Mars Cargo Mobility System (MACRO) Proposal - Project 3

Team 30

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To Dr. Martin Ortega,

The increasing interest in space exploration calls for a machine capable of supporting the related research. Team 30's design of the Mars Cargo Mobility System (MACRO) does exactly this. We have designed a rover that can successfully analyze its surrounding environment with various sensors to follow a path to designated locations and safely deliver cargo in a timely manner.

Our design of the MACRO employs a unique cargo deployment system which doesn't compromise the integrity or structure of the MACRO, rather the added weight of the cargo improves the MACRO's performance since the weight is distributed over the wheels and thus increases traction which improves the turning and handling of the MACRO. Collected data shows that the MACRO has a 2-inch minimum turning radius and can even carry all 3 cargos at once without compromising structure. The MACRO's structure and design is incredibly sturdy and allows for easy modification to any system on the MACRO as it can easily adapt to any changes. This is a very unique advantage to our design that sets our design apart from other teams'.

The MACRO's cargo deployment system employs a container/gate system. A motor attached to the gate of the containment system controls the opening and closing of the gate. When opened, the gate, along with the angled container bed, acts as a ramp for the cargo to slide down. Side bars in the container bed direct the cargo down the ramp by funneling its movement and little tails on the end of the gate allow the cargo to be ejected upright. Along with other improvements to the ejection system, the MACRO has a 100% success rate for successful delivery of the cargo. Moreover, the MACRO also meets speed requirements with a 0.05% error, allowing for timely delivery of cargo. As delivery of the cargo is the most important aspect of this mission, our team believes that our design should be selected.

Our MACRO utilizes a 3-wheel tank drive design with rear-wheel drive. This pushes the MACRO forward instead of pulling it forward, as a front-wheel drive design would do. This design works well with our center of mass to keep the MACRO grounded and allow it to go over obstacles and ramps with a 100% success rate.

While the MACRO had difficulty sensing magnetic beacons and following broken lines (approximately a 45-48% success rate), our team believes that these issues can be easily solved with more time. By lowering the IMU sensor and utilizing more sensors, we can increase the scope of the magnetic sensor to better allow the MACRO to sense the magnetic beacon. More reliable and stronger motors will improve the turning mechanism of the MACRO to maximize the efficiency of the line following algorithm.

Overall, the MACRO is able to successfully deliver cargo in a timely manner and is strong enough to withstand heavy weights and traverse obstacles. Our team's malleable design also allows for easy improvement to the system when necessary. Areas of improvement for the MACRO, such as the line following algorithm and magnetic beacon detection system, can be easily fixed with more time and better resources. Our team has learned from our past experiences and has the proper skills and mindset to help your team develop and deploy the best rover on Mars. We hope you give our proposal consideration and we look forward to working with you.

Thank you.

Sincerely,
Team 30
Alyssa Devincenzi
Natalie Harvey
Matthew Stuber
Agathiya Tharun

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Executive Summary

The problem to be solved was building a robot capable of autonomously delivering cargo on Mars. To navigate to the drop off location, the MACRO was required to follow a black line that alternated between solid, dotted, and dashed. This line included turns with a minimum radius of curvature of 2.0 inches from the guideline. Various obstacles were present in the course such as hills, circular pipes, and wooden boards. The cargo consisted of a cylinder (mass of 450 grams), a rectangular box (mass of 350 grams), and a cone (mass of 250 grams). This cargo was to be delivered upright, in the center of the cargo delivery zone. To signify the turnoff to a delivery zone, a magnetic beacon was placed under the line and another was located in the center of the zone. The target speed for the MACRO was between 15 and 30 cm.

Two unique features of the MACRO are it's cargo unloading system and the front wheel. The cargo unloading system features a gate that lowers to create an inclined surface for the cargo to slide off of. This design kept the cargo stable during the journey and limited jostling at delivery. Instead of a traditional set up of 2 front wheels, this MACRO featured one larger, centered front wheel with little traction. This allowed the robot to turn more easily.

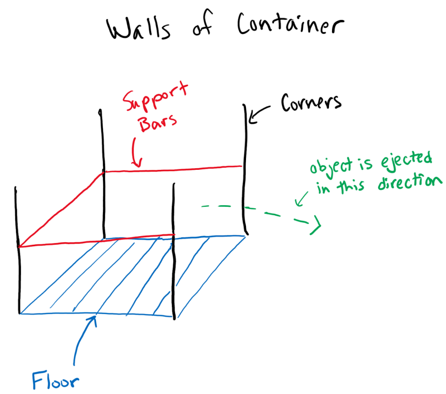
The MACRO performed well in some tasks and had difficulty in others. It reliably followed a solid line on both straight and curved sections, with a success rate of 95% in testing and success in the demo. The MACRO had difficulty on dashed and dotted portions of the line, successfully following them 45% of the time in testing, and failing in that section of the demo. With respect to obstacles, the MACRO made it over the wooden dowel and the hill 100% of the time while carrying all types of cargo, in both testing and the demo. The robot carried all types of cargo and delivered them without tipping 100% of the time. It ran into problems sensing the magnet, doing so accurately 50% of the time, and not during the demo. The MACRO was not able to deliver the cargo on exact drop off location accurately, being about 10 cm off of the target in the final demo and similar distances off during testing. Lastly, the MACRO successfully completed the speed test at a speed of 20 cm/s. Though the MACRO was not able to complete an entire run in the final demo, it did succeed in many of the required functions.

Design Considerations

Mechanical:

Cargo Unloading Mechanism

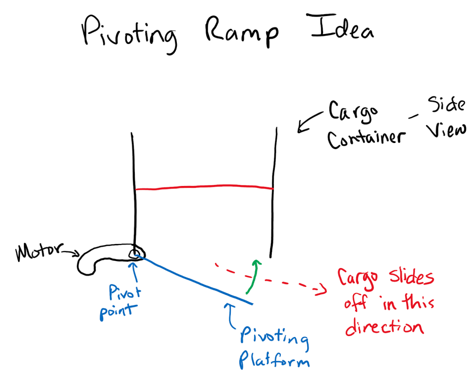
The team began brainstorming by thinking of potential ways to begin the building process. Since the cargo containment system seemed to be one of the most important aspects of the MACRO's design, it was decided to start with a solid cargo container and build around the final product. Starting with potential ways to load the cargo, the team immediately agreed to have the top of the cargo container open to provide easy access for manual insertion for the cargo. The team then considered ways to contain the cargo throughout the transportation phase. The container was required to have the ability to hold each type of cargo, one at a time, without having to make alterations to the MACRO. Also, since each cargo required a different unloading site, it would be difficult to unload only one piece of cargo at a time while carrying multiple, and maneuvering to different unloading sites could also present many issues for the final demonstration. The cargo would also be contained with bars on its sides, in order to prevent it from falling off the MACRO.



