Dynamically Reconfigurable Flywheel
Actuated Magnetic Cube Robotics
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1. Project Introduction

This project aims to design, build and characterize a demonstration set of modular cube robots that use a novel method of locomotion to achieve self-reconfiguration. Modular cube robots are one approach to form-changing robotics being developed in the programmable matter community, which enables robots to synthesize the most appropriate form on demand. Modular reconfigurable robots have been studied extensively and there are several existing solutions for reconfiguration of each modular "cell" robot. However, these previous implementations have significant limitations, several of which my project aims to overcome. The new design enables a unit module to move relative to a substrate of similar modules using flywheels to "roll" the cubes. There are many benefits of this proposed design, including the simplicity of actuation, the ability to hermetically seal the device, and the variety of possible motions, including isolated cube locomotion, and aggregate motions using synchronized actuation of the component flywheels. The project is funded through the MIT Eloranta Fellowship and will be completed over the summer of 2012.

2. Background and motivation

The most important characteristic that distinguishes biological machines from current human constructed machines is modularity – and the many fundamental benefits that this provides. The goal of programmable matter is to design a collection of modules we can think of as "smart sand" that are light and compact and will have the physical and computational capabilities to configure themselves into a desired shape as needed. Programmable matter will enable people to create parts or structures on demand (e.g. wrench, bench, tripod, splint, bridges, buildings). Areas of application of this concept include construction assembly and repair, creation of space-based robotic structures, and active formation of sensors, communication, and actuator arrays. Over the past two decades, programmable matter has utilized multiple research disciplines, including mechanical engineering, bio-engineering and electrical engineering in order to create self-assembling, self-reconfiguring, self-organizing, and possibly even self-replicating machines.

There are many different challenges to creating systems that are capable of self-organization including scaling, energy efficiency, communication, and computation, as well as developing the hardware. The unit-module should be as simple as possible and should have the ability to move relative to a substrate of similar modules. The collective movement of the modules in the system should be governed by rules that can manage the complexity of a very high degree of freedom system. The unit modules should be able to locate themselves, form attachments to neighbors, and communicate, and possibly share energy or actuation.

In the last 15 years there has been progress on many of these aspects of modular robotic systems. There are many existing systems and approaches to achieving modular robotic systems. An overview of these types of existing systems and research can be found here [1]. There are non-lattice module type robots, such as the conro module [2] snake-like modular robots as well as non-actuated module lattice based systems, including stochastic assembly methods, (e.g. Cornell's fluid based stochastic assemply [3]) and also modular disassembly such as K. Gilpin's work at MIT [4]. However the class of robots that is directly applicable to this project are modular lattice-based robots. Of this class there are again several different systems, including the CMU Telecube [5] and different types of electromagnetically actuated shapes including Ara N. Knaian's active electromagnet actuation [6] work, although none so far have proven practical for most tasks.

3 New proposed locomotion method

In this project we propose to develop a new approach to modular self-reconfiguring robot system that is based on a novel design insight. We propose to develop the basic module design, build a platform consisting of 12 modules, and demonstrate through systematic experimentation that the platform is capable of self-reconfiguration. We will characterize the unit-module locomotion relative to the substrate and show self-reconfiguration in the context of several canonical objects that can be built out of these 12 modules.

3.1 Unit-Module Locomotion

The basis of the proposed design for the unit module is the storage – and then transfer of angular momentum through quick locking of flywheels. If a spinning flywheel is "locked" in place with respect to the structure that houses it, it transfers its angular momentum to the structure, causing a tendency to rotate. However since a cube is not a natural shape for rotating, the edge of the cube hits the edge of the cube it is attached to, inducing an instantaneous center of rotation. The edge magnets help to guarantee that the cube rotates about this desired axis instead of losing control.

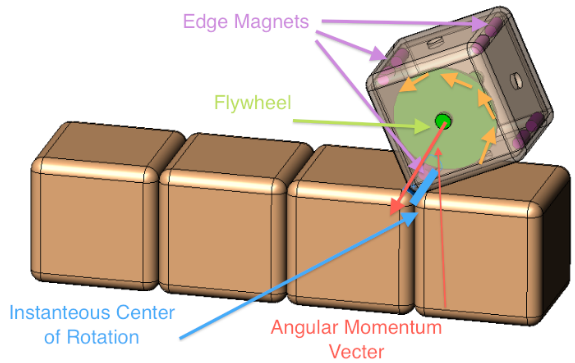

Figure 1. A model showing the important components of the proposed design.

