Toward Magnetically-Coupled Reconfigurable Modular Robots

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Abstract—This paper presents the design of a robotic module that is the building block for a magnetically-coupled reconfigurable robot network. The developed module has on-board computation, IR communication and integrated power. The development of this modular network and the associated reconfiguration methodology is motivated by the premise that magnetic latching is much more plausible than physical latching as scale decreases to the micro and nano levels.

Keywords: module; robot; reconfigurable; electromagnetic; magnet

I. INTRODUCTION

Reconfigurable modular robots are groups or networks of independent robots that work together to accomplish a common goal. Since the network is made of many robots, each individual robot is referred to as a module. The modules presented in this paper are homogeneous, meaning that each module is the same in every respect. The process of making and breaking the physical bonds between the modules as they reconfigure can be done via human interaction, or autonomously via self-reconfiguration [1]. The module designed in this undergraduate research project and presented here has been dubbed the Layered-Gear Module (LGM).

In every modular robot network there is some mechanism for holding the modules together in the desired configuration. Many current modular robot designs use physical/mechanical couples to link together. As the overall size of the modules is diminished, however, the actuator and linkage sizes for mechanical bonding between the modules cannot be diminished proportionally (linear miniaturization) [2]. This problem provides the motivation for investigating static, non-moving bonding strategies, such as those which utilize electrostatic and magnetic technologies. The LGM presented in this paper incorporate passive permanent magnets for latching, with temporary active electromagnetic flux modulation to effect autonomous two-dimensional reconfigurations. This approach provides an energy efficient strategy that shows potential as a linear (or better) miniaturization technology.

The remainder of this paper is organized as follows. Section II introduces the module geometry used in the reconfigurable network. Section III addresses the design of the magnetic latching system and its operation for reconfiguration. Physical parameters of the layered module are discussed in Section IV; while on-board processing, data collection and module-to-module communication are covered in Section V. Power issues are outlined in Section VI. Sections VII and VIII contain a summary of current LGM properties and a discussion of future work.

II. LAYERED-GEAR MODULE GEOMETERY

The issues surrounding the shape and size the robot module are by no means trivial. The LGM's final module geometry is a result of incorporating its magnetic coupling system as well as the ability to fit other components onboard. Preliminary investigations tested such shapes as a hexagon and a symmetric six-point star shape. The main issues involved in final selection of the LGM's shape were the greatest angle that a module could rotate before becoming uncoupled.
module would have to move to perform a reconfiguration, network geometry, passive stability, and dynamic stability.

Testing a layering effect with star modules atop circular modules, in combination with appropriate magnet placement, allowed us to conceive the three-layer module, LGM, seen in Fig. 1 and Fig. 2. The LGM consists of three rounded "plus sign" layers where the top and bottom layers are aligned vertically and the middle layer is rotated forty-five degrees about the center. The middle layer contains electromagnets under each of the four points. The top and bottom layers hold four pairs of polar aligned permanent magnets.

III. MAGNET/ELECTROMAGNET INTERACTIONS

The LGM's large correlation among size, power, weight, geometry, magnet placement, and desired movements makes it challenging to discuss each component separately. However, the magnet/electromagnet alignment was the main driving parameter in LGM design.

A. Magnetic Alignment

The LGM incorporates a magnet-electromagnet interaction that is a mesh of a vertical magnetic alignment and a horizontal alignment (Fig. 3).

1) Vertical Alignment

If magnet and electromagnet are vertically aligned, the magnetic field goes out the faces of the two items. This is a weak bond since the iron core does not "capture" all of the flux that leaves the face of the permanent magnet. The advantage of this alignment is that if the electromagnet were polarized opposite to the existing field then, in a two-dimensional case, the permanent magnet would always repel if it were attached to a module (i.e. it would have to flip the module over to align itself in the excited field – which it will not do).

2) Horizontal Alignment

In the horizontal case the all magnetic flux out the abut side of the permanent magnet goes through the iron core thus creating a stronger bond compared to vertical alignment. However, if a two-dimensional case is imagined where the two components are on protruding "arms" of two modules, an opposite polarity excited electromagnet could easily just repel the other module's permanent magnet just off to the side (in the same vertical plane) to cause it to look like a vertical alignment, which in this arrangement would also place the permanent magnet in the correct magnetic field alignment.

