Project 3 Written Report

Team 39

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**Cover Letter**

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Dr. Ortega,

One of the primary limitations to long-term human habitation and exploration of Mars is the acquisition of adequate resources for crews conducting research for extended periods of time. Providing sufficient resources for such operations requires regular resupply drops, however these drops must occur at least one kilometer from the habitation area to protect the crew living area and any delicate instrumentation. Because drops must occur so far from the habitation area, an unmanned vehicle must be utilized to transport materials between drop-off locations and the habitation area. Team 39 was tasked with designing a prototype of such a vehicle that is capable of navigating a preset track that contains various obstacles meant to simulate the harsh environment that can be found on Mars. The team’s MACRO design contains several unique attributes that make it a desirable choice for implementation in future MITEER sites, including its height, drivetrain, and trailer design.

The team’s prototype MACRO is relatively tall, allowing it to easily navigate over small obstacles such as sharp rocks, rather than having to navigate around these obstacles. Despite its height, the MACRO design is still sturdy enough to be resistant to falling over or tipping while navigating such obstacles. The design team has conducted thorough testing to ensure that the final prototype that is being presented is not likely to fall over during normal operation. Throughout all tests, the prototype MACRO has not tipped over when navigating both small and large obstacles, with and without cargo. If this prototype design was chosen for further development, its height would protect any fragile components that sat on the underside of the main body of the MACRO.

The prototype’s trailer design is easily adaptable to a wide variety of different geometries of cargo, due to its modular construction. It sits low to the ground, increasing the likelihood that cargo will land upright instead of falling over. This is important because the cargo containers have internal structures that mean they need to be deposited right-side-up to protect the contents. The trailer's wide base allows it to fit the largest cargo easily, yet it is still adaptable enough to securely hold the smallest cargo. Additionally, the arm that pushes cargo off the trailer onto the ground once the MACRO reaches the drop-off zone has a considerable amount of reinforcement that keeps it from breaking when it is transitioning cargo from the trailer bed to the ground, limiting the need for maintenance and repairs. The arm is also tall enough that it does not knock over cargo within the trailer bed.

Finally, the MACRO utilizes a front-wheel drive design. The team made this decision for several reasons. First, the team knew that the prototype would be required to navigate over a hill and knew that a front-wheel drive configuration would decrease the likelihood that the MACRO tips over while navigating hills. Second, using only two motors instead of an all-wheel drive configuration reduces the amount of power the MACRO must use, thereby reducing the time lost to recharging or replacing batteries.

In summary, Team 39's prototype MACRO makes use of a variety of unique design choices that make it a desirable option for further development. The team hopes that you take these into consideration when making your final decision.

Thank you,
Team 39
Ella Barnes, Fahim Hossain, John Kang, Heather Mello

## Executive Summary

L3Harris requested that the team develop a small-scale prototype for a Mars Cargo Rover (MACRO). It is necessary that the Mars Rover is capable of autonomous cargo dropoff to reduce the need for people to face Mars' harsh environment. It was explicitly stated by L3Harris that the MACRO must be able to precisely and autonomously navigate to specific sites, recognize and avoid potential hazards if necessary, and deliver cargo quickly from location to location without dropping or tipping it.

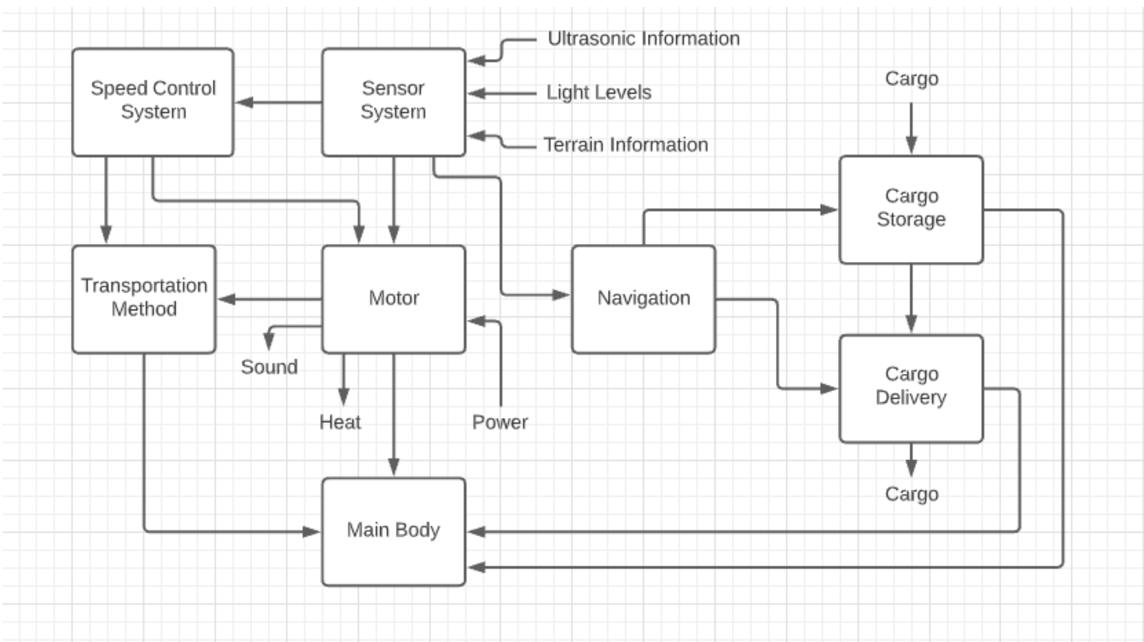
The trailer is low to the ground with an arm powered by a motor used to sweep the cargo onto the dropoff location. The reasoning behind the trailer being low to the ground was that the cargo would not have to fall very far, and would therefore be less likely to tip over. The trailer arm was relatively simple to build and successfully pushes cargo off of the trailer. The trailer was attached with an arm that could rotate, which allowed the MACRO to make turns easily without having to turn an entire trailer along with the body. When the body of the MACRO continued forwards after turning, the trailer would drag behind and straighten out, making the turns much easier.

