ENGR 142 Team 09

Autonomous Lunar Vehicle Performance Analysis & Final Report

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Memorandum

To : Mr. Pierce, Lead Engineer of Harris

From : Team at ENR14x in conjunction with Harris request for proposal

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Subject : Proposed Prototype for the Autonomous Lunar Vehicle

In recent years, there has been an increase in light pollution as well as an increase in radio signals, both of which decrease the quality of data received from telescopes. To solve this problem, scientists have looked to the far side of the moon. Placing a system of radio antennas there would allow for better quality images and radio signals to be received from outer space. However, establishing such a system would be challenging.

MIT has proposed a new solution for the furtherment of lunar exploration. There is debate about whether to use human astronauts or an autonomous lunar vehicle (ALV) to set up the network of antennas. Harris has tasked ENGR 14x with creating a possible ALV in conjecture with a request for proposal.

A solution has been actively pursued for the last three months to solve this issue. A path for design was created. The key technical requirements were identified for the ALV and their importance was ranked; the movement system was deemed most important, followed by navigation, detection of antennas, and finally deployment of antennas.

The ALV needed to carry the radio antennas boxes to the specified drop-off locations. The drop-off locations are distinguished by magnets so the ALV was equipped with a hall-effect sensor to identify the locations. The ALV would then need to deploy one antenna box to each location. A lunar satellite tracking system (LSTS) was used throughout the process in order to track the ALV’s progress. The ALV needed to be able to navigate over small obstacles of 1 inch or less and account for rough terrain and large obstacles.

First, a prototype capable of rotating along its axis with a deviation of less than 2 cm and an ability to travel 1 meter with only 10 cm of deviation was designed. Then, an antenna deployment system was created. The antennas could not experience peak vibrations of over 12 m/s^2 or average vibrations over 1.3 m/s^2. To get from the home base to the drop off location, the ALV had to navigate through rough terrain and avoid large obstacles with the help of a lunar satellite tracking system (LSTS). The code needed to take into account errors from the LSTS system, as well as incorrect coordinates.

The drivetrain developed consists of two wheels in the middle of the prototype that are balanced by a plow in the front and the antenna deployment system in the back. The ALV can travel a meter in a straight line while only deviating 10 cm, and when the prototype rotates 90 degrees, it deviates 2 cm from its central point. The deployment system consists of a bed resting on the ground behind the drivetrain with a treadmill above the bed. When the antennas are loaded into the bed, the treadmill pushes down on the antennas, so when the treadmill runs, the antenna boxes are deployed gently to the ground. The deployment system positions bins with a peak acceleration of 8 m/s^2 and an average acceleration of 0.25 m/s^2. The ALV is required to move obstacles 1 inch in height out of its path; the ALV can clear obstacles of a height up to 3 inches with the plow. The plow was used to replace the front wheels of the drivetrain to allow for a more compact ALV; otherwise, the plow would be placed in front of the front wheels. A magnetic beacon can be detected within 2 cm of its central point. Because this distance is less than the radius of the beacon, the ALV was deemed to be very accurate in detecting the beacon.

All of these design aspects are recommended in the actual development of the ALV as they all exceed the necessary target values to accomplish the mission. The team would enjoy further discussing the performance and individual design aspects of the ALV with you soon.

Executive Summary

The quality of data received from telescopes has decreased due to light pollution and an increase in radio signals. Images and signals of better quality could be obtained on the moon. A prototype for a lunar vehicle (ALV) was created to autonomously place antenna boxes at various locations on the moon. The prototype is capable of navigating to a known search zone by interacting with a satellite system. The prototype navigates through rough terrain and avoids large hazards. Once the ALV reaches a search zone, it locates a magnetic beacon and drops off an antennas package. Since the antennas are fragile, they must experience minimal vibrations during the trip and the deployment. The ALV then drops off two more antenna packages before returning back to the home base.

The physical ALV can be broken down into two main unique components: the drivetrain and the antenna deployment system. The drivetrain only has two wheels located at the center of the ALV and stabilized by a frictionless plow (see Figure 9). This central location allows the weight to be centered above the wheels, giving the robot a nearly zero degree turn radius. This is especially useful for navigation, as it allows the robot to turn around without deviating much from its current path. The antenna deployment system rests directly on the ground and consists of a low friction material. Also, the conveyor belt was placed above the antenna, which allows the antenna to be deployed to the ground while traveling very little vertical distance.

