Project 3 Written Report

Team #43

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Dr. Martin Ortega,

Team 43 has been assigned the task of creating a Mars Cargo Mobility System (MACRO). This system, once landed, must be capable of loading a piece of cargo from the payload and transporting it across the Martian landscape on a given route to one of several predetermined unloading zones. The goal of the team is to create a MACRO capable of delivering the cargo in a safe and timely manner. It should be able to traverse rough and unclear terrain while keeping the cargo safe.

As demonstrated in a series of Presentation of Competency (PoC) tests and the formal demonstration, the MACRO developed is more than competent in achieving the goal. In this demonstration, the robot was able to execute over 75% of obstacles on its first try and could increase its success to near perfection with the revision of only a few small features. This demonstration also included a formal vehicle speed test, which MACRO executed perfectly on the first attempt.

The MACRO uses a variety of features to accomplish these tasks. It has a line following system capable of tracking even over extremely rough terrain and an advanced wheel and slider array to negotiate past any large obstacles the MACRO might encounter. It has an elegantly simple cargo carrying system that has proven to be reliable and consistent. The vehicle also incorporates a self-correcting system that keeps the MACRO on course in the event of external forces. The MACRO is also capable of detecting potential hazards and avoiding them.

Combined, all these features and their applied success makes the MACRO the ideal device for accomplishing the goal of this project: delivering cargo through a rugged environment in a safe and timely manner.

Thank you for your consideration,

Team 43

Executive Summary

The team has been tasked with the design and construction of a Mars cargo rover (MACRO) prototype. MACRO must be able to reliably navigate along a specific course and to designated sites, recognizing, and combating obstacles along the way. It must also carry designated cargo containers sturdily and deliver them to these locations with minimal human intervention and in a timely manner.

The final model developed can successfully fulfill all the given requirements. It was developed using the provided kit including LEGO parts and motors, Raspberry Pi, Grove Pi, and Brick Pi boards, various sensors, and all other corresponding wires and connectors. The frame of the design features two front wheels with differential steering and two sled supports in place of rear wheels to allow for free range of motion and the ability to traverse obstacles along the path.

There are unique factors of the MACRO that contribute to its effectiveness. For example, the cargo carrying apparatus must be manually operated and adjusted to fit each container shape, and the container is discharged by the dropping of a small support arm from below when the magnetic sensor is triggered. A V-shaped adjustable piece holds the top of the container to prevent it from moving around in transit, and it is resized between each delivery to fit each cargo piece. This allows for secure, reliable transit of each piece, while leaving little room for error by minimizing the number of moving parts involved. Additionally, the team employed an EV3 color sensor in place of a traditional line follower. This sensor detects reflected light from the path to differentiate light and dark, thus sensing the line in contrast to its white background. This allows for much smoother movement and enhanced ability to follow dotted lines.

During the demonstration, the MACRO was mostly successful. It was not able to get over the dowel rod, but it did get over the hill on its first attempt. It also paused and restarted successfully at the moving obstacle on its first try. At the cargo drop off locations, the MACRO had issues across all four attempts at detecting the proper number of magnets. It was able to deposit cargo at an average of 16 cm from the site. At the final "broken line" obstacle, the vehicle lost track of the line and went off course. It followed lines perfectly otherwise. The speed test took one attempt to cross the line in 10.0 seconds.

Design Considerations

One system that went through many iterations and alternatives was the cargo holding system. In the preliminary stages, the team used methods of traditional brainstorming and researching prior art to explore possible methods for holding and distributing the cargo from the MACRO. Some examples that were developed included a conveyor belt, a ramp (Figure 1), a trapdoor system, and a small, modified trapdoor arm (Figure 2). The conveyor belt was ruled out because it was far too difficult to ensure accurate placement of the cargo. It would slide an indefinite distance based upon discharge from the vehicle, making it difficult to refine and perfect the drop off distance. It also would have required a very complex part and motor system that would be difficult to revise or repair. The trapdoor system was ruled out for the same reason. The team was concerned that relying on too many parts on motors would result in issues that would be difficult to adapt to in the event of a malfunction. The final decision was on the trapdoor arm, which had only two pieces attached to the motor. It was the best choice for the design because of its simplicity and ability to precisely drop the cargo without moving or sliding upon discharge.

