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Switchable magnets for robotics applications

Mahmoud Tavakoli[1], Carlos Viegas[1], José Carlos Romão[1], Pedro Neto[2], Aníbal T. de Almeida[1]

Abstract— **The goal of this work is to study the application of switchable magnets (SM) for climbing robots. A switchable magnet is a device which uses moving permanent magnets to change the magnetic flux path and switch on or off the magnetic attraction force. In our work we used *Comsol Multiphysics*, a physics simulation software in order to simulate the flow of the magnetic flux on switchable magnets on its different states and study the effect of different design and material parameters on the attraction force of the unit. Bearing in mind the lessons learned from this study, we developed a novel device in a smaller scale with the best holding force/mass ratio, for using in climbing robot applications. As a case study, three of these optimized SM units are then equipped with an actuator that can rotate the moving magnets, turning the device on and off. This new device is employed in a novel adaptive adhesion unit for the *OmniClimber* robot, replacing its previous system which was relying on electromagnets magnets. We demonstrate this novel device application on a climbing robot and the advantages relative to electromagnet or permanent magnet based devices.**

I. INTRODUCTION

Climbing inspection robots are required to carry a payload of tools or instruments. It is desired to develop lighter systems that benefit from a higher payload/weight ratio and to minimize the power consumption of the system to reach a higher energy autonomy. A major issue in the design of these devices is their adhesion mechanism. When the surface is ferromagnetic, magnetic force can be used to provide adhesion. Coils, electromagnets or permanent magnets have been extensively used as attachment mechanism. In most cases it is necessary to control the magnetic force, or at least to switch the magnetic adhesion on and off. For this purpose electromagnets can be used. However, the main problem for the application of electromagnets in climbing robots is their constant power feed requirement.

Switchable magnets only require to be actuated to switch their state, and maintain their on/off state without power consumption. The basic principle of all types of SMs relies on moving one permanent magnet, thus changing the orientation of the magnetic flux, directing it to the outside surface or making it flow inside the device, thus canceling the outside magnetic force. SMs have been widely used as workpiece holders in machining tasks and are normally manually turned on or off. However, if these devices are coupled with an actuator, their on/off state can be remotely controlled and can be programmed. *Miche* robots[1], use SMs driven by a servo motor on their sides for computer controlled-disassembly of individual actuated modules. SMs have also been used in mobile robots such as *TERMO* an inspection step by step based robot for ferromagnetic structures [2] and in *Tubulo* a train-like inspection robot for ferromagnetic tubes.

Rochat et. al. discussed development of different types of SMs for applications in mobile robots[3].

One example of an innovative magnetic switchable device for climbing robots is the permanent magnet wheel with induction pins [4].

For application on climbing and mobile robots, the adhesion force to weight ratio should be optimized, and in some cases it is necessary to make the precise model and prediction of the applied force in order to be able to dynamically control such forces. To do so, it is important to study the flow of the magnetic flux for different parameters of the SMs and also the surface they are attached to. In this research work we mainly focus on the H-type SMs; and we explore the design parameters of SMs, such as the geometry and material of the housing. To do so we developed several models of SMs in the *Comsol Multiphysics* software [5] and simulated their magnetic flux flow for several parameters. Based on the observation of the magnetic flow and the resulting adhesion force, we gained some more knowledge about these devices, that can be used as a guideline for design of custom made SMs. As a case study for our work, we developed an optimized SM unit for climbing robot applications on thin ferromagnetic structures, with the highest attraction force to the unit of mass ratio. Both simulations and experiments were made to reach the final design of the SM unit and theoretical results were confronted with the real force values achieved with our prototype. Finally we explored the idea of a variable force SM unit rather than only switching between residual and maximum magnetic force. A variable force SM unit is interesting in the case of climbing robots, since it allows for a dynamic change of the adhesion force of the robot. In this way a climbing robot can adjust its adhesion force based on its stance (if the robot is static, ascending, descending or moving laterally) and on the material, thickness and surface conditions of the structure (existence of oil or dust).