The cargo unloading system took much more deliberation than the rest of the cargo system. The team began by brainstorming several ideas individually before meeting up to discuss all of them as a team. Many ideas were proposed, but several of them were discarded for various reasons.

One idea was a conveyor belt, which consisted of the platform made of the conveyor belt, and the cargo would be unloaded by moving the conveyor belt until the cargo fell off the MACRO. The team was not sure on how to construct this mechanism, as the materials provided did not seem sufficient to build the conveyor belt system, and the team felt that it could possibly cause the cargo to tip upon unloading.

The team also considered a pivoting ramp, which has the platform start horizontally, and when it would unload, the platform would pivot on one of the sides via a motor, creating a ramp for the cargo to slide down. However, the motors for the MACRO were very weak, and the team did not believe that the motor would be able to hold the platform and the cargo at a horizontal position during transportation.

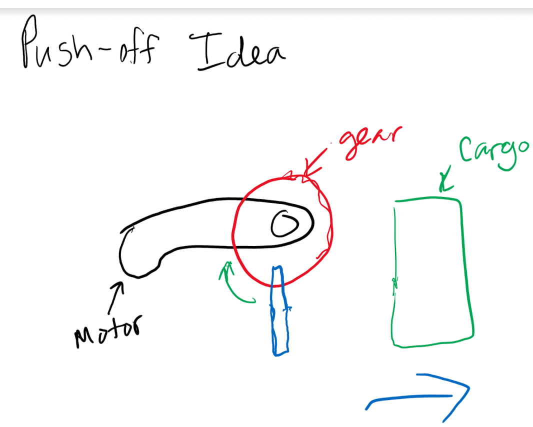


In addition, the team proposed a claw mechanism, which would hold the cargo in the back of the robot and simply release the cargo to unload. This mechanism would be extremely difficult to build, and it would be difficult to code once it was built, causing the team to potentially spend too much time working on this unloading mechanism, causing the idea to be discarded.

Another potential design was a trap door mechanism, which would consist of the platform being made of two smaller platforms that would start horizontally to hold the cargo, then rotate downward to unload. The cargo would simply fall down during the unloading, which would be unreliable when it came to keeping the cargo upright as it landed on the ground, as it could easily tip, causing this idea to be eliminated.

The team then discussed a lowering platform mechanism, which would keep the platform horizontal at all times. To unload, the platform would be lowered to the floor, and the MACRO would drive away, leaving the cargo behind. This mechanism would be extremely difficult to construct, and it would be difficult to code upon completing the construction, so this idea was also discarded.

Finally, the team discussed a push-off mechanism for the cargo. This mechanism would consist of a motor with something attached to physically push the cargo off the MACRO from behind. The team was



uncertain if the mechanism would cause the cargo to tip when unloaded, so this idea was left as a potential backup to the final design.

The final design for the unloading system was a combination of a few of the team's ideas. The platform for the cargo would be slightly tilted, and there would be a door at the back of the container. The door would rotate downward, creating a ramp when the door hit the ground. The cargo would slide down the ramp and onto the ground while the MACRO drove away to unload. Throughout the construction and testing process, the team continually extended the ramp; initial tests revealed that the ramp was too steep, causing the cargo to tip when it hit the ground. Eventually, the ramp was extended to the same angle as the cargo platform, and two extra bars were added to the end that lay flat on the ground when the bed is down. This helps provide the cargo a smoother transition to the ground, as it does not directly collide with the ground when it reaches the end of the ramp, preventing it from tipping during drop off.

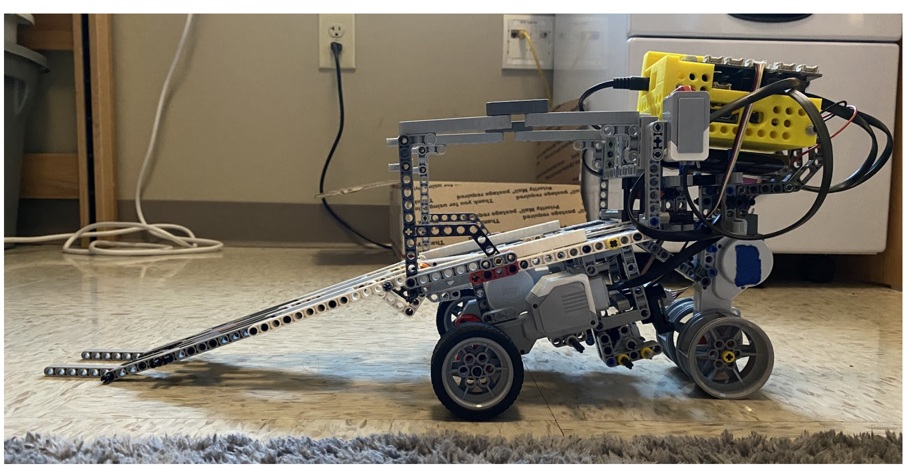
Drivetrain

The drivetrain was the team's next priority, as it was vital for the transportation of the cargo. The team wanted a design that could move the MACRO efficiently while also being able to clear obstacles with ease. The initial design included four wheels, two in

the front and two in the back, each with their own motor. The two front wheels were much larger in diameter than the back wheels, as the larger wheels would aid the MACRO to clear obstacles easier. Also, with the four wheels, it would be easy to turn the MACRO, as the two wheels on one side would turn one direction with the other two wheels turning the opposite direction. However, there were only four motor ports on the PI, and since the unloading mechanism required one motor, the drivetrain was limited to three motors. The team then discussed new ideas for the front wheels, including two free-rolling wheels in the front, or one thicker wheel, similar to a roller, in the front. The team decided to use the roller idea, as there was uncertainty as to how the free-rolling wheels would function when the MACRO turned, and the team believed that this could cause issues for the MACRO's movement. The roller was made from a motor connected to two slightly larger wheels, both with no treads. The team worked to make the roller more stable as testing went on, but it did allow for the MACRO to clear obstacles by providing the MACRO enough power to do so through the motor for the front wheels.