Figure 1: Cargo Ramp

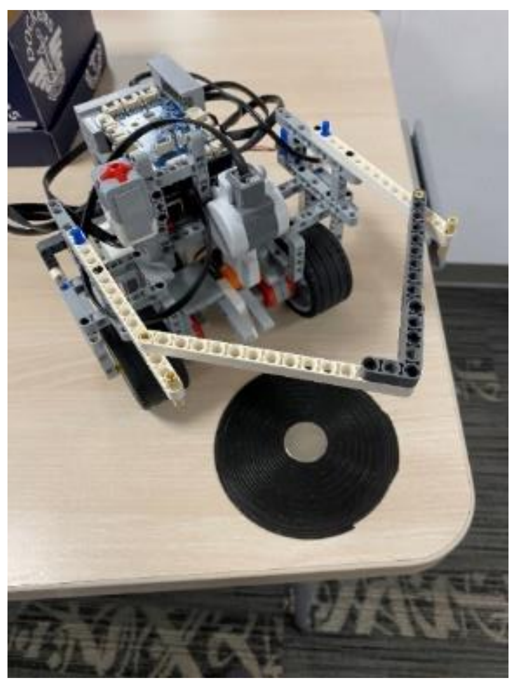


Figure 2: Final Iteration

Another decision made during the build process was the method of steering to use in order to maximize efficiency in the context of the given tasks. The two options that were weighed were pointed steering (car steering) and differential steering (tank steering). Below in Figure 3 is a decision matrix developed to help aid in the process. The best choice was decided to be differential steering, which was implemented into the design. There was a large enough disparity in the Quality Function Deployment (QFD) scores of the two steering methods that it was deemed unnecessary to explore the other option. The simplicity of programming the differential steering couples with the minimal turn radius to make this option optimal, eliminating the need to explore pointed steering as an option in total.

Decision Criteria		**Steering Method Options**			
		Pointed Steering		Differential Steering	
					
Requirements		**Satisfied?**	**Comments**	**Satisfied?**	**Comments**
2.4 - The rover must have a limited top spee		Yes	Will work at any speed	Yes	Will work at any speed
2.3 - The minimum radius of curvature for a guideline, as measured from the centerline of the guideline, will be 2.0 inches		Maybe	Depends on maximum angle of wheels	Yes	Can have a turn radius of 0 if necessary
Team Desires	**Weight**	**Value**	**Comments**	**Value**	**Comments**
Simplicity	0.3	0.5	Requires moving wheels	0.9	No moving wheels
Small turn radius	0.4	0.3	Turn radius will be large	1	Turn radius can be 0
Number of motors required	0.3	0.5	Requires one motor for steering, and 1+ for movement	0.6	Requires only 2 motors
Total Merit:		0.27		0.67	

Score Key	
Good	1
Ok	0.5
Poor	0.25

Figure 3: Steering Method QFD

The decision-making process with respect to the sensor array was generally a choice between two alternatives, which were decided on based on the team's needs and how well each sensor fit the build for the project. The sensor array included the Grove color sensor, Hall sensor, ultrasonic sensor, gyro sensor, and a light sensor to start it. For a line following mechanism, a choice was made between the Grove line follow sensor and color sensors. The color sensor was used because the gyro sensor was decidedly necessary for the vehicle, and the line follow sensor could not have been used in tandem with the line follow and touch sensor due to port unavailability. Since the touch sensor could not be used, the light sensor was the option available to start the program. With respect to magnet sensor, the options were between the IMU and Hall sensor. The Hall sensor worked better with the frame of the vehicle and was easier to operate and develop code for. This was the only option with which the team experimented of the two, and its performance was satisfactory.

One of the main decisions when it came to the drivetrain was the choice of tire to use. A decision matrix (Figure 4) was developed in order to ease this process, which helped the team determine what would hypothetically be the best tire to use for the model. According to the matrix, the 56x34 wheel would be the best option, so that was originally what was used on the robot. However, it was realized that the weight of the robot did not affect the stability of the wheels as much as anticipated, and the high radius of the motorcycle wheel outweighed its instability under the weight of the robot. The final model of the robot used the motorcycle wheel and small caster wheels in the back.

