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Design and Optimization of a Magnetic Wheel for Hull Climbing

A NISE funded Applied Research Project

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ADMINISTRATIVE INFORMATION

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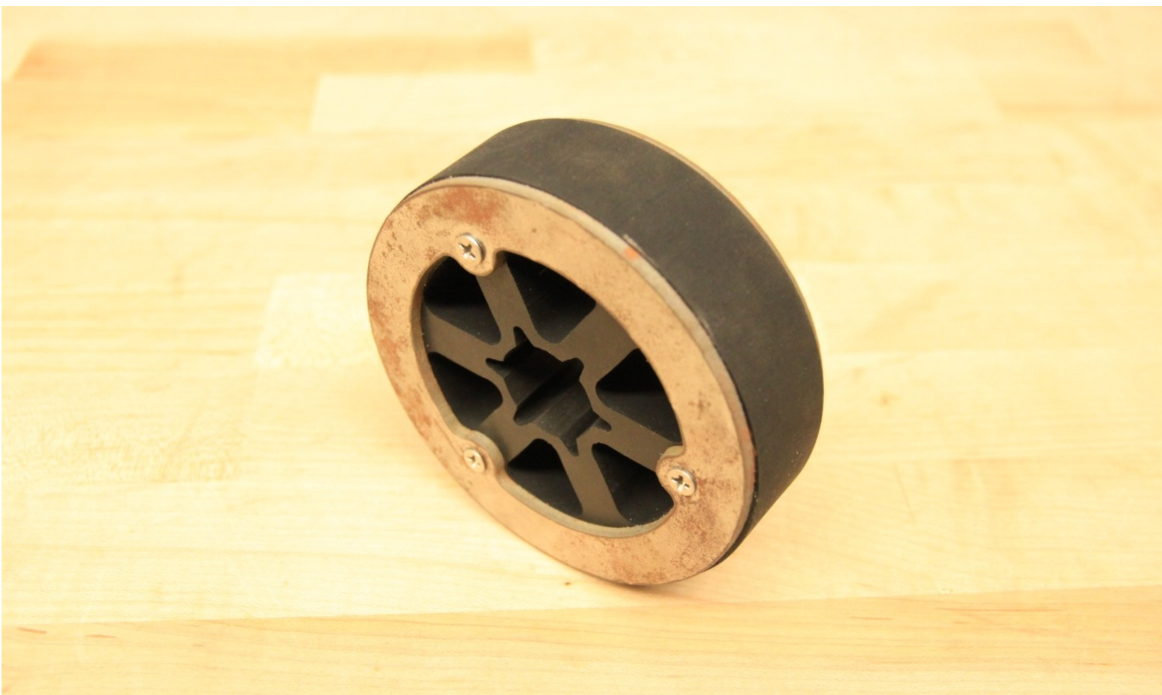
EXECUTIVE SUMMARY

A magnetic wheel was designed, optimized, prototyped, and tested for use on the Multi-segmented Magnetic Robot (MSM) project. The wheel provides magnetic attraction force to ferrous surfaces, allowing the robot to climb ship hulls. This capability could be used to meet the intelligence, surveillance, and reconnaissance (ISR) needs of Navy visit, board, search, and seizure (VBSS), Navy SEALs, and Marine Force Reconnaissance teams.

Two different magnetic wheel designs, the flux-plate wheel and conformal wheel, were evaluated to select the most promising design for use on the MSM robot. The flux-plate wheel was the clear winner, providing over four times as much attraction force as a similarly sized *conformal wheel.*

An optimization study of the flux-plate wheel showed that increasing the thickness of the flux-plate and the number of magnets in the wheel provided a greater increase in the attraction force than the varying of other design parameters. An optimized wheel was designed using measured results, simulated results, manufacturing, and design considerations. The optimized wheel was 1-inch thick, had a 4-inch outer diameter (OD), 36 0.25-inch OD by 1-inch long N52 Neodymium magnets, and 0.125-inch-thick flux-plates. The wheel weighed 1.22 pounds and provided an attractive force of 21 lbf (Figure ES-1).



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1. INTRODUCTION

1.1 BACKGROUND

The Multi-segmented Magnetic (MSM) Robot project addresses a capability gap in the intelligence, surveillance, and reconnaissance (ISR) needs of Navy visit, board, search, and seizure (VBSS), Navy SEALs, and Marine Force Reconnaissance teams. A successful design will expand the pool of available tools the U.S. Navy and Marine Corps will have to execute the maritime-interdiction mission while minimizing casualties. The technology is also promising for inspection of tanks and dangerous or hard to reach passages and voids within maritime vessels. Every year the U.S. Navy conducts thousands of maritime interdiction operations worldwide to enforce embargoes, intercept contraband, prevent drug and human smuggling, and fight piracy. These operations may be conducted in stealth by Navy SEAL and Marine Force Reconnaissance teams or in the open by VBSS teams.

The dangerous task of boarding a suspect ship demands a strong desire to view the deck remotely before climbing the hull and boarding. The MSM robot (Figure 1) is designed to address this ISR capability gap by providing acoustically quiet climbing and turning ability over a typical ferrous hull that often includes geometric discontinuities in the form of protrusions and indentations, especially where hull-plating sections meet. This ability will allow the MSM robot to stealthily climb the hull of a ship, provide perch-and-stare surveillance of the deck area, and wirelessly transmit audio/video for a covert look before the Navy team boards the ship. The key to its effective climbing lies in the design of its wheels and the multi-segmented approach. The wheels are designed to provide maximum magnetic adhesion while remaining acoustically quiet during operation. The design of the magnetic wheel is studied and optimized in this report to increase the effectiveness of the MSM robot.

Figure 1. Conceptual MSM robot climbing hull surfaces.

1.2 PURPOSE

This report documents efforts to model and build a magnetic wheel for use on the MSM robot and similar robots that climb ferrous surfaces. The goal of the simulation, analysis, and experimentation is to provide guidance for a prototype wheel design that meets the requirements of larger attraction force, minimized mass and volume, reasonable cost, and ease of manufacturing.

1.3 DESIRED PROPERTIES

The primary design attributes that drive the effectiveness of a magnetic wheel are adhesion force, surface friction, acoustic signature, shock absorption, mass, cost, service, and ease of assembly and manufacture. To climb a surface effectively, a wheel requires enough adhesion force to carry the weight of the MSM robot so the friction between the wheel and surface being climbed keeps the wheel from sliding. When climbing a surface, the acoustic signature of a wheel is important for stealth operations. Flexibility of the wheel provides survivability for the entire system under the high-shock loading seen during inevitable cases where the robot falls from a vertical surface. Minimizing the mass of the wheel and MSM robot in general reduces the required magnetic attraction forces, motor output torque, and power consumption. Design cost, assembly cost, manufacturability, and serviceability all affect the life-cycle costs of a military system and should be considered throughout the development process.