One unique feature of the code is the implementation of a friction factor. In all functions that involve turning or moving forward, a variable representing friction can be hard coded. This value can be changed for any surface the ALV is tested on, so the ALV can accurately move about a grid system on any type of surface. Another unique feature of the code is the orientation variable. The initial orientation is set manually but after every turn, the variable is updated based on the number of degrees turned.

During the final demonstration, the ALV could accurately correct its orientation, drop off the antenna within the specified average and peak accelerations 100% of runs, and it could navigate to the first location in 2/5 runs. However, it was unable to drop off the antenna in the correct location and deviated 10 cm for every 1 meter traveled.

Design Considerations

The design process began by creating a list of design specifications. The specifications went through multiple iterations and were produced based off of an interpretation of the customer's needs and how those needs translated into physical components of the design. The final copy of the specifications can be seen in Figure 1. The specifications were then ranked based off how important each aspect was to the overall function of the prototype. These ranks were incorporated into a decision matrix (see Figure 11) used to judge each individual component and whether or not that component should be included. The decision matrix was then broken into two sub-components: hardware and software.

Hardware Considerations

The first component was the hardware. This consists of design aspects that directly translate into the physical prototype. The main areas of the decision matrix are movement (moving straight and being able to turn), traversing obstacles, transporting antenna boxes, and deploying antenna boxes. Specifications pertaining to movement and traversing obstacles were given the highest rank. If the autonomous lunar vehicle (ALV) is not able to move in a straight line or rotate around its own axis with little deviation, the prototype will not be able to reach the areas to perform the other tasks such as antenna box deployment. This led to antenna deployment being given a lower rank of importance. A shortened decision matrix for the hardware can be seen in Figure 11.

The next step was to brainstorm different methods of completing each specification. The drivetrain was the first method to be assessed, since the movement is so important to the success of the prototype. Two main methods were considered. The first was to use a system similar to a zero turn lawn mower, where the back wheels are able to turn clockwise or counterclockwise independently of each other, while the front wheels can rotate freely. The other method consisted of two back wheels on the same axis with one front wheel that turned 90 degrees to swivel the prototype along its own axis. The system using a sole front wheel was attempted first (see Figure 2), but the team could not determine how to fix the front wheel to swivel and rotate simultaneously. Since this design could not turn, it was immediately scrapped.

The next design tested was the zero turn mower (see Figure 3 for the wheel design). This design could rotate along its own axis, but it still deviated from the prototype's central point by 2 cm. Also, the front wheels were slightly smaller than the back wheels, causing the prototype to be off balance. The prototype could also move in a straight line (1 cm deviation for every foot traveled). The zero turn mower method was chosen since it had the ability to accurately turn and move forward, but further development of the system was needed.

Next, a method to traverse small obstacles was brainstormed. The first idea was to use a plow in the front to push obstacles out of the path. The plow was able to move all obstacles that were smaller than 3 inches out of its path, so the plow exceeded the requirement of 1 inch. The plow was initially attached in front of the front wheels, but it was soon discovered that the front wheels could be replaced entirely by the plow (see Figure 3). This design was more stable and compact, which aided in the transportation of antennas due to less vibration and the dropoff of antennas due to compactness, so the design change was kept.

Now that the initial drivetrain was built, the antenna delivery system was developed. The initial idea was to create a conveyor belt that carried the antennas to a slide (see Figure 4), which the antennas would glide down to be deposited on the beacon. The conveyor belt was initially placed on top of the plow. The benefits of this design included having the drop-off location near the sensor, which improved the accuracy of the deployment, and a reduction in the distance the antennas must fall because of the lower height. However, the negatives were more severe. Since the center of mass was not above the wheels, there was not enough weight on the wheels, so they slipped while turning. Due to this change in the center of mass, the robot deviated 7 cm from its central point while turning (see Figure 13).

