Mars Cargo Mobility System Proposal

Team 50

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Dr. Martin Ortega
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Dear Dr. Martin Ortega,

We are writing to inform you of the Mars Cargo Mobility System (MACRO) Proposal we have been contracted to develop. We have gone through an extensive design process in order to develop the best solution to transport cargo on the surface of Mars. When creating a design for the MACRO prototype, we tried to focus on completing all the requirements efficiently while also keeping the entire MARCO as simple as possible.

We designed our MACRO with two distinct sections, the drive section, and the cargo containment section. We also utilized a color sensor in order to navigate the demonstration course and we also utilized a hall sensor in order to detect the various branch pathways, as well as the cargo delivery locations. Overall, the MACRO prototype contains all the necessary features to navigate the Martain surface, transport the different types of cargo, and deliver the cargo in a timely manner while maintaining a compact form to facilitate easier transportation to Mars as well as increased mobility on the Martian surface. We also created modular code that is not only easy to read but can be adapted as needed for many different use cases as well as being easy to maintain and build upon as needed. Our complete design rationale will be detailed within the design considerations portion of this report. While our MACRO prototype was not able to complete all the required tasks completely, our team believes that all the data collected, as detailed in the physical analysis, will be sufficient to successfully scale to a full Mars rover capable of completing all the mission requirements.

Our team wishes you the best as you move forward to select a final design and we hope you will consider our team to aid in the continuation of the MACRO project. We will be available as needed to answer questions you may have about our prototype design to aid in the development of the full-scale MACRO.

Sincerely, Team 50

Purdue Engineering Department

Executive Summary

The problem that the team aims to solve through this project is to design and create a prototype that represents a full-scale Mars Cargo Rover (MACRO). The MACRO would be used on Mars to pick up and deliver supplies to designated drop-off points while following a specific path and being able to traverse obstacles as well as various types of landscapes. These functions will be simulated on Earth by testing the team's MACRO by running it on simulated obstacles, terrain, drop-off points, and by making it follow a line that represents the real MACRO's physical path it would follow.

The team went through various iterations and redesigns of the MACRO and each time added new features that made the robot more unique and robust. In the final iteration of the MACRO, it has a cargo basket in the front, a rear-wheel-drive system, and a combination unit of a Hall sensor and a color sensor used as a line finder. The cargo basket in the front allows the MACRO to carry and deliver cargo to designated locations. The rear-wheel-drive system combined with the two low friction wheels in the front allowed the robot to achieve tank turning by allowing the front wheels to have a limited amount of slip. The positioning of the line and magnet sensor between the two front wheels was optimal for this robot because it was capable of tank turning around the robot center. The cargo basket is one of the most unique features of the robot, and the team designed it as a basket due to the ease of that design in storing cargo while moving and accurately dropping it off. These various features were housed in a two-compartment chassis, with the drive and sensory components in the rear and the cargo components at the fore

The team had aimed to achieve all the requirements that L3Harris requested but was not able to do so successfully. The MACRO did pass all tests the team had set for it in testing but was not able to achieve these goals repeatedly in the final test. The MACRO passed only the final portion of the test track due to issues with turning caused by poor weight distribution. The MACRO did, however, pass the speed control test. While the MACRO did not perform as desired, it gave useful feedback that could enable us to refine the prototype further if desired.

Design Considerations

While the MACRO in concept is not a complicated robot, its only real purpose is to deliver cargo, there are multitudes of design aspects that must have been considered and decided upon. Some of the physical aspects include the overall shape, choices of wheels, types of tool(s) to use, and sensor choice/placement among many other factors. Decisions regarding the code had to be made regarding the method that the robot moves with, the implementation of the various sensors, and in what way the team wanted to structure the code to make it comprehensible to others. Below is a mostly comprehensive breakdown of the design considerations and choices the team considered and made organized by physical and code considerations.

The first choice the team had to make was of course the overall shape of the “chassis” and a broad idea of where the various required components would go, namely the Pi unit, motors, and storage for cargo. Since the team did not know exactly how much space would need to be devoted to the various systems, they chose to build a very large, squat, and boxy frame with a lot of internal space. While this design worked for initially figuring out how the movement system would function, the size of the frame made the turning radius far too large to be effective. The frame was shortened and remained that way for a considerable amount of time. But, after the team began testing going up a hill it was determined that the weight distribution of the robot was not above the wheels enough to get up an incline, so a final redesign was conducted. This redesign put the wheels of the robot underneath the chassis instead of in front of it and created two separate compartments. One compartment for the main frame contained the Brickpi, all the motors, and most of the sensors, and the other compartment contained the cargo storage basket with a release mechanism at the bottom. This gave the robot a much more maneuverable frame while also allowing it to be sturdier and less prone to tipping over. This final design became the team's final design used during the demonstration.

A series of design choices that were made alongside the chassis design were the choices of sizes and types of wheels. The team discussed several different wheels and wheel alternatives for the main drive wheel (Figures 1 and 2). The team had initially chosen the smaller wide wheel because it was easier to mount over its larger counterpart and provided more stability than the narrower wheel. This worked for a time, but when the team started hill testing it was determined that the smaller wheel was not providing enough grip and that, coupled with the weight distribution issue, was not letting the MACRO get up the incline. So, the team experimented with both the narrower wheel and the wider wheel, and it was determined that the wider wheel was the optimal choice for a drive wheel. It had much more grip and was able to drive up the hill more consistently than the other options. It was not perfect, but we were not given many options to work with when it came to wheels, we only had what was available in our kits, and due to limited parts, we were not able to make any highly customized builds. The other choice of wheel, or wheel alternative, was the non-drive wheel. This was to be just something to slide along the ground with minimal friction to give stability to the MACRO while also letting it turn easily. The team's initial thought was to create omnidirectional wheels or "caster" wheels that would let the MACRO turn much easier than a fixed-position wheel, but the team ran into various issues with this design. The main issue was that the parts the team had to build a caster with were limited, and the team's stock did not contain a few crucial parts that would have made a caster wheel effective. So instead, various alternatives were tested (Figure 3) and the team's initial choice ended up being two angled "sleds" which would just drag on the ground. The angled nature of the sleds would enable them to get over obstacles with ease. These worked until the team began testing on the paper tracks that the PoC events and final demonstration would occur on when they realized that the sleds would get caught on the easily deformable paper and cause issues with the navigation system. This was in addition to occasionally tearing the paper, which the team decided would not be a good idea. The team then reevaluated their options and decided to instead use a wheel without the rubber tire. This was easily able to roll over obstacles and did not interfere with movement.