1.4 APPROACH

For this project, two wheel design concepts, the flux-plate wheel and conformal wheel, were designed and prototyped. The primary properties of each wheel were assessed against the goals of the project, after which the more promising design was pursued for optimization.

2. FLUX-PLATE WHEEL

2.1 WHEEL DESIGN DESCRIPTION

The *flux-plate wheel* (Figure 2) consists of an elastomer wheel, two flux-plates, flux-plate locators, rigid hub, and an array of magnets oriented parallel to the central axis of the wheel. The magnets are positioned with all the north poles facing one side of the wheel and the south poles facing the other.

The elastomer wheel is 1-inch thick. In addition to locating the other components of the wheel, the elastomer is flexible, allowing the entire assembly to flex during impacts. The outer surface of the wheel has a high coefficient of static friction maximizing the traction with hull surfaces. The rigid hub in the middle of the wheel translates torque from the output shaft of the drive motors to the wheel assembly to facilitate motion. The flux-plates direct the magnetic flux of the magnet array through the surface climbed, providing adhesion. The flux-plate locators (not shown in Figure 2) help keep the flux-plates centered on the elastomeric wheel.

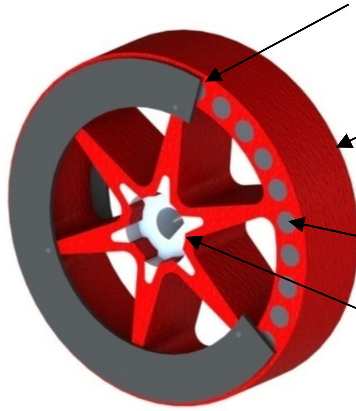

Figure 2. Flux-plate wheel components.

2.2 DESIGN PARAMETER IDENTIFICATION

Several design parameters can be varied to maximize adhesion force of the flux-plate wheel design. The first and most obvious is that by increasing the number of magnets in a wheel, the adhesion force can be increased. Other parameters considered included increasing the flux-plate outer diameter until it is just smaller than the elastomeric wheel outer diameter, increasing the flux-plate surface area by decreasing its inner diameter, moving the magnets toward the perimeter of the wheel, and increasing the flux-plate thickness. Flux-wheel-1 (Figure 3) was created to verify and quantify the role of these parameters, and its attractive force was measured on a force measurement test stand.

An Ametek Chatillon TCD 225 test stand was used to measure the attractive force between flux-wheel-1 and a 0.25-inch thick steel plate measuring 3 inches by 5 inches (Figure 4).

Five additional wheels were fabricated, each changing only one of the design parameters to evaluate the effective delta in adhesion force related to that parameter. Table 1 lists the results of the experiment. The attractive force of the baseline wheel was 4.3 lbf. By increasing the outer diameter of the flux-plate, which effectively reduces the distance from the flux-plate to the steel plate, the attractive force of the wheel changed from 4.3 to 5.1 lbf, an 18% increase. An increase from 12 to 15 magnets changed the force from 4.3 to 6.1 lbf, a 42% increase. Increasing the flux-plate surface area (measured as the surface area of one side of a flux-plate) by removing spoke lightening cut-outs made little difference, with only a 2% increase in attraction. Moving the magnets closer to the wheel perimeter also had little impact, with only a 3% increase in attraction. Increasing the flux-plate thickness from 0.041 to 0.075 inches had a signifigant improvement in force from 4.3 to 7.0 lbf, a 63% increase.

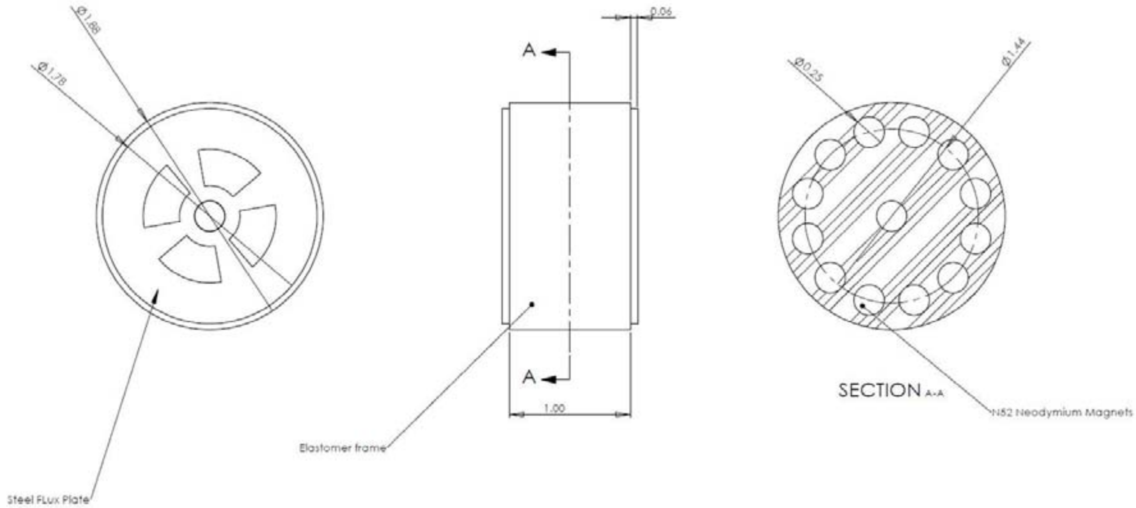

Figure 3. Flux-wheel-1 dimensions.

