Magnetic Omnidirectional Wheel for Ferromagnetic Surface Cleaning Robots

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Robots for cleaning/inspecting surfaces ferromagnetic are used to guarantee safety and speed. The robot's versatility is by using magnetic fields to obtain adhesion on a ferromagnetic surface. However, there are limitations to the magnetic force and maneuverability of the robot. This article aims to present the development of a magnetic mecanum omni wheel, using additive manufacturing to generate extra magnetic force to assist robots in adhering to ferromagnetic surfaces with high maneuverability. For this, we realized studies about the magnetic arrangement, topological optimization, structural analyses, and practical tests to determine the magnetic force until obtaining the final wheel concept.
Keywords: Robot. Cleaning/Inspecting Surfaces. Ferromagnetic. Magnetic. Mecanum Omni Wheel. Additive Manufacturing.

Introduction

Additive manufacturing (AM) has gained space in the manufacturing environment, becoming an excellent substitute for conventional manufacturing processes. We defined it as a highly automated manufacturing process by adding material, layer by layer, to form a physical part designed on 3D software [1].

One of AM's advantages over conventional processes is its sustainability, as it manufactures parts by adding materials and not removing them. In addition, one of the fields that benefited from additive manufacturing was robotics because of the design's freedom to obtain light and resistant parts, ideal characteristics for robots [2].

One use for robots is for cleaning and inspecting the hulls of ships. The application of robots, autonomous or remotely controlled, facilitates the cleaning, avoiding many risk exposures. These robots often use a central magnet system or suction cups to attach to the hulls and hydro blaster or rotating brushes to clean the surface.

Cleaning is essential because marine life can grow over the submerged hull surface (algae, barnacles, mussels, corals). As the vessels move around the world, they can cause the introduction of non-native species in different regions, provoking an imbalance in the ecosystem. Additionally, the accumulation of marine files causes an increase in surface roughness, thus increasing the drag force during the vessel movement and, consequently, higher fuel consumption [3].

However, robots usually present linear traction systems based on wheels or continuous tracks. These traction systems present limitations, and maneuvers can take longer to perform the desired movement. For this reason, using omnidirectional wheels on robots, which can move in any direction, could be an alternative.

This work proposes the combination of omni wheels with magnets to be applied in ship hull cleaning robots. The equipment should present better maneuverability and increased fixation on the ferromagnetic surface, being able to reduce the central magnet system. Furthermore, the wheel was designed for additive manufacturing to reduce costs and increase performance.

Omnidirectional Robots

Omni robot has 3 degrees of freedom (translating in two directions and rotating around itself the center

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of mass), allowing movement in any direction. In addition, the wheels allow this movement, also called omnidirectional [4].

There are two categories of omni wheel. The first is "conventional" wheels. However, they cannot be considered omnidirectional because there must be at least 2 of them in the structure, and each must have an actuator to reorient them in the XY plane. The other categories are "special drawing" wheels, considered genuinely omnidirectional. Figure 1 shows the two categories and their types [5].

Magnetic Principles

Magnets work by attracting some materials, called ferromagnetic, and this attraction is most potent at their poles. Every magnet has two poles (north and south), and like poles repel each other, different poles attract each other [6]. The force of attraction decreases dramatically with increasing distance between the magnet and the surface.

Using unique magnet arrays, such as Halbach's, creates a strong force of attraction. According to Masi (2010) [7], this array is defined as an organization of permanent magnets (90 degrees out of phase with each other) that maximizes the flux of the magnetic field on one side and minimizes it on the other side, provoking more required magnetic fields.

Materials and Methods

Figure 2 shows the workflow followed during the Project's development. Initially, we studied omni wheels' history, types, applications, and characteristics. Then, we also realized another study about magnetism and joined the two themes.

The omni wheel chosen was mecanum because it is genuinely omnidirectional, compact, and supports high efforts. Another decisive factor for our choice was many projects involving the universal omni wheel with magnetism.

An evaluation was performed to determine which printing process would be used to manufacture the wheel. The chosen process was MJF (Multi Jet Fusion) because the excellent printing speed, surface quality, and dimensional accuracy (±0,2%) make this method very attractive [8]. The material chosen for this printing process was PA12.

Practical tests involving magnets in different arrays seek to better understand the magnetic principles and obtain more reliable results. Therefore, the test was realized using 5x5x5 mm magnets acquired by IMÃSHOP website. According to the company, one of these magnets can vertically sustain a mass of approximately 940 grams in direct contact with the ferromagnetic surface.

