# Mars Cargo Mobility System - Research, Planning, and Results

Team 06

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Dr. Ortega,

The engineering design team has been active in finding creative solutions on making the most efficient MACRO for your needs on Mars. As a refresher, we were entrusted with the duty of delivering certain cargo from a drop off location to one of the MITEER facilities. The MACRO must deliver this cargo in an upright orientation, along with other requirements, such as being able to get over obstacles and follow a designated path. The team has focused on not only meeting these requirements, but also going above and beyond them to ensure that the MACRO is the best possible choice for MITEER.

The first feature the team wishes to draw your attention to is the Dual Ultrasonic System for obstacle avoidance and incline attainability. This system featured one ultrasonic sensor aimed at the ground that would detect an elevation change immediately before the robot. If one was detected, it indicated that there was an obstacle or a hill and the MACRO would need to respond to ensure it would overcome the hill or obstacle. The second ultrasonic sensor was aimed directly forward, this was used determine if there was a moving obstacle in the path of the MACRO. If this ultrasonic detected something within three centimeters it would alert the MACRO and adjust the actions accordingly.

Another feature the team wishes to highlight is the cargo delivery system that is in place. The MACRO has a magnetic sensor that detects the location of the drop zone, lowers a ramp to an angle of 23.5°, and raises the forward section of the platform the cargo rides on to a very slight angle that will allow the cargo to slide off the MACRO cargo hold and onto the drop zone with ease. This process in incredibly efficient and reliable in dropping off the cargo exactly as wished 55.56% of the time. There are many ways to confront this issue, but this version ensures accuracy, reliability, and productivity.

The last feature the team wishes to focus on is the line following capabilities. By featuring a dual line finder and color sensor system, the MACRO was able to follow lines. By using the system mentioned above, the team was able to feature a system that only strayed from the line by a maximum of five centimeters in either direction. This is incredibly reliable and much more accurate than any other method used to follow the line.

The team’s design for the MACRO also features:

- A Dual Rear Wheel Drive System
- A Low Friction Front Wheel System
- A Robust and Lightweight Chassis Design

The aforementioned features of the MACRO combine to embody a design that cannot be beat in performance for the desired mission. The team worked tirelessly to ensure that every possible scenario taken into account in guaranteeing a consistently reliable performance on which the MITEER Team could rely to ensure the success of the entire mission.

Another added benefit of the team’s design is the ability to be easily applied to the large-scale. The design can be taken nearly part for part and made into a full-scale version for on earth testing and implementation on the actual mission of the MACRO for MITEER and the Harris Corporation.

The team hopes that you are as excited about their design as they are and are eager to hear any feedback or questions that you may have. They wish to convey their gratitude for the opportunity to tackle this project for MITEER and Harris and hope that you will return to them with any future problems and projects that you wish to have solved.

Thank you for your time and your business,
Team 6

## Executive Summary

As time progresses into the future, the possibility of human exploration of Mars becomes more of a reality. With people living on the red planet, there needs to be a system implemented in order to deliver supplies to them via payloads. This project explores a design for an automated, robotic payload delivery system that is able to tackle the various challenges Martian terrain presents. The robot must be able to deliver the payloads both in an upright orientation as well as within a specified area so the neighboring facilities won't be damaged. Additionally, the rover must be able to carry the payloads without dropping them as it travels over both hills and rough terrain. Lastly, the robot must be able to follow a specified path given to it in the form of a line. It must be able to follow this line even if there are breaks in it or if parts of it are covered up.

The robot consists of a chassis frame with two wheels being motor driven in the back as well as two low-friction wheels that are not motor driven in the front. There are two ultrasonic sensors on the front of the robot - one facing downward to detect obstacles and the other facing forward to detect walls and other impassable obstacles. Also, a gyroscopic sensor is included on the bottom so the robot knows when it's traversing a hill. Two line following sensors and a color sensor are mounted on the front to keep the robot on course. On the back, there is a ramp mechanism that is used to deposit the cargo. Additionally, there is a touch sensor that is used to tell the robot which drop off location to go to.

Using an engineering specifications table, requirements were set for the robot design. As the robot currently stands, it can climb a ramp up to 31 degrees, follow a line with breaks up to 0.5 inches between segments, travel up to 40 cm/s, drive over obstacles 2 cm in height tall, deliver cargo in the proper orientation as well as carry the cargo without it falling out. At the demonstration, the robot was successfully able to follow the line around the cliff as well as successfully tackle the first obstacle. Unfortunately, after making it over the first obstacle, the robot did not continue to follow the line and began to venture off course. Overall, there are definitely areas of improvement for the robot, but it was fairly successful.

## Design Considerations

The design for the MACRO robot has gone through several iterations. Each one has gotten progressively closer to becoming a viable option for a Mars rover.