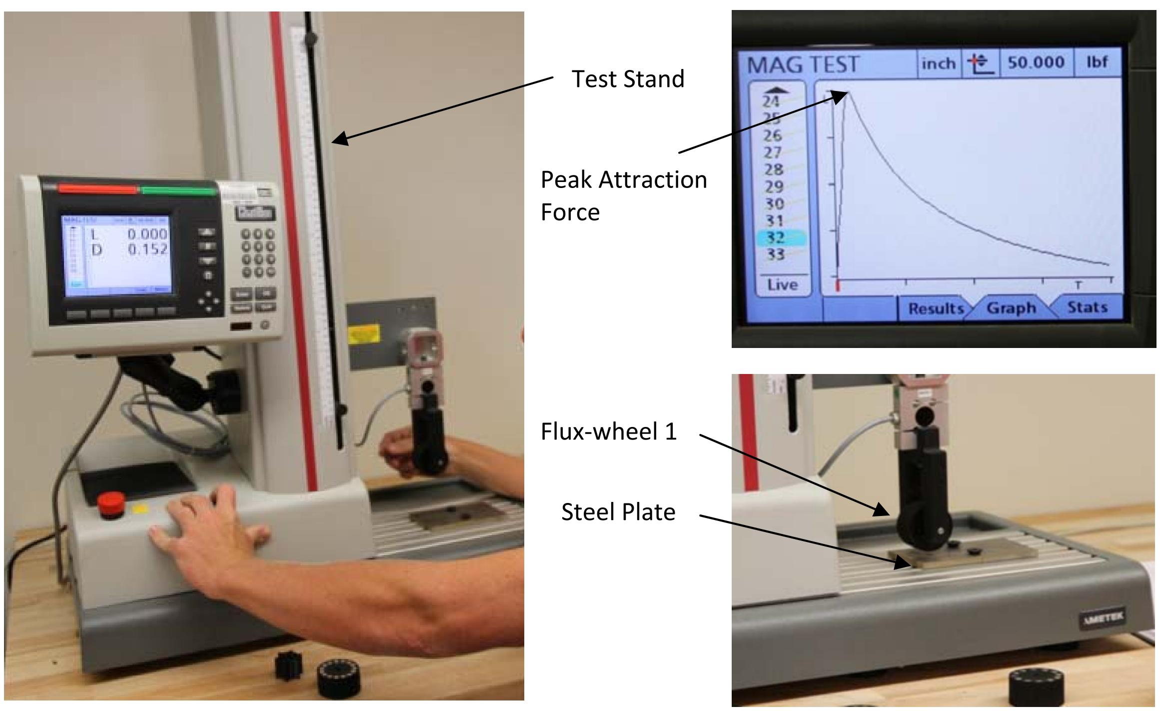

Figure 4. Force measurement test.

Table 1. Variable flux-plate wheel design parameters.

Parameter	Baseline Value	Final Value	Force (lbf)	% Increase
Baseline			4.3	
Flux-plate distance to perimeter	0.05 in	0.025 in	5.1	18
Increased number of magnets	12	15	6.1	42
Decreased flux-plate surface area	1.93 in^2	2.43 in^2	4.4	2
Magnets closer to wheel perimeter	0.095 in	0.054 in	4.4	3
Increased flux-plate thickness	0.041 in	0.075 in	7.0	63

2.3 SIMULATION VALIDATION

Fabricating prototype wheels for the optimization of the flux-plate wheel design was costly and time consuming. To increase the efficiency of design iterations while optimizing the performance properties of the flux-plate wheel design, Ansoft's Maxwell 3D v12 was used for simulating magnetic attraction[1]. The software calculates the force between the wheel and attraction plate. Figure 5 shows a Maxwell 3D model of a magnet wheel. The N52 magnet B-H curve used is from K&J Magnetics Inc.[2] The flux-plates and attraction-plate material is steel 1008, with material properties from the software library.

The software model was validated against measured results from flux-wheel-1 with the expectation that simulation results could be used to optimize the design of a larger 4-inch outer-diameter magnet wheel. Summarized in Table 2, the simulation results were always higher than measured but within 30%. This error was considered reasonable and may have been due to manufacturing tolerances, test setup, or other unknown causes.

2.4 FLUX-PLATE WHEEL OPTIMIZATION

Using the simulation setup from flux-wheel-1 (1.88-inch diameter), a 4-inch-diameter magnet wheel was simulated. This design is referred to as the "flux-wheel-2" design in this report and the schematic is shown in Figure 6. The magnetic wheel design features an elastomer frame for holding the magnets and gripping the hull, N52 strength magnets evenly distributed within the elastomer, and two flux-plates for magnetic attraction.

2.5 SIMULATION RESULTS

Results from flux-wheel-1 influenced the focus of simulations for flux-wheel-2 on the optimization of magnet quantity and flux-plate thickness. In addition, simulations were performed to determine if increasing the diameter of the magnets affected the attraction force. Figure 7 shows the simulation setup.

2.5.1 Flux-wheel-2: 0.25-inch OD Magnet Results

Magnetic attraction force results for 0.25-inch OD magnets are shown in Figure 8, with tabulated results provided in Table A-1 in the appendix. As expected, results showed significant increases in attraction for both increases in flux-plate thickness and increases in the number of magnets.

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[1] Ansys Maxwell (Formally Ansoft) [Online]: http://www.ansys.com/Products/Simulation+Technology/Electromagnetics/Electromechanical+Design/ANSYS+Maxwell

[2] K & J Magnetics. [Online] http://www.kjmagnetics.com/

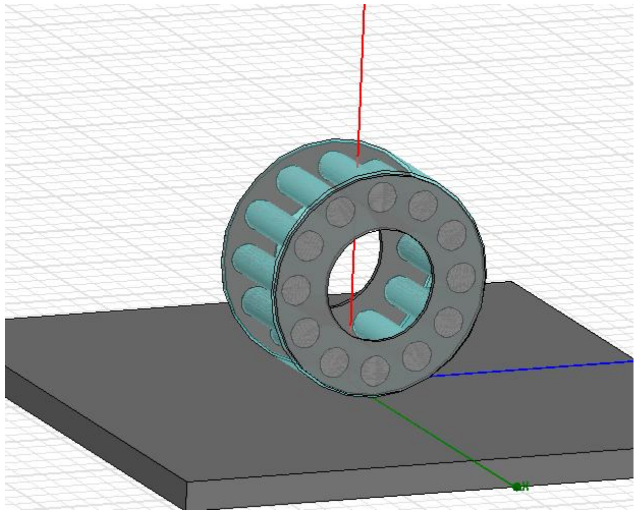

Figure 5. Flux-plate simulation model (flux-plate and elastomer semi-transparent).

Table 2. 1.88-inch OD flux-plate wheel measured and simulated results.

