Magnetic wheels optimization and application to the *MagneBike* climbing robot

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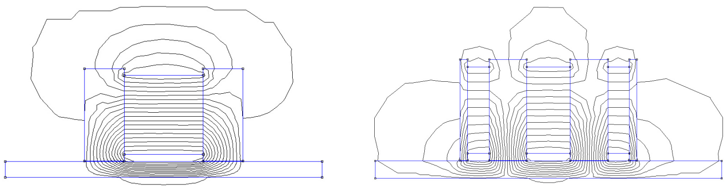
Magnetic wheels are a powerful solution to design inspection climbing robots with excellent mobility. Magnetic wheels optimization based on simulations and the results that were obtained on prototypes are presented. The measured adhesion was doubled between the classic configuration and a novel multilayer one sharing exactly the same four magnets and the same total volume of iron. This know-how is then applied to optimize magnetic wheels for the existing robot called *MagneBike*. The adhesion force has been multiplied by 2 to 3 times depending on the conditions. Those amazing improvements open new possibilities for miniaturization of climbing robots or payload's increase.

Keywords: robot, climbing, mobility, magnetic wheels, adhesion, FEM simulation

1. Introduction

Industrialists require climbing robots to inspect complex ferromagnetic environments, like the ones encountered in power plants. The use of magnetic wheels is an effective solution to achieve high mobility.[1] The classic way to design them is to have a cylindrical magnet with axial magnetization encompassed between two ferromagnetic guides (Fig. 1(a)).

In this paper, two different wheels are presented that were made with the exact same volume of magnet and of steel. Their dimensions is optimized



(a) 2D FEM simulation of magnetic wheel with classic configuration.

(b) 2D simulation with three magnets in opposite magnetization direction.

Fig. 1. 2D simulations of cross sections of the conventional configuration and the multilayer wheel with pole inversion.

with 2D and 3D simulation tools. The results show the advantage of a multilayer construction for wide wheels.

This know-how is then applied to improve the magnetic wheels for the existing robot named *MagneBike*.[2] It is a climbing robot with a motorbike like wheel configuration. It exhibits advanced mobility thanks to its two patented coaxial and lateral lifters. Measurements on the novel developed wheels are given and compared with the results of 3D simulations.

2. Wheels optimization

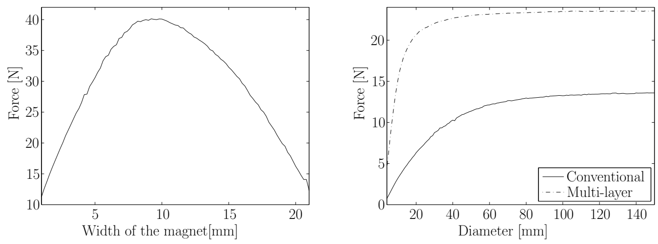
A magnetic wheel for climbing robots needs: a high adhesion force, a low weight and a good friction coefficient. The latter is usually obtained by covering the ferromagnetic wheels with a layer of rubber. Since it creates a constant airgap, it imparts negatively the adhesion force. Hence it has to be as thin as possible while being sufficiently robust. The rubber layer's lifetime can be improved with features on the ferromagnetic circuits like shoulders or surface renderings. Those can lower further the adhesion force.

Physics give the equation for the force of a magnetic circuit:

$$F = \frac{B^2 \cdot A}{2\mu_0} \qquad (1)$$

where B is the magnetic flux in the airgap, A the surface of this airgap and μ_0 the permeability of free space. Increasing the force means maximizing the numerator. Saturation puts an upper limit to the magnetic flux. The numerator's product has to be maximized in the worst case. Geometrical dimensions and magnetic design are the free parameters to maximize the force of a magnetic wheel.

In the conventional configuration (Fig. 1(a)), the distance between the iron guide is the height of the magnet — this dimension is referred as the



(a) Magnetic force of a 40 *mm* wide magnetic wheel in the conventional configuration for different width of magnets.