Decision Criteria		Drive Wheel Options					
		81.6x15 Motorcycle Wheel		56x34 Wheel		43.2x26 Wheel	
							
Requirements		**Satisfied?**	**Comments**	**Satisfied?**	**Comments**	**Satisfied?**	**Comments**
2.2 - To simulate rugged terrains, obstacles of size… H is the height above the path (1/8 inch ≤ H ≤ 3/4 inch)		Yes	1.6" wheel radius	Yes	1.3" wheel radius	Yes	1.1" wheel radius
Team Desires	**Weight**	**Value**	**Comments**	**Value**	**Comments**	**Value**	**Comments**
Large wheel radius/clearance	0.3	0.8	1.6" wheel radius	0.6	1.3" wheel radius	0.5	1.1" wheel radius
High traction	0.3	0.4	Skinnier wheel, less friction	0.6	Lots of surface area	0.5	Decent surface area
Shock absorption	0.2	0.6	Thicker rubber	0.4	Thinner rubber	0.4	Thinner rubber
Load bearing capability	0.2	0.2	Poor stability under weight	0.6	Good stability under weight	0.4	decent stability under weight
Total Merit:		0.52		0.56		0.46	

Score Key	
Good	1
Ok	0.5
Poor	0.25

Figure 4: Drive Wheel QFD

In terms of software design, the process was trial-and-error by testing. First, the main functions for motor power and turning were established and thoroughly tested, because those formed the basis of the rest of the code. A decision to add a gyro sensor for stability was made, which ensured that the robot would drive straight regardless of terrain conditions.

The line following algorithm was built from the turning motor function and tuned for multiple months for accuracy. Originally, the algorithm was just an off/on line sensing that would turn left or right depending on the conditions. Due to issues following dashed and heavily curved lines, a more advanced algorithm was developed. The new algorithm used a proportional line following system that uses a color range to determine robot turn. This algorithm performs much better and can easily track lines without loss. This algorithm is detailed in the Design Notebook as well as the flowcharts in Figures 5 and 6 below.