Magnet Wheel Configuration	Measured Force [lbf (N)]	Simulated Force [lbf (N)]	% Difference [%]
Normal	4.3 (19.1)	5.6 (24.9)	26.3
Flux-plate 1.83” OD	5.1 (22.7)	6.7 (29.8)	27.1
15 magnets	6.1 (27.1)	7.8 (34.7)	24.5
Flux-plate thickness 0.075”	7.0 (31.1)	8.5 (37.8)	19.4

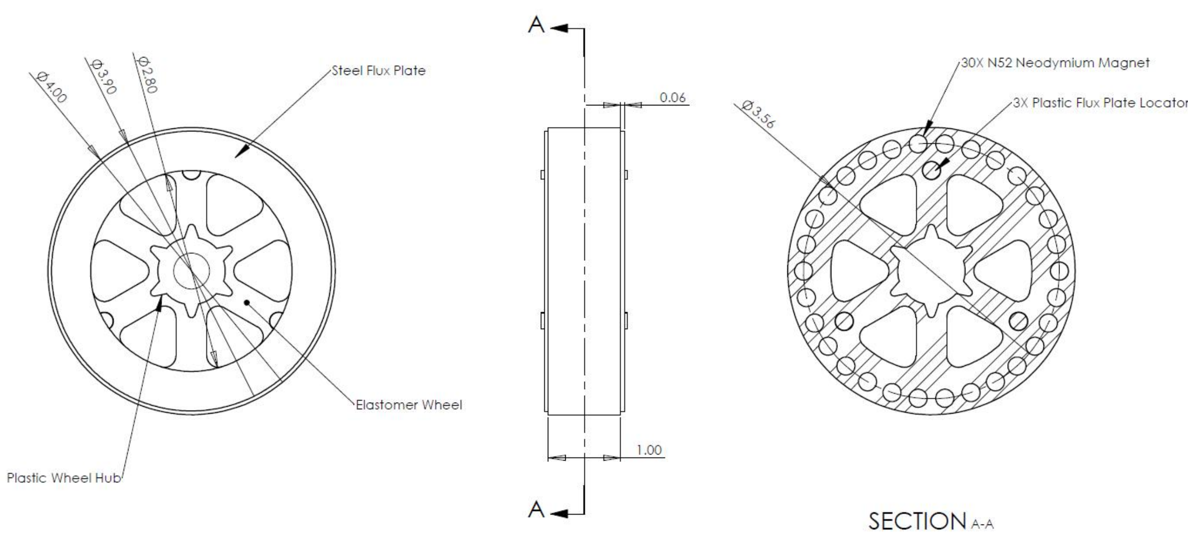

Figure 6. Flux-wheel-2 schematic (units are in inches).

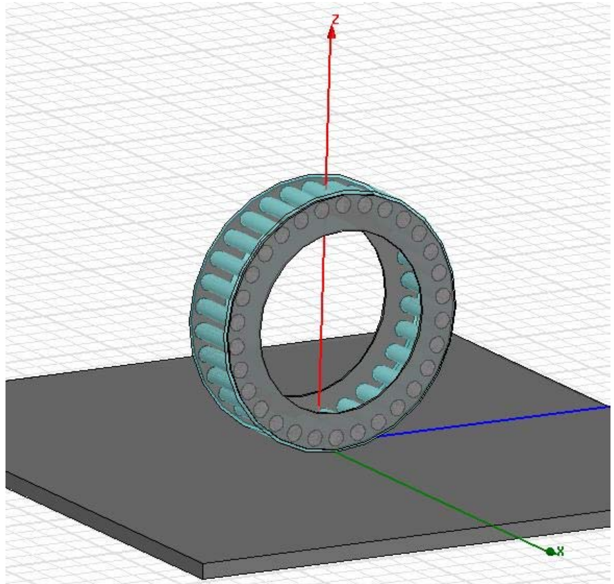

Figure 7. Simulation space of 4-inch OD wheel with 0.25-inch OD magnets (flux-plate and elastomer transparent).

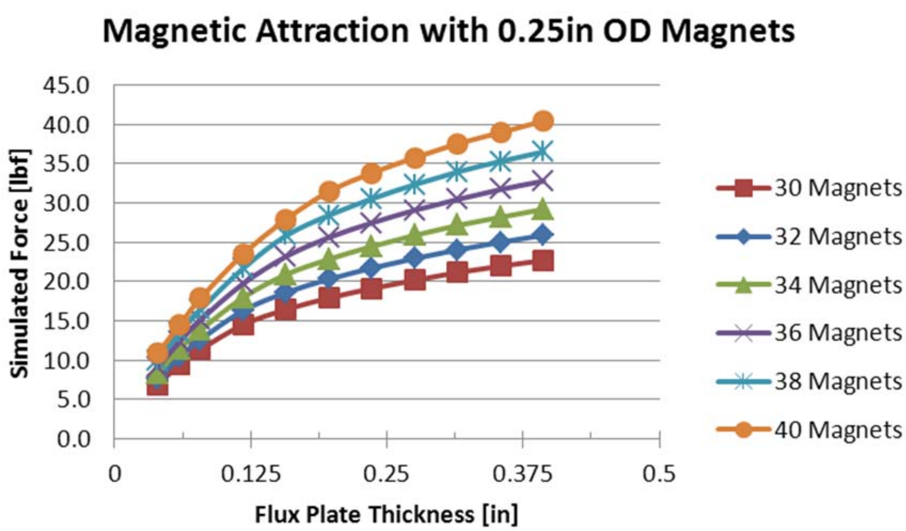

Figure 8. 25-inch OD magnet simulated attraction force (simulated).

To verify the results of this simulation, a prototype wheel was fabricated with 0.25-inch-thick flux-plates and 30 magnets. Using the force measurement test stand, attractive force was measured at 39 lbf. The simulation result was 19 lbf, which is about half the measured force. Closer examination of the test setup showed that prototype wheel was not sitting evenly on the texture fixture, allowing one of the two flux plates to contact the steel 3-inch by 5-inch plate on the test stand. A second simulation was run where one flux plate was in contact with the steel plate, producing an attraction force of 52.2 lbf, results similar to the prototype. Small changes in flux plate distance to the steel plate provide large changes in attraction force, making test fixturing and wheel manufacturing accuracy important for comparison of measured and simulated forces.

2.5.2 Flux-wheel-2: 0.375-inch OD Magnet Results

Magnetic attraction force results for 0.375-inch OD magnets are shown in Figure 9. Thicker flux-plates and more magnets increase force. Generally, 0.375-inch OD magnetic wheel designs have larger attraction force than wheels with 0.25-inch magnets. This may be due to an increase in magnet surface area. A force comparison when accounting for surface area is in the Section 3. Results are listed in Tables A-1 and A-2 in the appendix.