The next design choice that the team needed to make was which of the sensors provided would be utilized. To do this, the team reviewed the requirements the MACRO needed to accomplish and based on that, determined which sensors would need to be used. The first requirement the team decided they needed a sensor for was the line following requirement. Line following is an integral part of the tasks the team was required to do, so it made sense to figure that component out early. The team had the opportunity to use three different types of sensors that could be used to detect the solid, dashed, and dotted black lines. A Grovepi light sensor, a grove pi line finder, and an EV3 color sensor. The first sensor that the team ruled out was the Grovepi light sensor as it did not detect black lines as effectively as the other two sensors and the data that was received from the sensor was not quite as consistent as the other two sensors. This could be due to any number of reasons from external light sources to the sensor not connecting properly to the Grovepi board. Since consistency was very important to the team, this option was quickly ruled out. The team then had to decide between the Grovepi line finder, of which the team had 3 available, and the EV3 color sensor of which the team only had one available. After some initial testing of the Grovepi line finder sensors, the team decided not to use them because they did not give enough feedback as to the exact position of the robot on the line. The sensors essentially only returned a Boolean value (a 1 or a 0) as to whether or not the MACRO was on a black line. The EV3 color sensor, on the other hand, gave a value between 0 and 100 for the amount of light reflected back to the sensor. This could be used to tell exactly how close to the line the MACRO was. This scaled value also enabled the team to use a proportional line following program to follow the line smoother and more accurately than either of the two other sensors (details of this can be found briefly later in this document and more in-depth in our project workbook). This also allowed the team to more easily detect the buried magnets under the path with the hall sensor because the sensor would be directly over the line. The second requirement the team needed to meet was being able to detect the magnets underneath the path indicating branches from the main path and the exact delivery locations. In order to do this, the team used a digital Hall sensor because it was the only sensor they had available that was designed solely to detect magnets. This sensor ended up being rather difficult to work with, however, as it needed to be close to the magnet in order to detect it. This made the team place the sensor very close to the ground to ensure it would detect the buried magnets. This did end up interfering with obstacles on the ground because of how close the sensors needed to be placed to the ground and gave the MACRO much less ground clearance. The next sensor needed was the inertial measurement unit (IMU). This sensor would be used to detect whether the MACRO was going up a hill. We would use the value from the (IMU) to increase the power of the MACRO when it was going up a hill and reduce it once it makes it to the top of the hill. The next sensor the team utilized was the EV3 gyro sensor. While this sensor was not entirely necessary, it aided in the team's ability to turn accurately. The sensor was used to turn the MACRO an exact number of degrees regardless of how much the wheels slipped or other external factors that could have impacted the robot’s ability to turn. The final sensor the team decided on using was the EV3 ultrasonic sensor. This sensor was used to detect obstacles in front of the MACRO and stop the MACRO so that it would not run into them. This sensor’s values were simple to use, and the team just set a minimum distance for an object in front of the MACRO for it to stop and wait until the obstacle has moved.

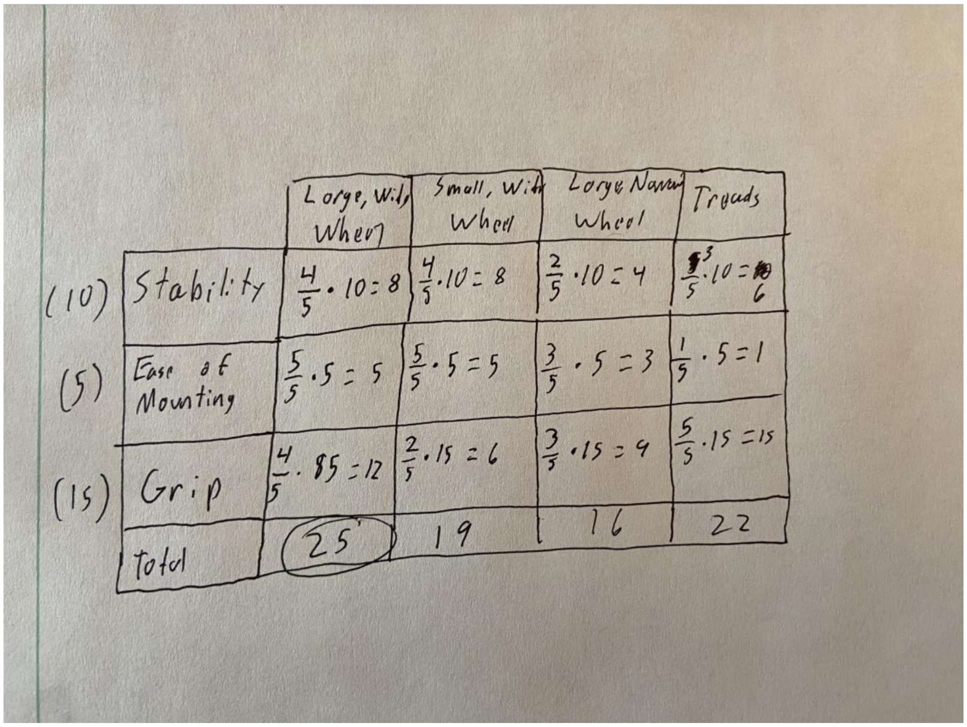
When creating the code used for the MACRO, the team focused on simplicity over complex solutions and code modularity. When the various tasks the MACRO needed to complete were programmed, they were separated into individual functions. This not only made the individual components of the code easier to read and much easier to debug in case of something malfunctioning, but it also allowed the main program to be much easier to create and much simpler to read. Keeping the code broken down into functions allowed the team to test each part of the code individually before compiling it all together into the final program. This also allows the code to be customized in the future by using each of the individual functions created and allowing them to be utilized as needed in a separate mission or other various path layouts. The most significant challenge in the code that the team had to overcome was the line following. Once the team decided on the type of sensor that would be used, they then needed to determine the best method for utilizing that sensor to follow the line. In order to do this, the team utilized what is known as a “state function”. This function essentially determines whether the MACRO is on a black line and executes code accordingly. If the MACRO is on a black line, the MACRO utilizes its proportional line following function. This function allows the MACRO to follow a solid black line smoothly without frequent jerking side to side allowing the Hall sensor to detect the magnets buried in the path. If the MACRO is off the line, however, it uses its search-for-line function which repeatedly moves the MACRO forward and moves back and forth to look for a line. This allows the MACRO to follow any sort of dashed or dotted lines efficiently.