(b) Force of the conventional and multi-layer configurations when the diameter varies from 4 to 150 *mm*.

Fig. 2. 2D simulations of the median cross sections of various wheels.

width in the cross section of the wheels. To maximize the flux circulating through the plate — the one contributing to the adhesion force — the flux going directly from one iron flange to the other without going through the plate needs to be minimized — they are leakages.

The first design rule to achieve this goal is to have a large distance between the flanges in comparison with the airgap. A second design rule to minimize the leakage between the flux guides is to have the outer diameter of the magnet having the same diameter as iron flanges. Otherwise, leakage will increase drastically between the flanges. This is also dependent of the distance between the flanges. The effect will be less significant for wider magnet.

Those design rules can be proven with the aid of simulations. We used *FEMM* for 2D simulations and *COMSOL* for 3D simulations. It is easy to script 2D simulations and their interpretation is easy. The flux lines are easy to see, interpret and understand. Simulations in 3D can confirm the efficiency of a design before prototyping it. But they are slow, have high computational cost and the results are hard to read. Fast improvements in hardware and software led to broader accessibility and impressive results.

The geometry of the circuit can be addressed further. A 2D simulation of the median cross section of a conventional magnetic wheel with 40 *mm* diameter and 21 *mm* width with a 0.4 *mm* airgap is done. The width of the central magnet varies from 1 to 21 *mm* while the overall outer dimensions of the wheel are kept constant. Results can be observed in Fig. 2(a). This shows the importance of a well chosen geometry. For given dimensions, too thick or too thin magnet respectively iron will both deteriorate the force.

Another idea to increase the force is to increase the diameter. Simulations results of the variation of the force for both conventional and a multi-layer wheel (Fig. 1) with 40 mm width, 20 mm total width of magnets and with a 0.4 mm airgap while diameter varies from 4 to 150 mm for the median cross section are shown in Fig. 2(b). When the saturation is reached — either in the flange or the plate — increasing the diameter is useless. A well designed circuit will saturate simultaneously in both components. However, the global force of the wheel improves thanks to the rise of the near contact area. This means that a certain volume of magnetic wheel is useless weight.

The gravity of it is of low significance compared to the magnetic force. However, for very big wheels, it would be more interesting to have a magnetic crown area free to move coaxially inside an outer tire. This construction induces to have a larger airgap, but is at the same time useful to keep the magnetic wheel clean from magnetic particles. Another possibility is to increase the width of the wheel. But this reduces the force and the turnability of the wheel on curved surfaces.

3. Multilayer configurations

An idea to increase the value of B is to built a multilayer construction with several magnets with alternating polarization spaced by irong guides. By alternating the polarization, the flux concentration will increase. We show the potential of that idea by building two wheels with different magnetic configurations, the conventional and the multi-layer one. Both are built with the same four $NdFeB$ magnets and the exact same iron volume as constraints. The magnets have the following dimensions: height 2 mm, diameter 8 mm.

The width of the iron guides is determined by a 2D simulation around the four magnets, placed on top of each other like if they were one single magnet. The optimization is based on the median cross section as shown in Fig. 1. Naturally, this is a first approximation since the flux will circulate from slices in front of and behind the central cross section. Indeed, since they have larger airgaps in their own cross section the flux prefers circulating through the path with the smallest permeance until it saturates. Hence the ideal flanges' width will be slightly larger than the one optimized for the central cross section. Once this is done, the same iron volume is optimized for the multilayer configuration.

As concluded above, it would be ideal to have the iron flanges with the same outer diameter than the one of the magnets. This is unfortunately impossible for constructive reasons. Indeed, since the goal of the multilayer

Table 1. Results of 3D simulations and measures for the two wheels configurations.