Sensors

The sensors were the final portion for the team to focus on. The line-finders were the first, and most important, sensors to be added to the MACRO, as they control the movement of the MACRO. The line-finders were placed just behind the front roller of the MACRO, as this would allow detect line changes earlier as opposed to later if the line-finders were placed in the rear. Also, the hall sensor was added underneath the pivot for the cargo door, as this would allow the magnets to be sensed in that location since the unloading sequence typically resulted in the cargo landing approximately below the initial position for the pivot of the door as the MACRO drives away. However, the hall sensor proved to be very unreliable (see subsection: Magnetic Beacon Detection), as its values would differ on many trial runs, causing the unloading sequence to sometimes not activate when it should. Thus, the team decided to implement the IMU, as its values were far more accurate than the hall sensor. However, the wire provided for the IMU was much shorter than that for the hall sensor, so the IMU needed to be placed near the front of the MACRO. It was connected between the line followers and the front roller to accommodate for the wiring.



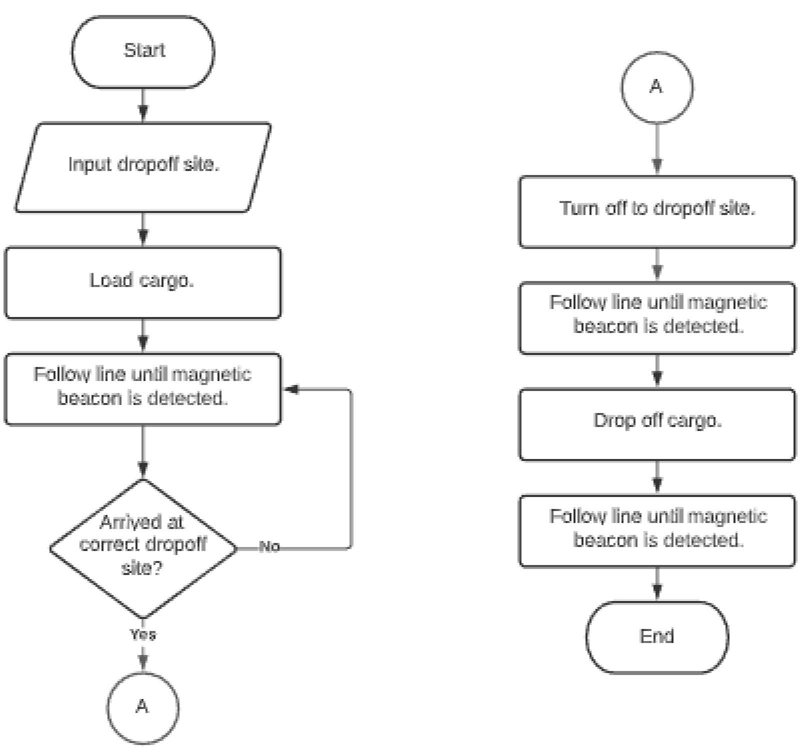
The Final Design

Software:

As the team neared the end of the mechanical design portion, software design began. Before writing any code, the basic functions that the MACRO needed to perform were determined based on the RFP document. In order for a cargo run to be successful, the following, six basic functions need to be performed by the MACRO:

1. Accept input for selecting a landing site.
2. Follow the guideline.
3. Detect the magnetic beacon.
4. Turn off at the correct dropoff site.
5. Drop off the cargo.
6. Return to the landing zone.

A complete cargo run is modeled with the flowchart below:



Once these basic functions were identified, each one was broken down and designed/tested individually.

User Input/Output:

In order for the MACRO to navigate to the correct dropsite, it must be given instruction by the user. The original plan was to use a touch sensor. The user would press the touch sensor 1 time to tell the MACRO to go to site 1, 2 times to go to site 2, and so on. The drawback to using the touch sensor was the lack of feedback to the user regarding the input. If the user was to accidentally press the touch sensor too many times, the MACRO would be unable to tell the user they have selected an invalid landing site.

To fix this issue, the program was altered to prompt the user via the console for input. By utilizing the console, the user is able to view their input before the MACRO accepts it. In addition, the MACRO can error check their input for validity, so as to avoid telling the MACRO to travel to the wrong (or nonexistent) dropsite. Before the MACRO executes the program, it accepts input in the form of a number representing the dropsite (ex. 1-3) and asks the user for confirmation. If the user enters an invalid drop site (ex. 5), the program will give an error message and re-prompt the user until a valid selection is made. During this process, the user has the chance to terminate the program by entering "-1" and, again, the MACRO asks for confirmation before terminating the program.