Throughout these various iterations of the various systems of the MACRO, the team tried their best to make all of these decisions objectively and logically. The team was mostly successful with this but was not completely perfect and some decisions were made because they were easier to implement than others. The team did pay for these half-baked decisions later in the design process by having to completely rebuild the MACRO on one occasion and rebuilding various systems more often than any member can recall. But the final design of the MACRO was the culmination of all the decisions made above, including, but not limited to, a tall, compartmented frame, large and wide drive wheels, bare wheels for non-drive wheels, using the EV3 light sensor for the line following sensor over the Grovepi counterparts, and using a state machine function to find the line should it be lost. There were undoubtedly many more small design decisions and considerations made other than the ones listed in this document, but the ones in this document are regarded by the team as the most important to understand how we reached our final design (Figure 5) and the intent of that final design.

Figure 1 Morphological Chart

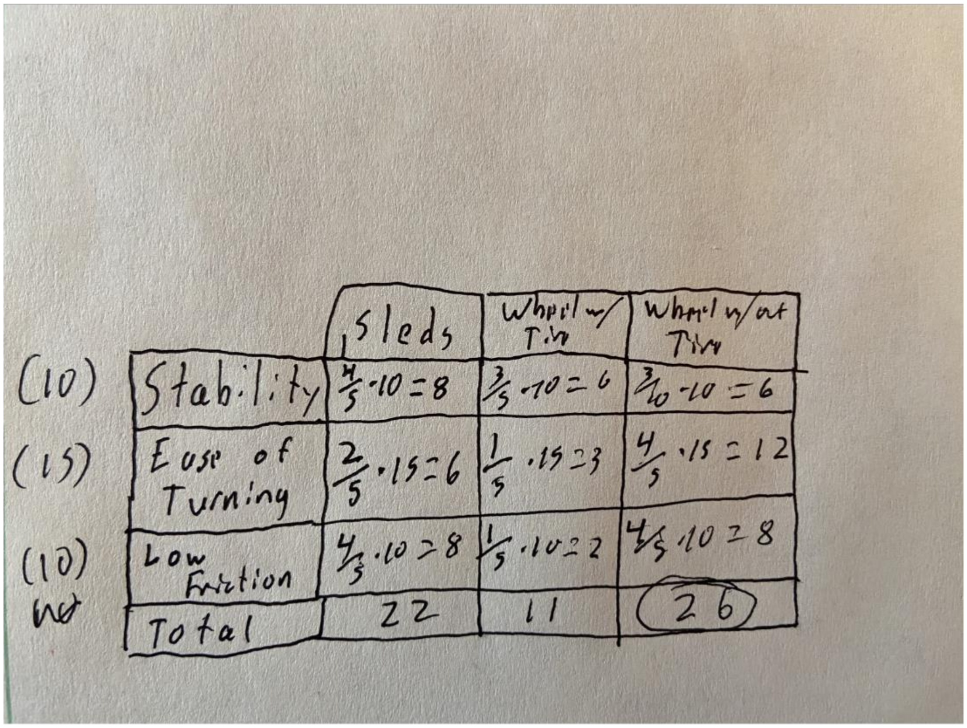
Drive Wheels	Large, wide wheel	Small, wide wheel	Large, narrow wheel	Treads	
Non-Drive Wheels	Sleds	Wheel w/tire	Wheel w/out tire		
Cargo Storage / Delivery	Conveyor w/ elevator	Conveyor w/ drop off	Push off edge	Basket drop	Slide

Figure 2 Drive Wheel Matrix



		Large, Wide Wheel	Small, Wide Wheel	Large Narrow Wheel	Treads
(10)	Stability	$\frac{4}{5} \cdot 10 = 8$	$\frac{4}{5} \cdot 10 = 8$	$\frac{2}{5} \cdot 10 = 4$	$\frac{3}{5} \cdot 10 = 6$
(5)	Ease of Mounting	$\frac{5}{5} \cdot 5 = 5$	$\frac{5}{5} \cdot 5 = 5$	$\frac{3}{5} \cdot 5 = 3$	$\frac{1}{5} \cdot 5 = 1$
(15)	Grip	$\frac{4}{5} \cdot 85 = 12$	$\frac{2}{5} \cdot 15 = 6$	$\frac{3}{5} \cdot 15 = 9$	$\frac{5}{5} \cdot 15 = 15$
	Total	25	19	16	22

Figure 3 Non-Drive Wheel Matrix



		Sleds	Wheel w/ Tire	Wheel w/out Tire
(10)	Stability	$\frac{4}{5} \cdot 10 = 8$	$\frac{3}{5} \cdot 10 = 6$	$\frac{3}{10} \cdot 10 = 6$
(15)	Ease of Turning	$\frac{2}{5} \cdot 15 = 6$	$\frac{1}{5} \cdot 15 = 3$	$\frac{4}{5} \cdot 15 = 12$
(10)	Low Friction	$\frac{4}{5} \cdot 10 = 8$	$\frac{1}{5} \cdot 10 = 2$	$\frac{4}{5} \cdot 10 = 8$
wt	Total	22	11	26

Figure 5 Robot Final Design

Physical Analysis

Keeping a Mars cargo delivery rover compact and easily transportable is vital to the cost-effectiveness of a mission that utilizes them. In order to maintain a low size footprint, the team decided to aim for an overall rover volume less than ten times the volume of the largest object it is designed to carry. The largest object L3Harris tasked Team 50 with carrying was a 12.7 cm diameter cylinder with a height of 12.7 cm. Assuming storage in a rectangular-prism-shaped container gives a target maximum rover volume of roughly 20,000 cubic centimeters (cc). Maintaining compact size was a core tenet of the team’s design philosophy throughout the design process, and this allowed the team to effectively design a MACRO rover prototype that met this size requirement. The final dimensions of the team's MACRO can be seen in Figure 1, along with the final rover volume of roughly 16,900 ccs.