After the tests, the final 3D model was made using Solidworks CAD software. Finally, static and topological analyzes were realized by using the Altair Inspire software.

Material Analysis

The material choice was PA12 from the company HP. According to O'Connor, Dickson, and Dowling (2018) [9], this material is one of the most used MJF processes because its melting temperature

Figure 1. Classification of omnidirectional wheels.

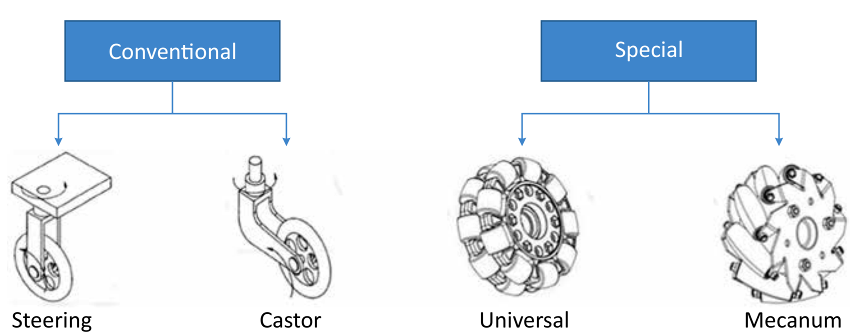
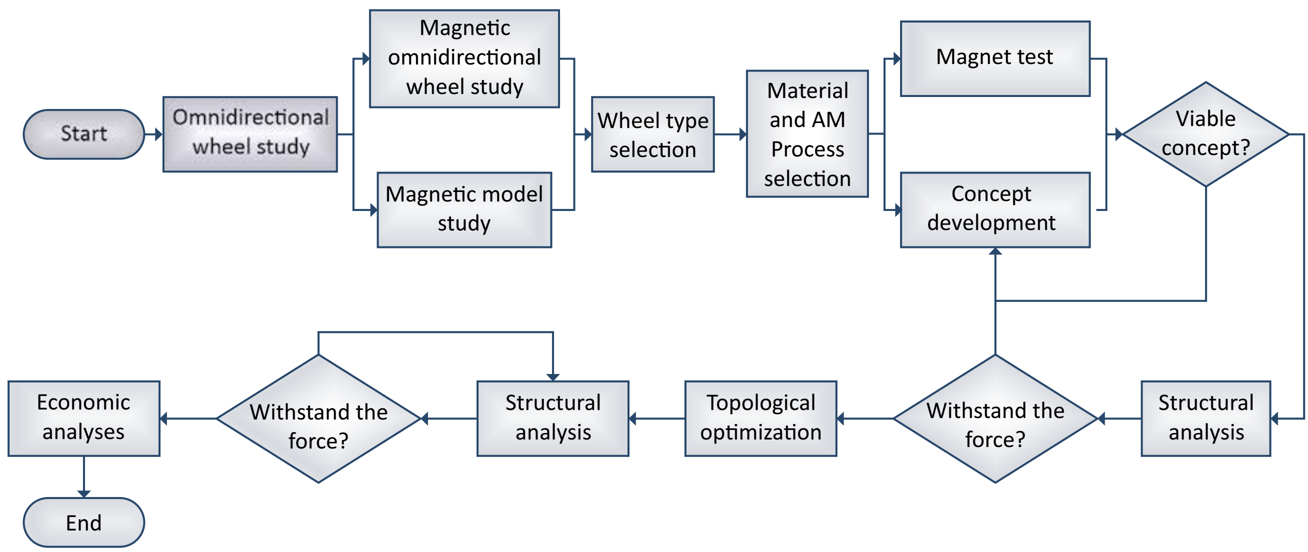


Figure 2. Workflow.



is higher than that of crystallization, and this delay in the recrystallization process during the manufacturing, causes a reduction in the residual stresses and distortions in the piece. However, PA12 is not waterproof, and as the wheel will have contact with the water, a post-process of the piece after printing is required. According to Dizon *and colleagues* (2021) [10], adding a thin layer of epoxy resin, vinyl acrylate, or silicone is sufficient for post-processing.

Another issue is the failure criteria for the material. Since PA12 is a polymer, the failure criterion to be adopted must be based on the deformation. According to Erhard (2006) [11], a good practice for operating with polymers is to adopt the working stress associated with 80% of the yield stress. O'Connor and Dowling (2018) [9] realized the tensile test with PA12 samples by MJF, and the yield region is similar until entering the plastic zone to the failure (Figure 3). The tensile strength is similar to HP's PA12 (50 MPa).