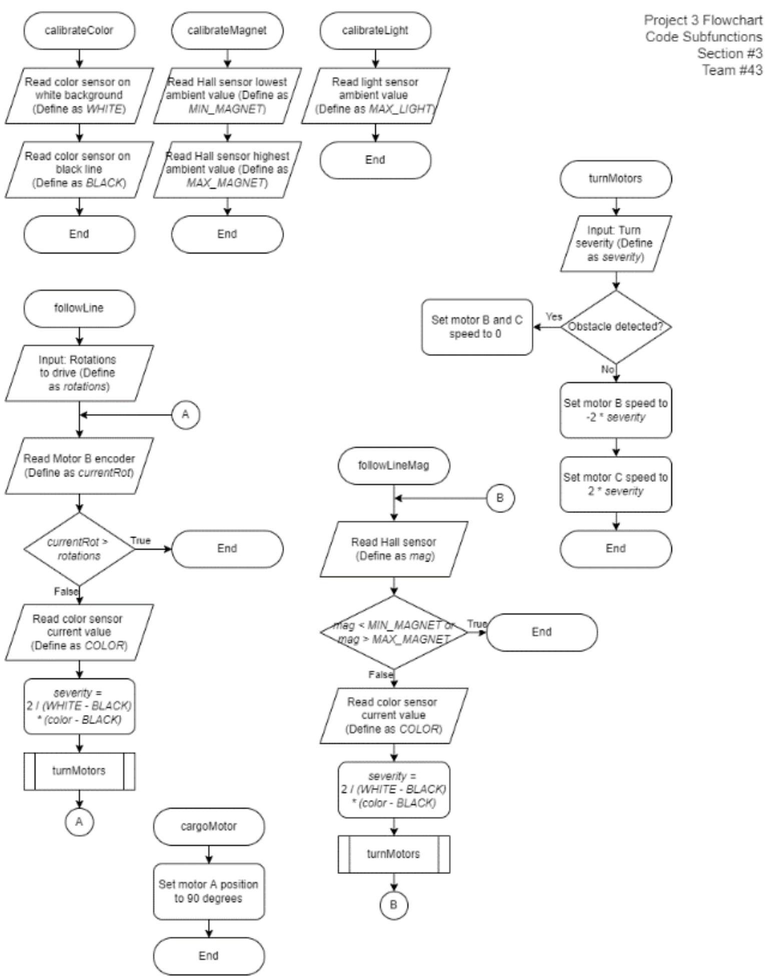


Figure 5: Flowchart 1

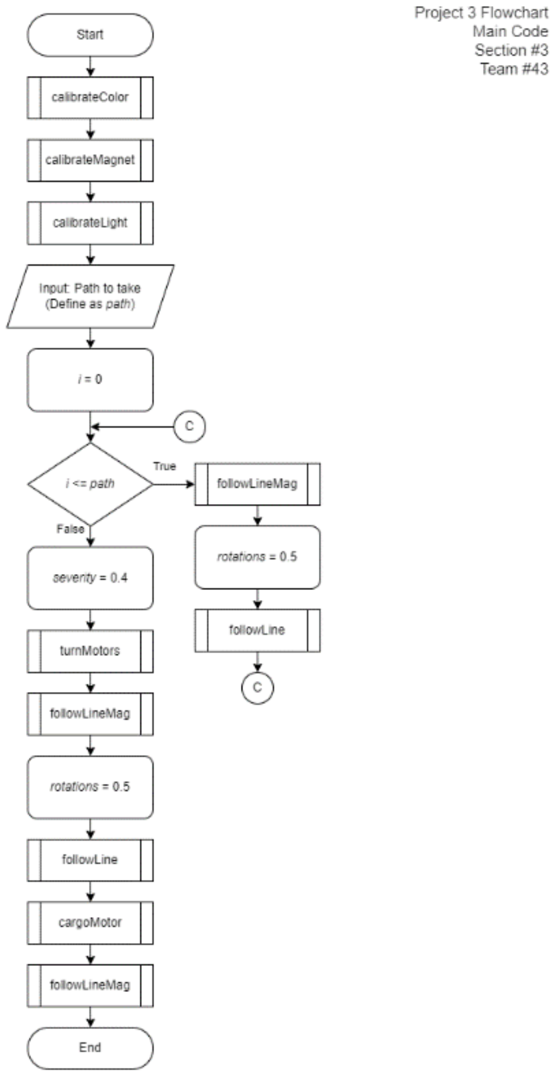


Figure 6: Flowchart 2

Another notable feature of the software that was incrementally iterated over time was the calibration functions. The color sensor, Hall sensor, and light sensor were all calibrated prior to each run in order to ensure the robot could handle the different environments it might encounter.

MACRO Physical Analysis

Customer Need	Technical Need	Technical Requirement	Target Value
Ability to navigate given course	Must be able to accurately track solid and dashed lines	Loses line every 1 in 5 runs	Line is only lost once every 10 runs of the given course
Ability to scale obstacles	Must be able to traverse a steep slope	Maximum slope between 30 and 45 degrees	45 degree slope
Ability to transport cargo safely	Must maintain vertical stability	Maximum canter from vertical center is between -5 and 5 degrees	0 degrees
Ability to deposit cargo in correct location	Must be capable of detecting magnets and moving accordingly	Ideal distance of cargo from drop zone between 0 mm and 128 mm from center of drop-off location	64mm
High mobility	Small turn radius	Ideal turn radius between 0 and 51 mm (2 inches)	0 mm

Ability to Navigate Given Course

Out of the 4 times the MACRO started the demonstration course, it lost the line once. This exceeds the expectations of the team's target value of the MACRO.