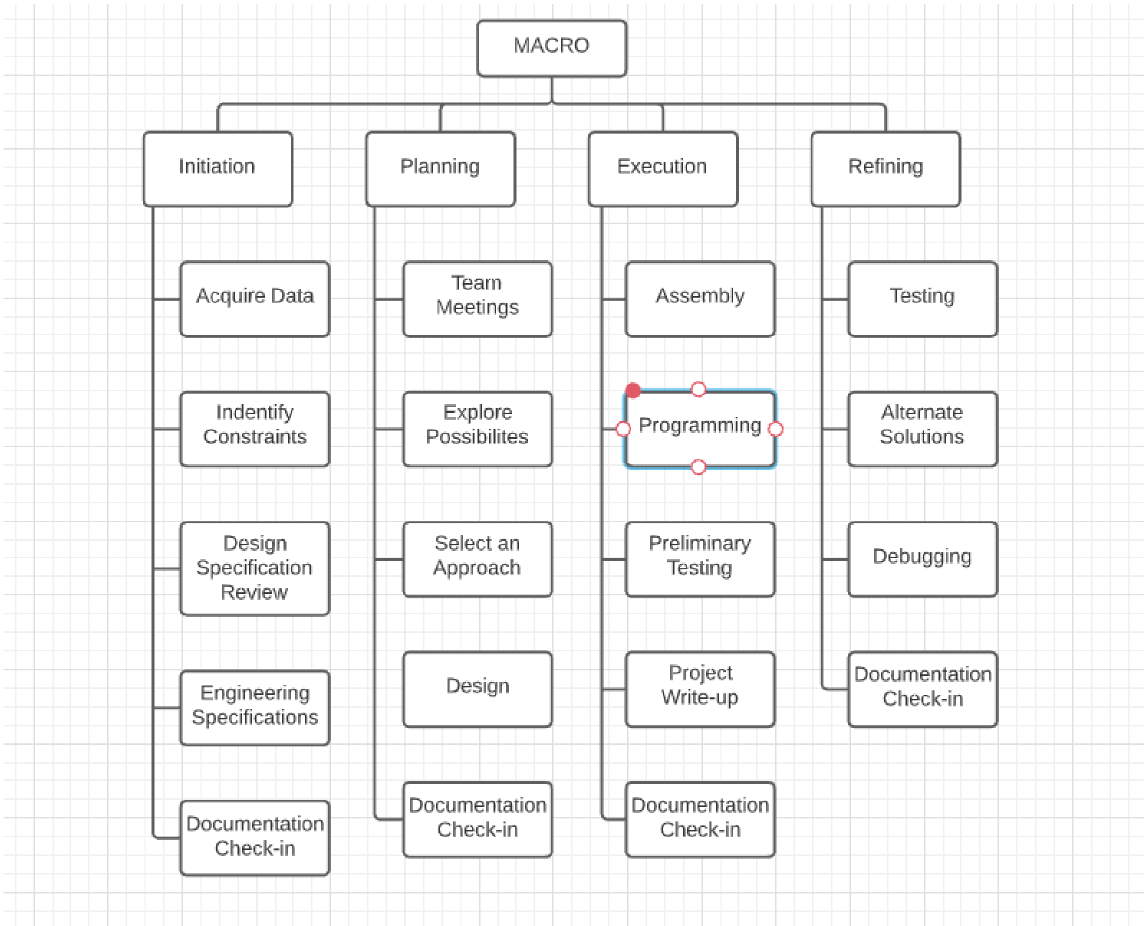
The narrow body allows the robot to make turns easily, but the weight of the motors ensures that the MACRO does not tip over during these turns or on rough terrain. The vertical positioning of the motors elevates the body of the MACRO, making it relatively tall. This tall frame allows it to avoid rough terrain from scraping the bottom of the robot, potentially sending it off course or stopping it all together. Because of the tall frame, the MACRO was able to easily traverse the small obstacle.

At the demo, the MACRO was only partially successful. Although the MACRO was capable of following a solid line and turning, it could not follow a dotted line. The robot was able to make it past the first small obstacle, but the team decided not to attempt the second obstacle, since they were not confident in the MACRO's ability to sense an object in front of it and stop. The MACRO also failed to drop off cargo due to issues with the hall sensor not sensing magnets properly based on its placement. Because the team spent most of the demo time trying to make it past early obstacles, there was no time to confirm whether or not the MACRO could follow the broken path, which also constitutes a failure.

**Design Considerations**

The team's design process began with brainstorming and other on-paper planning. The team made a functional block diagram that describes the different systems necessary for a successful MACRO prototype, including a navigation system, transportation method, and cargo storage and delivery system, among other required systems for a functional prototype. The team also made a work breakdown structure to clearly lay out all the actions that would need to be taken in the coming months to successfully design and build a prototype MACRO.



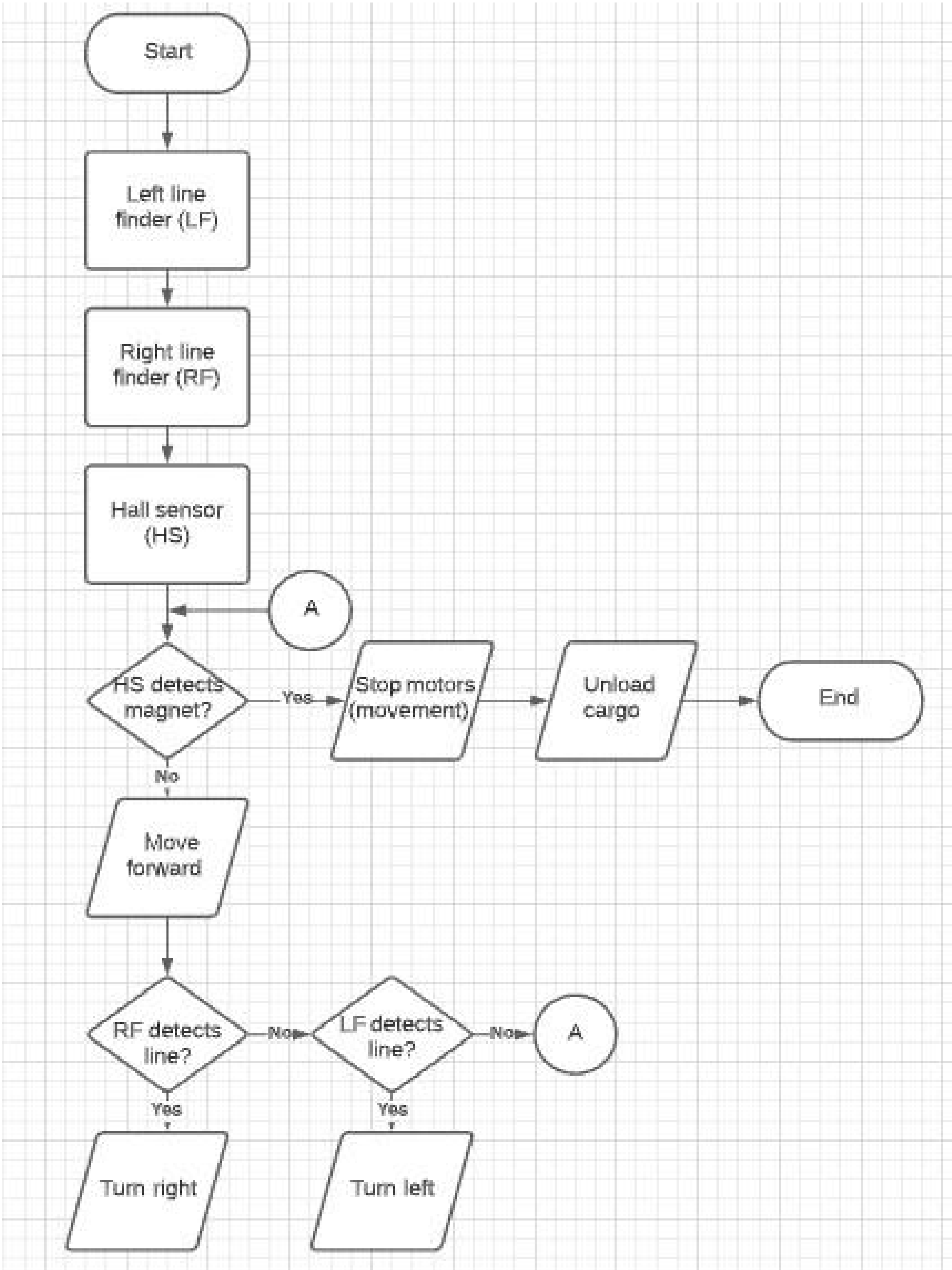



The team then made a preliminary engineering specifications table. Because the table was made so early in the design process, the team elected not to include technical requirements or target values. These were added in a later iteration of the project's engineering specifications that were established further in the design process. The team amended the engineering specifications in response to the earliest functional design's performance at the first Presentation of Competency event and outside testing, as well as the provision of new information regarding the details of the project from the instructional team.

| Customer Need | Technical Need |
|---|---|
| Precise navigation to specific sites | Distance from target site |
| Recognition and handling hazards | Proportion of hazardous conditions that are avoided/otherwise successfully managed |
| Timely delivery of mission hardware | Time of delivery |
| Transporting cargo from location to location without dropping or tipping | Proportion of cargo that is successfully delivered |
| Speed restriction | Maximum speed |

| Customer Need | Technical Need | Technical Requirement | Target Value |
|---|---|---|---|
| Powerful motor | Maximum Axial Torque Output | 20N*cm or greater | 20 N*cm |
| Is able to make different size turns when necessary | Turning Radius | 1.5 inches to 2.5 inches (3.81 cm to 6.35 cm) | 2.0 inches (5.08 cm) |
| Transporting cargo from location to location without dropping or tipping | Max cargo dimensions (Area of base) | 45.01 $cm^2$ to 127.68 $cm^2$ | 127.68 $cm^2$ |
| Speed restriction | Maximum speed | 15 cm/s to 30 cm/s | 22.5 cm/s |

The programming subteam then made a flowchart detailing the code processes necessary for a functional prototype. Though the flowchart was very high-level, it served an important purpose in guiding the programming team throughout the course of the project.