Based on cargo dimensions listed in L3Harris' original RFP, the team decided to aim for a cargo container that could effectively store each type of cargo while minimizing unused space. The team's final MACRO prototype's cargo basket dimensions can be seen in figure 1. Due to the cargo basket having an open top, and all system-vital sensors are either mounted in front of the basket or underneath, the effective height limit for stored cargo only depends on changes to the balance of the rover. If cargo is stored in the basket that raises the total body's center-of-mass too high, the rover may become unstable and have the potential to cause damage to itself or the cargo. However, for the purposes of the MACRO demonstration requested by L3Harris, the maximum height that any cargo extends above the height of the rover body is only at most 2 cm (cone-shaped power generation unit). The team's MACRO rover can store cargo the length and width of items provided by L3Harris and theoretically even taller. Additionally, the heaviest object given in the RFP by L3Harris had a mass of approximately 450 g. To ensure the stability of the rover, the team decided to aim for a theoretical maximum payload mass of 550 g. Through testing cargo of increasingly heavy objects, the team found their MACRO prototype could support a cargo of 758 g, more than which would cause the rover to become unstable. Overall, Team 50's MACRO prototype exceeds both the size and weight requirements set by L3Harris Technologies.

In order to ensure timely delivery of cargo to a drop-off zone, L3Harris requested a MACRO rover capable of accurately traveling any speed between 15 and 30 cm/s. Team 50 decided their rover should be capable of a higher maximum speed, to ensure that the rover could accurately travel at any given speed without the need for maximum power output. This was because putting maximum power output on the motors also puts them under considerable strain, not something a rover designed for long-term use needs. The team tested their rover's maximum speed by measuring the time the rover took to travel a set distance. In the end, the team produced a MACRO prototype capable of accurate 60 cm/s movements.

Early on, the team decided to implement a cargo basket with an under-side claw cargo release system. Because of this feature, the team decided that minimizing cargo impact speed was a priority to ensure the safety of said cargo. Modern smartphones can survive ~1 m drops with no significant damage[1]. Using simple kinematics, and assuming a drop in Earth's gravity, this corresponds to an impact speed of roughly 450 cm/s. To be thoroughly safe, the team aimed to design their MACRO prototype to drop cargo at less than half this impact speed (225 cm/s). Through testing cargo-drop off with a small book, the team found the rover's claw system to release inserted cargo at an average of 6 cm above the ground (dependent on cargo width). In testing the release height of the cargo basket, the team also recorded the effectiveness of the claw at maintaining the cargo's orientation (100% success). Assuming average gravitational acceleration on Earth, this 6 cm drop height corresponds to a cargo-ground impact speed of ~108.5 cm/s (see Figure 2). Assuming no extremely delicate equipment, and with normal ground and cargo materials, this impact speed is very unlikely to damage any electronic or delicate equipment. The change in gravity from the surface of Earth to the surface of Mars would not affect the results of this in a negative way due to Mars having a weaker gravitational pull.

Given the size of the hills the MACRO rover was tasked with crossing (exact measurements unknown), the team decided to aim for a maximum stable incline angle of 25 degrees. At the end of the design cycle, the team tested the rover's true maximum stable incline angle. By locking the rover's wheels with a simple apparatus and placing it on a binder, then incrementally increasing said binder's angle relative to the horizontal, the team could measure the angle at which the rover started to tip backwards. The measured maximum angle of 31.8 degrees is displayed in figure 1. At any angle greater than this, the rover's center of mass moves behind the rear wheels, causing the MACRO to no longer be stable or able to recover. Incidentally, at ~31.8 degrees, the rover begins to break the static friction between the rubber rear wheels and the ground, resulting in rearward slippage. Evidently, both systems were well optimized, and the maximum incline angle is greater than the team's target value, allowing their MACRO to safely traverse any hills in its path.

From the RFP given to Team 50 by L3Harris, the team learned that the minimum possible radius of curvature their rover would need to turn about was 2 inches. Equating 2 inches to 5.08 cm (~5 cm) gave the team their target value for the minimum turn radius of their rover. Early in the design process, the team considered using a rotating front-wheel-drive turning system that would allow for a sufficiently tight turn radius. However, by sticking to their design principle of "simplicity over complex solutions," the team eventually decided to implement a two-wheel drive system whereby the rover turns by simply adjusting the power to the rear wheels. One major benefit of this system is that it allows the team's MACRO rover to rotate around the center-point between the two rear wheels, representing an effective minimum turn radius of 0 cm. Using this friction-based tank-turning system, the team designed a rover capable of completing turns tighter than those given in the MACRO rover demonstration.

In a study originally designed to help select NASA's two MER landing sites[2], the team found figures stating the frequency distribution of different rock diameters appearing at different zones on the Martian surface. In general, it's safe to assume that no more than 2 rocks of diameter greater than 0.1 m appear per square meter at many potential landing zones on Mars. Given this information, and the relative scale of Team 50's MACRO to a full-scale Mars rover (about 1:10), the team decided their rover should be able to safely roll over rocks 1 cm in height (barrier 1 cm in height). Any obstacle larger than 1 cm would be infrequent enough to be avoided altogether. In order to test their rover's performance against this goal, the team stacked notebooks to find the maximum possible obstacle height the rover could clear. After testing, the maximum height the rover cleared was 1.3 cm, greater than the team's initial 1 cm goal. This maximum height was primarily limited by a) the radius of the front wheels, and b) the ground clearance of the rover dictated by the height of system-critical sensors above the ground. The team successfully met their design goals and identified increased wheel radius and sensor height as two low-cost fixes to improve performance.

Figure 1

Customer Need	Technical Need	Technical Requirement	Target Value	Team 50 Rover Value
Compact rover	Volume (cc)	Vol: 20,000 cc	same	L: 35 cm W: 22.5 cm H: 21.5 cm Vol: 16,900 cc
High cargo capacity	Cargo dimensions (cm), max cargo mass (g)	L: > 12.7 cm W: > 12.7 cm H: > 15.2 cm Mass: > 450 g	Dimensions: same Mass: > 550 g	L: 12.9 cm W: 14.5 cm H: > 15.2 cm (open top) Mass: 758 g
Quickly deliver cargo	Max rover speed (cm/s)	> 30 cm/s	> 40 cm/s	60 cm/s
Safely deliver cargo	Impact speed of cargo from cargo basket (cm/s)	< 225 cm/s	same	108.5 cm/s
Stable rover	Maximum balance angle	> 25 deg.	same	31.8 deg.