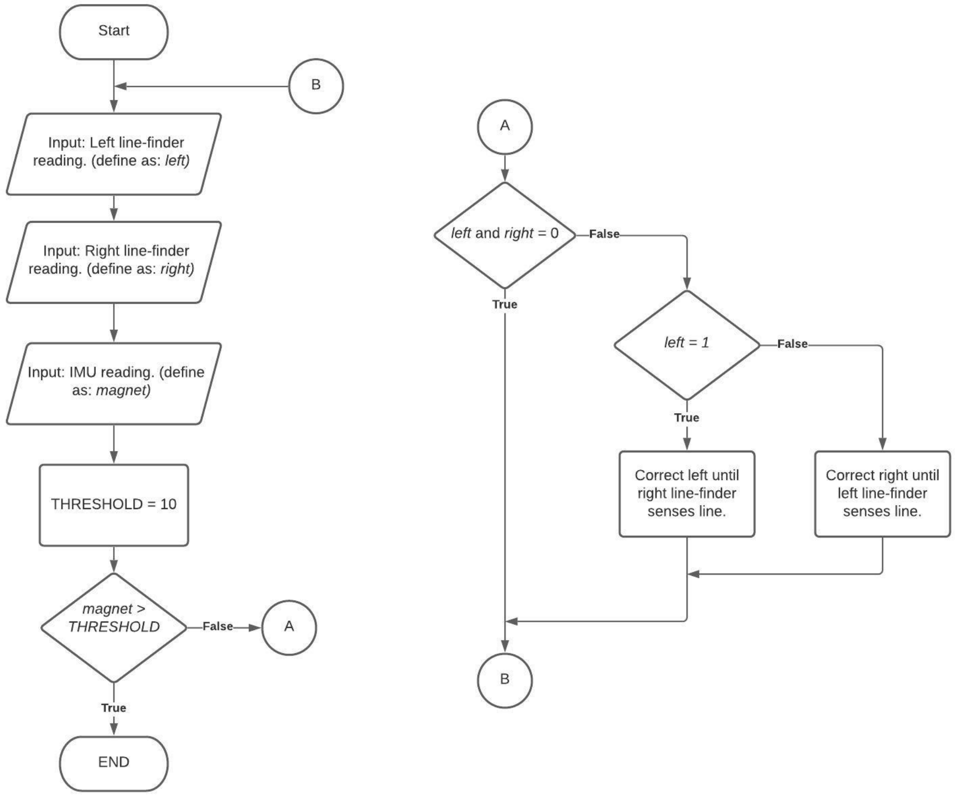
Following the Guideline

After the MACRO receives instructions for which dropsite to travel to, it must guide itself using the guideline painted on the floor. Using a line-finder array consisting of two Grove line-finders, straddling the line, the MACRO made its movement decision based on reading in the line-finders' data. Multiple ideas were thought of as to how the algorithm should function. The most basic of which being a bang-bang style control where the MACRO moved based on the current states of the line-finders. For example, if the right line-finder sensed the line, the MACRO would turn right until the right line-finder sensed whitespace.

The benefits to using bang-bang style control system are that it is simple and easy to code. However, the major drawback to this style is the inability to navigate sharp curves. During testing, the MACRO would perform adequately on straight and slightly curved sections of track, but on 90 degree curves, the MACRO would shoot through the curve, and as a result, both line-finders would end up on the same side of the track, leaving the MACRO thinking it was still heading in the right direction because it would sense whitespace on both sides.

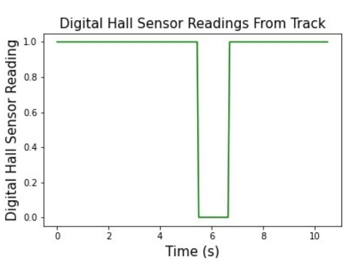
The next iteration of the line finding algorithm was a proportional-integral (PI) style control. This style builds on how the bang-bang algorithm functions by introducing an integral input and the longer the MACRO senses it is off the line, the more it will turn to correct the error. A PI control is slightly more complicated than the bang-bang control in the sense that it must take into account the time since it last was on the line, but it corrected smoother than the bang-bang control style. However, it still was unable to make it all the way through the 90 degree curve for the same reasons mentioned previously. Furthermore, it was discovered that as the integral constant increased, the NXT motors would begin to oscillate directions, resulting in the MACRO “dancing” out of control. This is believed to be due to the fact that the program was telling the motors to turn at a power outside their range, leading to the motor “looping over” to the opposite direction.

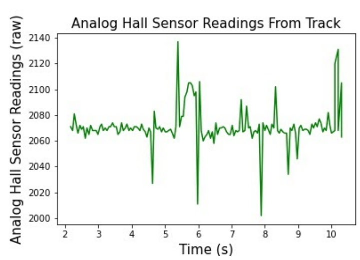
Next, the idea of overcorrecting was implemented. Overcorrecting means that when the MACRO senses it is off the line, it will correct itself until it senses error in the opposite direction. For example, if the right line-finder sensed the line, the MACRO would correct left until the left line-finder sensed the line. This guaranteed the MACRO would not lose the line, assuming a solid line existed throughout the course. The idea of overcorrecting was ultimately implemented with the bang-bang style control as it worked most reliably in every single line-following test. The final line-following algorithm is as follows:

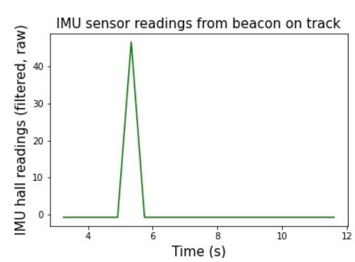


Magnetic Beacon Detection

Three different types of hall sensors were tested. These included the Grove digital hall sensor, the BrickPi analog hall sensor, and the Grove IMU. To decide which sensor to use, each option was reviewed based on its range, reliability, and simplicity. In order to compare the different sensors, each sensor had to be characterized. To accomplish thes, each sensor was attached to the MACRO as it navigated over the magnetic beacon and the readings were recorded. The results can be seen below.







After each sensor was characterized, thresholds were selected as to what constitutes the magnet being “detected”, each specification was assigned a weight, and a decision matrix was compiled.

				Sensor Options		
Design Need	Technical Need	Normalizing Function	Weight	Grove Hall Sensor	BrickPi Analog Hall Sensor	IMU
Range	minimum 1 inch	range (in) / 1 in	0.333	0.5	1	1
Reliability	% of successful attempts	successful attempts / total	0.5	0.8	0.2	0.8
Simplicity	lines of code	1 - lines / 10	0.166	0.8	0.7	0.2
			Total	**0.6993**	**0.5492**	**0.7662**

As the table shows, the IMU was the optimal choice as it provided the most reliability and range, although being more complicated to code.

Turning Off to Drop Sites

Before the MACRO can drop the cargo, it must first enter the dropsite. Each instance that the MACRO senses a magnet, it will increment a count. When that count equals the dropsite number, it will turn off and enter the drop site. The way in which the MACRO turns is simple, a time based function takes over control of the motors and turns the MACRO just enough in one direction so that when the line-finding algorithm takes over, it will automatically follow the path that enters the dropsite.

Cargo Dropoff

In essence, the method in which the MACRO drops off the cargo relies solely on gravity. The only function that the macro must perform is lowering its back gate. Once the MACRO senses the magnet in the center of the dropsie, it will pause all other functions and initiate the cargo dropoff sequence. Initially, when testing the code, it was found that the cargo would sometimes not slide off the ramp. To fix this issue, the idea of "jerking" forward was implemented. What this movement did was start the cargo moving, overcoming the static friction. Afterwards, all tests of the cargo dropoff sequence were successful, and the final pseudo code is as follows.

1. Lower the Gate
2. Jerk forward
3. Drive forward
4. Raise the Gate

Returning to the Landing Zone

Once the cargo dropoff sequence is complete, the regular line-following algorithm takes over. When the MACRO senses the magnet under the landing zone, it will pause and reset to execute another run.