To start off, basic research on the style of rovers and features was conducted. This was used as a jump off point to begin the design process. The problem was defined and then the research led into brainstorming for the initial design. Using the culminated ideas, the first iteration was constructed . The robot was analyzed in what worked and did not work, and then ideas for major improvements were noted for iteration two. The first iteration of MACRO included four wheels, two of which were connected to an axis mounted on a motor powered gear system, enabling it to turn. In theory, this would enable the robot to turn easily and be more controlled. Unfortunately, it did not allow for a complete turning radius and would end up running into the chassis of the robot. Therefore, in later models the turning axle was not used. Also, the Raspberry Pi was hooked onto the side of the chassis, which worked for the time being. But once the robot started to cross larger obstacles, the pi would wobble significantly, generating the idea that the uneven distribution of weight could potentially cause more issues when the cargo was added. Finally, for the cargo deployment a conveyor belt was going to be added in the center of the robot. When the magnetic field is sensed, the conveyor belt would be activated, letting the cargo be shipped off of the chassis. When applied, the cargo was not delivered in the proper orientation, a needed outcome from the project.  Several modifications also occured to iteration one. The first modification included removing the conveyor belt and turning the motors of the wheels upward. Varying the position of the back motors had a positive impact as it allowed for more space underneath of the chassis, increasing the suspension of the robot. This proved to be effective while driving over obstacles as there was plenty of room under the robot for the obstacles so that the back wheels were still able to apply power. In modification two, the color sensor was added to the front of the robot to be able to follow the line. To start out with the robot only had one sensor, but in future models there are variations based on what did and did not work.

In regards to the software during iteration one, it was elementary, as the MACRO's structure wasn't complicated at this stage. Throughout the entire project, there was the same set-up prior and after a 'while' loop where the code was always modified. The set-up essentially imported the proper modules to use the BrickPi and GrovePi, took the sensors as inputs/got them ready to use, and had errors jump out of the loop so they could be addressed. As for this specific iteration, the code could drive the MARCO forward, as well as turn when it was needed. This iteration did not have functioning line following capabilities, so the turning was completely arbitrary. There was an attempt to use the color sensor for line following, however, the sensor had to be incredibly close to the ground to detect the correct color. It would have came in contact with obstacles throughout the course, so the sensor and its respective code were removed.

Next, iteration two was created after an in depth analyzation of the performance. This design added several new aspects to improve the robot's ability to carry and deliver cargo. First off, the conveyor belt idea was brought back, but this time was appended to the back of the robot, allowing for a greater area to hold cargo. Through various methods of testing, it was determined that this idea was impractical as the belt was high off of the ground. Because of the great distance, it was highly unlikely that the cargo would be deposited in the correct orientation. Another issue was the robot's ability to be able to climb hills. Because of the great weight on the back of the robot, when it attempted to drive up an incline the front wheels would come off of the ground, inhibiting its ability to climb hills. Aspects that were still included was the turning apparatus on the front of the robot, which still had issues completing a tight turn.

As for the software, the cargo dropoff was simple. The code ran the motor that started the conveyor belt. The main software change in this iteration came with the turning apparatus. Rather than stopping one back wheel and giving the other more power, the code slowed down the back wheels and gave just a bit of power to the front wheels, which put the wheels at an angle so the robot would begin to turn. As outlined earlier, the turning radius was not large enough, and it would be very difficult for the MACRO to recognize when to turn the front wheels back to going straight, so the whole idea was removed.

Again, an analyzation of the design was completed. It was then determined that starting with a completely new design was the best method for improvement. So, more ideas were brainstormed and a new design was built. The back wheels were still powered by motors that were turned upright, but the turning apparatus was discarded. In its place was two treadless wheels connected by the same free rotating axle. By not having tire treads, the coefficient of friction between the wheels and the ground was significantly less, allowing the front end to slide back and forth. This improved the robot’s line following capabilities as the back wheels would change speeds to induce turning and the front wheels would slide along the track. Also, these wheels are still able to rotate so that it would not restrict the robot’s forward motion. On the chassis of the robot is an area where the battery pack is held in place, an issue that occurred in the past two iterations. One downside of this iteration is that there is no area for the cargo to be held in place. This was a major issue as the cargo is large and requires more space to carry it. Iteration three also featured the repositioning of the Raspberry Pi to be centered over the front of the MACRO chassis. This was aimed at redispursing the weight so the robot had greater ease in overcoming hills and obstacles. Iteration three also featured a single mounted line follower on the undercarriage of the MACRO.

The iteration three code was mainly focused around the line following capabilities. The code from iteration one was used for the power and turning of back wheels; the only code written was for the line following. The idea was to have the robot very slightly turn left whenever the line finder detected black, and it would start to turn slightly right when it hit white color. In order to determine how many sensors would be utilized in the design as well as the code, a decision matrix was created in table 1 to weigh the performance of one, two, and three sensors. This fairly clean ‘if-else’ structure proved to work well by sticking to the left edge of any line. Unfortunately, it didn’t work when it hit a dashed line.