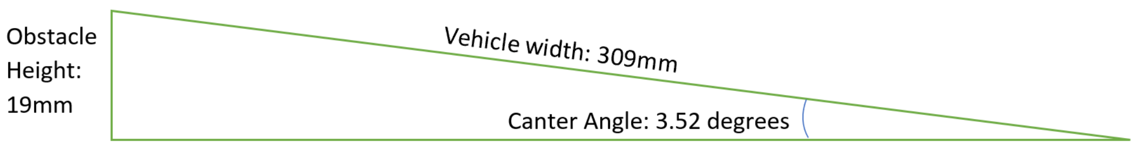
Ability to Scale Obstacles

To determine the MACRO's ability to scale obstacles, the team submitted the MACRO through a series of hill tests. These hills were of various angles between 30 and

45 degrees in slope. The team then recorded where the MACRO struggled to bolster the weak points to improve the ability to climb hills. In its final form, the MACRO was capable of scaling a 45-degree slope consistently for 5 test cycles with a cargo of 450 grams without slipping or losing the line.

Ability to Transport Cargo Safely

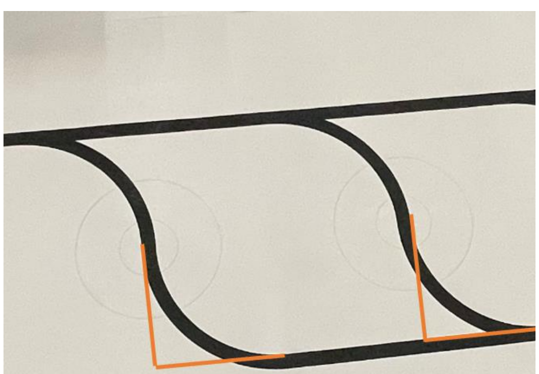
The team analyzed the entire demonstration course in an effort to find potential areas where the MACRO would tilt side to side. The team concluded that the area of maximum side to side tilt on the course would be scaling a small obstacle. If both front wheels of the MACRO make contact with the object simultaneously, the side-to-side tilt will be 0 degrees. However, if one wheel hits the object first, and the other wheel is still on the ground, a side-to-side tilt will be present. According to the Project 3 description, the maximum height of a small obstacle (excluding hills, etc) is 19 mm. With the wheelbase of the MACRO being 309 mm, the theoretical maximum side-to-side tilt can be calculated as shown below:



Equation: $\arcsin(19/309) = 3.52°$

According to the calculations above, the maximum tilt that the MACRO could experience side-to-side in either direction is approximately 3.5 degrees. This falls within the technical requirements of a maximum tilt of 5 degrees in either direction given by the design team to ensure cargo stability.

Ability to Deposit Cargo in Correct Location and High Mobility



In order deposit the cargo accurately, within a 128 mm radius of the center of the target (illustrated by the concentric), the team understood that the robot must be highly mobile and capable of detecting magnets. The magnetic markers signify where the MACRO should start the turn and the center of the target itself. The turn is a quarter-circle arc with a radius of approximately 60 mm. The MACRO must be capable of executing that turn in some form. The team decided that the current design of the MACRO would be more consistent in making this turn by continuing straight for the radius of the turn (60 mm) and conducting a 90 degree turn of radius 0 mm. In other words, the MACRO maneuvers off the line temporarily and rotates a quarter turn on its axis to perfectly align itself with the target magnet and line. In the tests performed by the team, this increases the consistency in finding the line and depositing the cargo on the target accurately. The path taken by the MACRO for each location is shown above.

Scaling to Official Mars Project

While the developed MACRO effectively performs on a small scale in a controlled environment, there will be several obstacles when scaling this project to a full-scale setting. According to the National Aeronautics and Space Administration (NASA), Mars rovers are generally the size of a standard car, which is a big shift from the small LEGO prototype that has been created.

One issue that would need to be addressed, both at the Flashline Station and on Mars, would be insulating the computers and motors. Canada and, to a more extreme degree, Mars experience extreme weather that is not encountered in the controlled prototype setting. To combat this, the Raspberry Pi case that currently encloses the boards would have to be transformed into an insulated box with heaters. One insulator that has proven especially effective for projects such as these is Aerogel, so this may be considered for the final product.