PA12, used by O'Connor e Dowling (2018) [9], was considered similar to HP. Thus, adopting the good practices of Erhard (2006) [11], 40 MPa was considered the maximum stress allowed. Therefore, the combined stress failure criterion adopted was von Mises.

Results and Discussion

Magnet Arrays

A smaller number of magnets were used in the Halbach array to get an increment in magnet force. For that, we developed three arrays to be analyzed in practical experiments. Figure 4 shows: (a) a circular array, (b) a linear array, and (c) an inner linear array that was idealized to be in the inner part of the roll and follow its curvature.

Magnets' Experiments

Experiments were performed with the acquired magnets to test the Halbach array's forces and compare them with its values in the usual array (magnets with the same poles faced the same sides).

For the linear array, experiments considered four values of the gap between the magnet and the surface: direct contact (0 mm), 0.642 mm,1.128 mm, and 1.608 mm. Plates of PLA (polylactic acid) were printed using an AM known as FDM (*Fused Deposition Modelling*) to get these gaps. On the other hand, the circular array just used a fixed value for the gap (1.258 mm) to make a structure for the experiments, and it already had

Figure 3. Stress-strain curve of PA12.

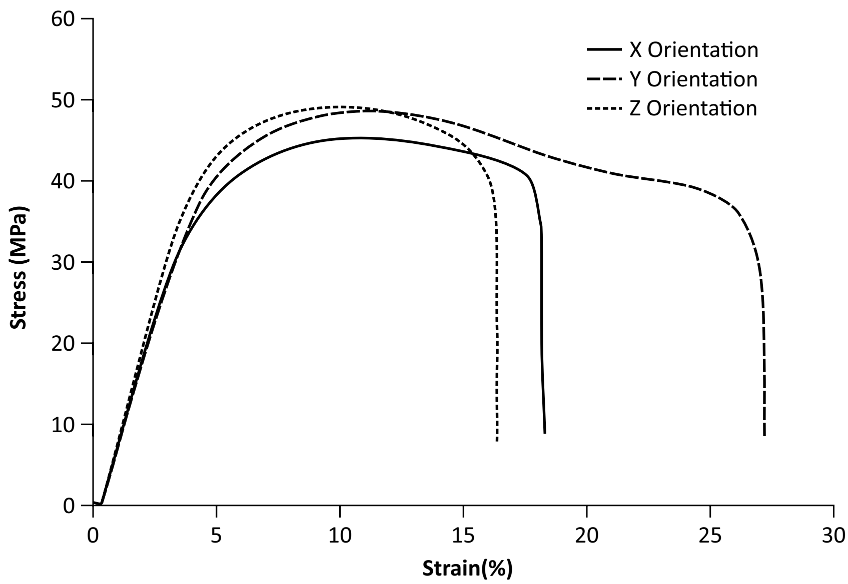
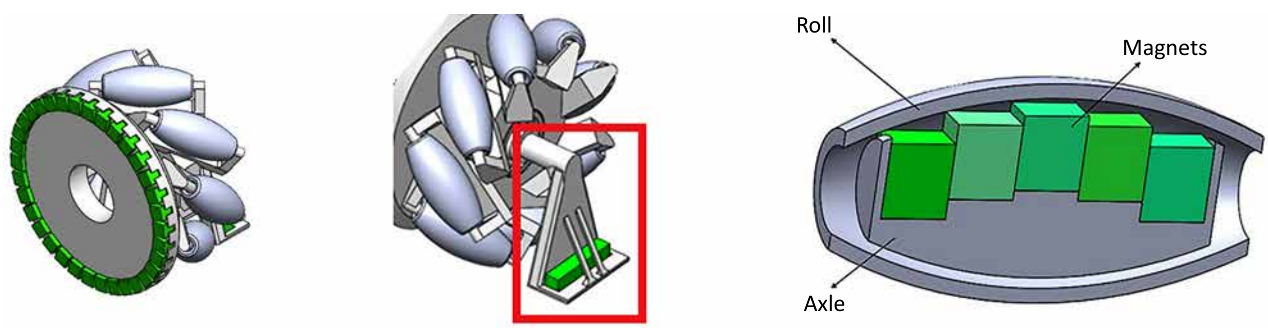


Figure 4. Halbach arrays proposed.



a specific thickness between the surface and the structure.

The experiments were done by binding the magnet arrays on a bottle (Figure 5). The weight of the bottle increases until the attraction force cannot hold, and the bottle falls by putting the water inside the bottle slightly using a funnel with a hose.