The delivery system was then moved on top of the wheels and tested. The wheels then had to be widened with the same width of the delivery system (see Figure 5). Now, the ALV only deviated 1 cm while turning. The problem was that the antenna system was now much higher up, so the antenna box reached accelerations that exceeded the maximum. The slide was made less steep to try and solve this problem (see Figure 6). The box still had too much acceleration, and the slide now extended a foot from the ALV. This introduced more problems such as inaccuracy when dropping off the antenna and increased potential of hitting large obstacles. All data concerning turning accuracy can be seen in Figure 11.

New ideas were brainstormed, and the delivery system was ultimately positioned behind the wheels with the conveyor belt above the boxes (see Figures 7 and 8). This system still allowed the ALV to turn with little deviation (2 cm), and the bins no longer exceed the maximum acceleration. All data concerning the acceleration of the boxes at different design phases can be seen in Figure 12. The new location of the deployment system added more friction during movement, but the benefits far outweigh the negatives, as can be seen by Figure 11.

The final design consisted of the two wheel drivetrain, a plow in the front, and the delivery system located behind the wheels with a tread above the bins. This can be seen by Figures 7-9. The hardware had three unique features. The first is the use of a low friction plow on the front instead of wheels, allowing the plow to rest directly against the ground. The use of only two wheels centrally located was another unique feature. This allowed the ALV to have its center of gravity between the two wheels, providing the most traction for turning. Another unique aspect was the antenna deployment system, which was also made with low friction material because it rested on the ground in the back. Having such a deployment system allowed the ALV to minimize the vibration and stabilize the overall structure.

Software Considerations

The foundation of the ALV's software structure began with a header file to control all basic movements. The file contained functions for moving forwards, turning, and tracking coordinates. Additionally, the header file included calibration variables that could be implemented globally.

One major advantage of this technique was modularity: by writing simple functions in only one place, redundancy was avoided and speed was optimized. By creating a global header file that could be implemented in scripts for each individual task, the code was kept consistent. Furthermore, during testing, this streamlined the process of calibrating variables to ensure that the ALV moved the correct distance physically.

For example, to calibrate the wheels to move a specific linear distance, we had to translate human measurements (centimeters) into a unit the robot could understand (motor encoders). The diameter of the wheels was measured, and a ratio was determined of centimeters to encoder ticks (360 / 8π [ticks/cm]). Finally, a unitless factor was multiplied into the ratio to account for differences in surface texture that might not otherwise be accounted for in the code. For example, testing showed that a higher tick ratio was necessary on the final demonstration paper than the testing concrete to account for losses due to friction and sliding. The team found it necessary to calibrate both rotational friction factors and the linear friction factor before testing on any new surface. The rotational friction factors, both clockwise and counterclockwise turns, were usually between 1.5 and 2.0, and the linear friction factor was 1 +/- 0.1.

To calibrate the magnetic sensor, 5 test runs were completed in which the ALV approached and passed the magnetic beacon. In the Shreve testing environment, the average hall effect reading ranged from 472 to 474, essentially a static raw value. As the ALV encroached a range of 2 inches or closer to the beacon, an average fluctuation magnitude of 10 was recorded. The initial calibration value varied based on environment, though it remained stable throughout runtime. To account for this, the code collected an initial static value marked as the magnetic calibration at the beginning of each run. With these test results in mind, the code was structured to notify the presence of a beacon when a divergence of greater than 10 was detected from the initial calibration sensor value.

As seen in Figure 10, three methods of finding a drop off zone were included in the final code. The first, most reliable method was the magnetic sensor, as discussed above. This sensor was given highest priority because it was deemed most accurate when considering consistency, ease of implementation, and accuracy, and therefore all motion was stopped upon magnet detection. Second priority was given to LSTS, which was checked after each movement function to realign position. Finally, a mathematical estimation of the ideal position was given third priority. This mathematical estimation assumes the functions moved the ALV to the goal position precisely with no inaccuracies caused by friction. This estimation was stored in a Position struct and used to keep a general idea of ALV location.