3) LGM Alignment

The LGM thus uses a combination of horizontal and vertical alignments shown in Fig. 4. LGMs latch to each other by placing the electromagnet of one module inside the field created by a pair of permanent magnets on another module.

The iron core of a de-energized electromagnet will align in the magnetic field lines (Fig. 5) for passive latching. The core will also center itself at the strongest point of attraction, located in the center between the two permanent magnets. The iron core has a large affinity for placement between the pair at the largest magnitude of flux. This creates a tolerance for misaligned electromagnet/ permanent magnet sets to naturally align themselves in the desired latching position. This is an important characteristic of the LGM since using only one permanent magnet and one electromagnet as a latching
Figure 6. Left-Before rotation—modules are passive. There are two points of connection.
Middle—Middle of rotation—modules are active. There is one point of connection.
Right—End of rotation—modules are passive. There are two points of connection.

Figure 7. Left-View showing how the flux lines of an excited electromagnet bend away from the flux of the permanent magnet field so that the module's arms move out of line. Note that the electromagnet must be active and must have an opposite polarity for this repulsion to occur.
Right-Top view of the modules in the middle of a rotation. The black dot is the pivoting point of the rotation.

Figure 8. Left-View showing how a passive permanent magnet field's flux will "grab" the ferromagnetic material of an electromagnet and pull it in line with its field. This happens because the permeability of air is much less than, in this case, steel. The electromagnet can also be excited in the proper attracting polarity to make this movement more expedient.
Right-Top view of the modules in the middle of a rotation.

This magnetic alignment was arrived at independently from the design presented in [3]. It therefore seems that the alignment presented in this paper is most feasible magnetic-latching design as far as stability is concerned.

B. Movement
The following sequence describes one complete movement of one module around another adjacent module. Fig. 6 shows a beginning, middle, and end state for this single movement (one-eighth a turn). Figs. 7 and 8 illustrate more closely the following chain of events.

Before rotation when the modules are static, a latching state seen from above on the left side of Fig. 6 exists. This is the passive state where two sets (one from each modules
perspective) of de-energized electromagnets are between a permanent magnet pair of the other module. When repulsion is excited in the electromagnet of module A by temporarily energizing it in a manner to create an opposite magnetic field polarity, a force is created and acts, causing the electromagnet to be pushed totally out from between the two permanent magnets of module B (Fig. 7). At the point when the electromagnet of module A is totally out of line with the permanent magnet pair of module B, the next electromagnet on the adjacent tip of module A is then in the field of its respective new permanent magnet pair on module B (Figure 8). The passive attraction between the new permanent magnet pair of module B and the adjacent electromagnet iron core of module A is often enough to complete the transfer. Temporarily energizing this adjacent electromagnet of module A in an attractive polarity can provide additional latching force, if necessary.

During a movement the non-exited, but latched electromagnet of A acts as a pivot point represented by the black dot on Fig. 8. This pivot point maintains an attraction while other sets of electromagnet/magnet pairs are moving. Of major note is that the size, geometry, and existing forces of the LGM does not require a momentum "swing" to achieve movement. More specifically, due to the opposite polarity created by module A, module A must move until the repulsive force between the modules equals the friction of modules on the surface. At the point this occurs, the side toward which module A is rotating has already gained enough attractive force to overcome friction in that direction. Of importance is that the modules are inclined to latch in a stronger state. That is, the modules desire to always be latched with a minimum of two sides not just one. Teflon has been added to the bottom of the modules to reduce friction and aid in movement, but not is required for normal operation. It simply reduces power requirements.

IV. SPECIAL PHYSICAL DESIGN SPECIFICS

The current version of the LGM completely assembled with all components is shown in Fig. 9 and 10. The major issues that were identified and overcome in LGM physical design were: a. the permanent magnet parameters; b. the length of the "arm" on the layers; c. the electromagnet parameters; d. thickness and material of layer levels; and e. separation of layer levels.

A. Permanent Magnet Parameters

The LGM uses rare earth permanent magnets. Ceramic magnets were considered, but their flux to weight ratios are inferior to the rare earth magnets. While ceramic magnets are less expensive, purchasing rare earth magnets in bulk reduced their costs almost 90%. The overriding permanent magnet characteristic was adequate magnetic field strength in a small size and weight, thus dictating the use of the rare earth magnets. The current LGM uses a nickel plated, 0.25 inch thick, one-inch diameter rare earth magnet. This size was chosen since it was the smallest size that could be used and still allow for the microprocessor (Rabbit 3100 microprocessor) to fit horizontally atop the module. This rare earth magnet choice was the constant in all other LGM design parameters, namely the electromagnet and geometric size.

