Design of *Magnetic Switchable Device (MSD)* and applications in climbing robot

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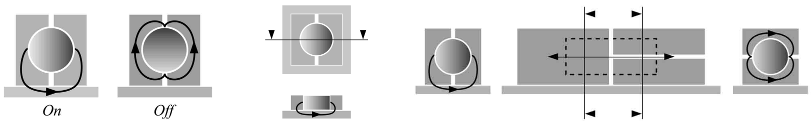
A *Magnetic Switchable Device (MSD)* is a ferromagnetic circuit using permanent magnets where the flux can circulate between different paths when its configuration is changed. This routes or cancels the flux trough specific surfaces, and thus turns on or off adhesion forces. We present classic and innovative magnetic configuration to realize powerful *MSD*. We designed and prototyped some miniature systems and give their characteristics. Finally various robotics applications for gripper, anchor and climbing robot are unveiled where the *MSD* solution has proved to be advantageous.

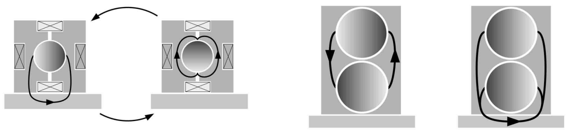
Keywords: robot, mobile, miniature, climbing, magnetic

1. Introduction

Ferromagnetic climbing robots are required to inspect many architectural constructions and industrial equipments. Coils, electromagnets or permanent magnets have been used extensively as attachment mechanism. An energy efficient solution is to use *Magnetic Switchable Device (MSD)*.[1] Although the configuration has been known for decades and has been widely used as holding device, only two previous robots use this working principle. The first known use in mobile robotics was on the *Neptune* robot,[2] which is a caterpillar climbing robot. The second use, which is very recent, is in the *MICHE* robot,[3] where they are only used as holding device that



(a) Classic parallel (b) Classic orthogonal (c) Classic linear



(d) Classic with activation coils (e) H-shaped double magnets parallel

Fig. 1. *Several Magnetic Switchable Devices (MSD)* configurations.

can detach. The potential of *MSD* has been underestimated and underused. Their use can revolutionize climbing robotics in ferromagnetic environment, especially required for industrial inspection.

In this paper,the working principle of *MSD* is explained. The development and implementation of miniature and innovative magnetic configurations is detailed. We present the results of the systems and compare with other solutions. Four different systems where the idea has been or will be exploited are presented – in a gripper for manipulating objects, in an docking station for a flying platform, in an anchor for a cable climbing robot and in the ongoing design of a climbing robot. We conclude with an outlook to future work and other future or possible applications.

1.1. *Description of Magnetic Switchable Device*

The classical configuration Fig. 1(a) of a *MSD* is composed of a fixed part – the stator – and a moving part – the rotor. The rotor is a diametrically magnetized cylindrical magnet which turns along an axis parallel to the adhesion surface. It turns between two u-shaped irons forming the stator. In *ON-mode*, when the *MSD* produce an adhesion force on the plate, the flux goes from South Pole through one u-shaped iron, through the plate and the second u-shaped iron to the North Pole. By turning the magnet by 90°, we reach the *OFF-mode*, where all the flux goes from South to North Pole through both u-shaped iron parts. The adhesion force on the plate is then cancelled. The torque required to turn the magnets varies depending on the external ferromagnetic circuit. It is the highest if you activate the system in

Table 1. Characteristics of *MSD* prototypes in configurations as in Fig. 1(a).

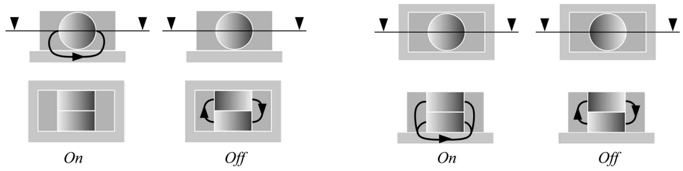
Characteristics	*Unit*	**Classic**	**Tiny classic**	**Light pin**
Size	mm^3	$5.7 \times 5.7 \times 16$	$6.8 \times 6.8 \times 4.8$	$12.4 \times 12.4 \times 24$
Weight	g	4	1	17
Torque in air	mNm	5.63	1.42	95
Torque in iron	mNm	1.74	0.59	30
Force	N	38.4	10.8	146

the air, and the lowest if you have a ferromagnetic plate in direct contact. This information can be used for control – the proximity and quality of an iron circuit nearby can be confirmed while activating the systems simply by measuring the torque. Two examples of characteristics are given for this configuration in two different sizes in Tab. 1: the classic and the tiny classic. A variation of this configuration is to use the surface orthogonal to the magnet as adhesion surface Fig. 1(b).

