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Design of an Active Magnetic Wheel with a Varying Electro-Permanent Magnet Adhesion Mechanism

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Abstract— **Magnetic adhesion mechanism is commonly used in mobile robots design for inspection tasks of ferric structures. The magnetic adhesion force is generated either by Permanent Magnets (PMs) or Electro-Magnets (EMs). Both methods have intrinsic limitations: fixed magnetic force in PMs or a constant electric power supply in EMs. Work in this paper presents a novel active magnetic wheel design by implementing Electro-Permanent Magnet (EPM) technology in its adhesion mechanism. EPMs allow to control the magnetic force by simply applying a short electric pulse. Controlling the amplitude of the electrical pulse, the magnetic force can be set into a chosen value enabling a continuous variation of the magnetic adhesive force. Implementing EPMs in adhesion mechanism will impact significantly on the mobile robot when manoeuvring in complex structures, avoiding difficult obstacles and energy consumption, thus enhancing its performance. Simulations of the proposed wheel design are performed in order to demonstrate the behaviour of the active magnetic adhesion mechanism and its feasibility. An improved design of the actual wheel is presented based on results of initial simulations. Further designs are suggested by adapting the adhesion mechanism to existing wheel designs.**

I. Introduction

The use of Unmanned Vehicles (UV) for continuous inspection, surveillance and/or maintenance tasks, in complex structures, is becoming more important and essential due to safety concerns for humans, time reduction, efficiency, and costs reduction, among others [1]–[5]. For these reasons, a wide range of platforms, combining different types of locomotion and adhesion mechanisms have been developed in recent years, to be used in different situations (ground, aerial or climbing) [6].

The present work focuses on UV for climbing complex structures, in the specific scenario of ferric (iron and steel) structures. For this scenario most platforms designed have been constrained by the absence of an efficient and flexible adhesion mechanism that could allow the UV to manoeuvre within complex structures and overcome difficult obstacles.

Even though different types of adhesion technologies can be employed for attaching to complex structures [1], [2], [7]–[14], these present several disadvantages when compared to magnetic technologies, Table 1.

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Likewise, it can be argued that new technologies in the construction and structural fields are moving towards the use of composites; nevertheless, up to now most of the structures are still built using steel or ferrite materials. These structures are expected to remain in use for several more decades, requiring the development of UVs for tasks such as: corrosion, fatigue, and damage inspection, among others that could put at risk the safety of these structures and people [4], [6].

Hitherto, most of the climbing UVs that use magnetic adhesion mechanisms have been designed to perform specific tasks and for a particular environment. This is mainly due to the limitations that current available magnetic adhesion technologies present [6]. These magnetic adhesion mechanisms can be divided into passive or active.

Permanent Magnets (PM) are employed in the design of passive adhesion mechanism as the source for the magnetic force, which results in a fixed magnetic attaching force [4], [15]. This constraint limits the movement of the mobile robot in complex environments and in avoiding different types of obstacles.

Alternatively, a different approach for overcoming the PM constraint is the use of Electro Magnets (EM), which is an active mechanism allowing continuous variation (increase or decrease) of the magnetic adhesion force, where needed [5], [16]. The disadvantage in using EM is the continuous need of power supply to maintain the mobile robot adhered to the surface. This results in a fast drain of the batteries, for the case of cordless UVs, or the necessity to use an energy supply cord, thus, restraining the manoeuvrability and range of the UV. [17]

In recent years, a new adhesion mechanism configuration named Magnetic Switching Device (MSD), has been proposed [18]. The mechanism uses a motor and different mechanical means to rotate a PM for switching On and Off the magnetic adhesion force in a magnetic wheel. Although it is a new approach for an active adhesion mechanism, it contains mechanical components to perform the switching of the magnetic force On and Off, making it bulkier, heavier and susceptible for constant maintenance. Moreover, the proposed MSD, does not allow to vary the adhesive force to a desired value (between On and Off states).

By employing the novel Electro-Permanent Magnet (EPM) technology in the design of a magnetic wheel, as proposed in this paper, the performance, efficiency and size of any previous magnetic-adhesion mechanism, active or passive, is enhanced considerably.

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TABLE 1 Comparison of performances of existing adhesion technologies and EPM technology.