Another issue that may arise would be communication of the rover with the user in the event of an emergency. Obviously, the team has worked to make the rover autonomously address many issues, but the harsh and unpredictable terrain of Mars will certainly result in unforeseen emergency circumstances. One feature that should be implemented before discharging the rover to Mars or the Flashline Station should be a communication tool that allows the user to know if the rover is stuck or caught up in a situation that would prevent it from doing its job. Since it will not be monitored for its whole completion of the course, a remote communication system is essential for monitoring the MACRO's status. An app, alarm, or beeper located in the station from which the cargo is deployed could be implemented to combat this issue.

Furthermore, the terrain of Devon Island and Mars is far rougher and more unstable than the prototype track, which will present at least two additional issues when upscaling: motor efficiency and tire traction. Since the surface of these two locations may not be compact, moving over gravelly or sandy terrain may cause the vehicle to lose substantial efficiency at the motors. This would require a larger battery capacity than would be required if the ground were solid, which should be considered when scaling up to a full-size model. Additionally, the loose ground will require greater tire traction, so wider front tires and a larger rear wheel radius that can be upscaled proportionately should be implemented for the final model.

Converted MACRO Design Specifications

Prototype

Customer Need	Technical Need	Technical Requirement	Target Value
Ability to navigate given course	Must be able to accurately track solid and dashed lines	Loses line every 1 to 5 runs	Line is only lost every 3 runs of the given course
Ability to scale obstacles	Must be able to traverse a steep slope	Maximum slope between 30 and 45 degrees	45-degree slope
Ability to transport cargo safely	Must maintain vertical stability	Maximum canter from vertical center is between -5 and 5 degrees	0 degrees
Ability to deposit cargo in correct location	Must be capable of detecting magnets and moving accordingly	Ideal distance of cargo from drop zone between 0 mm and 128 mm from center of drop-off location	64mm
High mobility	Small turn radius	Ideal turn radius between 0 and 51 mm (2 inches)	0 mm

Full Scale on Earth

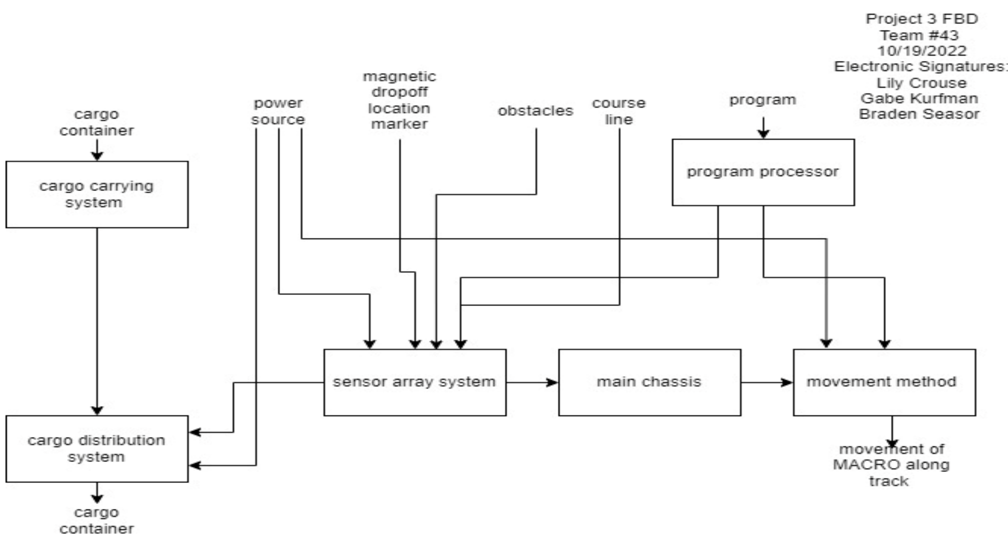
Customer Need	Technical Need	Technical Requirement	Target Value
Ability to navigate given course	Must be able to accurately pathfind across uneven terrain	Loses target path every 1 to 5 runs	Path is only lost every 3 runs of the given course
Ability to scale obstacles	Must be able to traverse a steep slope	Maximum slope between 30 and 45 degrees	45 degree slope
Ability to transport cargo safely	Must maintain vertical stability	Maximum canter from vertical center is between -5 and 5 degrees	0 degrees
Ability to deposit cargo in correct location	Must be capable of detecting magnets and moving accordingly	Ideal distance of cargo from drop zone between 0 m and 12.8 m from center of drop-off location	6.4 m
High mobility	Small turn radius	Ideal turn radius between 0 and 5.1 m	0 m