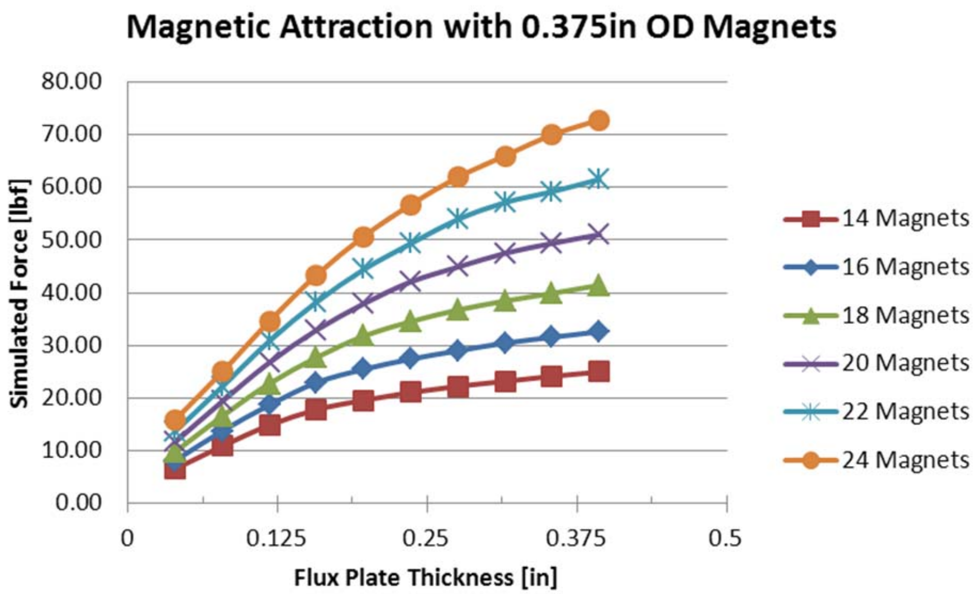

Figure 9. 0.375-inch OD magnets simulated attraction force (simulated).

2.5.3 Flux-wheel-2 Surface Area Comparison of 0.25- and 0.375-inch OD Magnets

From the previous results, it is apparent that using 0.375-inch OD magnets results in a larger attraction force. This is true, but when taking into account the total surface area of the magnets in contact with the flux-plate, both OD magnets have very similar attraction forces. Sixteen 0.375-inch OD and 36 0.25-inch OD magnets have the same total contact surface area, and the comparison in Figure 10 shows nearly identical simulated attraction force. More comparisons are in Section A-2 in the appendix.

2.6 OPTIMIZED DESIGN SELECTION

Based on the results from the simulations and practical constraints of engineering and manufacturing, a series of trade-offs were made to develop an optimized flux-plate wheel. The primary goals of the optimization were to maximize the attraction force and to minimize cost and weight. The overall weight of a robot drive-module with two wheels is planned to be 10 pounds. For a safety factor of 4, the target optimization was for a single wheel to have at least 20 pounds of attraction force. Increasing the attraction force considerably higher was not desirable because it requires greater motor-torque output in situations where the robot is trying to drive off a ferrous surface.

Table 3 summarizes the optimized values chosen and justification for each parameter. A more in-depth discussion of chosen parameter values follows the table.

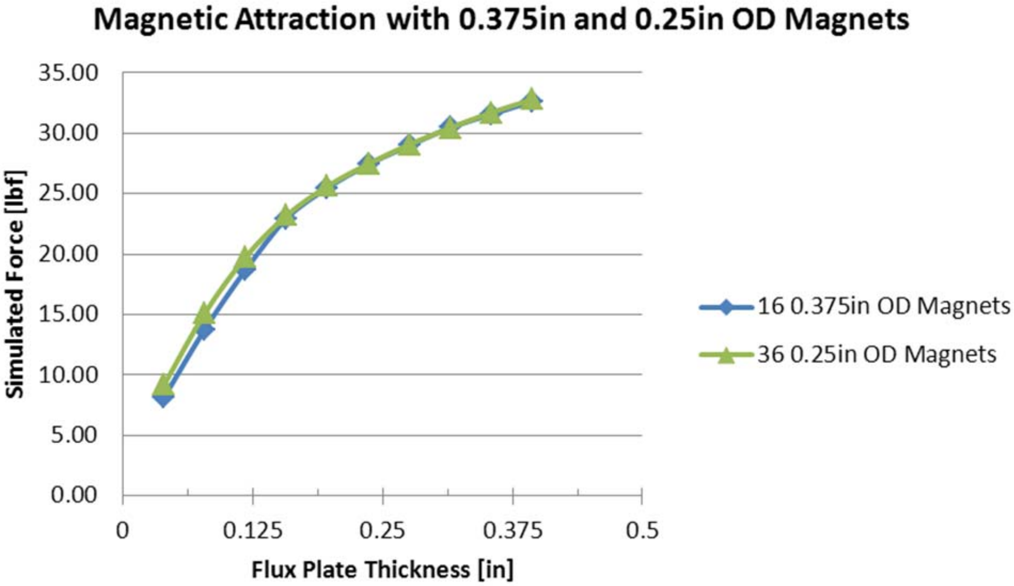

Figure 10. 0.375- and 0.25-inch magnet OD force comparison (simulated).

Table 3. Selection of optimized wheel parameters.

Parameter	Optimized Value	Selection Justification
Flux-plate distance to perimeter	0.05	Minimized distance while leaving elastomer for traction and shock absorption
Increased number of magnets	36	Maximized quantity while leaving 0.07 inches of elastomer between magnets for shock absorption
Increased flux-plate surface area	6.016 in^2	Minimized surface area; increased flux-plate area added weight and provided little improvement in attraction
Magnets closer to wheel perimeter	0.094 in	Minimized distance while leaving elastomer for shock absorption and traction
Increase flux-plate thickness	0.125 in	Selected to meet 15-lbf target while minimizing weight

To maximize the attraction force, 0.05 inches was chosen as the distance from the flux-plate perimeter to the outer edge of the elastomer. Increasing the flux-plate diameter was not pursued because it is undesirable for the flux-plate to contact the hull, as this can cause unwanted noise (acoustic signature) and a loss in traction.

Increasing the flux-plate surface area (by decreasing the ID) created limited improvement and increased the weight of the wheel significantly; thus, the flux-plate surface area was minimized to benefit overall system performance.

Increasing the mounting diameter of the magnets produced a limited improvement in the attraction of the wheel. The magnets were moved toward the outside of the wheel as far as practical while still leaving a significant amount of elastomer to act as a tread and cushion the magnets from impact. A thickness of 0.094 inches of elastomer was left on the outside of the magnets.

Simulations showed that using 0.25- or 0.375-inch-diameter magnets with similar surface area produced similar results. The 0.25-inch-diameter magnets were more available and more cost effective for the design.

A fabrication test was performed using a Flow Mach II water-jet cutter. Magnet mounting holes were cut with array spacing of 32, 36, and 40 (Figure 11). The 36-magnet spacing provided for the greatest number of magnets while still maintaining the structural integrity of the elastomer. The thinnest portion of elastomer on the 36-magnet spacing was 0.075 inches, while the 40-magnet spacing provided 0.040 inches of rubber.