Technology	Adhesion	Dusty surfaces	Different surfaces	Attachment	Detachment	Range of materials	Quiet/Non-damaging	Cost
Electro-static adhesion [7], [8]								
Dry adhesives [9], [10]								
Vacuum Adhesion [1], [11]								
Aerodynamic Suction Adhesion [2], [12]								
Mechanical Adhesion [13], [14]								
Magnetic Adhesion [4], [15]								
Electro-Magnetic Adhesion [5], [16]								
Electro-Permanent Magnet Adhesion [19]								

	Excellent Performance	**Moderate Performance**	**Poor Performance**

By using EPMs, all mechanical components used to control the magnetic-adhesive force, are removed from the mechanism. Therefore, the active, continuously varying, control of the adhesive force is accomplished by means of just a single short electrical pulse, reducing the consumption of energy. In addition, it is possible to control the amplitude of this electrical pulse, to achieve a desired value (between the minimum and maximum) to a specific magnetic force.

Previously, EPM has been suggested for a continuously varying adhesion mechanism for mobile robots [19]. The main contribution of the present paper is the implementation of EPM technology in the design of an actual wheel, which could be implemented in different UVs. The use of EPM as adhesion mechanism in the design of a magnetic wheel allows it to continuously regulate its adhesive force. This advantage permits the control of the magnetic-adhesive force at will, with the aim to overcome different types of obstacles, such as ridges, flanges or right angles among others. Enabling the UV to adhere and perform on unstructured and complex scansorial (wall and ceiling climbing) scenarios, thus enhancing its manoeuvrability.

The working principle, advantages and different applications of EPM will be discussed in more detail in Section II. Next, in Section III the design of a magnetic wheel with EPM technology is presented. The section also includes the simulations, and the proposal of an optimized design of the initial wheel, based on results from simulations.

II. Theory and Principles of Electro-Permanent Magnets

The basic design of an EPM device contains three main components, Fig. 1: (1) two magnetically different PMs, the first made from a magnetically-hard material (e.g. Neodymium) and the second made from a magnetically-semi-hard material (e.g. Alnico5-); (2) two poles made of a magnetically-soft material (e.g. iron); and (3) copper enamelled wire. Both PMs are placed with their magnetic fields being parallel. The semi-hard PM is coiled with the enamelled wire. Finally, the steel keepers are placed at both ends of the PMs, to act as the poles of the EPM [19].

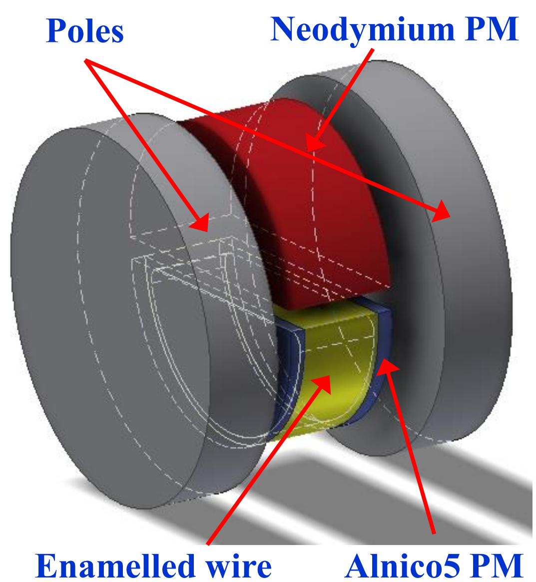

Figure 1. Basic EPM design and main components.

A. *Working principle*

Fig. 2 shows the On-Off hysteresis curve of an EPM. By applying a single short electrical-pulse through the coil windings, an external magnetic field is generated. This external magnetic field must be strong enough to modify the magnetic field (strength and direction) of the semi-hard PM.

During the OFF state, the magnetic field of both PMs (Neodymium and Alnico5) are aligned in opposite directions. As a result the magnetic flux keeps in a closed loop between both magnets. Thus, there is no magnetic force exerted to the target plate. For the ON state, the magnetic field of both magnets have the same direction, therefore the magnetic flux flows through the poles to the target (outside the device), exerting a magnetic force to the target plate. To perform the switching between both states (ON and OFF) an electrical pulse, is applied through the windings generating an external magnetic field. This field will only affect the Alnico5 PM, due to its lower coercivity compared to the Neodymium PM.