*Table 1: Decision Matrix Comparing the Performance of Various Numbers of Sensors*

| Customer Need | Technical Need | Weight | 1 sensor | 2 sensors | 3 sensors |
|---|---|---|---|---|---|
| Ability to follow a line | Minimum deviation from line | 10 | 7 cm<br>(0.24) | 9 cm<br>(0) | 5 cm<br>(0.49) |
| Be able to make tight turns | Small turning radius | 7 | 8 in<br>(0) | 6 in<br>(0.29) | 4.5 in<br>(0.38) |
| Sum of scores | | | 0.24 | 0.29 | 0.87 |

After that, iteration four was created and included an advanced cargo carrying apparatus. A platform was created where the cargo would be set and held in by the robotic arms. When the magnet was detected, the arms would open and a motor would turn a hinge that pushes the plate upward, creating a larger slant for the cargo to slide down. After some trial and error, it was determined that the arms were not strong enough to be able to hold the cargo on the robot. Therefore, in modification one the arms were taken off and instead a powered ramp that can move up and down. In order to decide which form of cargo to build, a decision matrix was created as demonstrated in table 2. Overall, the ramp method performed the best based on the customer needs. When the magnet is detected, power is given to the ramp, it lowers, and the platform is raised as to allow for the cargo to slide down the platform and ramp. This required lots of testing to determine if each variation of cargo would be able to slide down in the correct orientation. After several trials, this ended up being the best method to deliver cargo yet. Also within iteration four is an advanced line following mechanism that consists of two line sensors on the left and right side of the robot with the color sensor in between the two. This allowed multiple types of code to be tested using one, two, or three sensors.

*Table 2: Decision Matrix Comparing Various Types of Cargo Carrying and Delivery*

| Customer Need | Technical Need | Weight | Claw Arm | Cage | Push | Ramp |
|---|---|---|---|---|---|---|
| Not use lots of power | Minimize number of Motors | 3 | 1<br>(1.5) | 2<br>(0) | 2<br>(0) | 2<br>(0) |
| Not use lots of materials | Small volume ($mm^3$) | 5 | 952.5<br>(2.675) | 2,048.383<br>(0) | 806.45<br>(3.03) | 1,183<br>(2.11) |
| Deliver in the Proper Orientation | Maximize percentage of successful cargo depositations (20 trials) | 10 | 50%<br>(6.25) | 70%<br>(8.75) | 45%<br>(5.625) | 80%<br>(10) |
| Ability to carry large objects | Maximize mass (g) that the apparatus can hold | 10 | 100 g<br>(2.22) | 450 g<br>(10) | 450 g<br>(10) | 450 g<br>(10) |
| Sum of Scores | | | 12.645 | 18.75 | 18.655 | 22.11 |

On the coding side of things, there were two spotlights to focus on: cargo drop off and line following. The cargo drop off was fairly clean-cut; if the robot sensed a beacon (using experimental values for the magnet sensor), it would open the arms and push the ramp up so that the cargo could be slid off. It would then reset the arms and move along with the code. The line following was a bit different; code had to be written for the color sensor and the two line followers. After trial and error, a certain algorithm was settled upon. The color sensor acted like the line follower in iteration three - it would hug one edge of the black line by turning left when it hit anything but black and turned right when it did detect black. After that, the line finder code was predictable. If the left finder detected black, there was a fairly sharp turn and the robot was told to turn left. If the right line finder saw black, then it would obviously turn right. Even though this algorithm isn't complicated, it worked far more often than all of the previous tries, so this was the option to go with.

Once iteration four was passed, iteration five, what would be the final iteration, was created. The goal of iteration five was to refine the design to make it the best possible version. Iteration five had some of the most significant changes, most notably was the addition of many more sensors than in iteration four. It featured a dual ultrasonic sensor system in the front in which one was aimed down at the ground, and one was aimed directly forward. The one aimed at the ground detected whether or not there was a change in the elevation immediately before the robot indicating an obstacle or the beginning of a hill and the MACRO would respond appropriately. The one aimed forward would detect if there was a large obstacle in front of the macro. If this was such the MACRO would also respond appropriately. There was also the addition of a gyroscopic sensor mounted on the undercarriage to determine if the MACRO was still on an incline. Apart from that, the only other sensor added in the final iteration was the touch sensor. The touch sensor was to receive the user input for the cargo drop zone. Iteration five also featured a minor change to the cargo drop feature. The original ramp featured in iteration four was integrated into the chassis rather than just being mounted on top of such. The ramp that was eventually included in iteration four was also extended to decrease the angle the cargo would slide at. Iteration five also featured the addition of a battery back case mounted on the front to allow ease of holding the batteries in a specific place without the need to expend other materials.

In regards to the software, all the sensors that were added were simply coded up. The ultrasonic sensor facing forward was just told to stop the robot if anything was very close to it. The ultrasonic facing down detected the ground most of the time, but if there was something higher than the ground, it was assumed to be an obstacle and the power was increased for a second. At the beginning of the code, a 'for' loop was utilized, allowing a few seconds for the touch sensor to be pressed. The code only recognized when the input changed (0 to 1 or 1 to 0) and then it was divided by two to find how many times the user pressed the touch sensor. It could be pressed one, two, or three times to signify to which zone to turn into. Essentially, if the touch sensor was pressed twice, it would tell the robot to skip the first beacon and turn in to the second zone. After that, the previously made cargo code would take over to drop off the cargo. All of that combined is what made up the final MACRO code.

## MACRO Physical Analysis

To determine the maximum power output research was done on how to calculate the actual power. One equation that was determined to be incredibly useful was that the power of a system is equal to the voltage of the system multiplied by the current of the individual components of the system:

$$P = V \times \Sigma I$$

To determine the theoretical draw, research was done on the current of a battery in ideal scenarios. It was found that the theoretical current of a single battery running for 2 ½ hours was .9 A.[1] This resulted in a total current of 7.2 A. This value was used in conjunction with equation above to determine that theoretically the maximum power output by the system was 36 W.