	(before rover tips) (deg.)			
Rover maneuverable	Min. Turn radius (cm)	< 5 cm	same	0 cm (tank turning)
Safely traverse obstacles	Max. Passable obstacle height (cm)	> 1 cm	same	1.3 cm

Figure 2

$$\underline{V^2 = V_0^2 + 2ax}$$

$a = g$ ← gravity is only force

$g_{earth} = 9.81\ m/s^2$

$V_0 = 0$ ← cargo initially at rest

$V = \sqrt{2gx}$

cargo impact speed:

$$V_{impact} = \sqrt{2(9.81\ m/s^2)(0.06\ m)}\ \boxed{= 1.085\ m/s}$$

[1] Orellana, V. (2021). iPhone 12 drop test: The ceramic shield screen went above and beyond. Retrieved 9 December 2021, from https://www.cnet.com/tech/mobile/iphone-12-scratch-drop-test-ceramic-shield-durability/

[2] Golombek, M., Grant, J., Parker, T., Kass, D., Crisp, J., & Squyres, S. et al. (2003). Selection of the Mars Exploration Rover landing sites. Journal Of Geophysical Research: Planets, 108(E12). doi: 10.1029/2003je002074

Scaling to Official Mars Project

The first environmental challenge a full-scale MACRO rover must overcome is Mars' frequent high winds, dust storms, and temperature fluctuations. For one, the rover's electronics and cargo will need to be shielded from temperatures averaging between -143 deg. C and 35 deg. C[1]**.** To effectively transform the team's prototype into a fully functioning rover, a housing would need to be built around both the electronics bay and the main cargo basket (separately, to avoid contamination when the cargo basket opens). The simplest design solution is a strongly insulated box that holds all the central electronics in the body, built with a few openings/extensions for and motors. Then, a similar protective housing could be built around the cargo with a motorized opening system on the bottom to allow the release of cargo.

Another significant challenge the rover's design must adapt to is the difference in friction between the Martian surface and the paper used to test the small-scale prototype. On Martian regolith, a rover's wheels can sink several centimeters into the surface, rendering a 2-wheel drive system very impractical[2]. The team's prototype relied on low surface friction in the front wheels, so introducing a higher-friction environment to the rover would result in drastically lower turning ability. One option, a 4-wheel drive system capable of providing different power to each of the 4 wheels, would result in greatly improved turning on high-friction surfaces. Another way to improve steering would be to rotate the front two wheels around the rover's z-axis, comparable to a front-wheel-drive car's wheels. This system would increase the rover’s turn radius but could be further reduced by allowing the rear wheels to rotate as well. This design would allow the rover to turn more accurately around sharp corners and navigate in areas with limited space (such as a crowded landing site or habitation facility). It would require more components, but this system would increase the rover's overall efficiency, as less energy would be lost to friction (see Figure 3). The need for such a design depends on the number of obstacles in the potential MACRO's landing site.

Depending on the fragility of the cargo carried by the MACRO, simply scaling-up Team 50's prototype could result in unsafe impact speed of cargo on the ground. Although Mars' comparatively low gravity partially mitigates this issue, introducing a system to allow lower release of cargo by the basket claw would ensure the MACRO's capability to transport a wider range of sensitive items. However, simply designing the cargo basket lower to the ground would cause ground clearance issues. As such, the team recommends a cargo elevator system for both full-scale rover designs. The elevator could remain at its highest position during cargo transport, allowing the rover to clear higher obstacles, then lower itself to a safe release height once at the drop-off zone.

To maximize rover carrying capacity while still allowing the rover to be built using roughly standard-sized parts, Team 50 recommends the final Mars rover be built 10 times larger than the small-scale prototype. Such a rover would have a length of 3.5 m, a width of 2.25 m, and a height of 2.15 m. This would place the final rover's volume at 16.93 cubic meters.

Using the same scale, the final rover's cargo basket would have a length of 1.29 m, a width of 1.45 m, and a height of 1.52 m, resulting in a volume of 2.45 cubic meters. However, since an object's mass increases more with size than its dimensions, the cargo basket will need to support 1,000x the prototype’s basket in order to carry objects of the same density. As such, the team recommends the rover be able to carry 800 kg of cargo without compromising stability. However, because of the difference in gravity between the Earth and Mars, the full-scale model designed to be tested at the simulation facility in Canada will be rated to hold less mass with the same components. In this way, the rover could be tested at the simulation site with less dense cargo. Using simple gravitational calculations, the team derived that the full-scale Mars rover will need to support ~760 kg, while the Earth full-scale model will need to be built to support ~290 kg (see Figure 5).

Although the full-scale Mars rover will likely drive far slower than its top speed to increase energy efficiency and hazard avoidance, designing it capable of traveling the same speed relative to its size as the small-scale prototype will ensure its capability to travel long distances if the need arises. This corresponds to a maximum rover speed for both the Mars and Earth variants of 6 m/s.

Since any delicate cargo's properties don't change on Mars compared to Earth, the full-scale rover should be built for the same cargo impact speed as the prototype. This impact speed requirement will correspond to different cargo drop heights for both full-scale variants due to the difference in gravity. So, the simulation test site rover should be designed with a cargo elevator that can lower to 6 cm above the ground, while the Mars variant can be designed to drop cargo 15.8 cm above the ground (see Figure 6).

Since both variants of the full-scale rover will require more batteries but not significantly more electronics than the small-scale rover, they can be designed to have a lower center-of-mass. As such, both variants of the full-scale rover should aim for a maximum balance angle of 35 degrees ensuring rover stability over obstacles or reasonably angled ramps.

Based on the test-track dimensions given to Team 50 by L3Harris, the team decided to aim for a minimum turn radius of 5 cm. Assuming this test track is a faithful recreation of a potential mission site, the full-scale rovers should be built for a minimum turn radius of 50 cm to maintain proportionality with the small-scale prototype (0 cm is possible with a 4-wheel z-rotation design).

Due to the difference in gravity between Earth and Mars, the two variants of the full scale-rover can be built to clear differently sized obstacles to effectively rate performance[3] (see Figure 7). Also, since both variants will be designed with 4-wheel drive systems, they will have intrinsically better climb performance than the prototype. Specifically, the full-scale Mars rover should be designed to successfully clear a 20 cm obstacle, while the Arctic Research Station rover should be designed to clear a 7.6 cm obstacle.