II. MAGNETIC HOLDING DEVICES

Magnetic plates for retention of a piece of ferrous metal are commonly used in machining and welding applications. Static permanent magnets suffer from the drawback that their energy output is fixed. They cannot be employed if a variation in magnetic field strength is required. To solve

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[1] Institute for Systems and Robotics, Dep. of Electrical and Computer Eng., University of Coimbra, Portugal. `{mahmoud}@isr.uc.pt` [2] CEMUC, Dep. of Mechanical Eng., University of Coimbra

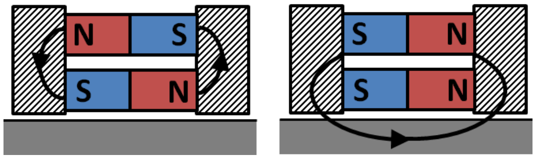


Fig. 1. H-type SM. When off the magnetic flux closes between the two magnets. Rotating the upper magnet 180°brings the magnets into the pole alignment and the magnetic flux follows a path outside of the device.

Fig. 2. Model range of the MagJig models from Magswitch (the model number relates to the holding force in pounds).[8]

this problem, engineers have turned to electromagnets, which offer the possibility of control the magnetic force. However, these also require constant energy consumption to maintain their magnetic field. Therefore for situations in which a device needs to stay in the same place during a long time and there is no easy access to a power source, SMs are preferred.

Comparatively to electromagnets, SMs with the same weight:

- Consume less energy; [3]
- Have a higher adhesion force; [3]
- Are safer in case of power loss;
- Are simple to manufacture and to use, and are less expensive;
- Can be completely turned off; [6]

III. TYPES AND APPLICATIONS

While there are many types and configurations of SMs, they all obey to the same principle of moving one permanent magnet to redirect its magnetic flux.

An H-type double magnet device, contains two cylindrical permanent magnets [7]. Rotating the upper magnet causes its magnetic field to neutralize or to add to the magnetic field of the lower static magnet, Fig. 1.

In this work we focus on the H-type SM device. We use a commercially available SM, the *MagJig* 95 as a reference and as a start point. *MagJig* 95, is the smallest and lightest of the range of SMs commercialised by *Magswitch*[8], for applications in woodworks and welding (figure 2). It possesses an advertised holding force of 423 Newton.

To find out a relation between their mass and their holding force, we studied the full range of models comparing their masses with their advertised holding force. In table I we present these values (mass of each model, excluding the handle and fixation support, as well as the total holding force and the holding force per unit of mass ratio). As can be seen, although the magnetic force increases proportionally to the mass (size) of the magnet, as one would expect, the ratio of holding force per unit of mass decreases with the same increase of mass.

TABLE I
ADVERTISED VALUES FOR MAGSWITCH RANGE OF SM

Model	Holding force [N]	Mass [g]	Force/Mass ratio [N/g]
MagJig 95	423	89	4.75
MagJig 150	667	161	4.14
MagJig 230	1050	306	3.43

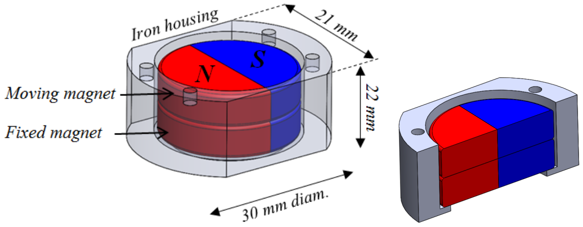


Fig. 3. On the right is the *MagJig* 95 model made in a CAD software with dimensions in millimeters and exported to *Comsol*. On the left is the section of the model where the magnetic flux lines will be traced.

IV. SIMULATIONS

We start by simulating the*MagJig* 95 magnets in *Comsol Multiphysics* 4.3, a finite element analysis solver package for various physics and engineering applications, with the *AC/DC Module* [5], in order to observe the magnetic flux in the magnets, the housing and the object in both states of on and off and estimate the magnetic attraction force. We then test the real unit and compare the results obtained with the ones from the simulations, to validate them.

To do so, we built a 3D CAD model of the *MagJig* 95, with its two magnets and housing (figure 3). Then we defined the materials and ferromagnetic properties of the housing (which is made from AISI 1018 metal), the surface an the magnets.

Since we did not possess detailed information about the permanent magnet used in used in the *MagJig* 95, we used for reference the characteristics of a commercially available magnet with the same dimensions, from HKCM [9]. The CAD model was exported to *Comsol*. The *Comsol* graphical representation of the magnetic flux is depicted on a section of the SM which is visible on figure 3. As can be seen, the shape of the SM housing is not cylindrical and includes two flat cuts on two sides. This feature will be further analyzed in this study.

As a start point and to get reference values, we simulated the SM in both states of on and off against a ferromagnetic metal surface with a thickness of 3 mm.

As we see in table II the flux between opposite poles goes though the surface when the device is on, and through the housing when it is off, as expected. In practical experiments the maximum force achieved was of 324.8 N, close to the value achieved in the simulations.