The overall goal of this is to be able to have a system that can move any cube to any position and orientation. While the system in figure 1 is limited to "right" or "left" rolling actions, by combining two or possibly three flywheels at orthogonal angles, any motion should be possible. It should be able to travel on flat surfaces (Rolling 90 degrees), up vertical walls, over edge corners (rolling 180 degrees), and hopefully even upside down. Figure 2 demonstrates a possible model of what a three-axis cube traveling on an arbitrary structure could look like.

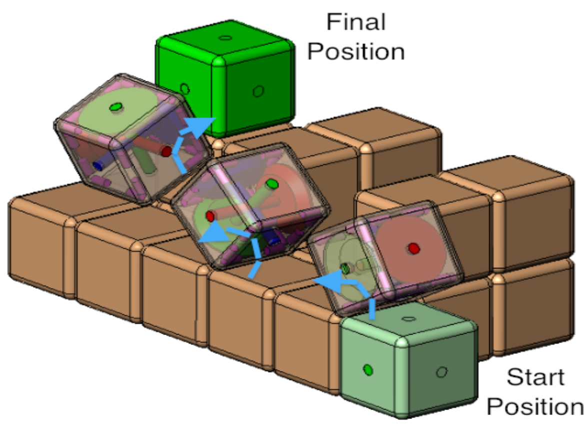

Figure 2: Showing a more complicated system with three different flywheels capable of 3d motions. The transparent cubes are several "snapshots" of the cube between motions.

3.2 Module Component Details

There are several physical interactions occurring during the movement of these cubes, the most significant involving angular momentum. Flywheels are well researched and are a superb method of storing energy, and are an especially excellent method of storing angular momentum. Different maneuvers should be possible by changing the speed (and therefore the angular momentum) of the flywheel before locking.

The second significant component I will discuss is the locking mechanism of the flywheel. The actual clamping of the flywheel will be a key component of the robot, since high levels of wear are possible due to the high levels of energy transferred through this interface. The most likely type of clamp would be a flexural-based clamp like the as shown figure 3 actuated through a solenoid.

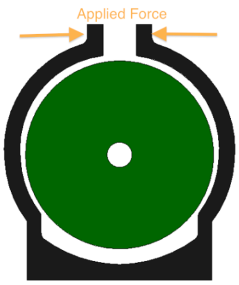

Figure 3. Proposed clamping system.

The third element we will examine is the attachment and rolling mechanism. The current design uses high power permanent neodymium rare earth magnets. There would likely need to be 24 edge magnets (two on each edge), and possibly magnets on the faces to further help align and attach the cubes. The design already overcomes any difficulty in magnet alignment compatibility by leaving the magnets unconstrained in one degree of freedom, so that they automatically and nearly instantaneously align themselves with the nearest magnet.

3.3 Benefits of this system

This design has many advantages when compared to existing systems. The modules contain no external moving parts, and keep moving parts in general to a minimum. This helps the system robustness, and allows the devices to be completely sealed. It also helps make the device manufacturable using traditional fabrication processes.

The cube movements are simple and easy to control. Only the cube that is directly moving needs to be actuated or controlled – bypassing complicated coordination and allowing the non-moving modules to be passive. It is also theoretically capable of moving cubes in almost into almost any configuration, without complicated path planning, although a limited subset of possible motions might not be practical (such as moving a the cube surrounded on four or five sides).

The system also allows for many types of motion on different scales. For example each individual cube can move on the ground by jumping and rolling. But perhaps the most significant benefit of this type of system over existing modular lattice robots is the possible ability to move the combined structure in non-trivial ways due to aggregate flywheel motions. Due to the properties of moments (a change in angular momentum) the effects are the same regardless of where they are located on a rigid structure. So by synchronous locking of the parallel flywheels the applied torque to the whole rigid body is cumulative. Therefore structures made up of many of these cubes should be capable of large-scale robust motions.

3.4 Extensions and future applications.

Depending on the available time, there are several ways in which this proposed unit-module could be extended to demonstrated increased capabilities. We will explore miniaturization to reduce weight and power. We will also explore group coordination and behaviors for multiple unit-modules. We will also explore introducing morphing capabilities within the design, for example to turn each individual cube into a sphere by inflating a covering over the flat faces of the cube. This is possible due to the sealed nature of the system, and could turn each cube into a highly mobile spherical robot. Permanent locking would also provide added functionality. It could help make practical the construction of structures such as bridges or temporary buildings.