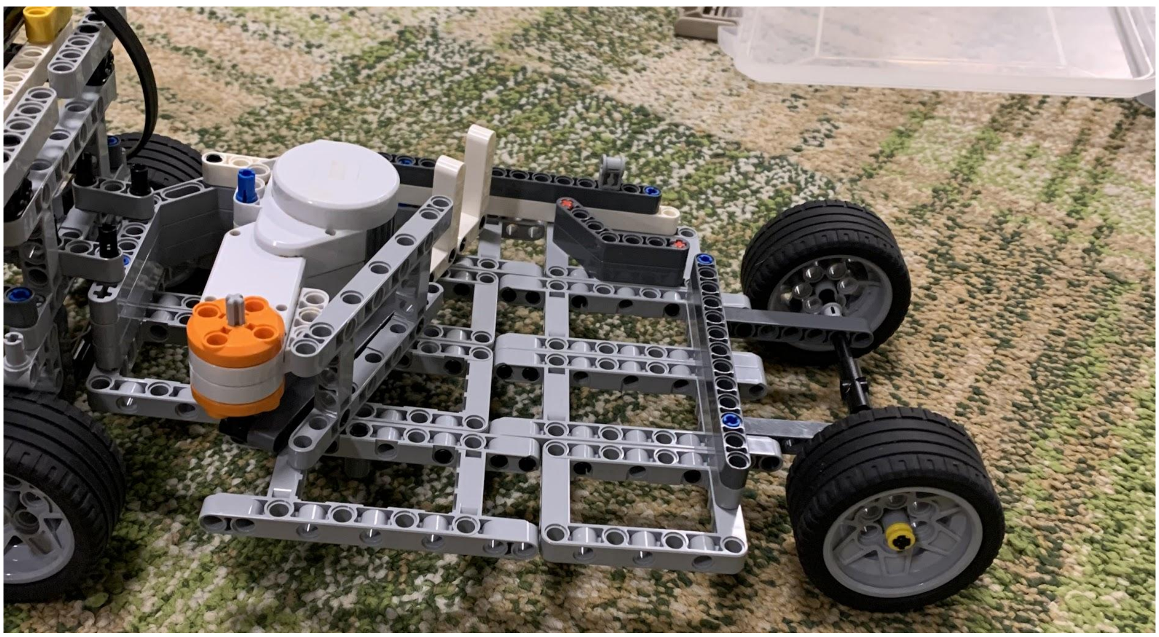

Start
Left line finder (LF)
Right line finder (RF)
Hall sensor (HS)
A
HS detects magnet?
Yes
Stop motors (movement)
Unload cargo
End
No
Move forward
RF detects line?
No
LF detects line?
No
A
Yes
Yes
Turn right
Turn left

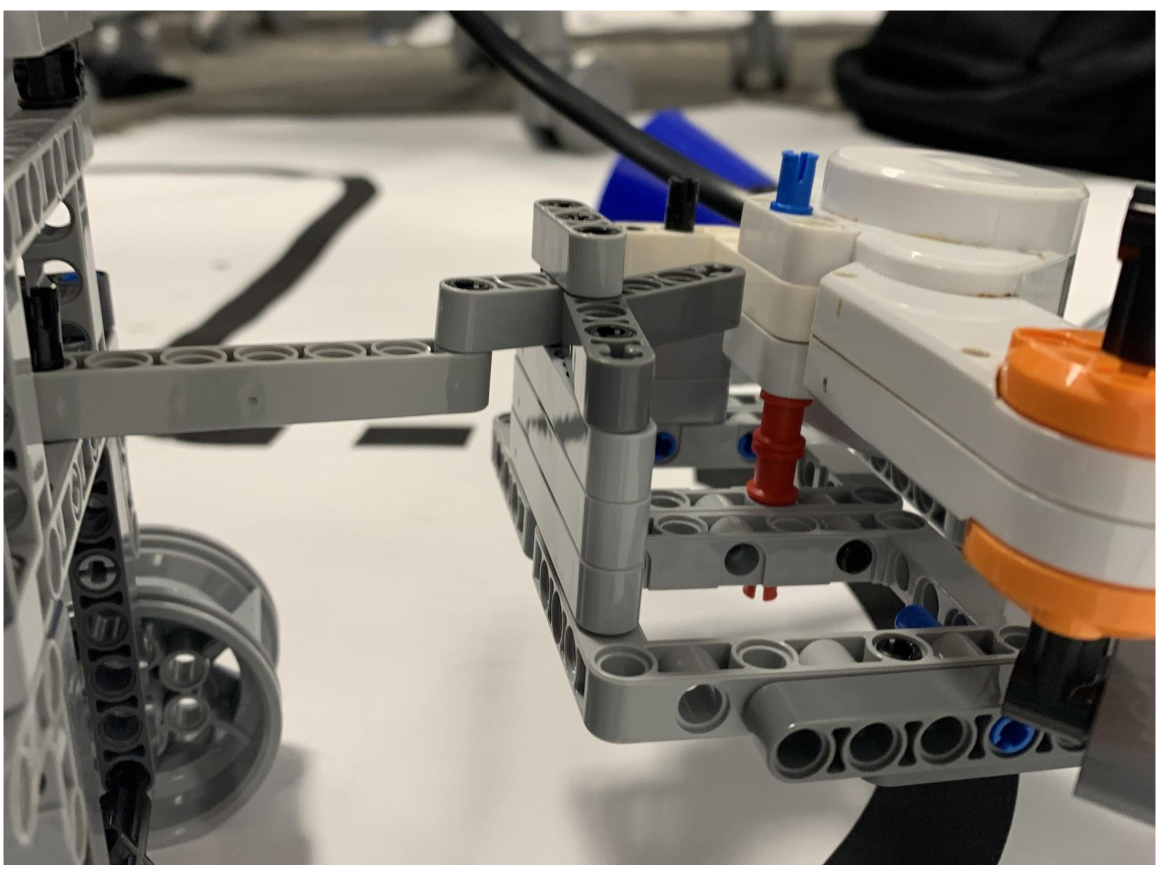
The next step that the team took in the design process was determining a method to use to transition cargo from the trailer bed to the ground. The team's first idea for this process consisted of a floor on the main body of the MACRO that pulled out to the sides once the target area was reached, thus dropping the cargo straight down. The building subteam decided not to follow through with this design because it was believed to be too resource-intensive and difficult to design in the given timeframe. Additionally, this design would have required a very tall MACRO, which the team felt would be more likely to fall over while navigating obstacles. The team's second cargo delivery design was a floor that tips over (akin to a dump truck), allowing cargo to slide off onto the ground. Ultimately, the team decided not to use this design because of concerns that the floor would tip over inappropriately while traversing the hill or small obstacle. The building subteam also could not think of a way to make this design functional with the given resources.