A. *Modifications*

In order to find out the effect of different design aspects and materials on the performance of the SM, we introduced a series of modifications. These aspects which we evaluated

TABLE II

BASE MODEL SIMULATION IN COMSOL, SHOWING THE MAGNETIC FLUX PATH AND THE HOLDING FORCE CALCULATED BELOW.

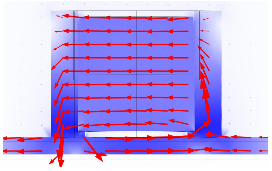
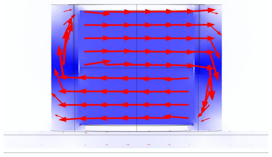
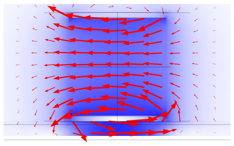
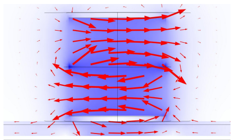
Device on	Device off
	
338.4 N	1.4 N

TABLE III

SIMULATION RESULTS FOR A PLASTIC MAGNET HOUSING, SHOWING THE MAGNETIC FLUX ON SECTION VIEW AND THE HOLDING FORCE

Device on	Device off
	
59.3 N	26.8 N

include the housing material; the housing shape and the housing diameter; For each modification, the corresponding graphical representation of the magnetic flux is also presented. Keeping in mind that the purpose is to have a device with the least weight possible, a housing made of plastic was tested. Results show that this solution is far from being optimal, with a reduced holding force of 59.3 N (table III). This can be explained by the lack of a conductive core to direct and concentrate the magnetic flux, clearly visible on the representations of the flux path.

As can be seen in figure 3, the original housing of the *MagJig* 95 unit, includes two flat cuts at two sides. We would like to understand how these flat cuts affect the attraction force, so we made simulations with a circular housing, without the flat cuts.

As can be seen in Table IV, the holding force is much smaller when the device is on (81.6 N vs 338.4 N). This shows that without the flat cuts at the two sides of the housing, the magnetic flux passes through the housing, and thus it does not pass through the ferromagnetic object that should be grasped. To explain this, we should notice that, when the SM is on (magnet poles aligned such as in figure 3), the magnetic flux should not be closed between the two permanent magnets. Instead, the flux should go to the surface where the magnet is attached to. A fully cylindrical housing provides a way for the flux to go around the housing axis, from one magnetic pole to the other, thus not forcing the flux to pass through the surface and reducing significantly the adhesion force. Therefore the shape of the housing, specially the effect of the flat cuts on the adhesion force, is very important.

TABLE IV

SIMULATION OF A CIRCULAR MAGNET HOUSING, THE MAGNETIC FLUX PATH AND THE HOLDING FORCE

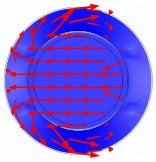
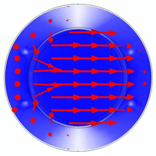
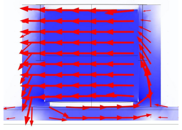
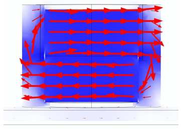
Device on	Device off
	
	
81.6 N	0.5 N

TABLE V

EFFECT OF HOUSING DIAMETER ON HOLDING FORCE

Housing diameter [mm]	Total mass [g]	Holding force [N]	Force/Mass ratio [N/g]
28	79.6	289.4	3.64
30	87.7	338.4	3.86
32	95.7	364.9	3.81

In order to study the effect of the diameter of the chamber, we simulated a slightly bigger chamber (Ø32mm) and a smaller one (Ø28mm), and compared the results with the original device (Ø30mm). The results are present on table V and show, as expected, an increase of the holding force with the increase of the chamber diameter. The optimal solution in terms of force per mass ratio is the Ø30mm housing chamber.

V. OPTIMIZATION OF SWITCHABLE MAGNETS

We set out to design a SM with the maximum holding force per unit mass ratio and specifically suited for climbing robots. In addition to the weight optimization, for climbing robots, it is important to keep the center of mass as close as possible to the surface where it attaches (figure 4).

In this context we tried to design a device based on the *MagJig* 95, with a lower height, which is more appropriate for climbing applications due to lower detaching torque. A high contact surface is important for a good adhesion. For this reason we decided to maintain the current diameter for the device. We do not set the required force in this step, instead we try to increase the holding force per unit of mass and then we will provide the required force for the example application, by increasing the number of applied devices.