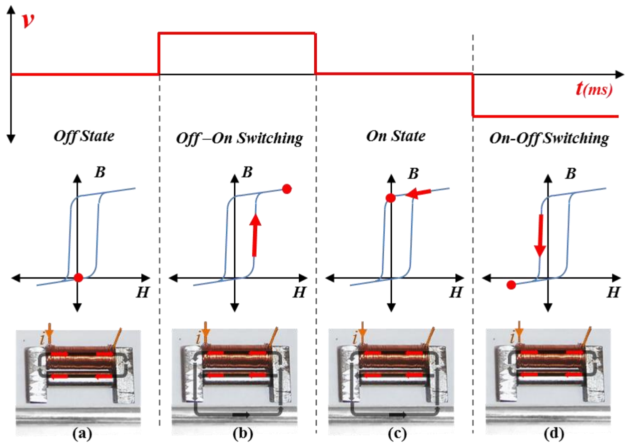

Figure 2. (Top) Electrical pulse cycle. (Middle) EPM magnetic hysteresis loop. (Bottom) Magnetic flux interactions of both PMs, arrows indicate direction of the magnetic flux. (Left to right) Steps of the Off-On cycle [20].

Depending on the amplitude of the electrical pulse the strength of the external magnetic field will be determined, consequently the amount of the Alnico5 PM internal magnetic field reconfiguration.

The main characteristics of EPMs are:

- Power Consumption: EPMs need just a small fraction of the energy an EM requires [20].
- Scalability: Increasing the volume increase the power needed to modify its internal magnetic field and vice versa, and by decreasing the area of the PM's poles the magnetic force is decreased and vice versa [20].
- Working cycle: Time required for switching between states in the order of milliseconds, usually less than 10 millisecond [20].
- Low Temperature Rise: EPMs have a low temperature rise due to the working cycle (they are active for a very short period of time) [20].

B. *Applications*

Up to now, the main use for EPMs has been its implementation in electro-magnetic lifters, providing extra protection and preventing them from failing when power supply (electrical current) is removed from the EM, by mistake or by a failure in the power supply.

In the last decade little research related to EPMs has been conducted in other areas, which resulted in the development of: a micro optical switch, which used a micro EPM to move a set of micro-mirrors [21]; a vibration suppression device [22]; and an EPM chuck [23].

In 2010, [20] presented his PhD thesis, in which he researched the use of EPMs to build connectors and actuators in a centimetre scale, known as Micro Electro-Mechanical Systems (MEMS), in the micro-robotics field. Based on Knaian work other devices, in different fields, were developed. Such as: the Robot Pebbles [24] in the programmable matter field; the Electro-Permanent Actuators [25] and The Milli-Motein [26] in the mini robot field; miniature switchable connection systems for modular robots [27]; and programmable connection mechanisms for robots separated by a surface [28].

In 2012, [29] replicated a part of the work on EPMs presented in [20] and suggested that EPM could be use in the adhesion mechanism for climbing robots in ferric/ferromagnetic structures, however no further work was conducted in the development of such mechanisms.

Having presented the working principle and main applications for EPMs, its use in the adhesion mechanism for a magnetic-wheel design is presented through the next sections. The aim of this magnetic wheel design is intended for scansorial (wall and ceiling climbing) robots that are employed in unstructured environments and complex ferric structures.

III. Design, Simulations

This section is structured as follows. The proposed magnetic-wheel design with EPM technology is presented. Transient magnetostatic simulations are performed with different values for the electrical pulse to determine the operational range and exemplify the EPM behaviour.

A. *Proposed magnetic wheel design*

From the basic concept of the EPM working principle, presented in Section II, a wheel design is presented. The design in Fig. 3 was constructed using the EPM design shown in Fig. 1 as the main core of the wheel. The wheel is intended to be connected to the drive mechanism by a shaft.

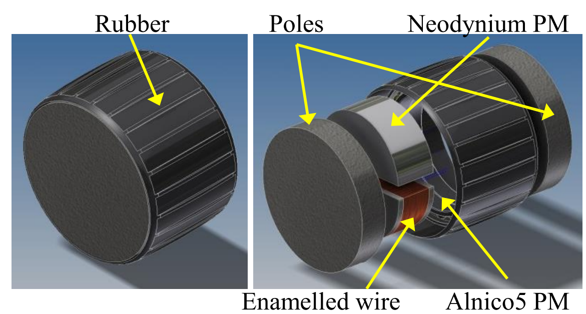

Figure 3. EPM wheel. (Left) Initial design with full steel poles. (Right) Components of the EPM wheel.