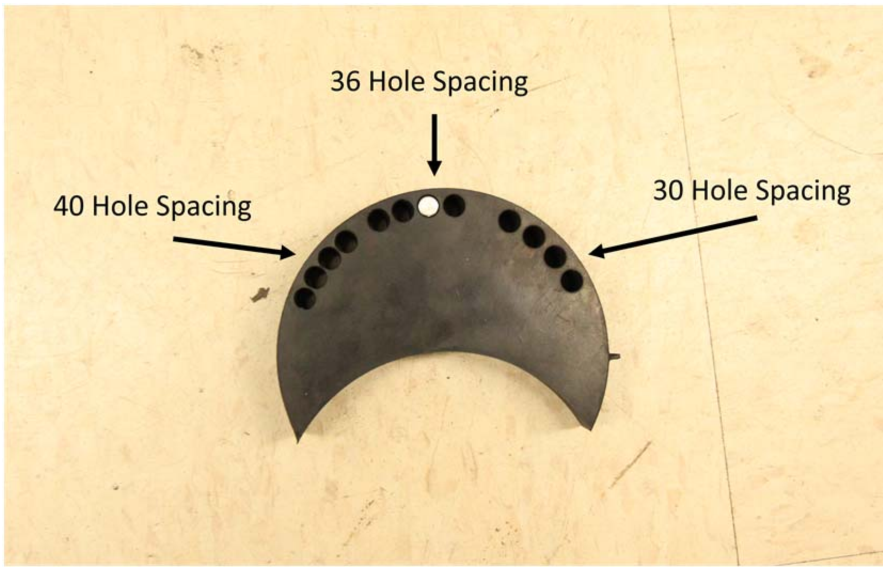

Figure 11. 10-magnet spacing test fixture.

Finally, using all the previously selected parameter values and the preferred 15 lbf of attraction force, the corresponding flux-plate thickness was determined at the intersection of the 36-magnet curve and the 15-lbf line. The corresponding value for flux-plate thickness is 0.125 inches. Increasing the flux-plate thickness further is expected to increase the attraction force but will also increase manufacturing costs and system weight.

2.7 OPTIMIZED DESIGN PERFORMANCE

A prototype wheel was fabricated using the optimization results. The fabrication and assembly of the optimized flux-wheel-2 was simple and required no special equipment or assembly processes. A solid model of the flux-wheel-2 is shown in Figure 12.

The wheel was placed on the force-measurement test stand to compare the actual attraction force against the simulated force. The measured force was 21 lbf. The measured attraction force was slightly lower than the 21.4-lbf result from simulation, and the variation between the simulation and measured results is reasonable. Manufacturing tolerances of the elastomer and flux-plate wheel could easily account for the difference.

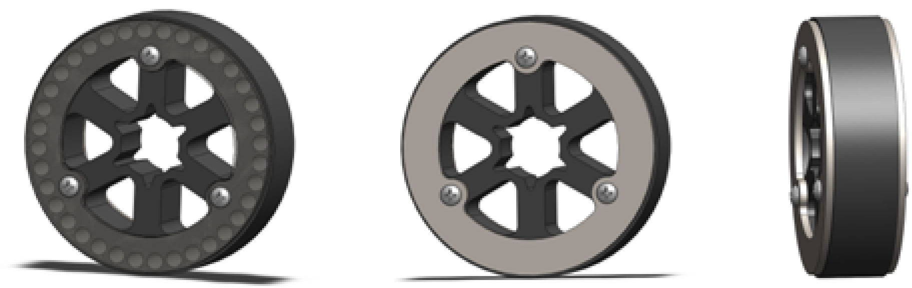

Figure 12. Solid model of optimized flux-plate wheel, without flux-plate (left), with flux-plate (middle), and head on (right).

3. CONFORMAL WHEEL

The conformal wheel (Figure 13) consists of a high-flex elastomer wheel, radial magnet array, magnet locator, rigid hub, and elastomeric tread. The theory behind the design of this wheel is that the highly flexible structure of this wheel will allow the wheel to deform so that it flattens where the wheel contacts the ferrous surface. This flattened edge of the wheel creates a larger surface area of contact, increasing both adhesion force and traction. The high-flex elastomeric wheel provides the structure and flexibility of the wheel, with the magnets positioned radially with circular north pole facing toward the surface climbed. The magnet locator is a highly flexible elastomer that holds the magnets in place and remains flexible to maximize the conformability of the wheel. The rigid hub transfers torque from the drive-shaft output to the wheel, and the thin elastomeric tread provides traction and constrains the magnets inside of the wheel.

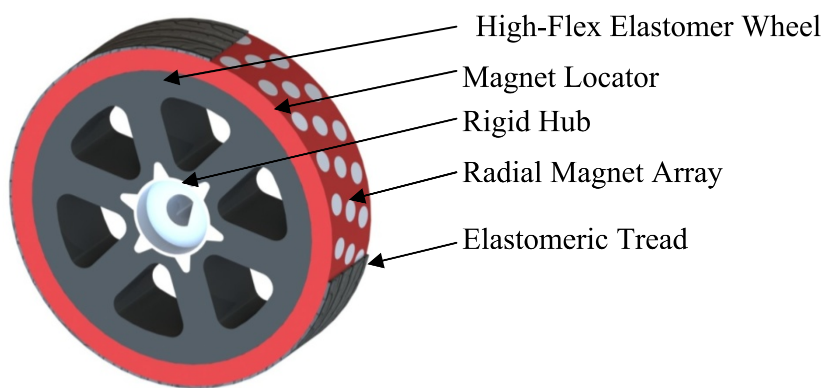

Figure 13. Conformal wheel.

The conformal wheel schematic in Figure 14 illustrates the prototype dimensions.

3.1 CONFORMAL WHEEL DESIGN RESULTS

The simulation setup in Figure 15 is shown with only half of the magnets placed to reduce simulation time. The assumption is that the magnets furthest away do not contribute much to attraction.