Due to our limitations in construction of magnets with

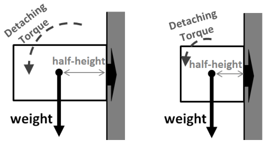


Fig. 4. Torque resulting from different shapes of the device: the closest the center mass is to the surface, the less the detaching torque.

TABLE VI

ADHESION FORCE OF DIFFERENT HOUSING DIAMETERS IN NEW SM

Diameter [mm]	Force [N]
26	162.2
28	183.4
30	180.0

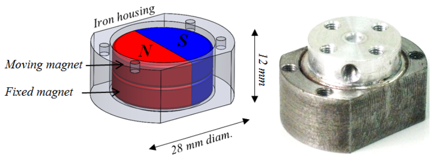


Fig. 5. The new developed SM. A metallic hub was added on top of the SM for later integration of an actuator

arbitrary sizes, we first selected a commercially available magnet within the objectives of this design (i.e. to construct a unit with approximately same diameter of *MagJig* 95, and a smaller height than the original device) i.e. a magnets with a height of 5 mm (compared to 10 mm from *MagJig* 95). Then, taking into consideration the lessons that we obtained from the previous simulations, we designed the housing for these units. Yet due to the changes to the magnet size, the size of the housing should still be minimized for a lighter device. We ran again the simulations, this time for the new design, and tested three different housing diameters (Table VI).

We concluded that the housing of Ø28mm, is the best solution. Therefore the new housing dimensions are (Ø28x12) compared to (Ø30x22) of the original unit. The housing's material is AISI 1018, the same from *MagJig*'s housing. The new SM developed for climbing robot applications is depicted in figure 5.

In the following sections we first compare the new device with *MagJig* 95. Then we evaluate the possibility of using this unit as a variable force adhesion unit rather than only a switchable device.

A. Comparison

We tested the new SM unit and the *MagJig* 95 on a 1 mm a 3 mm thick steel plate, and compared their adhesion force.

As can be seen in Table VII, for both cases of 1*mm* steel and 3*mm* steel, the adhesion force/mass ratio is improved comparing to the *MagJig* 95. In case of the 1*mm* steel, this ratio was increased 85%, while for the 3*mm* steel, the increase was 13%. This is mainly due to the fact that in thin plates, most of the large magnetic field of the *MagJig* 95 is not used, while the magnetic field on the novel device is much more focused on the region closer to the surface of the plate, thus is used more efficiently. This effect is depicted in figure 6. Furthermore, there is a significant reduction of the detaching torque of 73%.

TABLE VII

COMPARISON BETWEEN THE *MagJig* 95 AND THE NOVEL DEVICE

	MagJig 95	Novel device	Variation
Mass [g]	87.7	42.1	-52%
1 mm steel:			
Holding force [N]	112.6	100.1	-11%
Force/Mass ratio [N/g]	1.28	2.38	+85%
3 mm steel:			
Holding force [N]	338.4	183.4	-46%
Force/Mass ratio [N/g]	3.86	4.36	+13%
Detaching torque [N.m]	0.094	0.025	-73%

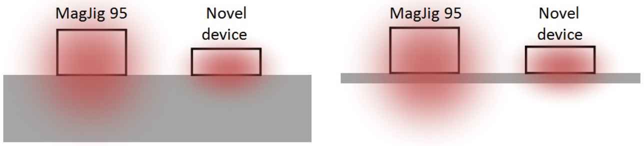


Fig. 6. Comparison between the magnetic field of the MagJig 95 and of the novel device in plates with different thickness

TABLE VIII

COMPARISON BETWEEN THE ELECTROMAGNET AND THE NOVEL DEVICE

	Electromagnet	Novel device	Variation
Mass [g]	108	42	-61%
Mass [g]*	108	97	-10%
Measured holding force [N] (1 mm steel)	45	57	+26%
Force/Mass ratio [N/g]	0.42	1.38	+229%
Force/Mass ratio [N/g]*	0.42	0.58	+39%
Energy consumption [J]**	6.48	5.00	-23%

*Novel device with actuator

**Considering the electromagnet is on for 3 s.

Now we make another comparison between an electromagnet unit that was previously used in the *OmniClimber* robot [10][11] and this new magnetic device. For a fair comparison, we have to add the mass of the actuator needed to drive the SM to the magnet itself.