In the literature, a linear configuration is presented.[1] Our simulation and implementation showed it is uninteresting. Magnetically, because the activation force is high, and mechanically, because the system is more complex, which is not ideal for miniaturization. However, for certain application, it can be interesting to switch from a rotational activation to a linear one well adapted for pneumatic or piezoelectric activation. Therefore, we break new ground in the field of *MSD* design by attaching two classical stator on top of each other but rotated by 90° Fig. 1(c). A diametrically magnetized cylindrical magnet is guided linearly and commutes the adhesion from one surface to the orthogonal one when the magnet is pushed or pull linearly. This can be very advantageous for climbing robot that would navigate in a very structured planar environment with inner corner passing.

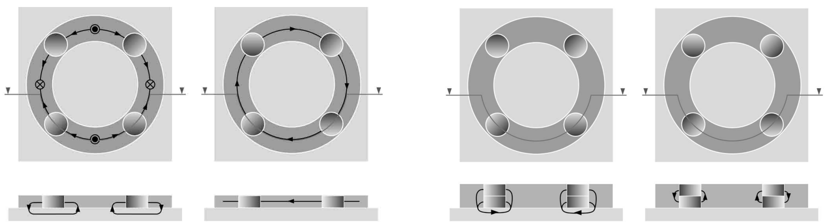
In another prototype, we showed that the classic *MSD* can be activated with two orthogonal coils Fig. 1(d). All those configurations need two separated iron parts that need to be held together. To allow miniaturization and to simplify the manufacturing process, a unique iron part would be advantageous and economic. A configuration with two magnets in one iron part named *"H-shaped double magnets"* was invented and realized. One magnet is fixed; the other rotates over 180° (Fig. 1(e)). As usual, this configuration also works orthogonally to the surface.

This last configuration becomes the *"pin configuration"* by folding along the horizontal symmetry plan. The two magnets find themselves on top of each other (Fig. 2(a)). One magnet is fixed; the other rotates over 180°. As usual, the adhesion can be realized on the four surfaces (Fig. 2(b)). We especially designed a prototype to be lightweight – it is named *"light pin"*.



(a) pin parallel (b) pin orthogonal

Fig. 2. *MSD* in the *"pin configuration"*



(a) single layer (b) double layer

Fig. 3. *MSD* in the *"ring configuration"*

Its characteristics are found in Tab. 1.

The idea can be extended further to systems with more magnets. A novel idea is to create a ring-shaped *MSD*. The version with one layer Fig. 3(a) is an extension of the *"H-shaped double magnets"* version while the double layer Fig. 3(b) is linked to the *"pin configuration"*. The inner and outer circumferences are also adhesive. Systems can be built with any revolution increment and numbers of magnets. The shape does not need to be circular nor planar. Crossing geometry are also possible. With a chosen sequence of movements on the magnets, the adhesion surface can turn on the circumference. Such systems can be used to make a self propelled wheel, manipulators or an attachment crown for mobile collaborative robots with several adhesion areas.

2. Energetic efficiency

Climbing autonomous mobile robotics requires attachment systems that are compact, lightweight and use low energy. Higher weight would result in higher energy consumption and heavier actuators. Higher energy consumption would result in higher payload in form of battery volume to afford sufficient energetic autonomy. Sizes, forces, energy consumption between

Table 2. Comparison between various attachment systems.

System	**Volume** mm^3	**Weight** g	**Force** N	**Energy** mJ
Isliker permanent electro magnet *GTP-20*	6912	41	36.0	10.8
Classic *MSD*	520	4	38.4	2.7
Classic *MSD* with actuation	6552	14	38.4	4.8
Light Pin *MSD* (ON-OFF)	2164	22.4	150	18.9
Grapnel *Hand-Bot MSD* (ON-OFF)	29201	22.4	142	28.9
Light Pin *MSD* (detachement)	2164	46.0	150	187.5
Tiny rotational *MSD* (ON-OFF)	143	1.4	5.89	0.5
Tiny rotational *MSD* (detachement)	143	1.4	5.89	7.4

various systems are compared in Tab. 2. The coils of an electromagnetic systems having a permanent magnet only uses energy to detach. The characteristics of the *Isliker* permanent electro magnet *GTP-20* are presented. Such a system could increase its adhesion force if required by activating its coils in the worse climbing situation at the cost of an high energy consumption, 3.6 W in that case. An electromagnetic systems with no permanent magnet would consume energy during the whole adhesion time and would thus be unsuitable for autonomous mobile robot. The required energy to detach various *MSD* system by turning the magnet or by detaching it mechanically is given. The energetic gain is at least 10 times. The energy required for *MSD* has to be doubled compared to the electromagnet, since you need it to activate and deactivated the system. The characteristics of systems with a DC motors and electronics are given for comparison (classic *MSD* with activation and grapnel.

