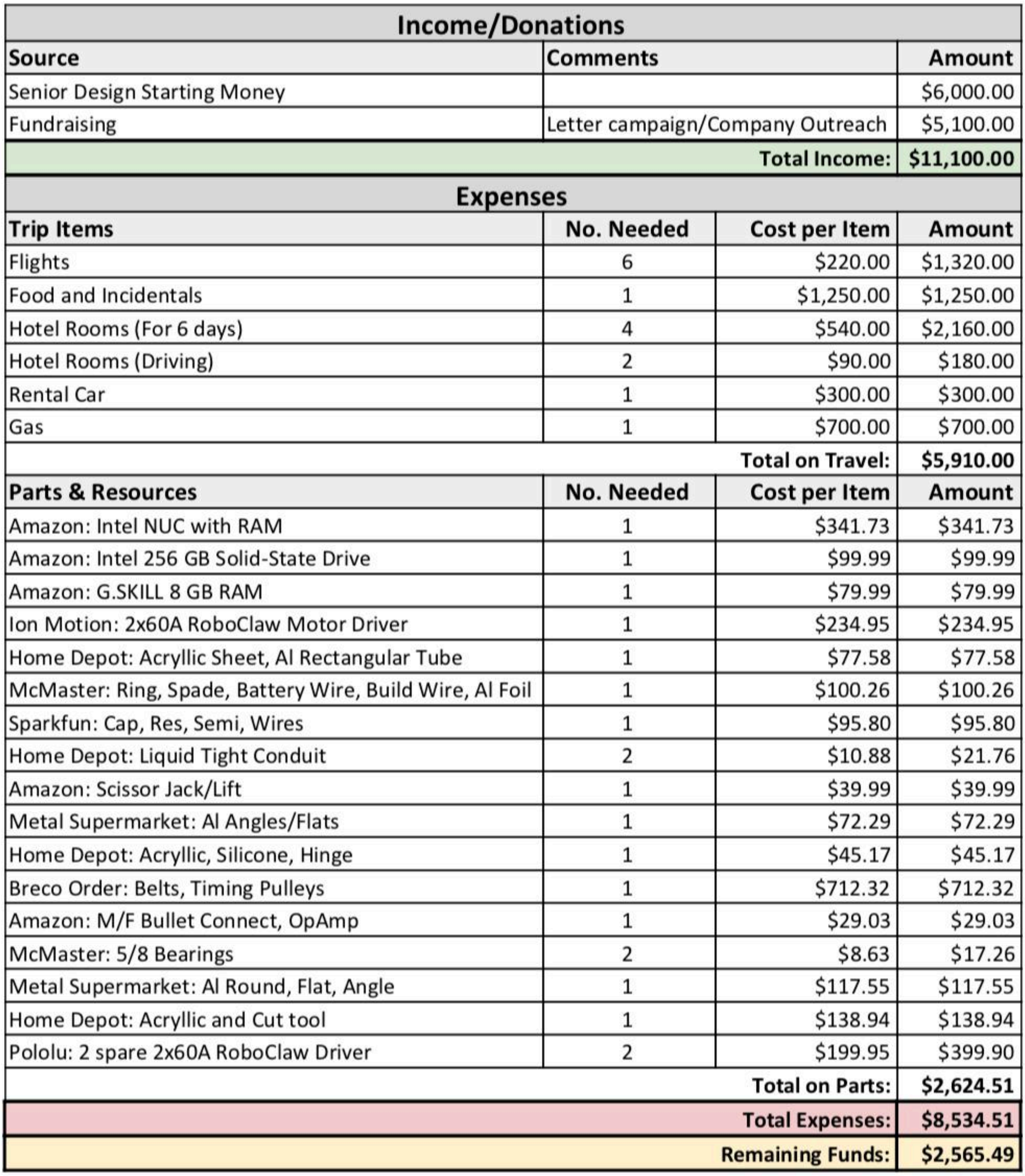
2018 NASA Robotic Mining Competition Official Scores

Rank	Team #	School	Systems Engr. Paper	Outreach Report	Presentation & Demonstration	Professional Conduct & Sportsmanship	Mining	Total
32	46	York College CUNY	8.33	11	9.25	7	0	35.58
33	42	Vanderbilt University	13.3	14	0	7	0	34.3
34	45	Worcester Polytechnic Institute	4.2	12.25	11.25	6	0	33.7
35	22	Texas A&M International University	4.3	11.75	10.75	6.5	0	33.3
36	19	Saginaw Valley State University	2	12.5	11.75	6	0	32.25
37	8	John Brown University	6.6	17.75	0	7	0	31.35
38	33	University of Michigan	5.4	16.5	0	7.5	0	29.4
39	39	University of Tulsa	5.58	18	0	5.5	0	29.08
40	10	Milwaukee School of Engineering	4	16	0	9	0	29
41	30	University of Houston	4.6	13.25	0	6.5	0	24.35
42	40	University of Virginia	2.8	17	0	4.5	0	24.3
43	28	University of Arkansas	2.6	11.5	0	8.5	0	22.6
44	6	Illinois Institute of Technology	6.2	9.5	0	6.5	0	22.2

APPENDIX E: FINAL DRAFT OF THE ROBOT



APPENDIX F: BUDGET



Income/Donations			
Source	**Comments**		**Amount**
Senior Design Starting Money			$6,000.00
Fundraising	Letter campaign/Company Outreach		$5,100.00
		Total Income:	**$11,100.00**
Expenses			
Trip Items	**No. Needed**	**Cost per Item**	**Amount**
Flights	6	$220.00	$1,320.00
Food and Incidentals	1	$1,250.00	$1,250.00
Hotel Rooms (For 6 days)	4	$540.00	$2,160.00
Hotel Rooms (Driving)	2	$90.00	$180.00
Rental Car	1	$300.00	$300.00
Gas	1	$700.00	$700.00
		Total on Travel:	**$5,910.00**
Parts & Resources	**No. Needed**	**Cost per Item**	**Amount**
Amazon: Intel NUC with RAM	1	$341.73	$341.73
Amazon: Intel 256 GB Solid-State Drive	1	$99.99	$99.99
Amazon: G.SKILL 8 GB RAM	1	$79.99	$79.99
Ion Motion: 2x60A RoboClaw Motor Driver	1	$234.95	$234.95
Home Depot: Acryllic Sheet, Al Rectangular Tube	1	$77.58	$77.58
McMaster: Ring, Spade, Battery Wire, Build Wire, Al Foil	1	$100.26	$100.26
Sparkfun: Cap, Res, Semi, Wires	1	$95.80	$95.80
Home Depot: Liquid Tight Conduit	2	$10.88	$21.76
Amazon: Scissor Jack/Lift	1	$39.99	$39.99
Metal Supermarket: Al Angles/Flats	1	$72.29	$72.29
Home Depot: Acryllic, Silicone, Hinge	1	$45.17	$45.17
Breco Order: Belts, Timing Pulleys	1	$712.32	$712.32
Amazon: M/F Bullet Connect, OpAmp	1	$29.03	$29.03
McMaster: 5/8 Bearings	2	$8.63	$17.26
Metal Supermarket: Al Round, Flat, Angle	1	$117.55	$117.55
Home Depot: Acryllic and Cut tool	1	$138.94	$138.94
Pololu: 2 spare 2x60A RoboClaw Driver	2	$199.95	$399.90
		Total on Parts:	**$2,624.51**
		Total Expenses:	**$8,534.51**
		Remaining Funds:	**$2,565.49**