To determine the actual power output, research was conducted on the current draw for their system. It was found that the Raspberry Pi 3 Model B had a current draw of 2.5 A.[2] It was then found that the current draw from a singular ultrasonic sensor is 8 mA,[3] so the value was doubled to represent the dual ultrasonic sensor system. When it was determined that current values would not be found online for the line finder, attention was turned toward making an estimation. Similar sensors, such as the color sensor, were used to estimate that the current draw was 5 mA. Next, attention was turned towards the current across the EV3 motors. It was found that one motor had a current draw of approximately .176 A,[4] this was multiplied by four to determine the current across all of the motors. It was also determined that the color sensor has a current draw of .096 A and the touch sensor has a current draw of .087 A.[3] Finally, the only other significant sub-component was the analog hall effect sensor. The exact hall effect pins that were used

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[1] (n.d.). AA ENERGIZER E91. Retrieved December 7, 2018, from http://data.energizer.com/pdfs/e91.pdf

[2] "FAQs - Raspberry Pi Documentation." https://www.raspberrypi.org/documentation/faqs/. Accessed 7 Dec. 2018.

[3] (n.d.). Grove - Ultrasonic Ranger - Seeed Wiki - Seeed Studio. Retrieved December 7, 2018, from http://wiki.seeedstudio.com/Grove-Ultrasonic_Ranger/

[4] (2013, December 4). Measuring EV3 Current Consumption - Dexter Industries. Retrieved December 7, 2018, from https://www.dexterindustries.com/ev3-current-consumption-measurement/

for the sensor were found,  indicating that the current draw for the hall effect sensor was 25 mA.[5]

After this, the system voltage of 5 V[1] and the total current were used to determine that the maximum actual power output was 14.065 W. This has a large discrepancy from the theoretical value of 36 W, but it accurately reflects the situation because all of the theoretical values are based on the conditions being ideal, and simply this was not the case. Energy in the system was lost to heat, sound, friction, and various other ways. With all of these factors coming into account, the power output determined represents the situation well.

To measure the maximum speed of the robot, both of the rear wheel driving motors were set to their maximum power value. Then, the robot was driven along a straight line alongside a tape measure. Speed can be calculated by dividing the distance travelled by the time it takes to do so. With this, several trials were done to see how long it took the robot to travel various distances. After these measurements were taken, outliers were removed and the average speed was calculated which came out to be 40 cm/s or 0.4 m/s. To calculate a comparable velocity value, the same current value found above in the power output section was use. From this value the calculated power for the 2 drivetrain motors was 1.76 W. Searching for the instantaneous velocity, the value of power was then divided by 1s to convert to energy. From there, the kinetic energy equation was used, knowing the mass of 1.394 kg, it was determined that the ideal theoretical maximum velocity was 1.589 m/s. This value seems very unrealistic, but one again the system was not ideal. It can be assumed that when conditions are not ideal, friction, and other energy loss forms are included, the velocity actually found is about ⅓ of the theoretical value.

The maximum size of obstacles that the MACRO prototype could over come ranged from 0 cm to 2.0 cm. To measure this value, obstacles were place in front of the robot that gradually increased in height. The robot tackled the 1 cm and 2 cm obstacles

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[5] (2018, January 3). A3144 Hall Effect Sensor Pinout, Working ... - Components101. Retrieved December 7, 2018, from https://components101.com/a3144-hall-effect-sensor

with ease but could not make it over the 2.5 cm obstacle. Theoretically, the MACRO should be able to conquer objects that are approximately two thirds as large as the radius of the wheel as the robot, as seen in Figure 1.

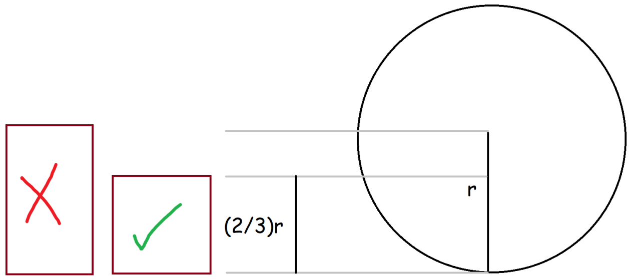

*Figure 1: The MACRO can cross obstacles up to ⅔ of its radius*

The size of objects is relevant to the mission as the MACRO will need to be able to cross different sizes of rubble on the planet. There is no way to know the exact sizes of the objects on Mars, and therefore the MACRO will need to be able to cross objects of various sizes to avoid wrecking the robot. If the MACRO is unable to cross an object, it will become stuck on Mars with no outside sources to set the vehicle back on track. Therefore, the maximum size of obstacles that the MACRO is able to overcome is imperative to its successful implementation on Mars.

To measure the turning radius of the robot, power was given to the left wheel motor and right wheel motor. These power values were of the same magnitude but opposite direction so the robot would drive in a circle. The robot's circular driving path could then be used to determine its turning radius, which was 4 inches.