Team 50's sensory input system suffers from one main design flaw: the low height of the color sensor and Hall sensor above the ground (~0.7 cm) limits the rover's ground clearance. To mitigate this issue in the full-scale rovers, both sensors should be raised to be closer to the rover's body. While this would require more sensitive sensors, the increase in ground clearance of the rover would be worth the cost. The team's small-scale prototype’s ground clearance of ~3 cm places the full-scale rover's ground clearance at ~30 cm. The team recommends both Earth and Mars full-scale rovers be designed with a sensor height of at least 30 cm above the ground assuming the robot would be following a line as its main navigation system.

To ensure the stability of the rover's locomotion system, the wheelbase should be extended so that the front wheels are positioned in front of the cargo basket. The team's small-scale prototype suffered from increased force on the front wheels due to the cargo basket acting as a lever. The full-scale rover should implement a wheel-base length of 3.5 m, the same as the length of the rover itself.

Team 50's prototype's pathing system (code) used a side-to-side line-searching algorithm. When the rover lost the black line, it would repeatedly turn left-to-right and vice versa, until it found the line again. While very simple and quite effective, this algorithm led to one main issue. When going around sharp corners, the rover would travel too fast and require side-to-side line-searching when it wasn't strictly necessary. To combat this, both full-scale rovers could implement a system to slow down the rover during sharp corners to increase the minimum effective "smooth turn radius," the radius of curvature at which the rover can follow a pathing line without turning side-to-side. During testing, Team 50 found their rover prototype had a minimum effective smooth turn radius of ~7 cm. To maximize the functionality of both full-scale variants, this should equal the true minimum turn radius of the rover, 50 cm.

Because of the requirement for rover ground clearance, a Hall effect sensor wouldn't provide the full-scale rovers with much utility, as the effective sensing range is quite small. Additionally, the same Martian dust storms that require the cleaning of solar panels would render any sort of optical location sensor useless. For example, a red "X" on the ground to signify the drop-off point could become completely covered in dust in a matter of hours. Instead, a system of radio proximity sensors would be much more reliable. But thankfully, such parts can be purchased from a variety of electronics vendors for a relatively low cost. For example, low power consumption radio proximity beacons can be purchased online for under 20 USD[4]. Triangulation using 3 of these beacons would be cost-effective and reliable.

Because of the nature of software, algorithms tailored to a specific rover design can't easily be purchased off-the-shelf. If L3Harris were to decide to outsource software development for their MACRO system, the pricing could vary wildly. Any software, including a system to slow down the rover into turns, allowing a lower smooth turn radius, would likely need to be developed in-house.

To meet the weight and grip requirements of both full-scale MACRO rovers, wheels will likely need to be manufactured in-house. NASA's Perseverance rover, for example, utilized 6 highly custom wheels which can't be easily purchased from any vendors. However, motors the use of electric motors in many different applications means that electric motors can be purchased from a vendor to meet the right power and efficiency requirements. For example, their use in the growing EV market means there are many global candidates for electric motor suppliers.

Figure 1

Rover Specification	Small-scale prototype	Full-scale Earth rover	Full-scale Mars rover
Volume (m^3)	Volume: 0.0169 m^3	Volume: 16.93 m^3	Volume: 16.93 m^3
Cargo dimensions (m) and mass (kg) capacity	L: 0.129 m W: 0.145 m H: > 0.152 m Mass: 0.758 kg	L: 1.29 m W: 1.45 m H: 1.52 m Mass: 290 kg	L: 1.29 m W: 1.45 m H: 1.52 m Mass: 760 kg
Maximum rover speed (m/s)	0.6 m/s	6 m/s	6 m/s
Cargo drop height for 1.085 m/s impact (cm)	6 cm	6 cm	15.8 cm
Maximum rover incline angle (deg.)	31.8 deg.	35 deg.	35 deg.
Minimum turn radius (m)	0 m	50 cm	50 cm
Maximum passable obstacle height (cm)	1.3 cm	7.6 cm	20 cm

Figure 2

Subsystem specification	Small-scale prototype	Full-scale Earth rover	Full-scale Mars rover

Sensory input system height above ground (cm)	0.7 cm	30 cm	30 cm
Locomotion system wheelbase length (m)	0.22 m	3.5 m	3.5 m
Pathing system dictated min. Smooth turn radius (cm)	7 cm	50 cm	50 cm