We chose a *Robotis Dynamixel AX-12* [12] as actuator for the SM. However, in our experiments we saw that it is possible for this motor to drive simultaneously at least three magnets. This shows that a lighter motor could be used, so for the record, this comparison was made for the worst scenario possible. This motor is driven by a voltage of 11.1 V at a max current of 900 mA and changes the state of the magnets in 0.5 s. The electromagnet is driven by a constant voltage of 12 V at a current of 180 mA. In our case study, which will be depicted in the next section, the electromagnet is required to be on for at least 3 seconds. This means that despite the SM requires more power to switch state, it then consumes much less energy comparatively to the electromagnet, because to maintain its state the motor can be turned off.

As can be seen in Table VIII, on a 1 mm thick plate, the mass of the novel device without actuator is 61% inferior to the electromagnet and can exert an adhesion force of 26% superior than the electromagnet. Even with the actuator, the novel unit has a holding force per unit mass 39% percent bigger than the electromagnet. Adding to the small weight

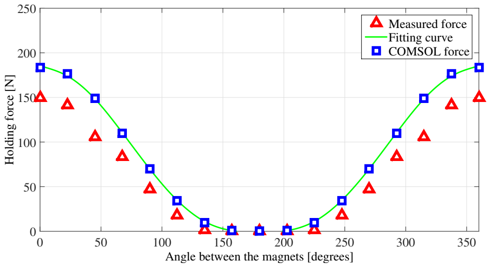


Fig. 7. Results of the tests and simulation for the holding force with the angle of rotation.

of these devices, there is the reduction in energy consumption of the SMs, compared to the electromagnets, of 23% (for the 3 second duration of electromagnet use in our case study), so we can clearly see advantages in the application of SMs rather than electromagnets in climbing robots.

B. *Variation of the holding force*

For climbing robots, it is beneficial to be able to control the adhesion force, rather than only switch it on and off. For instance, if a magnetic unit is placed on the chassis of a wheeled based climbing robot, the adhesion force can be changed dynamically, considering the structure material, thickness, and surface condition, as well as the payload of the robot. We both simulated and tested the new SM on a 3 mm thick steel plate for different relative angles between the magnets, from 0 to 180 degrees with increments of 22.5 degree each time. Figure 7 demonstrates the results of these experiments. As can be seen the results closely follow each other.

The difference between the simulated and the practical holding force may be attributed to the surface not being as magnetizable as the theoretical model. Nevertheless the sinusoidal shape of the curve is similar for both simulation and experimental values, Fig. 7).

Using *MATLAB*, we made a non-linear regression to find a function that describes the measured holding force depending on the angle for the simulation results. The one that showed the best results was a polynomial of the fourth degree with the mean square error of 0.9962:

$$F = -2^{-7}\theta^4 + 0.0001\theta^3 - 0.0219\theta^2 - 0.1607\theta + 186.3 \quad (1)$$

Where:

- F is the attraction force [N];
- θ is the angle between the magnets [°].

VI. OMNICLIMBER MAGNETIC HOLDING DEVICE

As a case study for our novel SM for robotic applications we set out to develop a novel attachment unit for the *OmniClimber*. The *OmniClimber* is an omnidirectional climbing robot for inspection of ferromagnetic structures, equipped with both permanent and electromagnets and a mechanism which enables it to perform perpendicular plane transitions, Fig. 8. For more information about the Omniclimbers, reader is invited to see [10] [11] [13] [14] [15] [16].

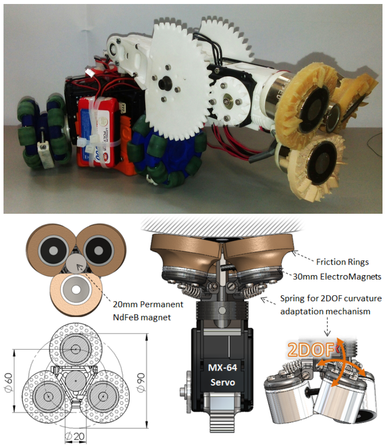


Fig. 8. OmniClimber uses three omnidirectional magnetic wheels to achieve omnidirectional movement on ferromagnetic structures. It uses an attachment unit (shown below) composed of three electromagnets and a single DOF arm to transit between perpendicular planes.[11]

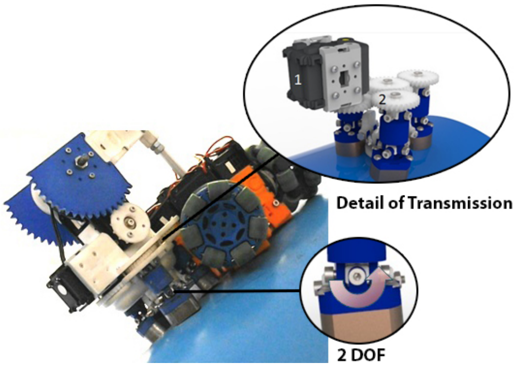


Fig. 9. Novel attachment unit using SM, showing the detail of the transmission mechanism (Actuator (1) and transmission gears (2)) and the degrees of freedom accomplished by the transmission axle of the SMs.