Nevertheless, one design obstacle of using modular code was that the main loop had to call individual functions many times in a row. In a sense, the functions themselves were almost too modular, and as a result, physical deviations were observed during runtime. For example, to both move forward and check the location, two different functions were called in a loop, causing the motors to start and stop repeatedly. Though this start and stop pattern was hard to detect with the human eye, in the long run, this pattern created a significant deviance in movement accuracy. To correct this error, the second iteration of demonstration code included slightly broader user-defined functions, essentially deconstructed iterations of their predecessors. These functions were specialized for multitasking in a large scale loop without causing physical deviations. For example, the functions for moving to a specific coordinate would accept a current coordinate and a goal coordinate as input. By comparing these two coordinates, the function would calculate the distance to move and activate the motors without the abrasive start/stop pattern. Additionally, the function would stop the motors if a magnetic value different enough from the calibration value was detected. Though this upgrade slightly sacrificed modularity, the benefits in performance were undeniable: during the second Presentation of Competency (PoC), the ALV passed Task 1 and 3, forward mobility, on the first attempt.

Results and Discussion

Based on the testing done before the PoC, the ALV was predicted to pass all Tasks except Task 6. Task 6 was deemed unachievable due to a connection issue between the ALV and the LSTS interface. A connection could not be achieved, so the code for Task 6 could never be truly tested. However, all other tasks were passed during the testing phase.

Tasks 1 and 3 required the ALV to turn 30 degrees counterclockwise, move in a straight line, and then navigate through rough terrain. In testing, the ALV could turn within 3 degrees of the desired 30 degrees and only deviated 1 cm while traveling one foot. During the PoC, the ALV performed exactly as expected. The ALV rotated accurately, then traveled forward with minor (less than 1 cm) deviation. All obstacles in the path were pushed to the sides by the ALV, creating an obstacle free path for the wheels. Task 4 required the ALV to detect and stop above a magnet. The ALV was calibrated to move 5 cm after initially detecting the magnet so that the center of the brick would be directly above the magnet. The ALV performed as expected. The reference point of the ALV stopped directly over the beacon, giving it an error of 0 cm.

The team predicted that the ALV would pass Task 2, due to test runs completed during team meetings. However, the ALV failed this task, most likely due to differences between the friction of the paper used during the PoC and the concrete surface used during testing. The difference in friction was initially calibrated, but the ALV still turned more than the desired 90 degrees. The team believes the problem arose because the axles were bowing due to a large amount of stress, making turning unreliable.

Task 5 was also not successfully completed. The problem was believed to be caused by the same issues encountered in Task 2. The ALV was turning almost 180 degrees rather than the desired 90. The code was not updated before the time to complete the task expired. Once the time expired, the team did test the updated code. The ALV then traveled the path correctly and dropped off the antenna box in the specified zone without exceeding the minimum or average vibration levels. Task 6 was not successfully performed. Prior to the start of the PoC, the ALV was only able to establish connection with the manual LSTS once, and the same problem persisted in the PoC tasks.

During the final demonstration, the ALV was expected to correctly identify and drop off the bin at the first location, but the team was unsure if the ALV could correctly find the second location. The ALV corrected its orientation within 2 degrees of its goal orientation; it then performed 90 degree turns with less than 2 degrees of error again. The ALV deviated 10 cm to the left while traveling forward 1 meter. When the ALV was able to successfully reach the beacon, the beacon was detected within 1 cm of the reference point. The antenna box was initially dropped off correctly with the correct orientation and was within the allowable accelerations. A problem arose because of the length of the ALV. It ran into the canyon wall while trying to deploy the antenna box, causing the box to be shifted to the side while turning, which was then outside of the drop-off zone. The code used to correct location based off of a second LSTS coordinate could not be used because the ALV kept running into the canyon walls as well. The error in travelling straight was believed to be caused by unequal weight distribution in the ALV but was intensified by the small bumps created by the tape. Since the plow was directly against the ground, the ALV's plow got caught on the tape, and the orientation was offset.

The ALV was able to meet most of the team's expectations. The performance versus target goals can be found in Figure 14. The ALV exceeded expectations in moving small obstacles, turning precisely, safely deploying antenna boxes, correctly detecting current location, and detecting a magnetic sensor. The ALV did not meet the team's expectations in the areas pertaining to turning accurately (minimizing deviation of the ALV's central point in a 90 degree turn) and moving to a target location using LSTS. The ability to move straight was believed to be inaccurate due to unequal weight distribution. Because more weight was centered on the left wheel, it had more friction and moved more slowly than the right wheel. Although the ALV did not meet the target value of turning accurately, the ALV met the technical requirement of 2 cm. Since the ALV met the technical requirement, the team believes the drivetrain is still a formidable design.