B. *Simulations*

Finite Element Method (FEM) was employed to simulate the magnetic field interactions and to determine the magnetic-adhesive force exerted, with different magnitudes of the electrical-pulse applied through the windings. The simulations were performed using ANSYS Maxwell-3D.

For the design presented in Fig. 3 six electrical pulses with magnitudes from 5 to 42.5amps were selected for the simulations. The length of ON state of the electrical pulse was 10ms and the number of turns in the coil was set to 150.

Fig. 4 presents the magnetic flux lines for the initial Off (top) state and the final On state (bottom). In the Off state most of the magnetic flux lines are in a closed loop between Neodymium and Alnico5 PMs. For the On state it is observed that most of the magnetic flux lines are redirected through the poles to the target plate.

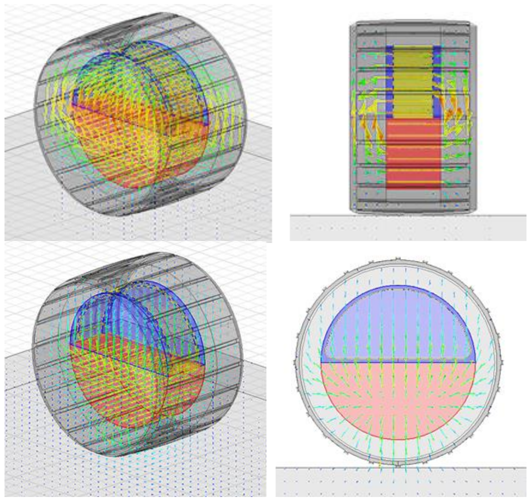

Figure 4. Simulation results of the magnetic wheel. (Top) Magnetic flux lines flowing in a closed loop between both PMs for the Off state. (Bottom) Magnetic flux lines flowing through the poles to plate target for the On state.

Fig. 5 shows the results from simulations for the Off-On switching cycle. When the pulse is applied through the coil, it charges exponentially generating the external magnetic field that modifies the internal magnetic field of the Alnico5 PM, in this cases reducing its strength as the amplitude of the electrical pulse is increased until the point the magnetic field is reversed. From the graph the behaviour of the magnetic force can be observed. During the ON state of the pulse, an exponential increase in the adhesion force is generated due to the addition of the magnetic field of the PMs and the magnetic field of the coil. Once the external magnetic field is removed, the magnetic force returns to an offset point, this offset point will depend on the strength of the external magnetic field generated by the coil. It can also be observed that a higher amplitude of the pulse, bigger than 27.5amps, will not add further final magnetic force to de EPM. The reason for this, is that the Alnico5 PM reaches saturation.

From simulations results, is possible to determine the maximum magnetic force the proposed design will have, which is around 28N and the magnitude of the electrical pulse needed to achieve it, 27.5amps.

Performing the above simulations permitted to determine two main parameters of the magnetic wheel design. Next section presents an improvement for the design which will enhance its performance.

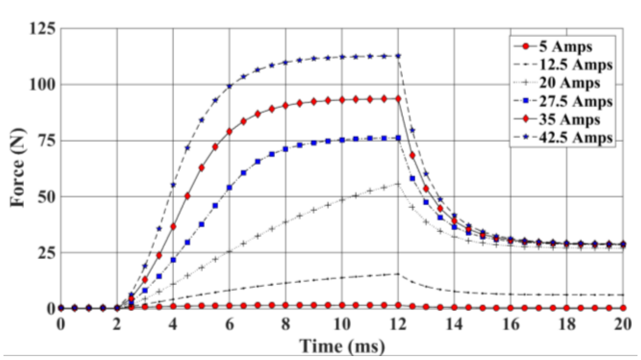

Figure 5. Off-On switching cycle for different magnitudes of the electrical-pulse applied to windings.

IV. Alternative Design and Simulations

A. Poles volume reduction

After performing the simulations (above) and analysing the results obtained, it was decided to modify the steel poles by reducing their volume and adapting their shape in order to concentrate the magnetic flux lines and redirect them to a specific target, Figure 6 6. The aim was to increase the magnetic adhesive force exerted through the poles, along with a reduction in the weight of the whole wheel.