Adhesion force in N	**Simulations**	**Measures**
Conventional configuration	12.60	11.5
Multi-layer with inverted poles	27.53	24.5

configuration is to place the magnets with alternating axial polarization, they repulse themselves. Therefore, the construction has to hold them together. We choose to have a shoulder on the iron part and an aluminium hollow tube around the magnets. The repulsive force is sufficiently low to make the construction possible. An alternative is the construction with a central hole like in the *MagneBike* case. Both configurations reduce the force in comparison with the ideal wheel. The construction with hollow holes in the magnets and flanges would achieve a higher force. Still the other solution was chosen due to the direct availability of the magnets. Finally both prototypes are molded with a 0.3 mm layer of rubber in order to improve the adhesion coefficient.

We simulate the force in 3D for the conventional configuration, the multi-layer configuration with inverted poles and the multi-layer configuration with non-inverted poles. The latter was not built, since it was judged not interesting based on the simulations. It was worse than the two other wheels. The results can be seen in Tab. 1. The measurements on the conventional configuration give 11.5 N and 24.5 N on the multi-layer configuration with inverted poles (Fig. 1). The proximity of the simulation results and measures proves the validity of 3D simulation. Variations can be explained by dimensional differences – for example the rubber airgap is deformed by pressure – and by parametric differences for materials.

Measurements give a force increase of 108%. Using materials with higher saturation, like *vanadium-permendur* instead of ferromagnetic iron, would increase further the absolute force, but the possible gain is limited and machining is a nightmare. The multi-layer construction is adapted to wheels with high width against diameter ratio, since the distance between the iron flanges has to be large in comparison with the airgap. The diameter has to be small to reduce the repulsive forces. Due to their shape and magnetic configuration, those wheels are ideal to go on flat surfaces or on curved surface following a circumferential path. They are however not well adapted to move longitudinally or turn around the normal axis of a curved surface. Their shape can be adapted and optimized for a robot going longitudinally inside tubes of constant diameter.

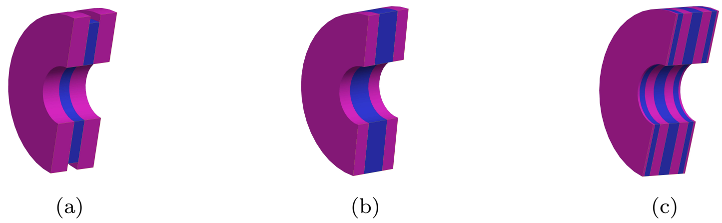


Fig. 3. (a) Initial *MagneBike* wheel, (b) optimized wheel and (c) multi-layer wheel.

4. Application to the magnetic wheels of the *MagneBike*

The goal of the *MagneBike* project[2] was to develop a mobile robotic platform to inspect power plant facilities, with the inner casing of steam chests as case study. Due to size constraints and the complex shape of the environments, the first challenge was to develop a compact system with climbing and obstacle passing capabilities. In this framework, the *MagneBike* locomotion concept was designed.

The robot consists of two aligned magnetic wheels units with integrated lateral lever arms. These arms have two complementary functions: they can be used to slightly lift off the wheel in order to locally decrease the magnetic attraction force when passing inner corners or to laterally stabilize the robot when gravity is unfavorable. Steering is ensured by an active degree of freedom on the front wheel and surface adaptation is provided by a free joint on the fork.

This locomotion concept has a very high mobility and allows driving on complex 3D real industrial environment. The robot can climb vertical walls, follow circumferential paths inside pipe structures and can also pass over complex combinations of convex and concave step obstacles with almost any inclination regarding gravity. It requires only limited space to manoeuvre because turning on spot around the rear wheel is possible. The climbing robot is compact and lightweight ($180 \times 130 \times 220$ mm^3, 3.5 kg).