MACRO Physical Analysis

Minimum Cargo Hold Dimensions

In order for the MACRO to hold all three cargo types, the overall dimensions of the cargo hold need to accommodate the largest piece of cargo. Upon reviewing the cargo specifications, the cargo hold must measure at least 12.7 wide and 12.7 long to accommodate the habitat containers, and 12.7cm tall to accommodate the water harvester. In addition, it was also decided by the team to add a .5 cm tolerance on each side to account for possible differences in actual cargo sizes. The final dimensions measure 13.65cm (.1365 m) wide and 15cm (.15 m) long with the top open, therefore ensuring all types of cargo can be contained properly.

Bed Angle & Coefficient of Static Friction

The MACRO's cargo delivery focuses on a slanted bed and ramp system. Let θ be the angle of the bed, and M be the mass of the cargo, and μ be the coefficient of static friction. In order for the cargo to slide, the following condition must be met.

$$F\ gravity > F\ friction \rightarrow Mg\sin\theta > \mu Mg\cos\theta \rightarrow \tan\theta > \mu \rightarrow \theta > \arctan\mu$$

During transportation, the cargo needs to remain upright. The team clarified what "upright" meant with the project oversight team and was given feedback that the cargo cannot be tilted more than 30° from the horizontal. This mean $\arctan\mu < \theta < 30°$, and once the coefficient of static friction is known, the bed angle has a lower and upper bound.

Using the same derivation from above, it is found that $\tan\theta = \mu$. This means that if the angle of the gate in which the cargo starts to slide is known, θ, the coefficient of static friction, μ, can be calculated. The team ran an experiment, testing for the critical angle that the cargo started sliding at, and found that angle to be 17°, resulting in a μ of .306 and a minimum angle of 17° needed for the cargo to slide off. The final slope of the ramp was .34, which when converted to degrees, is 18.8° and resulted in the cargo sliding down the ramp when the gate was lowered.

Minimum MACRO Acceleration

It is expected that the MACRO will be able to achieve its top speed in a reasonable amount of time. Based on the RFP, that top speed is 30 cm/s and the MACRO has 50cm to accelerate from a stop to top speed. This means that the MACRO must have a minimum acceleration if it is to achieve its top speed in 50cm.

1. $\int adt = at + vo = v \rightarrow \int vdt = vt = d$

2. $\Delta d = \overline{v}t = \frac{(v+vo)}{2}t$; assuming constant acceleration

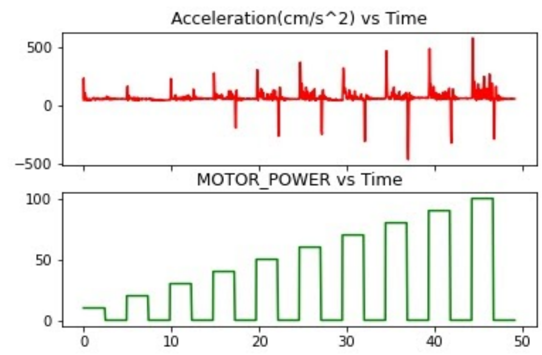
3. $v = at + vo \rightarrow t = \frac{(v-vo)}{a}$; solving for t

Substituting equation 3 into equation 2:

$$\Delta d = \frac{(v+vo)(v-vo)}{2a} \rightarrow a = \frac{v^2-vo^2}{2\Delta d} \rightarrow vo = 0 \rightarrow a = \frac{v^2}{2\Delta d}$$

Knowing the final speed to be, at maximum, 30cm/s, the minimum acceleration required was calculated to be 9cm/s.

To test the acceleration of the MACRO, the team attached the IMU to the chassis and measured the acceleration of the MACRO starting at a motor power of 10, incrementing by 10 until reaching a final motor power of 100. The raw data was then graphed in the figure on the right.



Based on the graph, the MACRO had no difficulties in reaching the required minimum acceleration of 9 cm/s (.09 m/s^2) as the maximum recorded value for acceleration was 585 cm/s^2 (5.85 m/s^2)

Turning Radius

The MACRO needs to be able to follow the guideline, and in the RFP, the document states that the sharpest curve the guideline features will have a minimum curvature radius of 2 inches. As a result, the MACRO must have a minimum turning radius of 2 inches. The team tested the turning radius of the MACRO and evaluated it using the formula below

$$Turning\ Radius = \frac{difference\ between\ the\ centerpoint\ of\ the\ wheel\ base\ before\ and\ after\ a\ 180°\ turn}{2}$$

To test the turning radius, the team would mark the starting outside locations of the wheels. Then, the MACRO would complete a 180° turn and the final outside locations of the wheels would be marked. Next, the midpoint was found between the starting and end sets of wheel locations and the distance between the two midpoints were measured and divided by two to find the calculated turning radius. This test was completed 3 times and the average calculated turning radius was 1.87 inches. Therefore, the MACRO meets the requirement of having a 2 inch minimum turning radius.

Maximum Speed

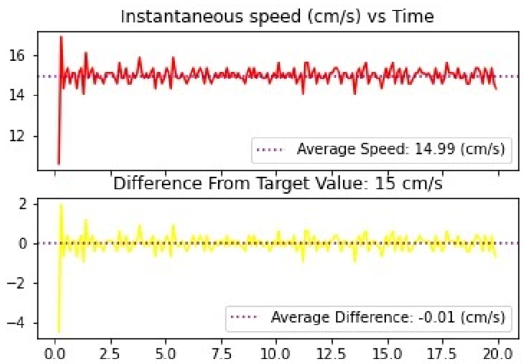
In order for the MACRO to deliver mission hardware in a timely manner, it must be able to reach and maintain its top speed. Based on the RFP, that top speed can be anywhere from 15 cm/s to 30 cm/s. In order to confirm the MACRO is able to achieve and maintain this speed, the team used the motor encoders and the "set_motor_dps" function. Knowing the linear speed, *v*, and the radius of the wheels, *r*, the angular speed in degrees per second (DPS) can be calculated as follows.