Ultimately the team decided to use a cargo trailer with an arm that pushed cargo off the bed of the trailer onto the ground as the final design. The team decided to use this design because it was easier to build and rework in response to performance test results, it would provide extra stability for the main body of the MACRO, and it was less likely to break when heavier cargo was placed on it.  This decision was supported with a decision matrix that the team made after discussing the various options for a cargo delivery method.

The cargo trailer itself was another challenge for the design team. The initial design was far too small for any but the smallest cargo because it was designed and assembled hastily, without proper measurements or testing. Because of this, the trailer had to be resized several times to adequately fit all the cargo. The trailer arm was another problem for the design team. Initial designs were too weak to push cargo off and the arm broke frequently. To overcome this challenge, the team redesigned the arm and arm motor to be stronger and more resistant to breaking and falling over the edge of the trailer bed.. The programming subteam also reworked the code to time the arm's pushing motion in such a way that it did not overshoot the edge of the trailer.

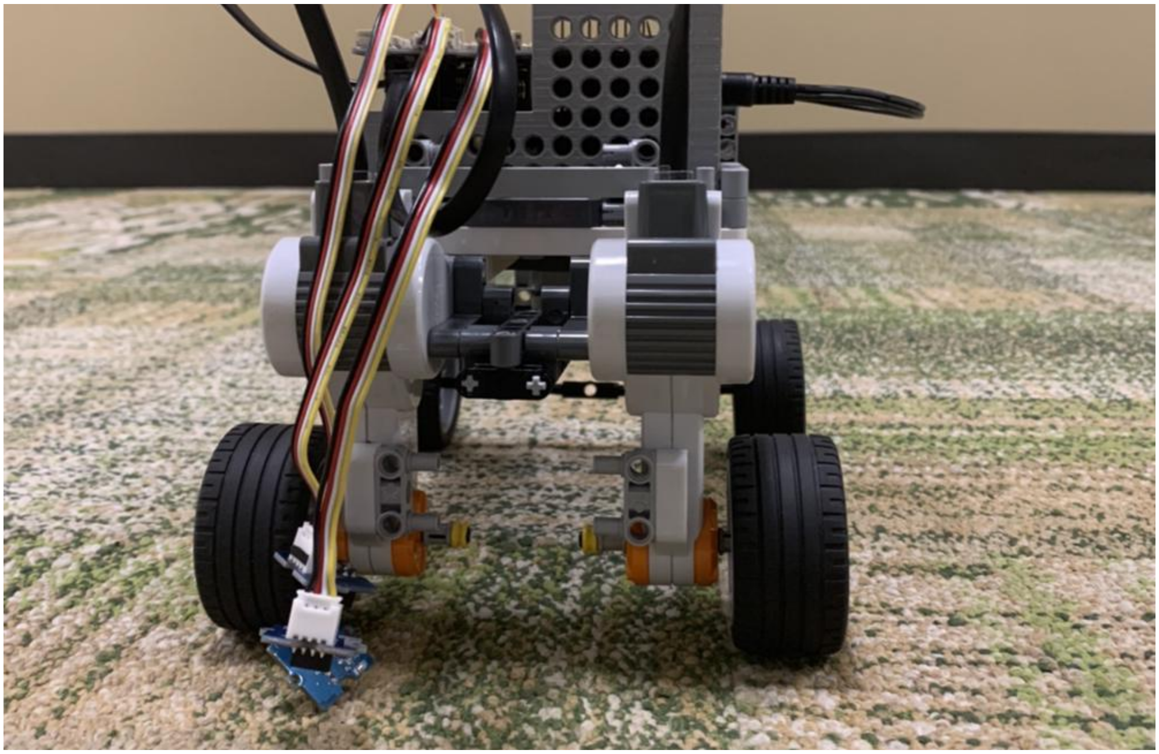
| | | | Alternatives | | |
|---|---|---|---|---|---|
| | | Weight | Garbage Truck | Floor slides out from underneath | Trailer with arm |
| Criteria | Ease of building | 1 | 1 | 1 | 2 |
| | Structural Stability | 2 | 2 | 1 | 2 |
| | Efficient Use of Materials | 2 | 2 | 2 | 2 |
| | Total Score: | | 9 | 7 | 10 |
| | | | | | |
| | Ranking Scale: | | | | |
| | A score of 2 indicates yes | | | | |
| | A score of 1 indicates partial yes | | | | |
| | A score of 0 indicates no | | | | |