To figure out the energy efficiency, a few factors were determined to be needed. One of which being the equation for energy efficiency which was determined to be:

$$\eta = \frac{Eexperimental}{Etheoretical} \times 100\%$$

However, the value of energy was not as straightforward as desired; however, it was determined that, using the equation for power given above and the definition of power in terms of energy, the equation to be used for solving for energy is:

$$E = V \times A \times T$$

By using the same values for voltage, 5V, amperage, 2.813 A experimentally and 7.2 A theoretically, and a time of 2 ½ hours, or 9,000 s. This 2 ½ hours come from the total length of time the MACRO was able to run before the batteries died. Using this, the energy for the experimental data was 126,585 J, and the energy value for the theoretical scenario was 324,000 J. These values give us an overall energy efficiency of 39.069%.

## Scaling to Official Mars Project

The environment here on earth is drastically different from the environment on Mars. In order for the prototyped robot to be successful on the red planet, there are several factors that must be taken into account. According to Space.com, the average temperature on Mars is about minus 80 degrees fahrenheit, dropping to as low as minus 195 at the poles and rising as high as 70 at the equator in the summer.[6] Considering Space.com also states the average temperature on earth is around 59 degrees fahrenheit,[7] this will definitely call for some redesigning of the robot. As seen in Figure 2, battery life and capacity are both affected by temperature changes, with temperatures below minus four degrees fahrenheit being considered non-operational.

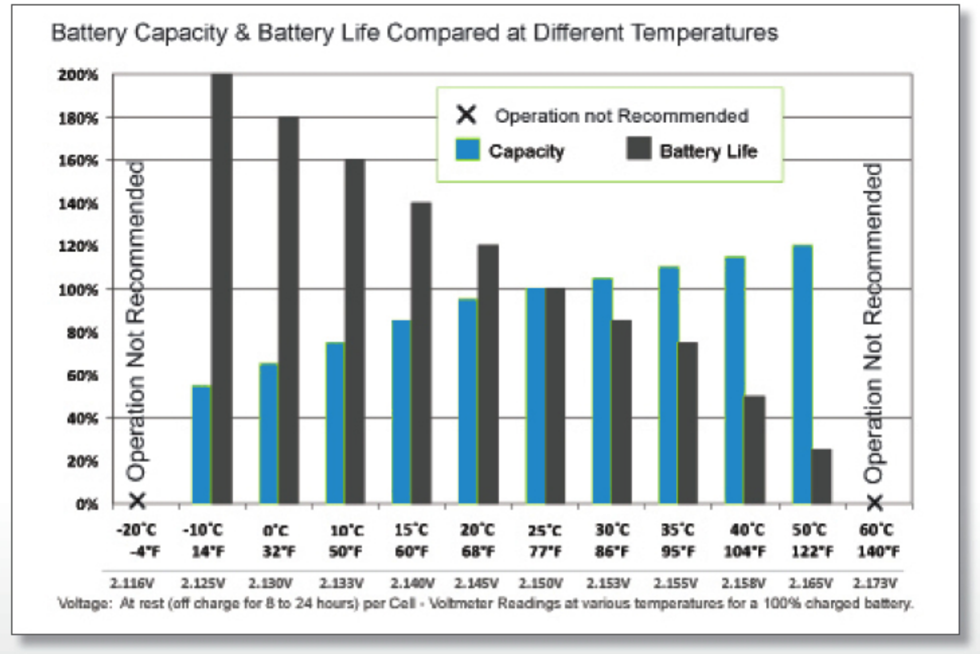

*Figure 2: Battery Life and Capacity vs Temperature*[8]

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[6] (2017, November 29). What is the Temperature of Mars? - Space.com. Retrieved December 7, 2018, from https://www.space.com/16907-what-is-the-temperature-of-mars.html

[7] (2018, April 23). What is the Temperature on Earth? - Space.com. Retrieved December 7, 2018, from https://www.space.com/17816-earth-temperature.html

[8] (2016, September 8). How temperature affects batteries - Tawaki Battery - Charge your way. Retrieved December 7, 2018, from http://www.tawaki-battery.com/how-temperature-affects-batteries/

Since the temperatures on Mars are on average significantly below the minimum operational temperature of batteries, it will be necessary to find a new way to power the robot. On approach could be solar power as stated by Universe Today, scientists have already determined that solar power will be the best possible approach to powering future martian colonies despite the issue of dust storms being prevalent on the planet.[9] Another idea is nuclear power. MIT Technology review states that NASA's Mars rover, Curiosity, is powered by a nuclear generator which is evidence that this approach would also work successfully.[10]

Another significant difference between Mars and Earth's environments is gravity. Science Trends' website explains that the acceleration due to gravity on Mars is only 3.71 $m/s^2$ - only 38% of Earth's 9.81 $m/s^2$.[11] This will have a number of effects on the robot. Many of them would be exhibited when the robot is attempting to traverse obstacles. Since there isn't as much gravitational force holding down the cargo, the probability of it potentially falling out of the robot when it passes over rough terrain is significantly higher. Additionally, the robot would likely have to tackle the obstacles slower than before since the decrease in gravitational force could cause it to become a lot more unstable when traversing, increasing its likelihood of tipping.