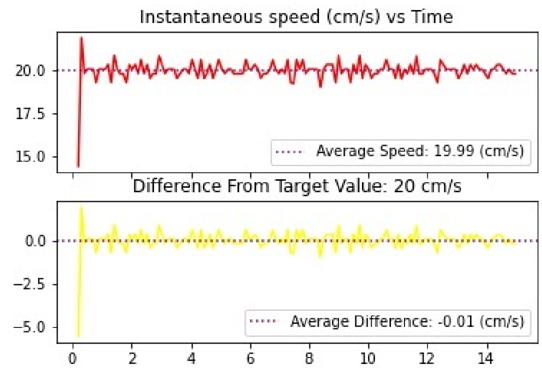
$$DPS = \frac{v(180)}{r\pi}$$

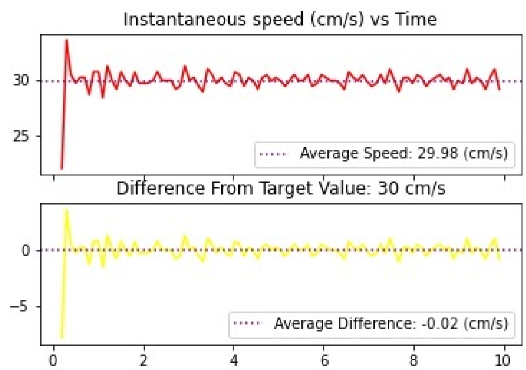
Furthermore, the instantaneous speed of the MACRO can be calculated using the returned motor encoder values. Let θ be the motor angle in degrees, and ω, angular velocity. is defined as $\omega = \frac{d\theta}{dt}$, which, when *dt* approaches zero, becomes: $\omega = \frac{\Delta\theta}{\Delta t}$. Therefore, once the change in encoder values is known, the instantaneous speed can be calculated:

$$v = \omega r = \frac{r\pi\Delta\theta}{180\Delta t}$$

Taking readings of the instantaneous speed and comparing the readings to the expected, the following graph was produced for three speeds: 15 cm/s (the minimum), 20 cm/s (the demonstration speed), and 30 cm/s (the maximum).







As the figures show, the MACRO was able to maintain its speed within a maximum of .02 cm/s.

Scaling to Official Mars Project

Significant Issues to Overcome:

Dust Storms on Mars

Mars experiences frequent dust storms. These storms are a problem because they put a significant amount of sand and dust in the air. These particles will get into the motors, sensors, and computer system, causing them to malfunction or stop working. A possible solution to this issue is to add a protective case around these components. A thin metal box could be constructed around the computer system and the motors, with small openings for the wires and axles that are connected. This would greatly reduce the amount of sand and dust that these components are exposed to. The sensors could have a clear plastic case constructed around them in a similar manner to allow them to sense while being protected from the elements.

Gravity on Mars

The gravity on Mars is much less than that on Earth. The acceleration due to gravity on Mars is 3.711 m/s^2 while the acceleration due to gravity on Earth is 9.81 m/s^2. This could pose several issues for the rover once it is scaled up and placed on Mars. The lesser gravity causes the wheels to have less traction with the surface of Mars, causing the wheels to slip more often, hindering the movement of the rover. The best way to counteract this issue would be to add dead weights to the rover, specifically above the wheels. This would allow the rover to have more traction, as the wheels would be pushed harder against the surface of Mars, allowing the rover to move easier.

Surface of Mars

The surface of Mars is very similar to sand and dirt, so the rover would drive on this surface very differently from the surface used to test the MACRO on Earth. The MACRO was tested on concrete and paper, both solid surfaces, while Mars consists more of the grainy sand, which would not be as sturdy of a surface for the rover. The sand and dirt will move much easier than the solid surface, so when the rover attempts to move, the sand around the wheels could be moved instead, causing the rover to not move as far or as efficiently. The structure of the sand and dirt texture on Mars could pose several issues for the movement of the rover, so there would need to be some alterations made to the wheels, or even the motors, to adjust sufficiently. One option would be to make the wheels larger, both in diameter and width. This would provide more surface area for the wheels, which would aid it in crossing the sandy surface of Mars.

Scaling Physical Specifications:

Minimum Cargo Hold Dimensions

NASA has researched possible solutions to providing an affordable and reliant power generation method. Recently, they have been able to produce a working prototype of the Kilopower Reactor Using Stirling Technology (KRUSTY). This device will produce energy converted from energy generated by nuclear fission. (Hall, 2017) The final device measures approximately 6.5 ft (198 cm) tall. If it is assumed that the Power Generation Unit (PGU) cargo container is to hold this device, an estimated scaling factor for the MACRO bed dimensions can be found by comparing the KRUSTY height to the PGU height. The result is: 198 cm / 15.2 cm = 13. Therefore, it can be reasonably assumed that the bed should be scaled by a factor of 13 to accommodate the needs of missions at the Flashline Mars Arctic Research Station (FMARS) and on Mars. If the current cargo hold dimensions are scaled up 13 times, the final dimensions are 1.77 m wide by 1.95 meters long.

Bed Angle & Coefficient of Static Friction

Revisiting the equation from the section: MACRO Physical Analysis, Bed Angle & Coefficient of Static Friction, gravity is not a factor in determining the optimal bed angle as it cancels out in the equation.

$$F\ gravity > F\ friction \rightarrow Mg\sin\theta > \mu Mg\cos\theta \rightarrow \tan\theta > \mu \rightarrow \theta > \arctan\mu$$

Therefore, the bed has the potential not to be altered, assuming the materials used in manufacturing cargo containers and the MACRO have a coefficient of static friction less than the tangent of the bed angle.

Minimum MACRO Acceleration

Assuming a fully operational MACRO would need to deliver all 3 types of cargo within 12 hours, the total distance it needs to travel is around 6km (RFP states that all surface assets must be a minimum of 1km from the landing zone) assuming the MACRO completes 3 round trips. If the MACRO is to accomplish this task, it needs to travel at an average speed of around 8.33 m/s. Furthermore, if the subtrack used for the speed test is taken to represent the straight-line distance between the landing zone and drop sites, there exists a scaling factor of 333. Therefore, the distance in which the MACRO must attain its top speed becomes 166.5 m. Using the same equation as before, the minimum acceleration of the full scale MACRO becomes:

$$a = \frac{v^2}{2\Delta d} = \frac{(8.33\ m/s)^2}{2(166.5\ m)} = .21\ m/s^2$$

Turning Radius

In the subsection: Minimum Cargo Hold Dimensions, it was estimated that the MACRO should be scaled up by a factor of 13. If the entire MACRO is scaled up 13 times, the turning radius becomes: 13 * 1.87 in = 24.3 in