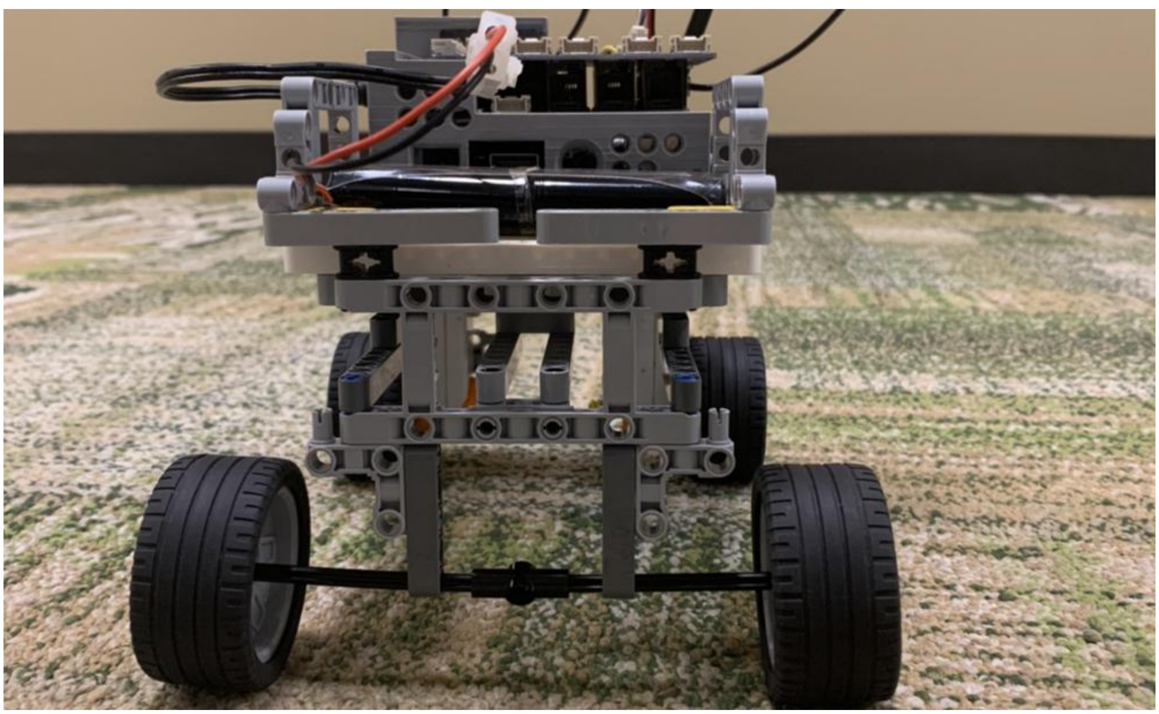


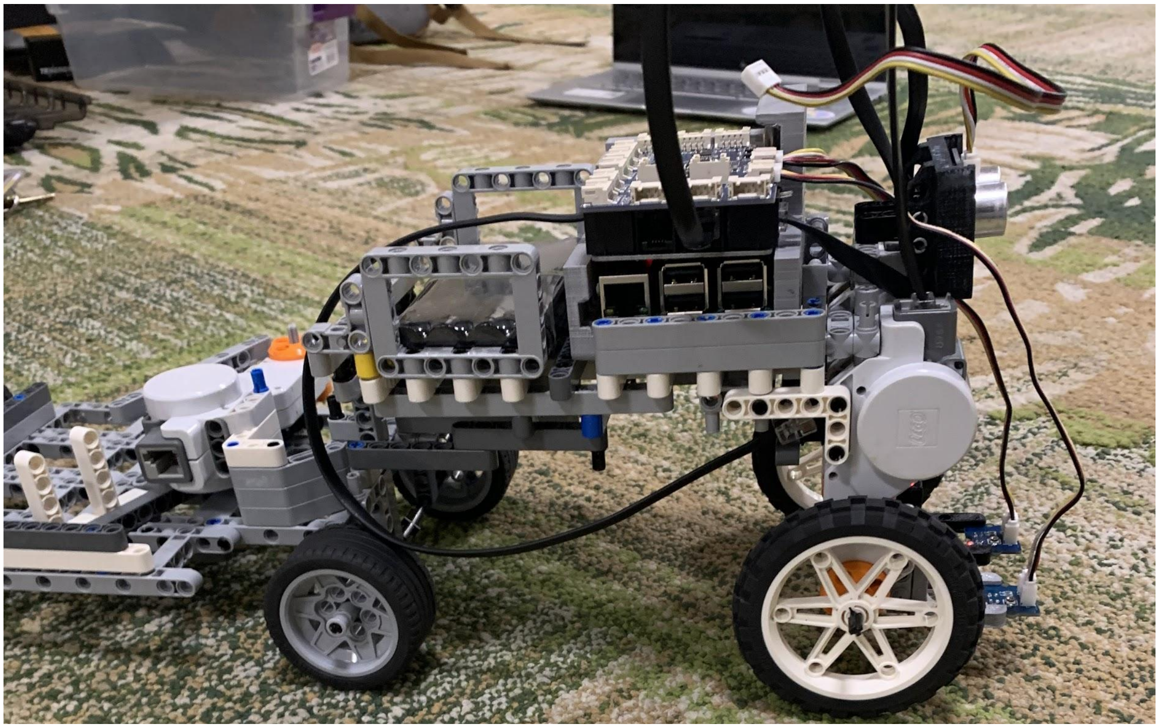


The next major hurdle that the team faced in the design prototype was the wheel configuration. The team had already decided early in the design process that a front-wheel-drive configuration would be best for the MACRO because it allowed for easier turning via modifying the amount of power going to each front wheel individually and decreased the likelihood of the rover tipping over on hills, but struggled with choosing which wheels to use and how to reinforce them so they did not collapse inward when the prototype moved forward. The team tested every wheel size provided and found that each had its own challenges. The larger, “motorcycle” style wheels got stuck on the track with the wheel turning but not adhering to the tire, the smaller wheels could not get over the small obstacle, and the larger wide wheels got stuck both on obstacles and the test tracks. The team decided to use the motorcycle style wheels in the front and the larger wide wheels in the back without the tires on them because this configuration allowed the prototype to navigate hills and obstacles the most easily. Like the cargo delivery method, this decision was supported with a decision matrix.

| | | | Alternatives | | | | |
|---|---|---|---|---|---|---|---|
| | | Weight | 4 Wheels, front wheel drive | 4 Wheel Drive | Treads | Motorcycle Wheels | Medium Size Wheels |
| Criteria | Height | 2 | 2 | 2 | 0 | 2 | 1 |
| | Width (want it to be narrow) | 2 | 1 | 1 | 1 | 1 | 0 |
| | Ease of building | 1 | 1 | 1 | 0 | 2 | 2 |
| | Structural Stability | 3 | 2 | 2 | 1 | 1 | 2 |
| | Efficient Use of Materials | 3 | 2 | 0 | 1 | 1 | 1 |
| | Total Score: | | 19 | 13 | 8 | 14 | 13 |
| | | | | | | | |
| | Ranking Scale: | | | | | | |
| | A score of 2 indicates yes | | | | | | |
| | A score of 1 indicates partial yes | | | | | | |
| | A score of 0 indicates no | | | | | | |







In developing the code for the MACRO, the programming subteam felt that it was best to divide the code into four main functions—hill navigation, obstacle navigation, cargo unloading, and turning/driving—each one broken into its corresponding sensor inputs and motor outputs. These inputs and outputs were tailored to the current working design at every iteration.

For the hill navigation, the team decided on a minimum threshold for motor output of 45. This threshold was determined experimentally at project office hours and in-class work days. This minimum threshold was also used for obstacles, under the logic that if the motor was strong enough to get up the hill with a certain motor output, it should also be able to get over a smaller obstacle using the same output.

The cargo unloading section of the code had the robot come to a complete stop before activating the motor that controls the trailer arm. The motor was activated for only a short period of time, just enough to push the cargo off the trailer bed but not enough for the arm to overshoot the bed and begin sagging downward. This time period was also determined experimentally by testing the amount of time needed to successfully push the largest cargo off of the trailer bed with an arm motor output of 50. This section was supposed to activate in response to the hall sensor detecting the magnetic beacon under the path, however it was inconsistently successful because the rover's hall sensor was not placed properly and was therefore inconsistent in its detection.

The programming subteam also had to work with line finders, as line finders were the only sensor used for general navigation along the path. Initially, the design made use of three line finders—one on each side and one in the middle. In theory, this design would see the robot moving forward when only the middle sensor detected a black line and turning in response to either of the side sensors detecting a line. This design was very accurate with adjustments and turned appropriately, however the middle line finder dangled loosely from the front of the main body because the team only had two mounts for the line finders. This made the middle line finder inconsistent in its readings, so the team decided to eliminate the middle line finder and only use two, one on each side. Using only two sensors proved to be challenging, especially when it came to the dashed and broken lines of the test tracks. Ultimately, the MACRO was unable to successfully navigate the dashed and broken lines because of these sensor difficulties. The team also modified the turning function, making use of a contra-rotation method instead of keeping the initial design, which had one motor turn off while the other stayed on. This changed the axis of rotation from the inactive motor to the center-front of the prototype, allowing the MACRO to turn much faster against the resistance of the sliding rear/trailer wheels. The team also added a reversal, moving the robot slightly backward while turning to more accurately read data.

The prototype's turning method was initiated by line finder readings and used a time loop during which speeds were intentionally slowed to avoid overshooting the turn and going off course. Without the use of the time loop, the use of the ".sleep()" delay from the time library would cause the GrovePi to periodically read the line finder sensor input, leading to inconsistencies in line detection. Instead, the issue was resolved through the use of the ".time()" function, also included in the time library. The process would be initiated if only one sensor detected a line and the robot would be slowed down for ten seconds.  Slowing the MACRO during turns allowed the line finders to keep up with the line, thereby triggering the end of the turning process once both sensors detected a line again. One downside of using the time loop was that, when climbing the hill, the robot would sometimes need to self-adjust causing the program to fall into the ten second time loop and decrease the motor output below the threshold value. Although this led to a loss in time, the MACRO would eventually exit the ten second time loop and return back to the threshold motor output, allowing the MACRO to successfully clear the hill.