Figure 3

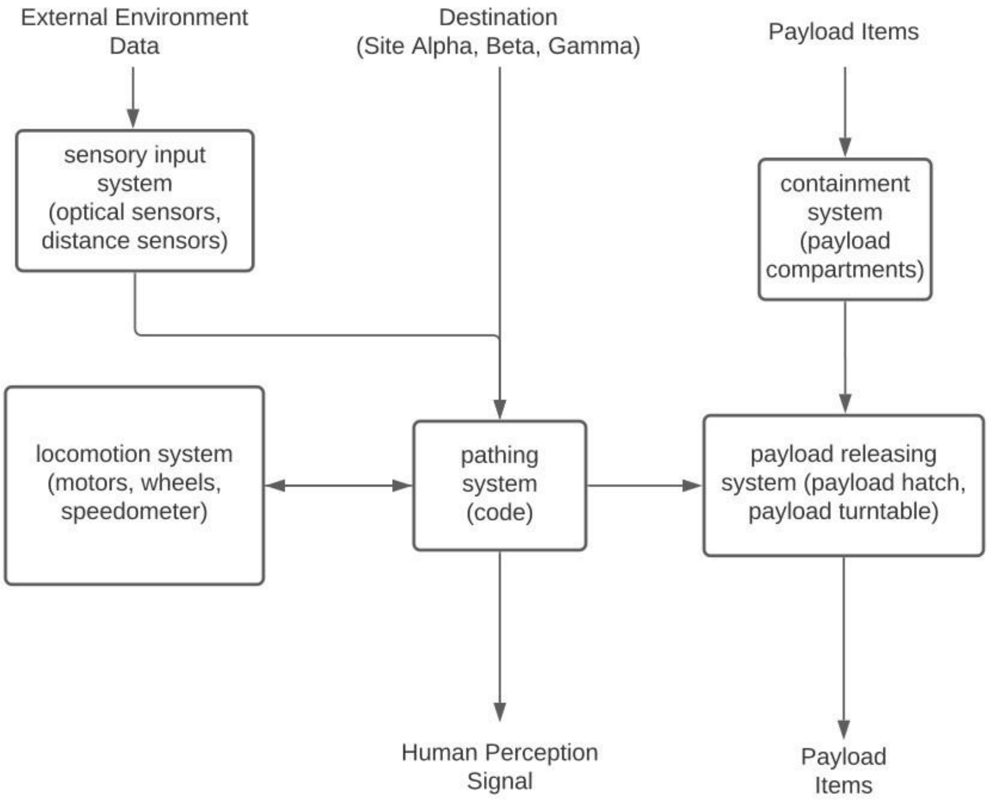
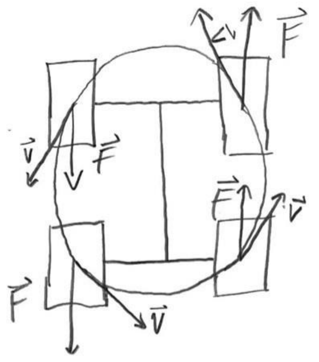
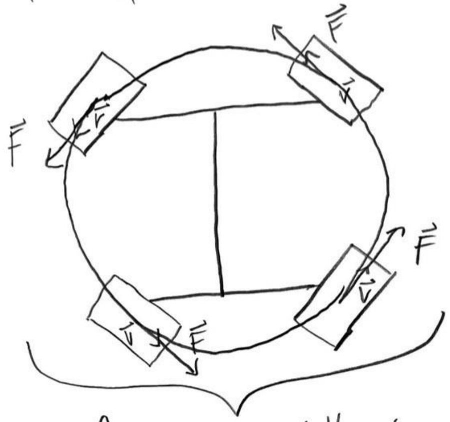


Figure 4



4-wheel z-rotation:



force on regolith always tangent
to direction of turing circle

Figure 5

full-scale cargo volume $(V_1) = 16.93\, m^3$

small-scale cargo volume $(V_2) = 0.0169\, m^3$

full-scale cargo weight capacity $= (M_1 g_1)$

small-scale cargo weight capacity $= (M_2 g_2)$

Since cargo mass is a function of its volume:

$$\frac{V_1}{V_2} = \frac{M_1 g_1}{M_2 g_2} \Rightarrow M_1 = \frac{V_1 M_2 g_2}{V_2 g_1}$$

on Earth:

$$M_1 = \frac{16.93\, m^3 (0.758\, kg)(9.81\, m/s^2)}{0.0169\, m^3 (9.81\, m/s^2)} \boxed{\approx 760\, kg}$$

on Mars:

$$M_1 = \frac{16.93\, m^3 (0.758\, kg)(\overset{g_{Mars}}{3.72\, m/s^2})}{0.0169\, m^3 (9.81\, m/s^2)} \approx 290\ kg$$

Figure 6

$$V^2 = V_0^2 + 2ax$$

$a = g$ ← gravity is only force

$g_{earth} = 9.81\, m/s^2$

$g_{mars} = 3.72\, m/s^2$

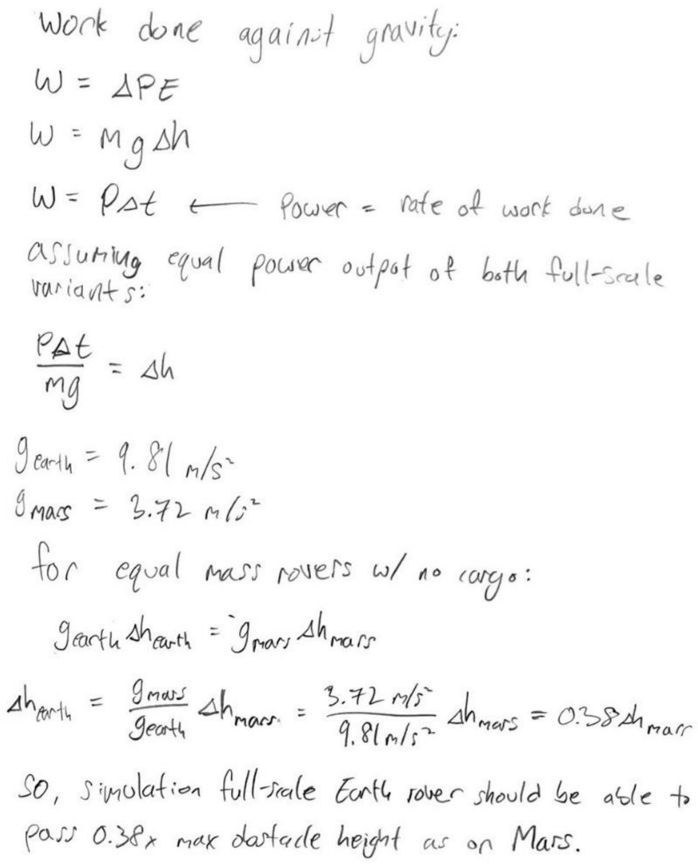
$V_0 = 0$ ← cargo initially at rest

$$V^2 = 2gx \Rightarrow x = \frac{V^2}{2g}$$

Earth drop height: same as small-scale, 6 cm

Mars drop height: $x = \frac{(1.085\, m/s)^2}{2(3.72\, m/s^2)} = 15.8\ cm$

Figure 7



Work done against gravity:

$W = \Delta PE$

$W = mg\Delta h$

$W = P\Delta t$ ← Power = rate of work done

assuming equal power output of both full-scale variants:

$$\frac{P\Delta t}{mg} = \Delta h$$

$g_{earth} = 9.81\ m/s^2$

$g_{mars} = 3.72\ m/s^2$

for equal mass rovers w/ no cargo:

$$g_{earth}\Delta h_{earth} = g_{mars}\Delta h_{mars}$$

$$\Delta h_{earth} = \frac{g_{mars}}{g_{earth}}\Delta h_{mars} = \frac{3.72\ m/s^2}{9.81\ m/s^2}\Delta h_{mars} = 0.38\Delta h_{mars}$$

So, simulation full-scale Earth rover should be able to pass 0.38x max obstacle height as on Mars.