Conclusions and Recommendations

The goal of this proposal was to develop a prototype for an autonomous lunar vehicle (ALV). The ALV would land on the surface of the moon and would begin receiving a transmission from a lunar satellite tracking system (LSTS) containing the current position of the ALV. The ALV would then navigate to predetermined search zones while maneuvering through rough terrain and obstacles. Once at the zone, the ALV would find a beacon, safely deploy an antenna box, and then drop off the remaining boxes before returning to the base.

In the final testing, the ALV was successfully able to interact with the LSTS in 100% of requests (5 out of 5 requests). The ALV could correct its initial orientation within 2 degrees of its goal orientation, and the ALV could perform 90 degree turns with less than 2 degrees of error. The ALV deviated 10 cm while driving straight for 1 meter. Small obstacles less than three inches were pushed out of the way 100 percent of the time, effectively creating a path to navigate. The ALV was able to detect magnetic sensors within 1 cm of the beacons. The antenna boxes were initially deployed within 5 cm of the beacon, and the boxes experienced an average acceleration of 0.3 m/s^2 and peak acceleration of 8.66 m/s^2. The ALV ran into the canyon wall while trying to detach from the box, so when the ALV turned, it pushed the antenna box out of the drop-off region.

The system can be improved by making the ALV more compact. This can be done by lifting the NXT brick vertically, increasing the distance between the two motors, and shifting the deployment system underneath the brick. By being more compact, the ALV can navigate tight paths, lessen the bending of the axles for the wheels, and centralize the weight making turning more accurate. Constructing a larger container to hold the bins would allow more bins to be carried. This would allow the ALV to transport more antenna boxes at once, decreasing the number of runs needed during the overall mission time and increasing the efficiency. The code could be improved by implementing an algorithm to correct the error in the ALV's orientation. The formula, using the difference in current coordinates versus the previous coordinates, was already derived by the team, so the implementation would not be difficult.

Appendix

Figure 1: PoC Specifications

Task	**Customer Need**	**Technical Need**	**Technical Requirement**	**Target Value**
1, 5	Move steadily	Move with a maximum degree of rotation of the chassis	Move with a maximum of 15 degrees of rotation from original setting	Move with less than 10 degrees of rotation
1	Move far	Move at least a set distance in a set amount of time	Move at least 8 feet in 1 minutes	Move at least 10 feet in 1 minute
1	Robot can turn	Robot can turn 90 degrees while deviating a max of x inches from the center point	turn 90 degrees with a max deviation of the central point of the robot not deviating by more than 2 cm	turn 90 degrees with a max deviation of 1 cm
1	Robot can accurately rotate its orientation	Robot can rotate its orientation within certain degree of desired orientation	Robot can rotate its orientation within 10 degrees of desired orientation	Robot can rotate its orientation within 5 degrees of desired orientation
1	Move straight	Move with less than a specified degree of displacement from original path	Move with less than 20 degree displacement	Move with less than 5 degree displacement

2	Correctly determine location	Can determine current location within a certain distance of actual location	Can determine current location within 5 cm of actual location	Can determine current location within 3 cm of actual location
2	Move to correct location	Move to coordinated location with specified precision	Move to coordinated location within 3 inches	Move to coordinated location within 2 inches
2, 4	Beep thrice when at known location	Beep thrice at location specified % of times	Beep thrice at location 95% of the time	Beep thrice at location 100% of the time
2	Return to start	Robot returns to point within the home base	center of robot is within 3 inches of center of home base	center of robot is within 1 inch of center of home base
2	Move around large obstacles	Robot does not come within x inches of the obstacle	Robot does not come within one inch of the obstacle	Robot does not come within two inches of the obstacle
3	Move over small obstacles	Traverse obstacles of a certain height without interfering with structure	Traverse obstacles at least 1/2 inch in height without interfering with structure	Traverse obstacles at least 1 inch in height
3	Traverse small obstacles quickly	Traverse 1 inch obstacles in a set time	Traverse 1 inch obstacles in less than 30 seconds	Traverse 1 inch obstacles in less than 15 seconds