Lastly, Mars is known for its high winds and dust storms. The robot is currently used to travelling exclusively in controlled environments. In order for the robot to be able to withstand these high winds, a wind gauge could be installed on the robot. If the robot senses winds above a certain speed it would burrow itself into the ground or put up shields to protect itself until the storm passes. The robot could also finish the cargo sequence and return to its base, However, no data was collected in regard to odd weather, so further research is needed on this topic.

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[9] (2008, November 20). Despite Dust Storms, Solar Power is Best for Mars Colonies - Universe .... Retrieved December 7, 2018, from https://www.universetoday.com/21293/despite-dust-storms-solar-power-is-best-for-mars-colonies/

[10] (2012, August 7). Nuclear generator powers Curiosity Mars mission - MIT Technology .... Retrieved December 7, 2018, from https://www.technologyreview.com/s/428751/nuclear-generator-powers-curiosity-mars-mission/

[11] (2018, October 19). What Is The Gravity On Mars Vs. Moon Vs. Earth | Science Trends. Retrieved December 7, 2018, from https://sciencetrends.com/gravity-mars-vs-moon-vs-earth/

According to nasa.gov, NASA's Curiosity rover, which was already sent to Mars, is around 10 feet by 9 feet by 7 feet, so to scale up the MACRO to that size, all subsystem dimensions would have to be multiplied by 10 for a rough estimation. The MACRO subsystems can be seen in Figure 3.

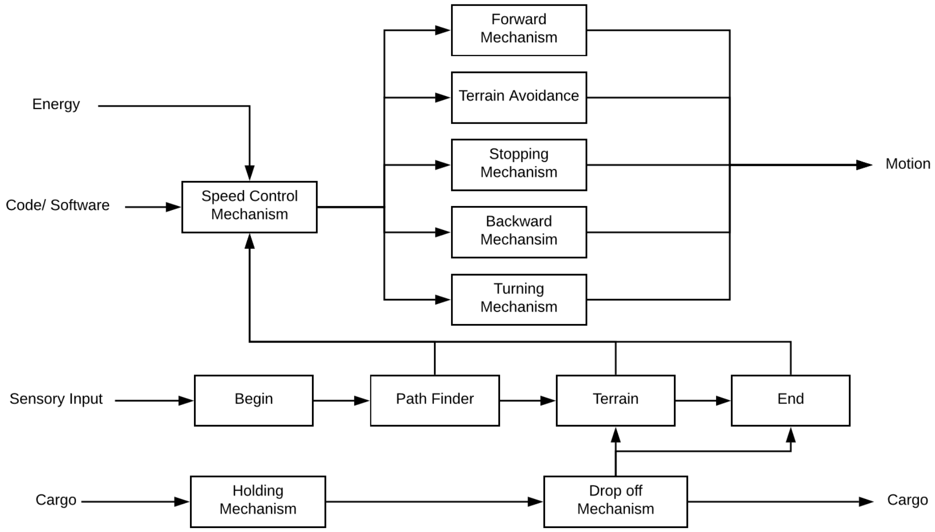

*Figure 3: Functional Block Diagram of MACRO Subsystems*

The line follow sensors are each 1.8 inches away from the centralized color sensor, meaning scaled up the line following sensors would be 1.5 feet away from the color sensor. The ultrasonic sensor that faces downward needs to be placed just above the top of the wheels to properly sense the obstacles. The diameter of the MACRO's wheels is currently  2.4 inches, therefore the ultrasonic would have to be roughly 2 feet above the ground. The MACRO's cargo dropoff bed is currently 5 inches by 4.8 inches, therefore in reality it should be 4.2 ft by 4 ft. If the MACRO were to be scaled up for Earth instead of Mars, the dimensions would most likely be the same. The biggest differences between an Earth model and a Mars model would be materials used as well as the overall weight of the robot. Dimensions aren't going to affect the performance of the robot from planet to planet. All of these values are summarized in Table 3. Scaling up the weight is not as easy of a calculation to complete due to uncertainties around which materials would be used on the final rover. NASA's Curiosity weighs around 894 kilograms therefore it can be assumed that the MACRO would have a similar weight once it was scaled up.[12]

*Table 3: Summary Table of Scaled up Dimensions*

| Subsystem | MACRO Dimensions | Earth Dimensions | Mars Dimensions |
|---|---|---|---|
| Line Tracking System | 1.8 inches between sensors | 1.5 ft between sensors | 1.5 ft between sensors |
| Ultrasonic Sensor placement | 2.4 inches off the ground | 2 ft off the ground | 2 ft off the ground |
| Cargo Bed Dimensions | 5 in by 4.8 in | 4.2 ft by 4 ft | 4.2 ft by 4 ft |

Spacing the line sensors out from 1.8 inches to 1.5 feet shouldn't be an issue, as increasing the space between them doesn't affect any other part of the sensors. However, it must be noted that the robot had GrovePi line finder sensors, which may not actually be able to be scaled up for use on the Mars robot. Fortunately there are replacements that would work, but no research has been done on that topic at this stage of the project.

On that same note, the GrovePi ultrasonic sensors worked quite well for the small prototype, but the same ones may not work on the full scale MACRO. The line finders would likely be changed with the scale up, so as a precaution measure, the ultrasonic sensors would likely updated as well. Similarly, no research has been done on the best types of sensors and how they perform, but there are options out there if or when the full scale robot is manufactured.

