Introduction

Electropermanent magnets are ones whose magnetic field can be controlled with a short pulse of high current. An electropermanent magnet is a system consisting of at least two magnets usually made of different magnetic metals. The polarity of one of the two magnets can be reversed, which alters the external magnetic field of the electropermanent magnet system. In addition, such reversal results in two distinct states for the magnet system. In one state, the electropermanent magnet can attract a magnetic metal and in the other it cannot do so. Unlike conventional electromagnets, electropermanent magnets do not consume any power during their operation. Once repolarized, the magnet system maintains its altered magnetic field properties without the need for a power source. Therefore, electropermanent magnets are used in applications where switchable magnets are required and low power consumption is desired. This paper reviews the electropermanent magnet as a holding force. It focuses on general applications of the technology in lifting and robotics.

State-of-the-Science and Commercial Products

The Electropermanent Lifting Magnet

EPMs can be used in processes that require lifting, holding or moving magnetic metallic materials. Because the magnet system is switchable at a low power cost, the electropermanent magnet makes an excellent substitute for electromagnet based lifting. Applications where electropermanent lifting magnets are used include steel factories, car manufacturing facilities, ship building industry and heavy-duty construction [1]. This technology offers its users the ability to remotely operate magnets and integrate them in larger automated manufacturing processes. Manufacturers such as Armstrong Industries offer users the ability to adjust the lifting capacity of the magnets by either controlling the magnitude of the current pulse or the number of pulses [2], [3]. The HEPM2 series, manufactured by Hawell Magnetics, includes magnets with holding capacity that ranges from 2000 kg to 8000 kg. Based on the magnet specifications, the price per unit ranges from $100 to $2000 and magnitude of the current pulse scales up from 72A to 320A [4]. The holding force increases with increasing contact surface area, but the pulse energy required for repolarization increases with increasing magnet volume [5].

The Electropermanent Magnet for Robots

Electropermentant magnets are used as grippers in robotic arms as well as a locking mechanism in self reconfigurable matter applications where more than one module connect to another. The feature this application exploits is that the repolarization process could be controlled provided the right circuit design, electronics and program. The use of batteries as a power source may impose some limitation on the magnitude of the switching pulse. Therefore, the locking circuit usually include a capacitor to accumulate voltage and dispatch it to reverse the polarity of the magnet when the right conditions are met. OpenGrab EPM v3 R5C is an electromagnet module that implements these switching power considerations. The magnet has a minimum holding force of 200N which is equivalent to holding a mass of 20kg [6]. The module comes with serial ports and well documented interfacing algorithms that could be found at [7]. OpenGrab is produced by NicaDrone and it costs $149.99 per unit [7].

M-blocks, a product made by researchers at MIT, are robotic cubes that use momentum generated inside themselves to spin and jump around other cubes in order to interlock and reconfigure into a collective structure. These cubes use electropermanent magnets to connect together. The magnets are mounted in the corners of the cubes and on each of its faces. The corner or edge magnets function as rotating magnetic hinges that assist in the initial locking process. The face magnets ensure complete and stable connection between the units. By activating and deactivating the magnets in certain patterns, a connection between two faces of two different cubes can be established [8]. The cost per unit for a cube made in a group of five different ones is $260, excluding the cost of manufacturing. The machining cost is estimated to be $200 per unit for a cube that is made in a group of 10 [9].

Underlying Technology of the Electropermanent Magnet

What makes the electropermanent magnet appealing is its switch-ability and low power consumption compared to electromagnets. The switch-ability of the magnet is achieved using two magnets mounted on a platform. One magnet has high coercivity while the other has low coercivity. A coil of wire is placed around the less coercive magnet and a pulse of current generated in the coil to re-magnetize the magnet in two ways depending on the direction of the pulse. When the magnetic flux of the two magnets in the system align, the magnet system generates an external magnetic field and the magnet system is said to be switched on. However, when the magnetic flux of one magnet opposes that of the other, the magnet system does not generate any external magnetic field and the magnet is said to be switched off [3], [5]. When the electropermanent magnet is switched on, it can attract magnetic materials. The holding force reduces dramatically with the increase of airgap between the surface of magnet and the magnetic metal to be held [1]. When the magnet system is switched off the magnetic field is contained within the two magnets of the system and no ferrous material can be attracted.

Building Blocks for Implementation

Force specifications, interface considerations, polarizing coil profile and circuit design adjustments are the building block for implementing the electropermanent magnet technology in an engineering design. Initially, the desired holding force must be calculated and the interface surface must be determined. In fact, the surface area of the magnet system can be determined based on the desired holding force. Once the dimensions of the magnet system are determined, the magnetic field needed to repolarize the magnets is obtained. Based on the size of the magnetic field, the magnitude of the current pulse and the number of coil turns can be computed. The electronic circuit design is greatly influenced by the application for which the electropermanent magnet is used. The circuit could be as simple as a power supply shorted by the coil of wire and a switching mechanism to reverse the pulse of current generated by the power supply. The circuit design may be more involved if the power supply cannot generate high magnitudes of instantaneous current. In such cases a capacitor bank may be required as in the OpenGrab EPM v3 R5C unit.

[1] “Electro permanent lifting magnet,” *alibaba.com.* [Online]. Available: https://www.alibaba.com/product-detail/Electro-Permanent-Lifting-Magnet_1881109143.html. [Accessed Oct. 25, 2017].

[2] “Working principles of electro permanent lifting magnets,” *Armstrong Magnetics*. [Online]. Available: https://www.armsmag.com/info-technical-data-lifting-magnets-knowledge-working-principles-eplm.html. [Accessed Oct. 25, 2017].

[3] M. Deffenbaugh, E. Buzi, L. Al-Maghrabi, G. Ham, H. Seren and G. Bernero, "An untethered sensor for well logging," 2017 IEEE Sensors Applications Symposium (SAS), Glassboro, NJ, 2017, pp. 1-5.

[4] Hawell Magnetics, “Electro permanent lifting magnet,” HEPM2 series (rectangular type) datasheet. [Online]. Available: http://www.hawellmagnetics.com/products/Electro-Permanent-Lifting-Magnet-620380.html. [Accessed Oct. 25, 2017].

[5] A. Knaian, “Electropermanent Magnetic Connectors and Actuators: Devices and Their Application in Programmable Matter,” PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, 2010.

[6] P. Kirienko, *OpenGrab EPM v3 R5C*, Zubax, 2017. [Online]. Available: https://kb.zubax.com/display/MAINKB/OpenGrab+EPM+v3#OpenGrabEPMv3-RCPWMinterface. [Accessed Oct.25, 2017].

[7] “OpenGrab EPM v3 R5C,” *nicadrone.com*. [Online]. Available: http://nicadrone.com/index.php?id_product=72&controller=product. [Accessed Oct.25, 2017].

[8] D. Rus, J. Romanishin, K. Gilpin, “Modular Angular-Momentum Driven Magnetically Connected Robots,” U. S. Patent 14, 067,132, 9 Oct., 2014.

[9] J. W. Romanishin, K. Gilpin and D. Rus, "M-blocks: Momentum-driven, magnetic modular robots," 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, 2013, pp. 4288-4295.