**MACRO Physical Analysis**

For a general physical analysis of the MACRO, the team decided that they would calculate or determine the values for turning radius, maximum cargo dimensions, maximum speed, maximum acceleration, and maximum axial torque output. The team believes that these values represent the ability of the prototype to accomplish the required tasks. To clarify, these tasks include navigating to specific sites, recognizing and avoiding hazards, delivering cargo in a timely manner, and transporting cargo without dropping or tipping. A table outlining these requirements along with technical needs, technical requirements, and target values is below.

| **Customer Need** | **Technical Need** | **Technical Requirement** | **Target Value** |
|---|---|---|---|
| Delivers cargo in a timely manner | Maximum Acceleration | No value determined before physical analysis. | No value determined before physical analysis. |
| Powerful motor | Maximum Axial Torque Output | 20N*cm or greater | 20 N*cm |
| Navigating to specific sites | Turning Radius | 1.5 inches to 2.5 inches (3.81 cm to 6.35 cm) | 2.0 inches (5.08 cm) |
| Transporting cargo from location to location without dropping or tipping | Max cargo dimensions (Area of base) | 45.01 $cm^2$ to 127.68 $cm^2$ | 127.68 $cm^2$ |
| Delivers cargo in a timely manner | Maximum speed | 15 cm/s to 30 cm/s | 22.5 cm/s |

First, to help fulfill the requirement of navigating to specific sites, the team determined that the metric of success would be turning radius. Since the team was told that the prototype would need to make turns with a 2 inch (5.08 cm) radius, that was the only radius tested. The MACRO was optimized to make this radius turn, so it is unlikely that it would be able to make an even tighter turn. This is mostly because turning tighter than 2 inches would impede the trailer, as it would be difficult to swing the trailer around even further than it was for a 2 inch radius turn. However, as turning radius is more of a minimum value rather than a maximum value, wider turns would likely be possible with the prototype. The MACRO was able to make 2 inch radius turns, so the team considers this to be a success.

Next, to accomplish the given task of transporting cargo from location to location without dropping or tipping, the team decided to measure success by determining the maximum cargo dimensions. This was measured using the surface area of the base of the trailer, since it was assumed that the largest piece of cargo that can be held would completely fill the trailer. The cargo trailer was designed specifically to accommodate the largest cargo size, as a trailer any larger would have increased the risk of smaller cargo falling out. Although this was assumed, the trailer was still a little bit larger than the largest piece of cargo. The surface of the trailer that is not obstructed by the arm was measured to be 5 inches by 6 inches, or 12.7 cm by 15.24 centimeters. Since this area was rectangular, it was calculated that the surface area of the usable part of the trailer was 30 square inches, or 193.5 square centimeters. This surface area is much larger than the surface area of the base of the largest piece of cargo, but this can be attributed to the fact that the largest piece of cargo was a cylinder, so it had a circular base. The diameter of the cylinder was 5 inches, so it fit in the trailer well and did not tip or fall out. Although the MACRO was successful in not dropping or tipping cargo, the trailer was unfortunately not optimized for cylindrical cargo and therefore the surface area does not fall within the target range.

The team assumed that L3Harris would request powerful motors to ensure that the MACRO could successfully traverse obstacles and navigate the demo course. To confirm the success of the prototype with this specification, the team decided that they would determine the maximum axial torque output of the motors. The team found that the motors used for the front wheels were EV3 Large Servo Motors, which have a maximum axial running torque output of 20 N*cm, per the Lego Mindstorms website. Since the team used these motors as they were received, they determined that no changes had been made and the maximum axial torque of each motor is 20 N*cm.

To fulfill the given requirement that the MACRO must be capable of delivering cargo in a timely manner, the team determined that success in this category would be measured using both maximum speed and maximum acceleration. First, maximum speed was calculated using the time it took for the MACRO to travel 1 meter. Through thorough testing, the team found that it took the prototype, on average, 3.51 seconds to travel 1 meter without cargo, and 3.95 seconds to travel 1 meter while carrying the heaviest cargo. The team followed the process used at the demo to calculate the maximum speed of the macro, which is to simply divide the distance traveled by the time it took to travel that distance. Using this process, it was determined that the MACRO's maximum speed without holding cargo is .284 meters per second (28.4 cm/s), while the maximum speed while holding cargo is .253 meters per second (25.3 cm/s). Maximum acceleration was calculated using the kinematic equations. The team's process for this is pictured below.

Kinematic Equation Used: $\Delta x = v_0 t + \frac{1}{2} a t^2$

$V_0 = 0$, so: $\Delta x = \frac{1}{2} a t^2$

Solve for acceleration: $a = \frac{2\Delta x}{t^2}$

Plug in and solve: $a = \frac{2\,(1m)}{(3.51s)^2} = .16\frac{m}{s^2}$ without cargo

$a = \frac{2\,(1m)}{(3.95s)^2} = .13\frac{m}{s^2}$ with cargo

Based on these calculations, it was determined that the acceleration of the MACRO is .16 $m/s^2$ when the trailer is not holding any cargo, and acceleration is .13 $m/s^2$ when the trailer is holding the largest piece of cargo. The team did not determine a target value for acceleration due to a lack of information, as material pertaining to the desired maximum acceleration was not specified in the request for proposal document. Because of this, the team cannot determine whether or not the MACRO was successful in this category. However, since the maximum velocity for the MACRO when it is both carrying and not carrying cargo falls within the predetermined range for successful maximum velocity, the team considers this to be a success.

Along with these physical properties, the team also decided to calculate the approximate drag force acting on the MACRO as it moves. In order to calculate this, it was assumed that the prototype was a cube, which means that the coefficient of drag ($C_D$) is 1.05 according to various sources. In addition to this, it was also assumed that Earth's atmosphere has a density of around 1.2 $kg/m^3$. The reference surface area of the robot was measured to be 5½ inches (14 cm) by 7½ inches (19 cm). Since the prototype was assumed to be a cube, the surface area was found to be 41¼ square inches, or .0266 $m^2$. Using these values along with the calculated velocity, drag force is able to be calculated. The calculation for drag force is pictured below.

Drag Force Equation: $$D = C_d A \frac{\rho V^2}{2}$$

Plug in and Solve: $$D = (1.05)\left(.0266 m^2\right)\frac{\left(1.2\frac{kg}{m^3}\right)\left(.284\frac{m}{s}\right)^2}{2}$$

$$D = .0014N$$

As pictured above, the drag force acting on the MACRO when it is not holding cargo is equal to .0014 N. Using the same process, the drag force acting on the MACRO when it is holding the heaviest cargo is .0011 N. Since there was no predetermined metric for success for total drag force, the team cannot decide whether or not the MACRO was successful in this category.