Full Scale on Mars

Customer Need	Technical Need	Technical Requirement	Target Value
Ability to navigate given course	Must be able to accurately pathfind across uneven terrain	Loses target path every 1 to 5 runs	Path is only lost every 3 runs of the given course
Ability to scale obstacles	Must be able to traverse a steep slope	Maximum slope between 30 and 45 degrees	45 degree slope
Ability to transport cargo safely	Must maintain vertical stability	Maximum canter from vertical center is	0 degrees

		between -5 and 5 degrees	
Ability to deposit cargo in correct location	Must be capable of detecting magnets and moving accordingly	Ideal distance of cargo from drop zone between 0 m and 12.8 m from center of drop-off location	6.4 m
High mobility	Small turn radius	Ideal turn radius between 0 and 5.1 m	0 m

All unknown values for the tests site are assumed to be approximately ten times larger than the prototype because the MACRO is increased in size by a factor of ten.



Scale MACRO Subsystems

It has been assumed that the dimensions of full-scale models on Earth and Mars will be the same. According to NASA, Mars rovers have identical models on Earth that are used for testing to ensure the reliability of certain actions on Mars (“NASA Readies Perseverance…”, 2020). Considering the long-term success of these rovers, it is safe to assume that dimensions of full-scale Earth and Mars models will be identical.

System	Dimensions of Prototype	Dimensions of Full Scale (Earth and Mars)	Design Specification
Cargo carrying apparatus	24.8x22.4x11.92 cm	2.48x2.24x1.19 m	Must be able to carry 18 kg of cargo
Main Chassis	30.96x23.2x16.32 cm	3.1x2.32x1.63 m	Must be capable of holding all other systems
Sensor array	14.32x5.6x4.72 cm	1.43x.56x.472 m	Must be able to withstand Martian weather/conditions

The motor for the cargo trapdoor arm would be easily available for purchase, assuming it is able to be effectively insulated. The cargo carrying apparatus would not be available for purchase, but it would be easily manufacturable. The best way to manufacture it would be to weld the frame out of aluminum alloy beams to remain somewhat lightweight, but still able to carry cargo with little concern for breaking down over time. Since the gravitational pull of Mars is far less than on Earth, its ability to carry very heavy cargo is not a large concern, assuming the mass of the cargo scales up proportionately with size.

The main chassis could potentially be available as commission from an automotive or metalworks company based on a modified car chassis. It would likely be easier to manufacture it within the company, though, for simplicity purposes and to ensure that it is exactly as needed. This could be made of any strong metal that will be resistant to the weather and able to support all other required systems and the cargo.

The sensor array would most easily be available to purchase. Hall sensors, light sensors, gyro sensors, color sensors, and ultrasonic sensors are all easily attainable for purchase. The light sensor will have to be tuned for lower contrast between the track and the landscape, so one of high quality would be preferable for the final model, but overall, the sensor array would not be difficult to duplicate for scaling.

Results and Discussion

At the time of the final demonstration, for a variety of reasons, the MACRO failed two tasks. One obstacle that the MACRO failed was the dowel rod, which was not anticipated by the team. During last minute redesign decisions, it was decided that a rear caster wheel with a small radius would be ideal for traversing large obstacles, neglecting to consider the effectiveness on small obstacles. It was assumed that the small rear wheel radius was not going to affect the MACRO's ability to traverse the dowel rod when making the change, so testing of this obstacle was not performed as the decision came very close to the demonstration of the MACRO. The reason the MACRO was unsuccessful at his task was because the height of the dowel rod was much larger than the radius of the wheel, which would not be able to be traversed by the front wheel drive force of the MACRO. If substantially larger rear casters were used, the MACRO likely would have been successful at this task.