B. Length of the "Arm" on the Layers

The original module size was chosen to be three and a half inches from tip-to-tip. This was the smallest feasible size that permitted using the one-inch permanent magnets. Since the magnetic fields of each module are aligned vertically, a repulsion force exists between the vertical stacks of two adjacent modules. The magnetic forces can be directionally decreased, but attempts at this will result in some decrease in all directions. The effective weakening of field is accomplished by adding ferromagnetic material to the edges of the permanent magnet around half of the circumference on the outward side of the magnet. This effectively short-circuits the flux, and thus greatly limits the range of the flux that comes out the respective side. However, doing this also has an effect on the non-shielded sides though the ratio between the strength of the side to that of the face is greatly decreased. The exact analytical equation for how much the flux out of the face of the shielded side is affected is not yet known. In a case where the

Figure 9. The final version of the LGM from the side. This image is about 80% to scale.

Figure 10. The final version of the LGM looking down. This image is about 65% to scale.
circumference and one face are shielded, however, it was found that the uncovered face's flux falls off much more rapidly, proportional to about $R^2$ versus the normal $R^3$ [4]. Intuitively, by just surrounding the half circumference with galvanized steel, the flux out of the ends can be expected to fall off somewhere between $R^2$ and $R^3$.

Since the original production of the LGM, a semi-circle of 0.075 inch galvanized steel has been added to the outboard sides of every magnet. The arm length was also extended 0.375 inches per side, or 0.75 inch on the tip-to-tip measurement thus yielding a total module diameter of four and a half inches. The final module dimensions were arrived at experimentally to assure proper docking, undocking, and pivot point rotation of a module without ejecting an adjacent docked module.

C. Electromagnet Parameters

The design of the electromagnet goes hand in hand with the arm length, which was a function of permanent magnet size and strength. The electromagnet parameters were experimentally determined after ballpark calculations. The size of the LGM's electromagnet's outer diameter (OD) was desired to be one inch. However to order an electromagnet with a desirable length, the availability of stock spools forced an OD of 0.875 inches. Current LGM design OD yielded a 28-gauge wire with 625 windings around a steel core of 0.13-inch diameter and a total length of 0.58-inch.

The number of windings and wire gauge acted together in the relationship of amp-turns. The amps are a function of resistance of the wire, which the gauge and length of wire determine. Since the number of turns determine the length of wire, it was not possible to just add as many windings as desired without affecting the amps via wire resistance. Therefore, the amp-turns are a balance of number of windings and gauge size. We were limited to an OD of 0.875 inch, thus there were a maximum number of windings (depending on gauge) that could fit on that particular spool.

The inner diameter (ID) and length of the spool dictated the size of the core of metal that was placed in the electromagnet. The core had to be large enough to have a good passive magnetic connection between modules, but be small enough that the available amp-turns would excite a large enough force proportional to about $R^2$ vice the normal $R^3$.

E. Separation of Layer Levels

This design item played hand in hand with the thickness of the metal. It is again noted that the separation between the layers cannot increase too greatly due to the rapid fall off of magnetic fields. There has to be some separation between the levels for the electromagnet to fit into the gap between the upper and lower permanent magnet levels in a self-reconfiguration. Therefore, spacers were added on the top and bottom. Spacers (0.075-inch) are used in the current LGM to allow "play room" during rotations.

V. INFORMATION GATHERING

The LGM gathers information in two ways: from opto-reflective sensors and communications to its other LGMs to which it is latched. Many efforts were put into making the LGM very simple. This came from imposing characteristics on the LGM that it would face in a network of millions of LGMs [1]. That is, it should only communicate with its direct neighbor and should only spatially know if there are LGMs latched to it.

A. Sensors

Originally the layered-gear module was designed using eight photodiodes as sensors to trip when another module joined the sensor's corresponding side. In practice it was found that these diodes were too fickle with regard to different ambient lighting conditions and the signal processing circuit took a great deal of physical room. Miniature opto-reflective proximity sensors were found to eliminate these issues. They are implemented in current LGM models.