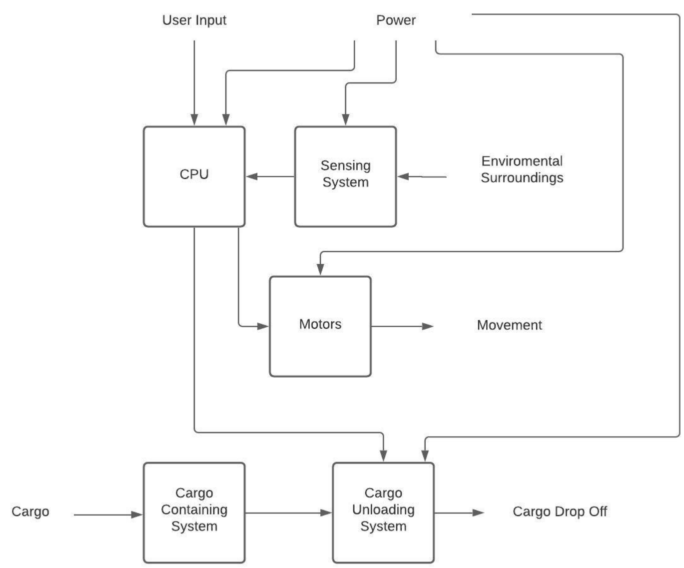
Maximum Speed

See section 3: Minimum MACRO Acceleration.

Summary

	MACRO Design		
Physical Specifications	Small Scale Prototype	Full Scale FMARS	Full Scale Mars
Minimum Cargo Hold Dimensions [width (m) x length (m)]	.1365 x .15	1.77 x 1.95	1.77 x 1.95
Bed Angle (degrees)	18.8	18.8	18.8
Minimum Acceleration (m/s^2)	0.09	0.21	0.21
Turning Radius (in)	1.87	24.3	24.3
Maximum Speed (m/s)	0.3	8.33	8.33

Scaling Subsystem Dimensions and Specifications



CPU - Central Processing Unit

The MACRO was controlled with a Raspberry Pi. These are not powerful enough to control a full scale rover, so the computer system will be scaled up. A Raspberry Pi has 1 GB RAM and operates at a speed of 1.5 gigahertz. A RAD750 will be used on the full scale rover in both Mars and Earth. This processor is specially developed for use in space, but also functions well on earth. These have 256 MB of RAM and operate at 200 megahertz speed (*Processors products*). It is common practice to put 2 processors in rovers in the event that one fails, so the full scale rover will have 2 RAD750s (*Rover Brains* 2020). These are readily available for purchase, but cost around $200,000 each (*Processors products*).

Motors

The motors used on the MACRO were NXT Lego motors, in the full sized rover on both Mars and Earth, these will be scaled up to a brushless EC 32 flat motor. There will still be 3 motors used, one on the front wheel and one on each of the back wheels. These motors have a torque of 25.5 N*m (*EC 32 flat Ø32 mm, brushless* 2020) each compared to the 17.3 N*cm (0.173 N*m) of the NXT Lego motors. The specific motor that is needed is not commercially available, but many companies can specially make them (Techbriefs Media Group, 2020).

Cargo Containing System

The cargo containment system on the MACRO is just large enough to fit the largest possible piece of cargo. The supporting area for the cargo would need to be scaled up to hold any cargo that could be used on Mars. It would also be recommended to make the sides of the cargo container solid, as leaving them open would expose the cargo to the elements, which could potentially damage the cargo or robot. Also, to protect the cargo more, a tarp cover could be added on the top, as the MACRO containment system has an open top in the prototype with no protection other than the support bars. Tarps are easily manufactured and can be found through multiple suppliers, making this idea cheap and efficient.

Summary:

	MACRO Design		
Subsystems	Small Scale Prototype	Full Scale FMARS	Full Scale Mars
Central Processing Unit (CPU)	1 GB RAM	256 GB RAM	256 GB RAM
Motors	NXT Lego motors	brushless EC 32 flat motor	brushless EC 32 flat motor
	0.173 N*m	25.5 N*m	25.5 N*m
Cargo Containing System	Open top and sides	Tarp on top and solid sides	Tarp on top and solid sides

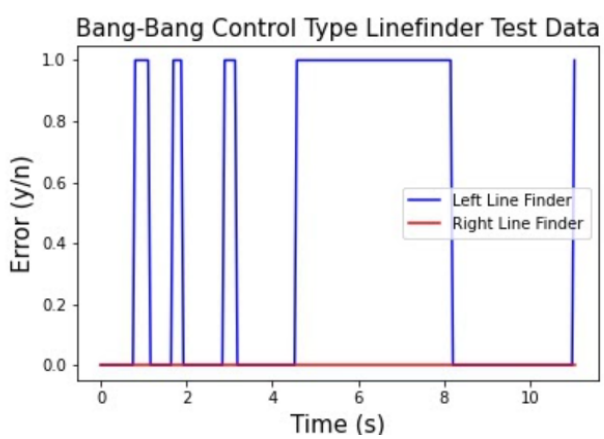
Results and Discussion

The MACRO was intended to follow a guideline (broken or solid) to navigate to sites, go over obstacles and hazards, maintain a specific speed to ensure a timely delivery, and transport and drop off cargo in the upright orientation in the general vicinity of a drop-off zone. As seen in the Engineering Specification Chart below, our team had expectations of a 95% success rate for many of the requirements.

Customer Need	Technical Need	Technical Requirement	Target Value
Navigate to sites	Success rate of runs per total number of runs	Success rate of at least 90%	At least 95%
Recognize and handle hazards	Rate of successfully recognizing and handling obstacles per total obstacles encountered	Success rate greater than 95%	Same as Technical Requirement
Timely delivery of mission hardware	Difference between desired and actual speed	A difference no greater than 2 cm/s	Same as Technical Requirement
Transporting cargo from location without dropping or tipping the cargo	Success rate of transportation per total attempted runs	Success rate greater than 90%	Greater than 95%
Drop off on target	Distance of cargo from the target after drop off	Distance less than 5 cm	Same as Technical Requirement

After several sessions of testing and improvement, the team made the following conclusions regarding the MACRO's performance for each of the 4 main tasks:

Line Following



The team expected the line following algorithm to work very well and even meet our expected target value as our algorithm was very simple and efficient. Little issues were expected since the general idea of the program was expected to work all the time given everything else in the MACRO functioned properly. In reality, flaws in our hardware design limited the MACRO's capability for turning and thus zig-zagging - an essential part of our line following algorithm. As seen in the graph below, between 4-8 seconds, there was a lengthened rise in the blue curve (which represents the MACRO going off the line) meaning the MACRO wasn't turning left fast enough to return to track and minimize error.