Citations:

[1]Martian Climate – Planetary Sciences, Inc. (2021). Retrieved 11 December 2021, from http://planetary-science.org/mars-research/martian-climate/

[2]Sullivan, R., Anderson, R., Biesiadecki, J., Bond, T., & Stewart, H. (2011). Cohesions, friction angles, and other physical properties of Martian regolith from Mars Exploration Rover wheel trenches and wheel scuffs. *Journal Of Geophysical Research*, *116*(E2). doi: 10.1029/2010je003625

[3]Mars. (2021). Retrieved 11 December 2021, from https://www.grc.nasa.gov/WWW/K-12/rocket/mars.html

[4](2021). Retrieved 11 December 2021, from https://www.amazon.com/Distance-Vibration-Consumption-Waterproof-Bluetooth/dp/B07P95JWJ3/ref=sr_1_2_sspa?keywords=radio+proximity+beacon&qid=1639171326&sr=8-2-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUExRVlFSkdBQVBLMFVVJ

mVuY3J5cHRlZElkPUEwODI3MTg1M1E1Rk5IR0JNTjAwNCZlbmNyeXB0ZWRBZElkPUEwODg5MzM4M0dRUzIyUjE2N0ZGRiZ3aWRnZXROYW1lPXNwX2F0ZiZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=

Results and Discussion

The results of the team's MACRO demonstration were suboptimal. Despite testing the robot many times and having success with all required MACRO functions earlier in the day, it failed to complete turns when performing in the actual demonstration. Due to multiple unforeseen errors in the MACRO's performance during the demonstration, the team prioritized testing each section at least once so that the MACRO had a chance of completing at least one section.

First Section: The team started at the beginning of the first section, but once the robot detected a curve and tried to turn by following it, the two front wheels locked up. This occurred an average of approximately 1 second after the robot recognized that it had lost the line and began trying to find it. The robot kept trying to turn sideways but as the front wheels tried to slide sideways as intended, they began shaking instead. The team quickly realized that this was the result of the cargo's weight pushing down on the front wheels, causing there to be a larger normal force and therefore more static friction between the front wheels and the ground. After realizing this, the team tried replacing the cargo with the lightest cargo. However, this did not make much of a difference as there was still too much weight on the front wheels. After multiple attempts and various changes to the MACRO's code, it still did not turn so the team opted to try for the next few parts of the demonstration course. This result did not match up with the team's testing because during the tests, the robot was able to follow turns extremely well and rarely veered from the line.

Second Section: The team's performance during the second section was just as unsuccessful as the first because there were multiple turns leading up to the hill, and the MACRO still could not make a single turn. It encountered the same problem as the first section and the team quickly realized that this problem would not be solved soon and moved on to the third section of the demonstration course. Like in the first section, the wheels locked up about 1 second after the robot "lost" the line and began trying to find it.

Third Section: After assessing the track to see which turns had the widest radius, the team decided that the third section might be the most doable for the MACRO because it had a very wide turning radius, so the MACRO may be able to make around the turn because it would only have to turn a small distance sideways with each forward movement to complete the turn. However, the robot still could not make this turn and after two attempts, the team quickly decided to try the last section of the course. The same turning error occurred at around the same time as the first and second sections.

Fourth Section: The fourth and last section of the course was far more successful than the rest. This was mainly because there was no cargo that had to be carried by the robot, so there was no weight placed on the front wheels. It turned as the team had intended it to according to the designs and design concepts. The success in turning confirmed the team's suspicions of the weight on the front wheels being the main problem behind the robot not being able to turn. The robot also met the team's target value of a displacement from the line of less than 8 cm. The robot excelled in that aspect during this section, as it did not veer farther than about 1.5 cm from the line when there was a break in the line. In addition, when confronted with the break in the line the MACRO lost the line for approximately 1 second, executed the line finding function, found the next part of the line, and resumed following it. This aspect of the demonstration was very satisfactory for the team and matched the results of the second PoC. In the second PoC, the MACRO was able to follow a curved dashed line on the first attempt. The line finding algorithm worked extremely well for finding a dashed line, so it was no surprise to the team that the MACRO was able to traverse the turns without cargo and find the line after the line break.

Speed Test: For the speed test, the target value to travel 200 cm was 10 seconds +/- 0.5 seconds. The team's MACRO took 10.3 seconds to travel 200 cm, which is within the target range and therefore satisfactory for the demonstration. During the speed test, the team decided to set the robot straight and run code to drive straight forward at a certain speed rather than have it follow the line as well. Due to this, the robot's maximum displacement from the line was about 9 cm, which falls out of the team's target range for line following. However, this is a minor mistake as the line following aspect of the speed test was determined by the team to be a less important measure of success.

Conclusions and Recommendations

The MACRO's performance at the demonstration was far from what the team expected, mainly due to one issue, that being that the MACRO could not make a turn with cargo due to the weight of the object weighing directly over the front two wheels. This caused the front two wheels to not be able to slide as they were intended. The increased friction caused the wheels to lock up and the MACRO was unable to turn as the team initially planned on and designed it to do. Instead, the front wheels tried to slide sideways but began shaking instead, being put under the stress of friction from the ground and power from the rear tires. After designing and testing the robot, the team decided that there are several aspects of the robot that could be improved for better performance. The aspects that could be improved upon could include a more evenly distributed chassis design, more centralized cargo system, a better line follower/magnet sensor location, and a more robust hill-climbing function.

The electrical component in the back of the chassis caused the MACRO to be too back-heavy. This part of the robot contained the Pi unit, the two rear motors, most of the wiring, and the bulk of the structural components. The team realized after the demo that the weight distribution was the main culprit of the perceived turning problem, so the best solution would be to redesign the chassis, so the mass would be evenly distributed across all four wheels. This would in addition help tighten the turn radius of the rover. In addition, the team could have benefitted from a central cargo system. The cargo system currently on the MACRO was easy to use but suffered from severe imbalance. Therefore, as an improvement, the team would place the cargo system in a more central location, likely with a holding system that was slanted to ensure easy drop-off. The most effective design change the team could make would be to change the fixed-position wheels that the rover currently slides side to side with to omnidirectional or "caster" wheels. These would enable the rover to turn easily in all directions and struggle less with getting over sudden changes in terrain. These various design changes in conjunction with each other would easily rectify some of the most pressing issues facing this prototype and make it far more ready for a mission to the Martian surface.