In order to adapt to both flat and curved surfaces, the *OmniClimber* passive adaptation attachment unit must enable two degrees of freedom for each magnet. Because we want to keep the same degrees of freedom on the support with the SM, each SM must be driven by a drive shaft. The drive shaft is composed by a universal joint at each end and a cylinder in the center, Fig. 9).

We intend to use one motor to drive 3 SMs. In order to do this a transmission mechanism with 2 stages was designed, to drive the rotation from one motor to each SM. We used a *Robotis Dynamixel AX-12* because it can provide 1.2 *N.m* of torque, enough to drive the three SM units. It drives a gear, which in turn drives a central axle that transfers the movement to three gears, one for each SM. By employing this solution, the total mass of the magnetic adhesion system was 181 g comparing to the 324 g mass of the electromagnet based solution. This means a reduction of 45% in mass. All gears use bearings to reduce friction and material wear. On the center of the support there is a permanent magnet which

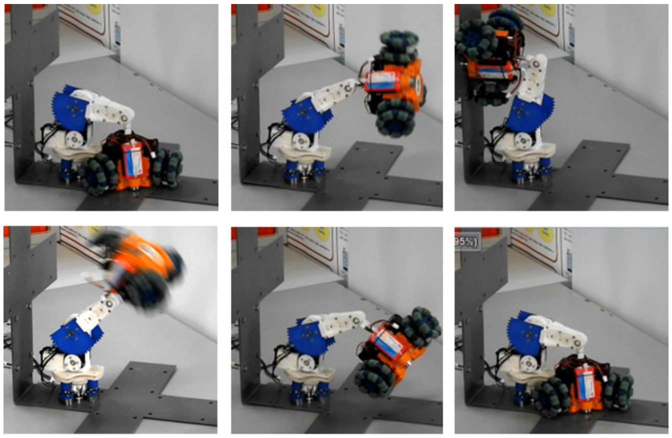


Fig. 10. Plane transition: from the initial position, with the center of the OmniClimber 13.5 cm away from the wall, the robot is raised, then the OmniClimber is fixed to the wall by a permanent magnet (above sequence), after it is lowered down by the arm, and it is again on initial position (below sequence).

provides a magnetic force that allows the support to approach the surface before the SMs are activated. The transition from one plane to another takes 3 seconds, meaning that the adhesion unit must provide force for at least that period of time.

On the experiments conducted, the SMs effectively adapted and attached to the curved surface and we were able to lift the OmniClimber to a perpendicular wall and to take it from there, Fig. 10. Using a single actuator to drive the three SMs, we accomplished also a very low energy consumption of 10 J (switch magnet state two times), versus the 39 J required for the three electromagnets for 10 seconds. A reduction of 74%.

VII. CONCLUSIONS

In this study, we developed a better understanding of the working principles of SMs in general and specially the H-type SMs. The simulations we made on the *MagJig* 95 enabled us to understand the different features of the device, and flow of the magnetic flux within the SM unit and the ferromagnetic structure. Based on these simulations, we developed a SM which is specifically designed for the application of climbing robots on structures with 1-3mm of thickness. Then by integration of an actuators, we could control the device not only to change its on and off status, but also as a variable force holding device. It was shown that the experimental results of the force control versus the rotation angle of the actuator matches quite well with the simulation results and can be modeled as a polynomial of the fourth degree.

Finally as a case study we successfully adapted the SM unit as the holding device for the arm of the *OmniClimber* robot. The new optimized SM adhesion unit is not only 45% lighter than the previous electromagnet based adhesion device, but it also consumes 74% less energy. Furthermore the novel device is less sensitive to the distance from the climbing structure. Future work includes replacement of the OmniClimber central permanent magnet with a SM in order to dynamically control the adhesion force based on the environment conditions, such as radius of curvature and thickness of the material, determined by the wheel's slippage.

VIII. ACKNOWLEDGMENT

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