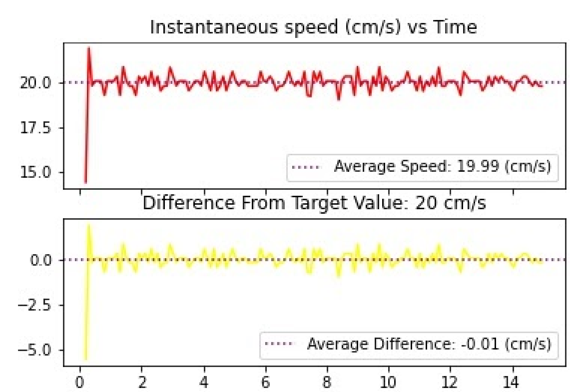
Due to the simplicity of the general algorithm, the MACRO was able to follow solid lines and struggled with broken lines due to the sensors not detecting the line.

Obstacle Handling

Our team's MACRO was very well structured and had a strong foundation that allowed accessories to be attached to the MACRO without compromising its structure or center of balance. Because of the sturdiness of our MACRO, our team expected the MACRO to successfully overcome obstacles and traverse ramps. In reality, the MACRO did well for that exact reason - a good center of mass and a rear-wheel drive mechanism pushed the MACRO forward and kept it stable, grounded, and centered at all times. The treads on the back wheels also gave the MACRO more traction and allowed it to better climb over obstacles.

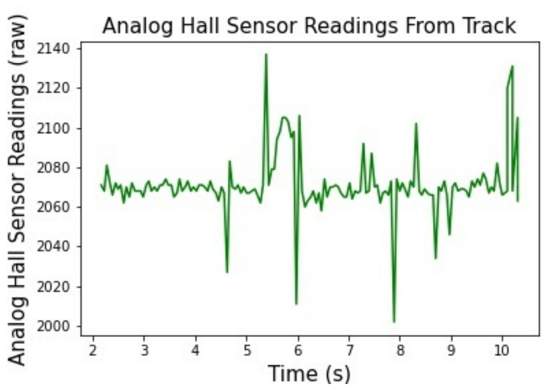
Timely Delivery of Mission Hardware

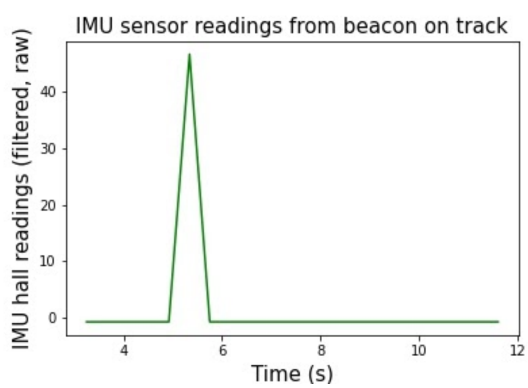
Our team was slightly worried about having timely deliveries since our line following algorithm required the MACRO to move slowly (as this offered better sensing of the line). Moreover, the lack of treads in the front wheel and the limited turning also posed threats. However, testing proved that this was not an issue and that our software can tell the MACRO to change speeds when necessary so that its only moving slowly when absolutely necessary. The strong structure also offered more traction which allowed the MACRO to stay more grounded and be able to completely capitalize on the full power of the motors; the MACRO's structure allowed it to move fast. As seen in these charts, the MACRO was able to move at a given speed while carrying cargo.



Cargo Delivery

Our team's unique cargo containment design gave us hope that the MACRO would perform flawlessly. We believed that we would meet all related technical requirements for the cargo transport and delivery. Due to the MACRO's structure and design, it had a 100% success rate of delivering the cargo upright and at the drop-off zone. The coefficient of friction in the gate ramp, the angle of the gate ramp and the mini tails at the end of the gate ramp to stabilize and slow the descent of the cargo all contributed to the success rate of the cargo drop off sequence. Furthermore, the structure and strength of the MACRO allowed it to be able to carry cargo without having it fall out and without compromising the integrity of the MACRO. While the cargo ejection sequence worked flawlessly, the site-detection (detecting magnetic beacons) mechanism had flaws. As seen in the graphs below, using the IMU sensor instead of the analog provided a more accurate reading of when the magnetic beacon is sensed. However, the sensor wasn't low enough on the MACRO and the sensor range wasn't large enough to always be able to detect the magnetic beacon and thus the cargo ejection sequence would never be initiated. Moreover the unreliable movements caused by the line following algorithm caused the MACRO to zig-zag around the magnetic beacon and not detect it.





Conclusions and Recommendations

After reviewing the MACRO's performance, it is now clear to us that a major issue was that the hall/IMU sensors were not sensing the magnets all the time due to a weak magnetic field and due to the unreliability of the line following algorithm, which would sometimes cause the MACRO to zig-zag right past the magnet. This led us to realize that utilizing multiple sensors, to increase the sensory range, would've been a feasible improvement. Another related improvement could've been lowering the PI closer to the sensors (to allow more freedom in cable lengths and thus placement of sensors) and lowering the hall sensor so that it can be closer to the magnet and thus have a higher chance at sensing it better.

Our line finding algorithm also had room for improvement. Due to a faulty motor, the line following was jerky and unreliable. The lack of motor strength and a mediocre line following algorithm also made it difficult for the MACRO to make sharp turns and thus the MACRO wasn't able to make short and quick zig-zags straddling the line. A better line following algorithm that accounts for faulty motors and has error catches could've been a significant improvement to the MACRO. Another related improvement is placing more weight on top of the wheels to maximize traction and thus improve turning. This would prevent jerky/jumpy movements in the MACRO when zig-zagging

In conclusion, we realized that a strong structure and foundation was incredibly essential to the robot. A sturdy robot offers a good center of mass, effective steering and acceleration, freedom to place sensors anywhere, resistance to damage and obstacles, and strength to contain cargo. While this project was extensively planned out in our Gantt chart, it's important to realize that it's impossible to expect everything to go well and that things have to be improvised. Over the course of the project, our team realized that certain issues were out of our control and that we had to adapt and change our designs to make up for other flaws. While there is always room for improvement, our team was still able to produce a functional robot capable of meeting requirements with varied degrees of accuracy depending on the specific requirement.

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