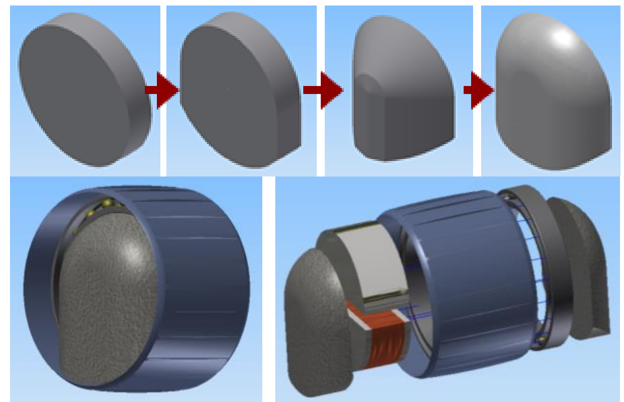

Figure 6. (Top) Modification of the EPM poles shape and volume. (Bottom) Alternative magnetic Wheel design with modified poles.

It is important to mention that in the new design the EPM core of the wheel is intended to remain fixed and the outer moving rubber be coupled by non-magnetic bearings to allow the rotation of the wheel.

Now, the new pole's design was replaced in the original design and the simulations presented above repeated. Fig. 7 shows how magnetic flux lines are in a more compact concentration and redirected to the target, in the On state, compared to the results in Fig. 4 were some flux lines get scattered in all directions of the circular plate.

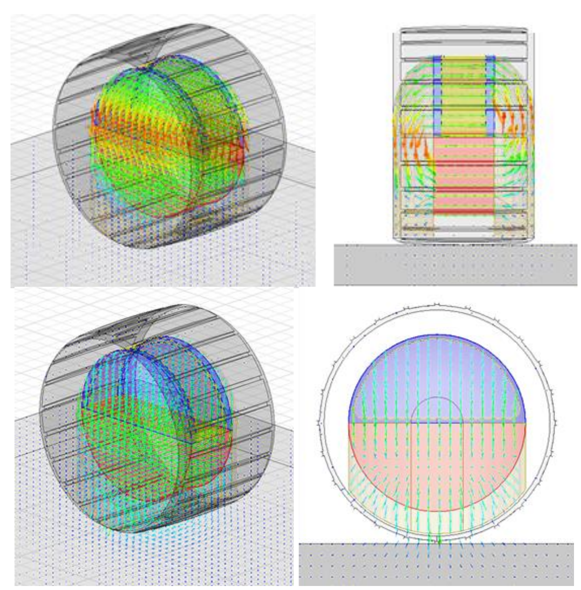

Figure 7. Magnetic flux lines in the magnetic wheel with the modified poles. (Top) Magnetic flux lines flowing in a closed loop between both PMs in the Off state. (Bottom) Magnetic flux lines flowing through the poles to plate target in the On state.

In the Fig. 8 results from the new simulations are presented. It is observed that the final maximum magnetic force increased from 28N to 49N, which represents an improvement of 75%.

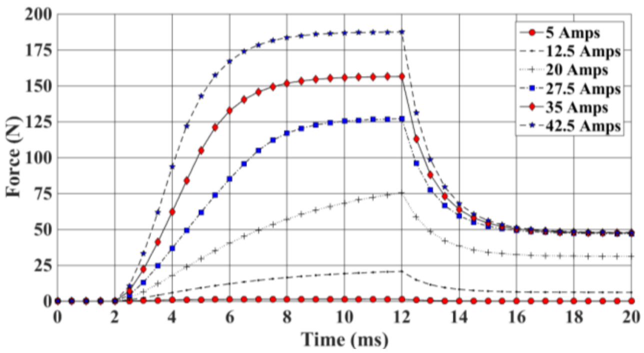

Figure 8. Off-On switching cycle for different magnitudes of the electrical-pulse applied to windings with the optimized design of the poles.

This improvement was achieved since the most of the magnetic flux lines got constrained into the smaller volume of the modified poles and redirected to a more specific target, resulting in a significant improvement compared to the initial design.

B. *Impact of the number of turns*

Another parameter that has a big impact in the performance of the magnetic wheel is the "coil. Varying the number of turns of the coil will affect the final magnetic force, the amount of energy consume per pulse and the time for completing the switching.