3. Applications

The developed designs of *MSD* are scalable to obtain the required force or several system can be used in parallel. Their shape and functionality are adaptable to the demand. Applications can be as anchor mechanism for robots from aerial to submarine, attaching systems for collaborative robots, brake systems or holding devices, gripper and manipulators, magnetic wheels, tool exchangers and precise positioning systems, magnetization systems or even a basic subpart for modular furniture among other ideas. Four different cases where *MSD* have been implemented and tested or are being used in robotics solutions are now described.

(a) (b)

Fig. 4. (a) An overview of the *Hand-Bot*. (b) The magnetic grapnel with embedded *MSD*.

(a) (b)

Fig. 5. (a) The *MarXbot* robot with the magnetic gripper module. (b) The docking station developed for a flying quadrator.

3.1. *Magnetic grapnel for the* Hand-Bot

The *Hand-Bot*[4] is an autonomous robot that aims at grasping objects and structures that you can see in Fig. 4(a). It will collaborate with other robots for locomotion in order to perform various tasks collaboratively. The robot embeds two manipulators that can grasp both objects or structures. It can throw a magnetic grapnel against a ferromagnetic roof. The anchor is linked to a mechanical cable, on which the robot can haul up and down. This anchor embeds a *MSD* and is energy autonomous thanks to supercapacitors. It has a motor to activate and deactivate the pin *MSD*. The robot communicates with the anchor with an infrared connection. The grapnel system is 46 g heavy. It is 26 mm of diameter and 55 mm of height. It can hold 142 N vertically (Tab. 2). The robot can launch and retrieve the rope autonomously, allowing multiple ascents.

(a)

(b)

Fig. 6. (a) A preview of the future climbing robot *Tremo*. (b) The developed magnetic anchor for *TREMO* with 3 emedded *MSD*s.

3.2. *Magnetic gripper for the* MarXbot

We designed a magnetic manipulator to endow the *MarXbot*[5] with the ability to grasp, displace and position small objects (Fig. 5(a)). This allows the *MarXbot* to build structures and to manipulate its environment.[5] The magnetic manipulator features 6 infrared proximity sensors, which allows the robot to precisely align with the objects to grasp. As the *MarXbot* can rotate on spot and move freely on the ground plane, the manipulator has only three degrees of freedom. The robot can elevate and rotate its manipulator to position at a given altitude and pitch angle. The manipulator uses a *MSD* to implement the prehension itself. The specially designed *MSD* is 120 mm long. It is based on the classic design, but with a square magnet inserted in plastic parts, since long magnet were only available in that shape. This shape adds an airgap, which reduces the required activation torque and force due to lower contact force and lower friction coefficient. This operation to grasp or release an object lasts about 1 second.

3.3. *Docking station for flying quadrator*

We developed a robust *MSD* that will be implement onto a flying quadrator. The idea is to be able to dock or land against a ferromagnetic boiler's waterwall to perform inspection at precise localisation. The docking station weighs 40 g and can attach 120 N. It is activated by a servomotor, hence simple to control. The use of *MSD* is advantageous into boiler, since some dirt is ferromagnetic. In *OFF-mode*, the dirt falls off easily, while the dirt is very difficult to remove from a conventional ferromagnetic wheel, for example.

3.4. *Anchor for bipedal climbing robot* TREMO

Our last applications is in ongoing development. The idea is to make a bipedal robot already named *TREMO* able to climb and move in complex 3D real industrial environments (Fig. 6). The arm joining the two anchors at both ends will have 5 degrees of freedom and its construction is currently ongoing. The anchor has 3 classics *MSD* and can hold above 90 N. The first prototype of the anchor is energy autonomous, embeds batteries and weighs 108 g.

4. Conclusion

We achieved designing several miniature and innovative *Magnetic Switchable Devices (MSD).* Their excellent energetic efficiency, compactness, robustness and high force make them an ideal attachment system for autonomous system like climbing robots for industrial inspection. Ongoing ideas are the development of anchor systems for submarine vehicles as for connecting collaborative robots.

5. Aknowledgment

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References

1. J. M. D. Coey, *Journal of Magnetism and Magnetic Materials* **248**, 441 (2002).
2. H. Schempf, B. Chemel and N. Everett, *Robotics I& Automation Magazine, IEEE* **2**, 9 (1995).
3. K. Gilpin, K. Kotay, D. Rus and I. Vasilescu, *The International Journal of Robotics Research* **27**, 345 (2008).
4. M. Bonani, S. Magnenat, P. Rétornaz, F. Mondada and M. X. e. al., The hand-bot, a robot design for simultaneous climbing and manipulation(2009 2009).
5. S. Magnenat, P. Schoeneich, F. Rochat, P. Rétornaz, M. Bonani, V. Longchamp, M. Voelkle, T. Barras, D. Burnier, P. Noirat, T. Baaboura, F. Vaussard and F. Mondada, Autonomous construction by a mobile robot in unknown environments with scarce resources (2010).