4	Stop with paperclip over beacon	Paperclip is within a certain distance of the beacon	Paperclip is within 1 cm of the beacon	Paperclip is 0.5 cm from beacon (directly over beacon)
4	Detect beacon	ALV needs to detect beacon from certain distance away from it	Detect beacon more than 3 inches away	Detect beacon more than 5 inches away
4	Stop at beacon	ALV must stop within specified distance of beacon	ALV stops within 1 cm of beacon	ALV stops within .5 cm of beacon
5	Release antenna	Antennas are released within a certain distance of the beacon	Antenna are released within 1 cm of beacon (closest part of antenna is within 1 cm of beacon)	Antenna are released within 0.5 cm of beacon (directly over beacon)
5	Antenna detachment	From the time the antenna touches the ground to the robot completely releasing the antenna, the antenna does not move more than a certain number of millimeters	The antenna moves less than 3 mm	The antenna moves less than 1 mm
5	Transport antennas	Transport antennas a certain distance	Transport antennas 5 meters	Transport antennas 7 meters

5	Transport antenna without exceeding average vibration level	Transport antennas without exceeding average vibration level	Transport antennas without exceeding average vibrations of 1.3m/s^2 (as measured by accelerometer inside of antennas)	Transport antennas without exceeding average vibrations of 1.0 m/s^2 (as measured by accelerometer inside of antennas)
5	Transport antenna without exceeding a peak vibration level	Transport antennas without exceeding specified level at any time	Transport antennas without exceeding 1.6 m/s^2 at any time	Transport antennas without exceeding 1.3 m/s^2 at any time
5	Set orientation of antenna	Antennas is deployed a number of degrees from the correct orientation	Antenna is deployed less than 20 degrees from correct orientation	Antenna is deployed less than 10 degrees from correct orientation
6	Receive coordinates and error codes	Correctly display coordinates to screen with specified % accuracy	Correctly display coordinates to screen with 99% accuracy	Correctly display coordinates to screen with 100% accuracy
6	Move to correct location based on LSTS input	Move to correct location within set distance	Move to correct location within 1 cm	Move to correct location within .5 cm
6	Recognize error code from LSTS system	Identifies error codes from LSTS system x percentage of time	Identifies error codes from LSTS 99 percent of the time	Identifies error codes from LSTS 100 percent of the time

6	Recognize error in human entered coordinates	Detects when coordinates entered are not on the map or are in crevices x percent of time	Detects error entered coordinates 99 percent of the time	Detects error entered coordinates 100 percent of the time