## Scaling to Official Mars Project (5 pages)

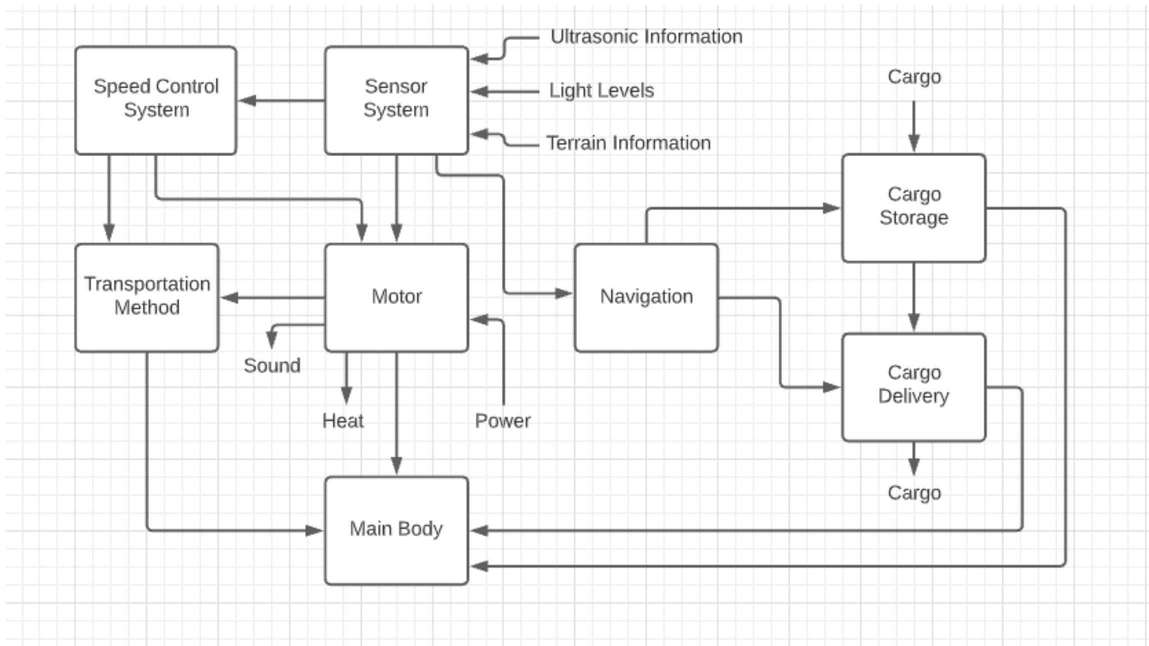
In order to scale the prototype MACRO to an official Mars project, many obstacles would need to be overcome. Significant among these obstacles are the need for stronger motors, the decrease in gravity when transitioning to a Mars environment, and a shift from a flat track to one with more small hills and rocks that the rover must be able to navigate.

A full-sized Mars rover is roughly the size of a small SUV. This increase in size corresponds with a major increase in mass—for example, the Curiosity Rover is 10 feet (3.048 m) long, 9 feet (2.7432 m) wide, 7 feet (2.1336 m) tall, and has a mass of 899 kilograms. Compared to the prototype MACRO, which has a cross sectional area of just 41.25 $in^2$ and a mass that could be measured in grams (the team did not have access to a scale and was therefore never able to accurately measure the weight/mass of the prototype, however when compared to the largest sample cargo provided, which had a mass of between 425 and 475 grams, the team agreed that the prototype did not feel significantly heavier or lighter), a full-scale Mars rover seems almost comically large. Scaling the prototype to this size would require much larger motors and a much greater power source. To overcome this issue, the team would simply need different resources, as there is only so much power that a Lego motor can output using rechargeable 9.6V NiMH batteries. The power source used would need to be solar powered, as there would be no sustainable methods to charge the batteries on Mars. Following the predicted lifespan of the Curiosity Rover, the team would need to be provided with or design a power source that could last at least 1 Mars year, approximately 23 months.

Mars has approximately 30% of the gravity of Earth, which could cause problems with the trailer bouncing up more easily and potentially losing cargo on the way from the initial drop location to the cargo's intended delivery point. This issue would be compounded by the fact that Mars has a much more rugged and rough terrain than the track on which the team tested the prototype, however this particular issue will be discussed later. To overcome the decrease in gravity when scaled to an official Mars project, the team would choose to add more weight to the trailer either by changing the material to something heavier, like titanium, and/or adding extra dead weight, likely around the back wheels and the connection point to the main body.. If changing the material did not add sufficient mass, the team would proceed with adding additional weights to the trailer. The team would choose these locations (back of the trailer and its primary attachment point) because any added weight would need to not interfere with cargo storage or removal, and the majority of the trailer is needed for the cargo. Additionally, having the added weight on top of the trailer in these locations would minimize the chance that the trailer gets snagged on any rocks or other debris, potentially damaging the trailer or straining the motors.

The final significant obstacle that would need to be overcome in scaling the prototype to an official Mars project, briefly mentioned above, is the difference in terrain quality between the test track and the surface of Mars. The provided test track was mostly flat, with smooth transitions between the hill and flat ground and no sharp rocks or other dangerous obstacles. Clearly, Mars would not be designed so carefully to protect the actual MACRO and terrain differences would need to be overcome for a successful rover. To compensate for the rugged terrain found on Mars, the team would modify the trailer attachment so that it could move up and down instead of just to the sides. This would allow the trailer more free motion and prevent it from getting caught. The team would also need better tires that are flexible but still durable enough to resist puncture when navigating sharp rocks and also capable of maintaining traction while driving through sand and dust. The design could be adapted to a sandy terrain by making the wheels wider, thereby increasing the surface area that is in contact with the sand and decreasing the likelihood that the wheels will dig into the sand or dust and get stuck.

| **Specification** | **Prototype** | **Full Scale on Earth** | **Full Scale on Mars** |
|---|---|---|---|
| Maximum Cargo Dimensions | 12.7 cm x 15.24 cm | 6 m x 8 m | 6 m x 8 m |
| Maximum Speed | .284 m/s | 2.5 m/s | 8 m/s |
| Acceleration | .16 $m/s^2$ | 1.32 $m/s^2$ | .63 $m/s^2$ |
| Drag Force | .0014 N | 189 N | 50.4 N |
| Motor Torque | 20 N*cm | 79 N*m | 79 N*m |




The team chose to scale 3 subsystems from the MACRO functional block diagram for the official Mars project. The team chose to scale the cargo storage, main body, and transportation method subsystems, characterized by usable area, drag force, and wheel design/configuration, respectively.

To design a larger cargo storage system, the team would need access to significantly more resources than were provided for this prototype. The team decided to model the full-size MACRO roughly after NASA's Curiosity Rover, with similar dimensions in width and height. Because the prototype's trailer is approximately the same length and width as the main body, the team decided to scale the trailer's usable surface area to $48m^2$, corresponding to dimensions of 6m x 8m.

A larger main body is associated with a greater drag force, even when accounting for Mars' less dense atmosphere. The team decided that the main body should be 2.4m high by 1.3m wide. This scale corresponds to a drag force of 2.10 N on Mars and 17.01 N on Earth, using the scaled maximum velocities summarized in the table above. To compensate for the increase in drag force and overall harsher conditions on Mars, the main body would need to be made of more durable materials that are able to withstand sand and dust.