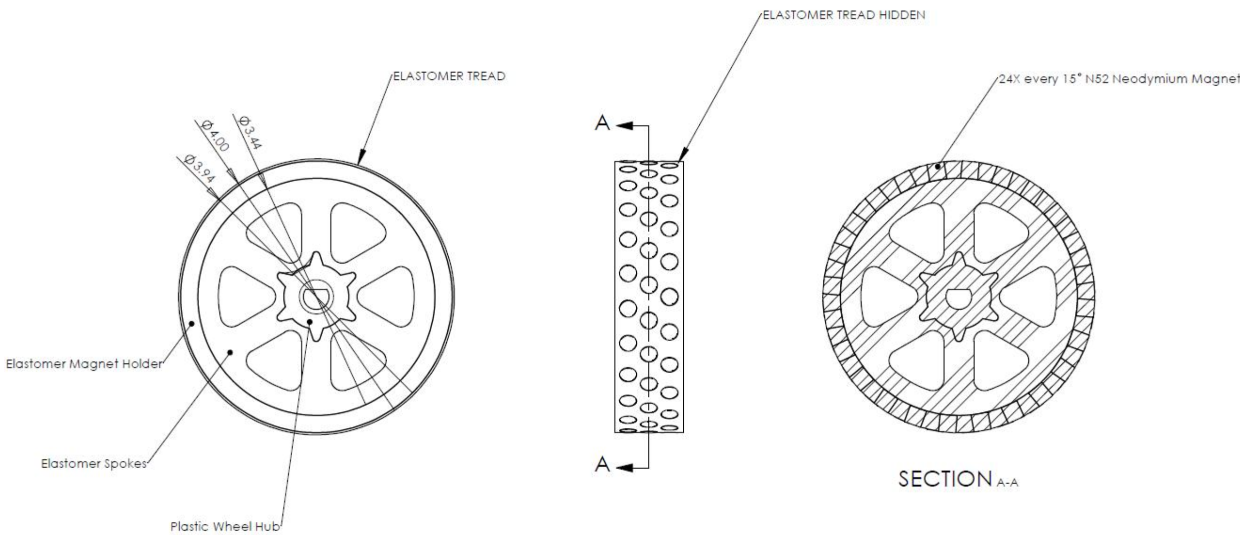

Figure 14. 4-inch conformal wheel dimensions (units are in inches).

3.1.1 Conformal Wheel Comparison with Flux-plate Wheel

Table 4 shows a comparison of the simulated attraction force for the initial magnet wheel prototypes.

3.2 CONFORMAL WHEEL PROTOTYPE

A prototype was fabricated to confirm simulation results for the conformal wheel. The peak force was measured at 6.3 lbf (Table 4).

Assembly of the prototype was especially difficult. As each magnet was placed into the radial array, its attraction to neighboring magnets was very high and often caused the magnet to leave its place in the array. Methods such as gluing and taping the magnets in place improved the assembly process, but assembly remained difficult. If this design was pursued further, a special assembly fixture would need to be created to hold the magnets in place as they are loaded. After the magnets are loaded, the tread must be installed. For the prototype, a thin layer of rubber was adhered to the elastomer magnet holder (Figure 14). This layer of rubber had to overcome the attraction force between the magnet and the surface climbed. The adhesive on the prototype eventually began to fail. A more reliable manufacturing method such as over-molding may address this failure.

The difficulty in assembling the conformal wheel and its much lower attraction force made it clear that the flux-plate wheel design was the better choice for hull-climbing applications. Simulation and testing on the conformal wheel has ended.

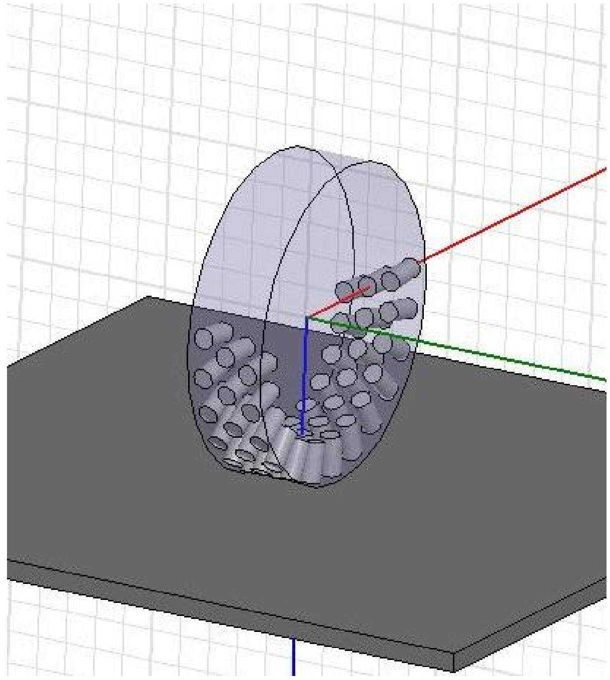

Figure 15. Conformal wheel simulation setup (wheel elastomer semitransparent).

Table 4. Initial wheel design comparison.

Design	Number of Magnet per Wheel	Simulated Force [lbf (N)]	Measured Force [lbf (N)]
Flux-plate wheel	30	19.1 (85.1)	35
Conformal wheel	72	8.4 (37.5)	6.3

4. CONCLUSION

Simulation results clearly showed that the attractive forces of a flux-plate wheel design can be optimized by increasing flux-plate thickness and the number of magnets. An optimal flux-plate wheel was designed, prototyped, and tested to verify the results of the simulations. Simulation and prototype results demonstrated that the flux-plate wheel design was superior to the conformal wheel design in both performance and manufacturability. A prototype robot with flux-plate wheels climbing a metal wall is shown in Figure 16. An optimized flux-plate wheel design will be pursued for use on the Multi-Segmented Magnetic Robot project.

Figure 16. Prototype robot with flux-plate wheels.

APPENDIX

A-1. 4-INCH OD WHEEL SIMULATION RESULT TABLES

Table A-1. 0.25-inch OD magnet force results (lbf).

Flux-plate thickness [mm]	30 Magnets (Schematic)	32 Magnets	34 Magnets	36 Magnets	38 Magnets	40 Magnets
1	6.9	7.6	8.4	9.2	10.0	10.9
1.524(Schematic)	9.5	10.4	11.5	12.4	13.5	14.6
2	11.4	12.6	13.8	15.1	16.4	17.9
3	14.5	16.3	18.0	19.8	21.7	23.5
4	16.5	18.6	20.9	23.2	25.9	27.9
5	17.9	20.3	22.9	25.6	28.4	31.5
6	19.1	21.7	24.5	27.5	30.5	33.8
7	20.2	23.0	25.9	29.1	32.4	35.8
8	21.2	24.1	27.2	30.5	34.0	37.5
9	22.0	25.0	28.2	31.7	35.3	39.0
10	22.7	25.9	29.2	32.8	36.5	40.4

Table A-2. 0.375-inch OD magnet force results (lbf).