Figure 2: Sole Front Wheel Design

Figure 3: Zero Turn Mower Design with Plow

Figure 4: Initial Antenna Deployment

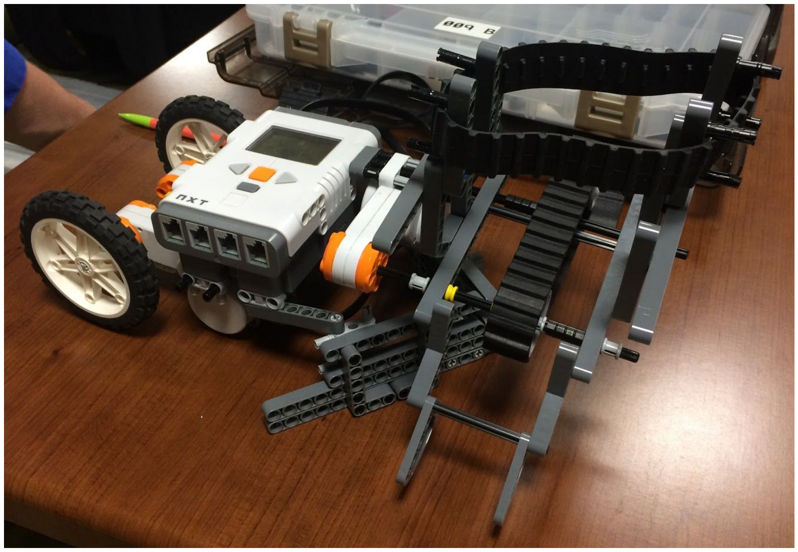

Figure 5: Antenna Deployment Centered on Top of Brick

Figure 6: Antenna Deployment System with Lengthened Slide

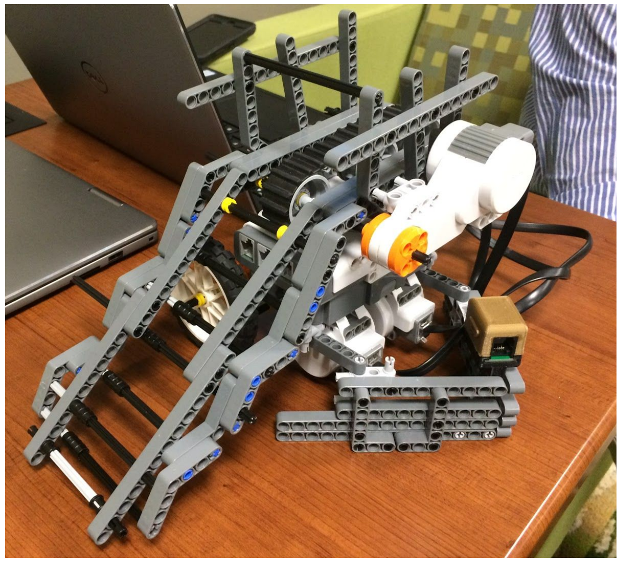

Figure 7: Final Design (Rear View)

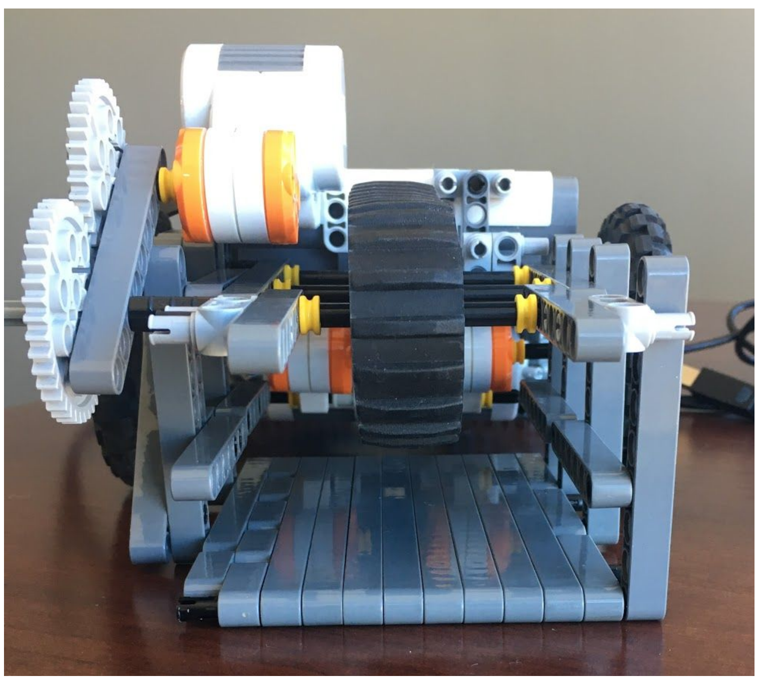

Figure 8: Final Design (Side View)