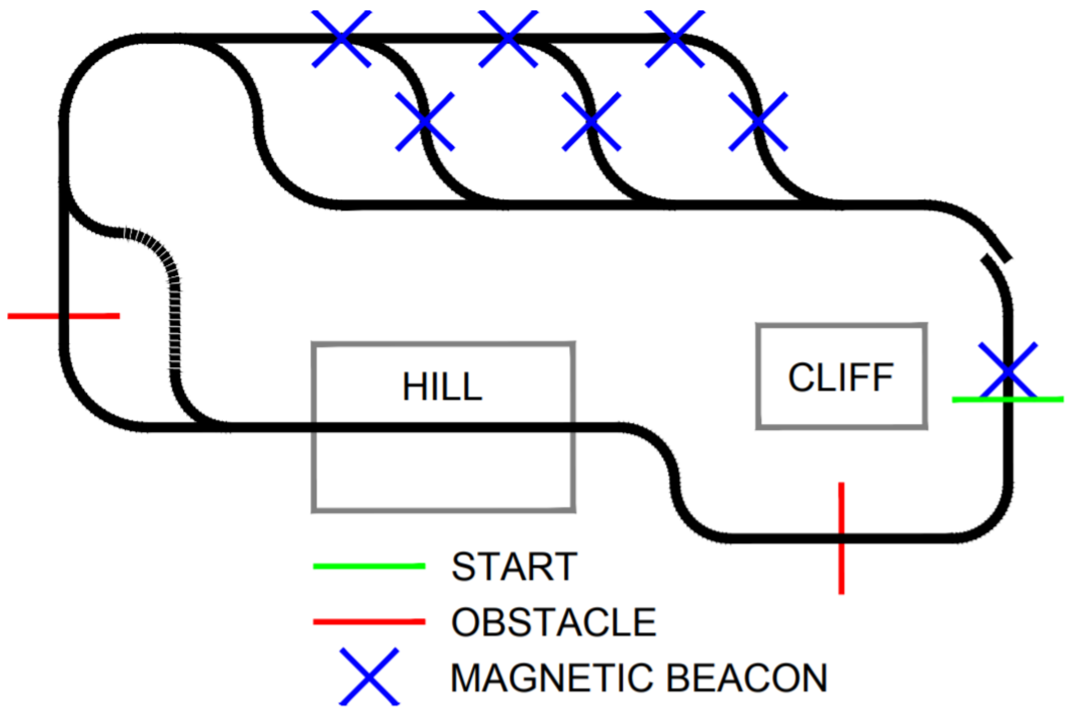
The final subsystem that the team decided to scale was the wheel design and configuration. The team decided to scale this subsystem by modifying the wheel design to be more adaptable to sandy and dusty conditions. This would be accomplished through the use of tank-like treads, rather than wheels. These treads would be less likely to get stuck in sand than the narrow wheels that are on the prototype MACRO.

The scaling of the above subsystems is summarized in the table below.

| **Subsystem (Characteristic)** | **Prototype** | **Full Scale on Earth** | **Full Scale on Mars** |
|---|---|---|---|
| Cargo Storage (useable area) | 0.01935 $m^2$ | 48 $m^2$ | 48 $m^2$ |
| Main Body (drag force) | 0.0014 N | 17.01 N | 2.10 N |
| Transportation Method (Wheel design/configuration) | Narrow, tall wheels in the front; large, wide wheels without tires on the back; 4 wheels on main body, 2 on trailer | 6 wide wheels with tires on main body, 2 pivoting wheels on trailer | Tank-style belt to minimize occurrence of sinking in sand/dust |

## Results and Discussion

Based off of testing done leading up to the demo, the robot performed the same as how the team expected it to. Although the team wishes that the prototype could have been more successful, it's performance at the demo was not at all disappointing. Although it failed at some tasks, it was still able to successfully follow a solid line, turn when necessary, traverse the small obstacle, hit a maximum speed of 20 cm/s, and make it over the hill without tipping or dropping the cargo. Factors that contributed to the MACRO's success in these categories include its large front wheels, mass, front wheel drive, and trailer design.




First, the positioning of the motors and the diameter of the frontmost wheels made navigation over the small obstacle easy for the MACRO. Because of its height, the vehicle was able to make it past the dowel rod (the first red line on the image above) without the bottom of the main body dragging against the obstacle, avoiding any additional friction. The MACRO's relatively lightweight body made turning easier on the motors, as they did not have to rotate a heavy object. Although this was not the final arrangement of items on the MACRO, by making the body just large enough to hold the pi and batteries side by side, the amount of materials used could be lowered along with its mass. The team chose to use front wheel drive in order to keep the MACRO from tipping when navigating over hills, and that was a successful decision. The vehicle did not tip at all while climbing the hill (labeled in the image above), meaning that it stayed flat on the ground and was able to continue pulling the trailer without difficulty. Lastly, the trailer design allowed for easy adaptation to different shapes of cargo. This means that the trailer was able to hold every size of cargo without having to make any adjustments to the trailer. The trailer was large enough to hold the largest piece of cargo without dropping it along the way, and since the cargo was simply held by placing it on the flat trailer base, there was no need to make adjustments for smaller pieces.

Although the prototype was successful at the start of the track, it was not successful for the entire demo. The team did not attempt to send the MACRO through the path where it would have to stop for an obstacle, the prototype was unable to drop off cargo, and it did not attempt to return to the start using the broken path. In addition to this, although the MACRO could successfully turn and make it over obstacles, the turns were very slow and the trailer frequently got stuck on the smaller obstacle. These failures can be attributed to design flaws such as having a bulky trailer, using wheels that did not support peak performance, not having the hall sensor securely attached, and having an unnecessarily long main body.

First, the trailer was a bit bulky and often hindered going over small obstacles. During the demo, the back wheels of the trailer got stuck on the dowel rod and the MACRO would struggle to pull the trailer over this obstacle because the wheel would seem to lock in place behind the dowel rod could not move. In addition to this, the wheels were not the ideal size that the team would have used. The front wheels were ideal, as they had the largest diameter and could easily traverse small obstacles, but unfortunately only two of these wheels were available so the main body of the robot could not have all four wheels with this diameter. The wheels on the trailer followed this as well. The only wheels available were either too large or too small compared to what the team wanted to use, so the team opted to use the smaller wheels. The MACRO failed to drop off cargo due to loose placement of the hall sensor. Since the team was not provided with a hall sensor mount, they decided to allow the hall sensor to simply hang from the main body in hopes that having the sensor so low to the ground would ensure that it could sense all magnets. However, the sensor ended up dragging on the track and could not properly sense the magnets. As mentioned earlier, having the pi and batteries side by side was not the final arrangement of items on the MACRO. Instead, the batteries were held underneath the pi. However, although this was not the final arrangement, the body of the MACRO was not updated for the new arrangement. The team decided that it was not worth it to sacrifice the amount of time it would take to fix this aspect of the physical design instead of using that time for additional testing.

## Conclusions and Recommendations

As mentioned earlier, the negative attributes of the MACRO include having a bulky trailer, not having the ideal wheel sizes, having the hall sensor dangle underneath the main frame, and being unnecessarily long. Now that the team has been through the design process and done thorough testing, there are quite a few recommendations for how the MACRO could be improved.

First, the trailer was bulkier than expected and would frequently hinder turning and getting over obstacles. If the team was able to rework this part of their design after the demo, they would include wheels on the trailer that pivot rather than simply dragging the trailer behind the main body. The trailer that the team ended up using had wheels, but they were not effective since the trailer was dragged behind the main body and would have done the same thing if it did not have these wheels. In addition to this, another alteration that the team could have made was to have the trailer be a part of the main body rather than separate. This way, the MACRO could have gotten over small obstacles much easier.

In addition to this, the wheels used on the MACRO main body and trailer were not the ideal size, which made turning difficult. Although this issue was mostly caused by the limited amount of materials, this complication could have potentially been avoided if larger wheels were used on the trailer or if all four wheels on the main body were the same size and width.

If the team had additional time allotted for testing as well as sensor adjustment and calibration, issues with the hall sensor could have been avoided. Since the team was not given a mount for the hall sensor, they opted to simply let the hall sensor hang off of the bottom of the main body, with the only other attachment being a bread tie wrapped around the wire and the piece holding the back axle. This could have been avoided if the team put time aside to design and 3D print a custom hall sensor mount for the MACRO.

Last, the main body of the MACRO was longer than necessary because of extra space leftover from where the battery pack used to be stored. Initially, the battery pack and pi were held next to each other, but by the time of the demo, the battery pack was being stored below the pi. If the team were to fix this issue, they would have put aside some additional time to deconstruct the main body and rebuild it slightly shorter.

## Use of External Code Appendix

No external code was used.

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