Flux-plate thickness [mm]	14 Magnets	16 Magnets	18 Magnets	20 Magnets	22 Magnets	24 Magnets
1	• 6.56	• 8.14	• 9.80	• 11.65	• 13.68	• 15.90
1.524 (Schematic)	Not Simulated	Not Simulated	Not Simulated	Not Simulated	Not Simulated	Not Simulated
2	• 10.91	• 13.79	• 16.60	• 19.39	• 22.17	• 25.00
3	• 14.88	• 18.72	• 22.77	• 26.77	• 30.85	• 34.62
4	• 17.84	• 22.97	• 27.73	• 32.93	• 38.24	• 43.37
5	• 19.62	• 25.48	• 31.78	• 37.92	• 44.41	• 50.71
6	• 21.10	• 27.44	• 34.55	• 42.09	• 49.36	56.77
7	• 22.27	• 29.00	• 36.75	• 44.89	• 53.94	• 61.96
8	• 23.21	• 30.47	• 38.46	• 47.52	• 57.14	• 66.02
9	24.16	31.58	39.91	49.40	59.21	70.00
10	24.98	32.63	41.44	51.04	61.55	72.83

A-2. MORE SURFACE AREA COMPARISON PLOTS

Other quantities of 0.375 and 0.25-inch magnets have total flux-plate contact surface area within 0.025 square inches of each other. Figure A-1 and Figure A-2 show magnet attraction force is similar for different diameter magnets as long as magnet surface area, in contact with the flux plate, is similar.

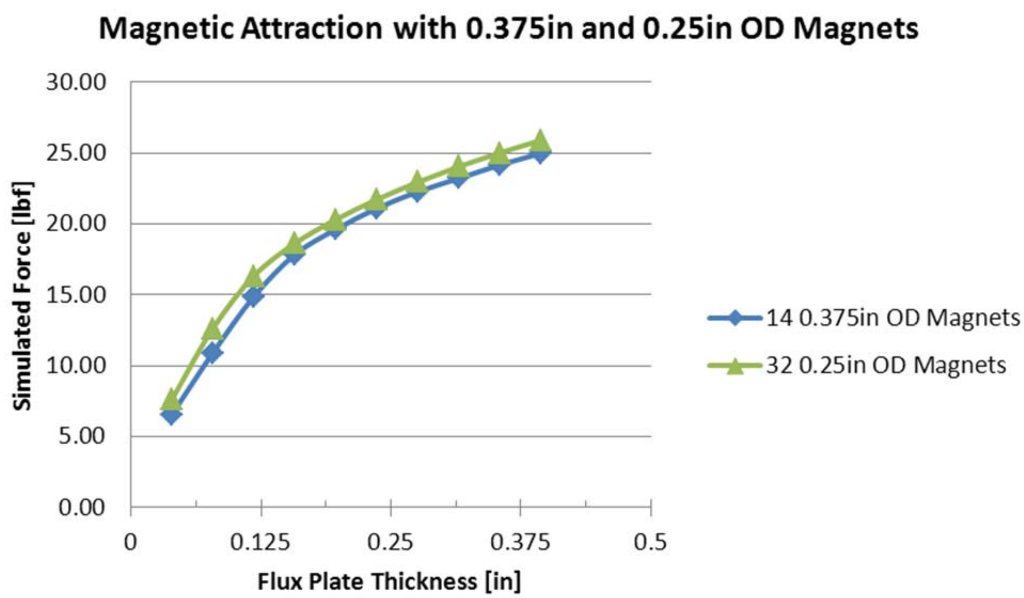

Figure A-1. Attraction force for 14 0.375-inch OD and 32 0.25-inch OD magnets.

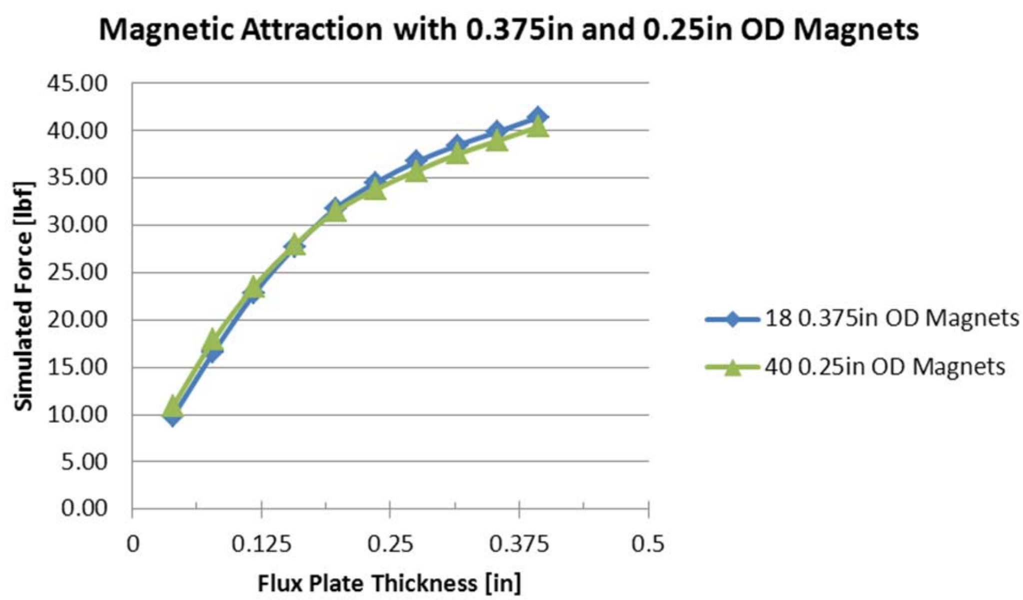

Figure A-2. Attraction force for 18 0.375-inch OD and 40 0.25-inch OD magnets.

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14. ABSTRACT

A magnetic wheel was designed, optimized, prototyped, and tested for use on the Multi-segmented Magnetic Robot (MSM) project. The wheel provides magnetic attraction force to ferrous surfaces, allowing the robot to climb ship hulls. This capability could be used to meet the intelligence, surveillance, and reconnaissance needs of Navy visit, board, search, and seizure (VBSS), Navy SEALs, and Marine Force Reconnaissance teams.

Two different magnetic wheel designs, the flux-plate wheel and conformal wheel, were evaluated to select the most promising design for use on the MSM robot. The flux-plate wheel was the clear winner, providing over four times as much attraction force as a similarly sized *conformal wheel.*

An optimization study of the flux-plate wheel showed that increasing the thickness of the flux-plate and the number of magnets in the wheel provided a greater increase in the attraction force than the varying of other design parameters. An optimized wheel was designed using measured results, simulated results, manufacturing, and design considerations. The optimized wheel was 1-inch thick, had a 4-inch outer diameter (OD), 36 0.25-inch OD by 1-inch long N52 Neodymium magnets, and 0.125-inch thick flux-plates. The wheel weighed 1.22 pounds and provided an attractive force of 21 lbf.

15. SUBJECT TERMS

naval visit, board, search, and seizure   flux-plate wheel   multi-segmented magnetic robot
hull cleaning   ship hull climbing   conformal wheel

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