The design rules of the previous section will now be applied to the existing wheels of the *MagneBike* robot in order to either increase payload or the safety margin against falling. Since the robot exists, the dimensions of the wheels – inner and outer diameter and width – cannot be changed so that the novel design can fit on the robot (Fig. 3(a)). Additionally, the existing wheels have on both side an outer 0.5 mm wide and 5 mm deep shoulder. The circumferential surfaces have a 0.5 mm deep rendering. The magnet has a smaller diameter than the iron flanges. All these features were designed to optimize the adhesion of the rubber tire onto the wheel

Table 2. Results of comsol simulations for the three wheels configuration

Adhesion force in N	**Plate**		**External corner**	
Wheels configuration	**Measures**	**Simulations**	**Measures**	**Simulations**
MagneBike no features	NA	328	NA	59
MagneBike with rendering	237	289	64	52
Improved wheel	469	474	161	122
Multi-layer inverted	284	334	90	65

to increase its robustness. For now, those adjustments will be neglected to find the maximum possible force and to understand their exact negative impact on the adhesion force. The features to improve rubber adhesion will be added and optimized in a future effort.

For *MagneBike*'s wheels, the rubber is considered as a 0.4 mm airgap. First, the wheel can be simulated in 3D to consider the impact of the central hole. This hole reduces the weight with 17% and only reduces the force with 8%. The flux avoids entering the central hole due to magnetic repulsion. Thus, the hole has an overall positive effect on the efficiency of the wheel.

Now the configuration offering the highest force will be sought. First the outer diameter of the magnet is widened to the same diameter than the one of iron flanges. Then, the width of the magnet and flanges are optimized to obtain the optimized wheel seen in Fig. 3(b). Results of simulations and measures can be found in Tab. 2. The force measurements done on the existing wheel on a 15 mm thick steel plate gave 237 N. This optimization almost doubled this force which was measured of 469 N. In the worst considered case, when the wheel is on an outer straight corner, the remaining force was 64 N on the existing design. The novel wheel scored 161 N, which is close to 3 times the initial force.

We note that differences between the simulations and measures can be explained because the real corner is not as sharp as in simulation due to manufacturing. However artefact due to the meshing also appears in simulations. Trials showed that the results are really closer if a 0.2 mm radius rounding is added in the simulations – a size coherent with observation of the real plate. Measures are also influenced by the variation in airgap – the rubber is deformed by the pressure.

The multilayer construction is not efficient because of the low ratio between the diameter and width of the wheel (Fig. 3(c)). Due to the large diameter and thick iron flange the wheel is really unstable. The verified precision of the simulations will allow in the future not building such prototypes.

5. Conclusion

Simulations proved to be reliable for designing and optimization of magnetic wheels or systems. The adhesion force on wheels with the same volume of magnet and of steel was doubled thanks to a novel multilayer construction. The advantage of this construction is however limited to wide wheels.

The gained know-how was applied in simulation to improve the existing magnetic wheels of the *MagneBike*. Despite the given dimension of the wheels, the adhesion could be improved. Measures and simulations showed that the multilayer construction is not adapted to the ratio width against diameter of that wheel. Measures showed that the adhesion force was close to be tripled on the worse case — the outer corner.

Our next step is to improve the adhesion and lifetime of the rubber tire for the *MagneBike* while keeping the adhesion force close to maximal force. Thanks to optimization either payload or safety margin against falling has been enhanced. This can be extended to other climbing robots or systems. Simulation tools have proven to be precise for the design of complex magnetic systems. This know-how has already proven itself useful in many other climbing robots designs.

6. Aknowledgment

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References

1. Y. Kawaguchi, I. Yoshida, H. Kurumatani, T. A. K. T. Kikuta and Y. A. Y. Y. Yamada, Internal pipe inspection robot, in *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on*, 1995.
2. F. Tâche, W. Fischer, G. Caprari, R. Moser, F. Mondada and R. Siegwart, Magnebike: A magnetic wheeled robot with high mobility for inspecting complex shaped structures *Journal of Field Robotics* **26** May 2009.