These sensors require very little signal processing. They use one logic gate for signal processing, a large improvement over the photodiodes. These sensors have worked flawlessly in all room lighting conditions, thus permitting the Rabbit 3100 microprocessor to create a matrix of latched sides. This matrix contains the only worldly information gathered by the microprocessors on each module, so these sensors must be virtually infallible.

B. Communications

The final module design uses serial communication between modules which each have their own integrated Rabbit 3100 microprocessors. The communications occur through one serial port and use a direction bit to determine which side to
transmit the serial data [5]. This occurs through the use of logic gates that use the serial data and direction bit to direct communication flow. The transmitter/receiver channels utilize fairly directional IR LEDs that are spaced throughout the eight sides. Due to the possible alignments of latching, there are two receivers for every one transmitter.

The receiver implementation is slightly more complicated than the transmitter. Because only one serial port is used, the module is unable to determine from which side data is coming based on the data stream alone. To solve this problem the LGM uses programmable logic chip to create a receiving side parallel bit along with the serial data. This output bit is read into the microprocessor, thus allowing the module to know what side the communication came from since each side has its own respective receiving bit. This scheme prevents other modules from talking to a module that is already using its communications. To eliminate extraneous noise, only sides that are active permit communication.

VI. POWER

The electromagnets are excited through an appropriate driver circuit. The circuit uses an h-bridge power amplifier to control on/off and direction of the electromagnet's field. This amplifier is controlled using a phase bit and an enable bit that are part of the programming. Since the electromagnets are only pulsed for 0.15 seconds, there is no problem with excessive heat buildup from the momentary large currents.

The power amplifier is capable of drawing its high current from Polapulse Batteries that can fit atop the LGM. This is a high-density 6-volt battery that can deliver 7.6 amp hours of energy at a one-amp drain. The power amplifier battery is only connected to the h-bridge for electromagnet control and does not drive any other part of the robot.

Three batteries are required to supply 18 volts which drives the electromagnets at about 2 amps. A separate Polapulse, via regulation, powers the microprocessor and other logic. The LGM, on a dry surface, draws around 4.86 joules per move (18V @ 1.8A for 0.15sec).

VII. CURRENT LGM ABILITIES

In general the LGM is independent, modular homogeneous, reconfigurable, and magnetically latched. The following is a list of the current LGM's abilities:

- The current reconfiguration program can have two or three modules move about each other to and from most any configuration.
- All processing is onboard each LGM and independent of other LGM's.
- All power requirements can be held onboard.
- The LGM uses only magnetic interaction to reconfigure.
- Communications schemes do not require module identification, only the spatial knowledge of the receiving LGM can determine.
- Only one type of sensor onboard.

VIII. FUTURE WORK

One of the major goals of this project was to make it applicable in the future to the nanoscale. The problem of power consumption is a major issue that must be resolved before onboard power on micro and nanoscale robots can be realized. For the motion actuation (magnets), the weight to strength ratio and, therefore, theoretical power consumption, decreases drastically as the size and mass of the modules decrease. This reduction is due to the fact that magnetic fields decrease proportional to R^-2. Though downsizing theoretically increases the strength to weight ratio, the actual interactions between separate magnetic fields become a major issue not easily analyzed. Due to the subtleties of quantum and other effects, this problem becomes even more acute as miniaturized modules approach nano dimensions [6].

Network communication complexity has been limited by eliminating the need to label modules, use pseudo random numbers to assign communication time slots, or otherwise assign identification for communications. Every module is considered to be the same. It does not matter which one is which, only that a goal formation is either achieved or not. The communications scheme that has been developed has accomplished this goal.

Future research should initially address the full implementation of a reconfiguration algorithm. Simulations will need to be developed once the dynamics of large networks of the LGM can be modeled. Once faithful simulations are available, reconfiguration algorithms can be refined and studied, and new algorithms implemented.

Module design can be further optimized. More time and funds should be invested into the current prototype to fully realize its potential. Certain design parameters that the current LGM uses can be changed and studied. It is hoped that a smaller version of this current module design can be constructed in the future. Even if full onboard realization of all control and power is not possible in miniaturized versions, future research still could prove more decisively that magnetic coupling and actuation is a preferred choice for future micro scale modular robots.

REFERENCES


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