Furthermore, the MACRO was unable to accurately identify cargo drop off sites and distribute the containers accordingly. This was not anticipated by the team. During the testing period, only one magnetic beacon was available for use at a time, so the team was not able to get hands-on testing experience with more than one at a time. However, the model was able to accurately and reliably deposit the cargo at the drop off location in this setting, so it was assumed that success would be transferable. When it came to the demonstration, however, the large quantity of beacons in proximity made it difficult for the MACRO to count the correct number of sensors to determine the drop off location. This resulted in several unsuccessful attempts at distributing the cargo to the assigned locations. The MACRO would count two sensors, then drop the cargo, but it would always miss at least one along the way, so in all four attempts, it was not able to make an accurate drop.

Lastly, MACRO was unsuccessful at the broken line obstacle. Once it reached the break in the line, it would miss the other side when sweeping for continuity in the path. This resulting in MACRO leaving the path altogether and failing the task altogether.

Alternatively, the MACRO was successful at the hill obstacle. This was expected because the frame of the MACRO was changed to better be able to climb the hill. The wider frame and larger front wheels allowed for the MACRO to be able to get over all the hills available for testing during office hours, up to a grade of 30 degrees. The actual demonstration course had a hill that only had a grade of about 15 degrees, so the team was confident that the MACRO would make it over, and it did.

In addition, MACRO was successful at line following as expected. The light sensor was used to differentiate the white background from the black line and was tested rigorously in different ambient light settings, so the team expected that the lighting in the demonstration area would not be an issue. The calibration readings fell within the normal range of values that were seen during the testing stage, so the line following was reliable throughout all trials.

Overall, the MACRO did not perform each individual task perfectly, but the team was satisfied with its performance. It was anticipated that all events would not go perfectly according to preparation, but that the MACRO would still be largely successful. This ended up being exactly the case. Some of the factors that contributed to the failures were regrettably preventable, which was a disappointment. However, some factors, such as the magnetic beacon inconsistency, were largely difficult to prepare for and are more acceptable failures. In the future, the team will use this performance to rework the failures and develop a more consistent model.

Conclusion and Recommendations

Upon completion of the Final Demonstration, the team concluded that the MACRO can satisfactorily complete each segment of the final course. The team found that the MACRO was able to maneuver and follow lines efficiently. All types of lines, including dashed, solid, curved solid, and curved dashed, were able to be followed without trouble. The MACRO was also able to scale large obstacles, such as hills, with ease. However, the MACRO did experience trouble with smaller obstacles, as well as inconsistencies in magnetic detection which led to further issues in depositing cargo accurately. The team attributed the first issue to the MACRO being tuned for larger obstacles due to concerns of extremely large obstacles being present on the course. The team's solution to give the MACRO an enhanced ability to scale small obstacles is to enlarge the rear castor wheels. Ideally, all four wheels on the MACRO, both the driven wheels and the castor wheels, should be larger. However, due to part restrictions, increasing the size of the castor wheels to be equal to the size of the driver wheels was not feasible. In the future, the team recommends that the wheel size be increased where possible. The team attributes the second issue, inconsistency in detecting magnets, to the Hall sensor's inexperience in testing with multiple magnetic beacons in readable distance. The system was tuned during testing to only have one field reading at a time, which caused confounding readings to limit the system's recognition of each precise drop off location. The magnet detection system also determined where the MACRO made a final turn to drop the cargo. Therefore, this system operating led to an suboptimal and inaccurate cargo deposit.

The team recommends a greater amount of time and effort allocated to the tuning of the hall sensor and related code after the construction of the MACRO is complete. Outside of the aforementioned issues, the team believes that the MACRO satisfied all other tasks as expected, and in some cases exceeded expectations. For example, during speed trials performed prior to the final demonstration, many trials yielded that the MACRO could replicate a constant speed consistently with approximately 0.3% error. During the actual demonstration, the MACRO performed the speed test in the exact target time of 10 seconds with 0% error. The team is extremely satisfied with these results.

Works Cited

NASA. (2020, October 6). *NASA readies perseverance Mars Rover's earthly twin – NASA mars exploration*. NASA. Retrieved December 7, 2022, from https://mars.nasa.gov/news/8749/nasa-readies-perseverance-mars-rovers-earthly-twin/#:~:text=Did%20you%20know%20NASA's%20next,to%20roll%20here%20on%20Earth.