Depending on the material used, the cargo bed will most likely be fairly expensive since it would be one giant sheet of material. That being said, large sheets of material are

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[12] (n.d.). Rover - Mars Mobile. Retrieved December 7, 2018, from https://marsmobile.jpl.nasa.gov/msl/mission/rover/

regularly manufactured so finding one shouldn't be difficult. Additionally, finding wheels that are 2 ft in diameter will not be an issue at all as this is a standard size for car tires that are manufactured today.[13] This will enable the ultrasonic sensor to be easily mounted at its desired location.

On the current MACRO, the top speed is 40 cm/s. Scaling this value up would make the full size robot be able to go 4 m/s, but this scale-up would require an immense amount of assumptions. The mass of the scaled robot would differ heavily from the change in materials, the gravity on Mars is much different of that on Earth, the motors would have to be exactly 10 times more powerful, the cargo would have to be 10 times more heavy, and even more reasons all show that the top speed of the MACRO would most likely not be 4 m/s. However, there are too many variables to make a fair assumption. For the purposes of understanding the full size, it can be assumed that the full sized robot would go 4 m/s, and if the scaled robot didn't quite go that fast, powerful motors could be added, the robot could be made lighter, or other design changes could be made to get the robot to move that fast (if that specification was needed). Compared to on Earth, the rover should be able to move quicker due to the atmospheric conditions. On Earth, the air is more dense and would therefore drag would have a greater effect on the top speed. Also, as the weight differs on Earth and Mars, so does the frictional force. Because friction follows the following formula on a flat surface:

$$F_f = \mu F_N$$

and the normal force decreases with the gravity of the planet, the MACRO will experience less friction on Mars. Therefore, on Mars the MACRO will have a greater top speed compared to on Earth.

Similarly, many assumptions are required to be made when scaling up the maximum power output. Aspects such as the density of the materials and power of the motors must be assumed to follow a factor of 10 when scaled up to a reasonable size. The MACRO's current output is 33.756 Watts. According to this assumption, the full scale robot would have to output at a bare minimum 337.56 Watts, but it will most likely be

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[13] (n.d.). Goodyear Tires. Retrieved December 7, 2018, from https://www.goodyear.com/

significantly more than that due to the use of different materials to maintain the durability and reliability of the MACRO.

The MACRO's wheels were 2.4 inches in diameter (which is roughly 6.1 cm) and the largest obstacle it could traverse was 2 cm tall. From this, it can be estimated that the robot is able to traverse obstacles up to two thirds the size of its wheel radius on Earth. In theory, the full size robot will have wheels around 2 ft in diameter (61 cm) therefore a reasonable specification for the full sized robot would be the ability to traverse obstacles up to 20 cm high. On Mars, the force of gravity is significantly less, causing gravity to perform less work on the MACRO. This makes it easier for the robot to transverse obstacles as less energy is needed to overcome the force of gravity and therefore obstacles.

The minimum turning radius was calculated to be 4 inches from the distance between axles on the MACRO. On Earth, the full scale robot would also have a turning radius equivalent to the distance between its axles, therefore its turning radius would be about 40 inches. On Mars, the MACRO would have the same dimensions, but may have a smaller turning radius due to the decreased amount of friction experienced in a low gravity environment. As the front two wheels of the MACRO prototype rely heavily on the amount of friction, it can be determined that on Mars the MACRO is capable of minimizing turning radius.

The current MACRO's energy efficiency is 39.069%. Assuming that the materials will be scaled by a factor of 10, its energy efficiency would be roughly the same on Earth. That being said, since the materials of the final robot will most likely be made out of metal as opposed to plastic, it will weigh more and thus be less energy efficient than the original MACRO. Additionally, the Mars scaleup version will probably be slightly more energy efficient than the Earth scaleup since the lesser gravitational force acting on the robot would mean less friction therefore less energy lost as heat or sound. Because of these and many other variables, we can only assume at this stage of the prototype that the efficiency is close to the current design.

## Results and Discussion

Overall, the MACRO prototype did not meet full expectations during the demonstration, where the MACRO completed the first turn and obstacle, but failed to continue following the line. Before the demonstration, a table of technical requirements, demonstrated in table 4, was created in order to set target values for each customer need. The target values were determined based upon the project description as to what values would be the minimum or maximum that the MACRO would endure. Values not included in the project description were determined through additional research. Although the MACRO met all of the technical requirements separately, when integrated, the performance values did not meet the same expectations.