Results from simulations presented above were performed with a coil with 150 turns. Adding more turns will result in a reduction in the magnitude of the electrical-pulse need to achieve a specific magnetic force value, and vice versa. The equation for calculating the magnetic force exerted by a coil is presented next.

$$\boldsymbol{F} = \frac{\mu^2 N^2 I^2 A}{2\mu_0 L^2} \tag{1}$$

Where F is the magnetic force, μ is the magnetic permeability, μ_0 is the permeability of free space, L is the length of the coil, A the cross sectional area of the coil and I is the current applied to the coil.

From equation (1) it can be seen that if the number of turns "N" is reduced, the amplitude of the current "I" must be increased in the same ratio in order to maintain the same magnetic force "F". Now, in order to reduce the amount of energy needed a logical step would be to increase the number of turns, but this would lead to an increase in the time required to generate the external magnetic field. This is since increasing the number of turns will increase the inductance of coil, thus the time for its charging. Fig. 9 presents results from simulations with values of turns were can be observed this behaviour. Furthermore, from Fig. 9 it can be seen that choosing a value of 150 turns the best option for this particular design.

Results presented in this section demonstrated the impact of varying parameters, such as the number of turns or the shape and volume of the poles, have in the behaviour of the magnetic force exerted from the EPM. Also, an additional improvement by reducing the poles volume is the reduction of the magnetic wheel weight, thus improving its efficiency.

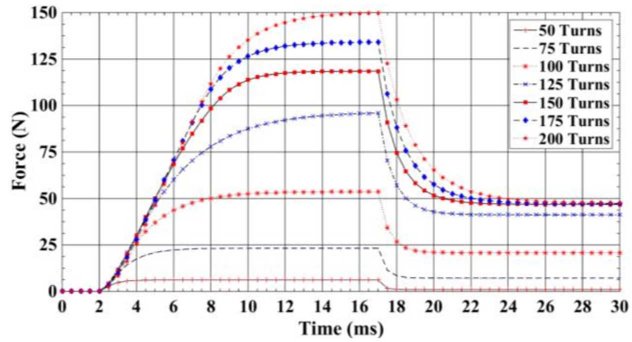

Figure 9. Effects in the charging time by increasing the number of turns in the coil

C. *Suggested implementation of the EPM adhesion mechanism*

One advantage of the EPM adhesion mechanism employed in the design of the proposed magnetic wheel is that it can be adapted to existing, regular wheel designs. Even more, to complex wheels such as mecanum wheels Fig. 10.

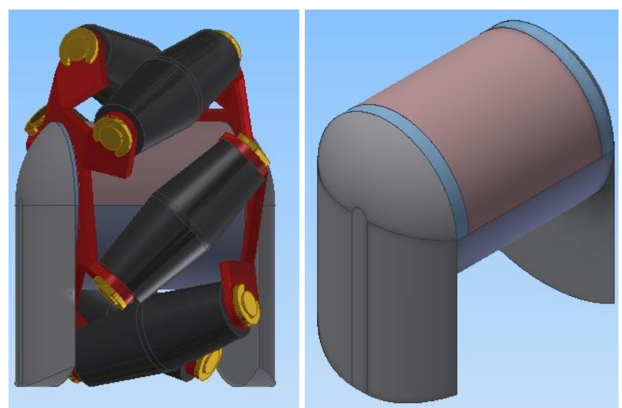

Figure 10. EPM adhesion mechanism adapted to a mecanum wheel.

V. CONCLUSIONS

The work presented in this paper proposes a design for a magnetic-wheel with a novel adhesion mechanism, which uses EPM technology. The main use of this design is to be implemented in UV employed in inspecting complex ferromagnetic structures. The use of EPMs as the core technology for the adhesion mechanism was proven and validated in a previous work by [19] through corresponding simulations and experiments. Results from simulations have demonstrated the feasibility of the proposed magnetic wheel design, as well as its working behaviour. It was shown how by just modifying the shape of the poles, and reducing its volume can make a significant improvement in the magnetic wheel performance. Based on the new pole shape, and alternative design was presented and simulated to demonstrate the effects of the modifications. Also, it was suggested the possible use of the use of the EPM adhesion mechanism in already exiting wheel designs.

Even though, the work was performed for the specific case of a magnetic wheel design, the same approach can be applied to most of the other locomotion mechanisms (i.e. legged or tracked). The use of this novel approach of EPM technology, as adhesion mechanism, enhances the mobile robot capability to overcome different types of obstacles and allows it to manoeuvre in complex environments, by just a fraction of the power need for EMs.

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