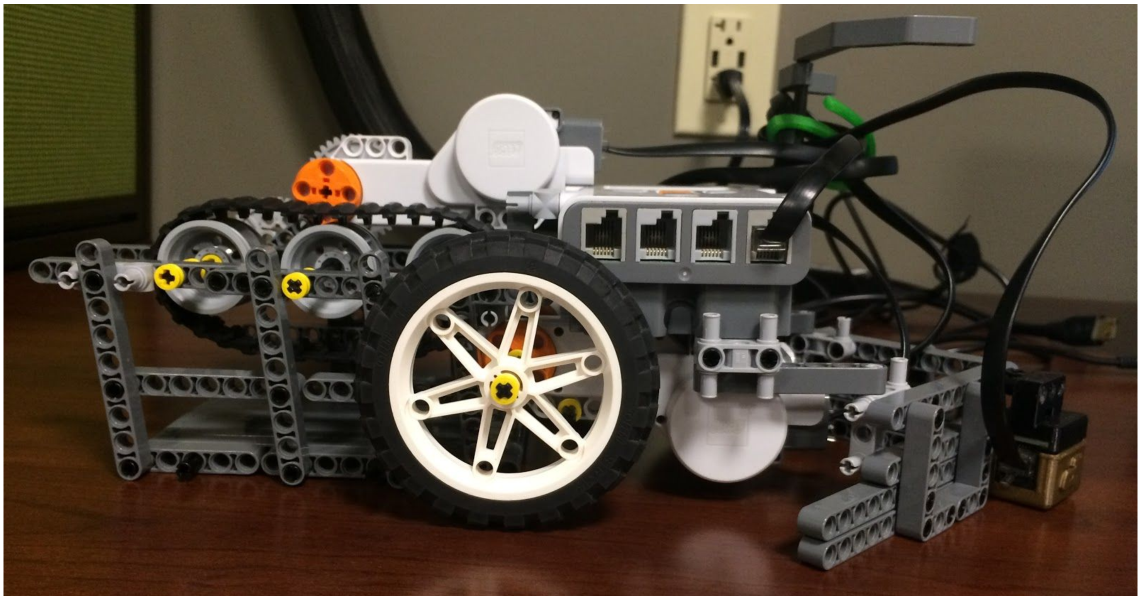

Figure 9: Final Design (Top View)

Figure 10: Decision Matrix for Prioritizing Method to Find Location and Drop off Bin

Consideration	Weight	LSTS	Magnetic Sensor	Mathematical Estimation
Consistency	4	3	4	4
Ease of Implementation	3	2	5	4
Accuracy	5	5	4	2
	Totals:	43	51	38

***Values assigned on a scale of 1-5.

Figure 11: Design Matrix for Hardware Decisions

Consideration	Weight	Deployment System behind brick, wide-wheeled drive train	Deployment System above brick, wide-wheeled drive train	Deployment System above plow, narrow-wheeled drive train
Turns 90 degrees accurately	5	4	5	2
Minimal deviation from origin	5	4	5	2
Deploy bins with minimal vibration	3	5	1	3
	Totals	55	51	29

***Values assigned on a scale of 1-5.

Figure 12 : Data from testing acceleration values for different designs

Design	Is force at a passing level (determined from office hours tests)
Conveyor belt on top with two piece slide	No
Conveyor belt on top with zig-zag (less steep) slide	No
Double conveyor belt slide	No
Bed on ground with conveyor belt above bed	Yes, four tests resulted in Average average - 0.3 m/s^2 (max = 1.3) Average peak - 8.66 m/s^2 (max = 12)

***Non-passing were rated on pass or fail. The maximum mark was 12 m/s^2 for peak and 1.3 m/s^2 for average.

Figure 13: Deviation data from different deployment systems

Design	Deviation from central point on 90 degree turn (cm)
Conveyor belt in front, wheels behind	7 cm
Conveyor belt on top, wheels behind	4 cm
Conveyor belt on top, wheels underneath brick (but are narrower)	3 cm
Conveyor belt on top, wheels underneath brick (as wide as possible)	1 cm
Conveyor belt behind brick, wheels underneath brick (as wide as possible)	2 cm

*** Conveyor belt behind the brick was ultimately chosen because it was the only design that the antennas were dropped off within the proper specifications

Figure 14 : Chart comparing Target Goals versus Target Performance

Customer Need	Target Goal	Performance	Ratio of Performance to Goal
Move over small obstacles	Traverse obstacles <= 1 inch in height	All small obstacles <= 3 inches pushed out of way	300 %
Move Straight	< 5-degree deviation	< 10-degree deviation	50 %
Turn precisely	< 10 degrees	< 5 degrees	200 %
Turn accurately	< 1 cm	2 cm	50 %
Safely deploy bins	• Peak < 10 m/s^2 • Average < 1 m/s^2	• Peak 8.66 m/s^2 • Average 0.3 m/s^2	• 115 % • 333 %
Correctly detect current location	• < 3 cm error	• < 1 cm error	300 %
Can move to target location using LSTS	< 5 cm	Average on first try ~ 15 cm	33 %
Can detect a sensor	< 1 cm	0 cm (reference point was directly above sensor)	∞ %