*Table 4: Technical Requirements for the MACRO Prototype*

| Customer Need | Technical Need | Technical Requirement | Target Value | Performance |
|---|---|---|---|---|
| Be able to make tight turns | Small turning radius (in) | 5 in | 2 in | 4 in |
| Significant Power Output | Maximum power Output | 10 W | 25 W | 14.065 W |
| Ability to travel over objects of varying size | Maximize range of heights (in) conquered | 1.5 cm | 3 cm | 2 cm |
| Ability to travel over hills | Maximize angle (°) of driving | 30 deg | 35 deg | 31 deg |
| Ability to follow a line | Minimum deviation from the line (cm) | 7 cm | 4 cm | 5 cm |
| Ability to carry various types of cargo | Maximize the mass of cargo (g) the MACRO can carry at once | 250 g | 500 g | 1100g |
| Ability to carry cargo of various sizes | Maximize area ($mm^2$) of the base of cargo that the MACRO can carry | 4,558.1 $mm^2$ | 12,661.3 $mm^2$ | 19, 500 $mm^2$ |
| Accurate dispersion of cargo | Distance (cm) from Center of Drop off point | 4 cm | 0 cm | 3 cm |

The MACRO performed well in the areas of ability to travel over objects of varying size, ability to carry various types of cargo, and ability to carry cargo of various sizes. For all of these customer needs, the MACRO met the target values. Within the ability to travel over obstacles of various sizes, the MACRO would sense an object and increase speed in order to continue on the course.While not integrated with other challenges, this concept worked well. But, as speed was increased the line sensing capabilities were diminished, and the robot would only move straight. For this reason, the MACRO was able to conquer the first obstacle, but unable to continue following the designated path toward the next challenge. Therefore, the MACRO was extremely effective at driving over obstacles ranging in 1 in of height.

For the customer need of holding cargo of various types, the MACRO was able to hold a large mass of cargo, but this decreased the performance of the MACRO. One factor that played into the failure of the MACRO was the lack of support in the rear wheels as weight was added. Throughout the design process, the bowing of the wheels was a constant issue that did not have a simple fix due to the lack of resources available. During the demonstration, the added weight of the cylindrical cargo caused the wheels to bow to a point that the MACRO was unable to move forward, causing significant repercussions on its abilities.

Although the MACRO may not have met the target value for deviation from the line, the deviation of 5 cm proved effective at following the course line. On the MACRO prototype were three sensors dedicated to line following, including one line finder on each side of the MACRO and a color sensor in the center. The color sensor followed the edge of the line, turning right when black was detected and left when white was detected. If black was detected by a line finder on either side, then the power to the motors was increased and the MACRO would make a sharper turn. This proved very effective for the line following capabilities. Overall, the final demonstration of the MACRO prototype left room for improvement on the robot to enhance its performance.

As demonstrated in the performance column of the technical requirement chart, the MACRO met all the technical requirements for the listed customer needs. But, the

MACRO did not meet all of the target values, including the values for turning radius, maximum angle of driving, minimum deviation from the line, and distance from center of drop off point. The performance for small turning radius was 4.5 in, only slightly below the technical requirement of 5 in. The lack of a small turning radius was one reason that the MACRO did not perform as expected, as the first turn on the course was extremely tight and had to be taken slowly. This was an issue as another mechanism was required in order to alert the MACRO to increase speed to conquer objects. Therefore, if the MACRO would have been able to follow the line at a faster speed, it would have been able to conquer the obstacles without accelerating to full speed and losing track of the black line.

For the maximum angle of driving, the robot endured multiple weight distribution issues that limited the maximum angle to 31°. In order to counteract the added weight of the cargo in the back of the chassis, the battery pack was attached to the front of the MACRO. This proved to be a sufficient solution for the final demonstration. Finally, for the distance from the center of the drop off point, the MACRO was able to meet the requirement of 4 cm, but the average distance from the center of the zone was 3 cm. This could be improved through more calibration of the time after the beacon was sensed that the MACRO would travel before sliding the cargo down the ramp.

## Conclusions & Recommendations

After the demonstration, multiple flaws in the MACRO prototype were found, many of which can be improved through redesigning of the robot structure. These include the obstacle detection and weight balance. However, the cargo drop off system and line following performed well, succeeding most of the time.

First off, as discussed earlier there was significant bowing in both the front and rear wheels due to the added mass of the cargo. To relieve the stress on these points, stronger materials must be used for the structural support of the system. Instead of using plastic for the connector pieces between the wheels, metals would be more effective at maintaining a sturdy chassis. Because of the lack of resources within the project, using different types of material was not a valid option before the final demonstration. Instead, the wheel could have been brought closer together to eliminate the space between the two that allows for the axels to bow, or an extra wheel could have been added on the bottom of the chassis. An extra wheel would take pressure off of the others and distribute the force to degree that is manageable by the structure.

Secondly, alterations in the MACRO's ability to sense and conquer obstacles on the course are necessary to complete the project's objectives. One alteration that would improve the system's functionality would be to have a more dynamic wheel base that would not have to increase speed in order to overcome obstacles. One viable option would be to utilize treds instead of wheels, which improve any vehicle's ability to go over obstacles. That way, no ultrasonic sensor would be needed to sense obstacles, and the MACRO would easily conquer the course.

Third, the use of treads to improve the system's functionality would also improve the MACRO's turning radius. Currently, to turn the prototype has the outside wheel more forward and the inner wheel move backward to create a pivot motion. Using treads allows the MACRO to execute a zero point turn and have an infinite turning radius. This would enable the MACRO to execute tighter turns and better complete the task at hand.

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## Use of External Code Appendix

All code used in the prototype of the MACRO robot is original content. Example code already on the Pi was referenced and utilized to ensure the sensors and motors were used correctly, but no external code was used in the project.