After that, the measurements of the system were to get the total mass that the array can hold and, as a consequence, the attraction force.

Figure 6 and Table 1 show the results for linear arrays and circular arrays, respectively.

Final Concept

After the test results and the 3D model, we observed that the magnets would be far from the surface (due to the rollers' shape) in the internal array, and the attraction force generated would be negligible. So, this idea was discarded.

Regarding the Halbach linear array, the distance of the magnets from the surface, combined with the size of the wheel, just three magnets could be used without exceeding the geometric limits of the wheel, making it difficult to move.

The final solution was developed using circular Halbach arrays in the structure. Figure 7 shows the final concept before and after the topological optimization.

It was not advantageous to use magnets around the entire circumference of the wheel because the magnets that were not close to the surface would not generate an attractive force, just increasing the mass of the system. For this reason, a rotating structure

Figure 5. Magnets experiments.

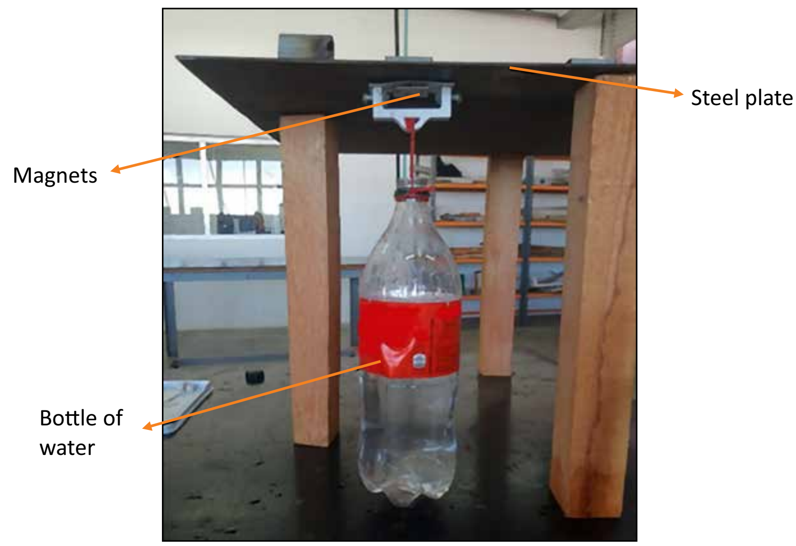


Figure 6. Test results for linear array (regular and Halbach).

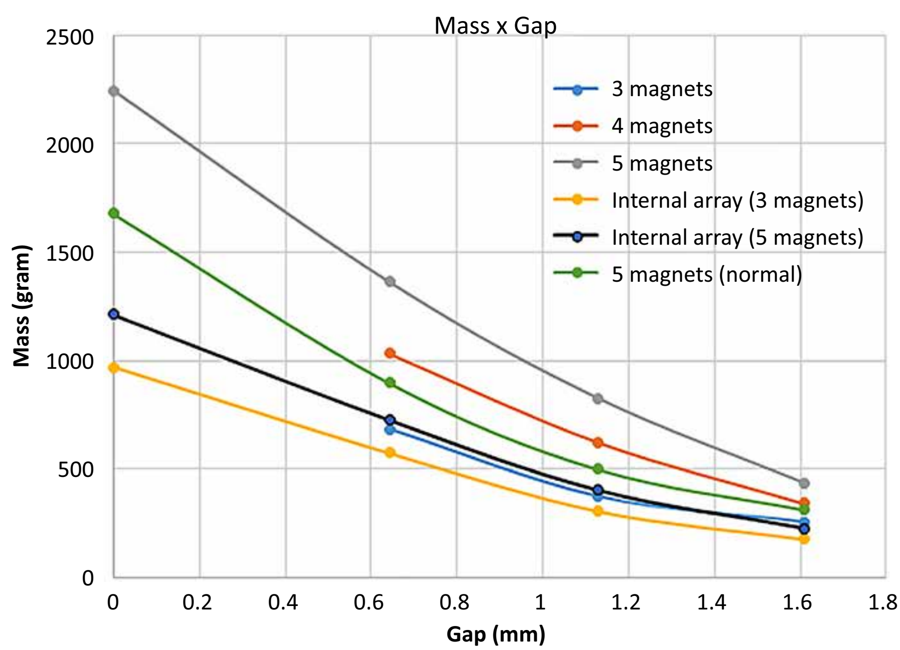


Table 1. Test results for circular arrays (regular and Halbach).

Circular Array	T1 (g)	T2 (g)	T3 (g)	T4 (g)	T5 (g)	Average (g)	Force (N)
Halbach	246	267	242	228	228	242.2	2.376
Normal	190	158	151	150	127	155.2	1.523

(arm) was developed to place seven magnets. Figure 8(a) shows the arm with the magnets in green and the bearings in blue, and Figure 8(b) shows the wheel body.

The static analysis was considered a force of 150 N (¼ of the estimated mass for the robots + attraction force of the magnets). As a result, a safety coefficient of 1.34 for the wheel body was obtained for the roller, 1.46, and a value above 2 for the arms.

Conclusion

Topological optimization reduced the system's total mass by 28% (96.2 grams to 68.92 grams). As a result, the structure in the vertical direction has a mass of 81.52 grams, generating an attractive force of 9.4 N, with seven magnets measuring 5x5x5 mm on each arm.

Future projects can be improved by adding one more row of magnets on each arm, increasing its thickness and/or increasing the size of the magnets with higher attraction force (example: 10x10x10 mm).

The following steps are:

1. Printing the wheel to evaluate clearances and interferences from printing an all-in-one step;
2. The effect of the water on sliding surfaces;
3. The movement of the bearing structure to maintain the magnets in the correct position.

Figure 7. Final wheel concept (a) and the topological optimization (b).

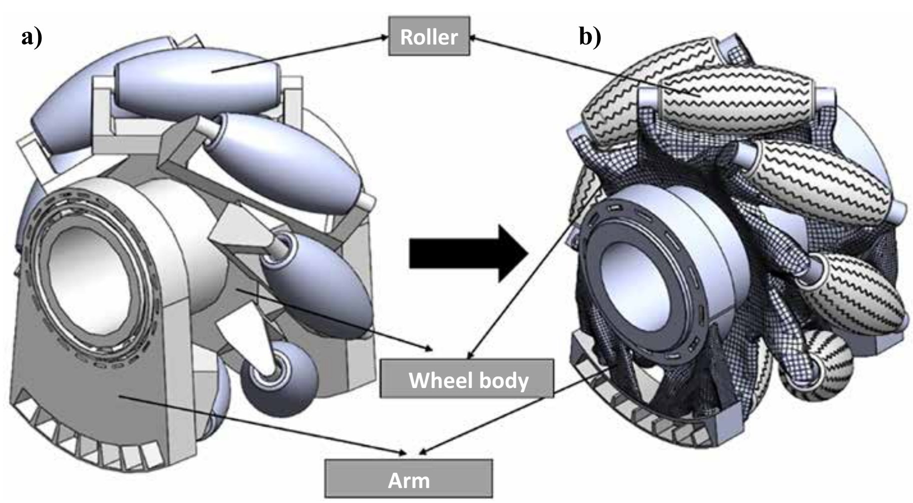
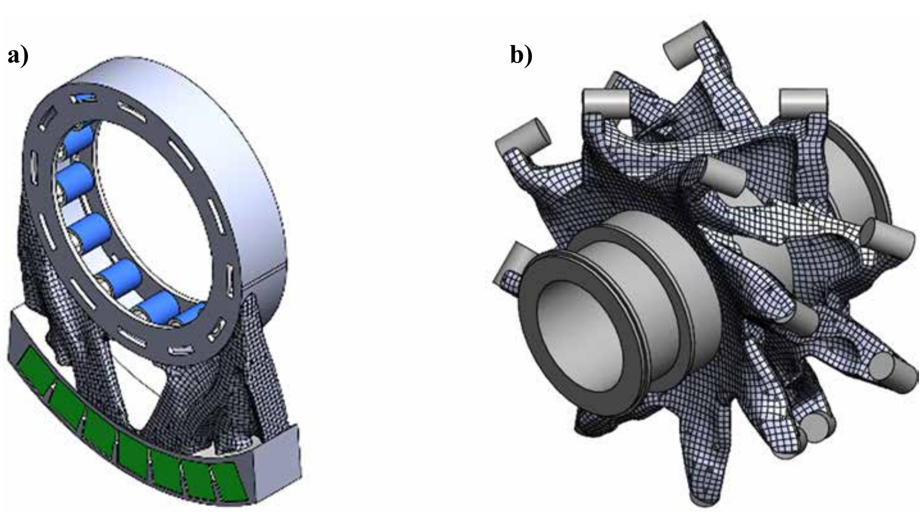


Figure 8. Designed components visualization.



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