4 Implementation details

In a very preliminary feasibility study we have built a single flywheel prototype. The model was successfully able to roll on a simulated magnet surface both horizontally and vertically. The details of the design can be seen below in figure 4. The device was build using rapid prototyping methods of fabrication including laser-cutting and water-jet machining.

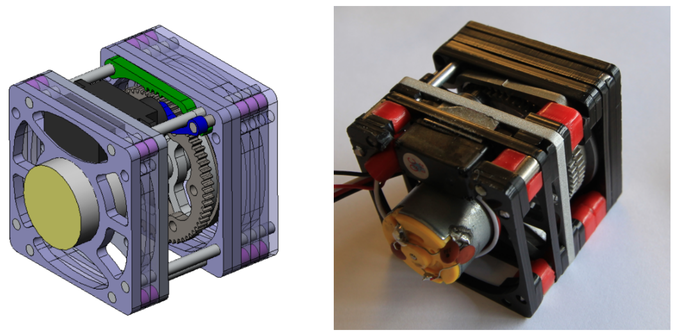

Figure 4. Existing proof of concept prototype (locking mechanism shown in green)

Additionally a flat plate was produced that had magnets simulating what a surface of other cubes would be like in order to provide a structure to demonstrate locomotion. The flywheel was powered by connection to a power supply, and then after several seconds, the clutch was actuated. The resulting tests were successful; the cube was first rolled along a flat surface, as the frames shown in figures 5 and 6 from demonstrate, and then rolled up a vertical wall. The actual moving event occurred in under a tenth of a second, underscoring the dynamic nature of this interaction.

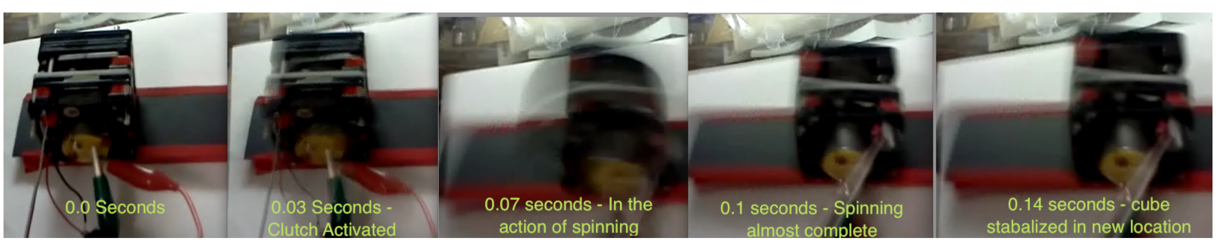

Figure 5. Showing the cube moving to the right. [7]

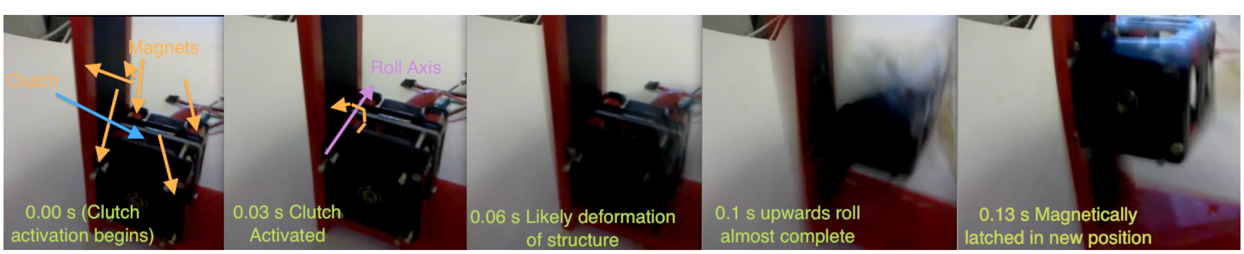

Figure 6. Showing the cube moving upwards. [8]

The flywheel consisted of several sheets of steel attached to a cheap DC hobby motor. The locking consisted of a servo pushing a piece of metal into the teeth of a gear (A very temporary solution). The prototype was also very heavy (almost 350 grams), and has many aspects that can be drastically improved.

4.1 Design iterations

We propose to build on this work by designing and building a three-degree of freedom system. A few of the immediate and significant improvements to the prototype include using better motors, bearings and locking system, and decreasing system weight. We will also design a control system likely based on the arduino in order to self-actuate the cubes.

The design of the physical cube structure will include finite element analysis in order to determine the desired mechanical properties of each cube, and materials analysis to examine which materials and manufacturing processes can optimize the design.

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[6] Ara N. Knaian Design of Programmable Matter, Masters thesis MIT medial Lab, 2008

[7] http://www.youtube.com/watch?v=FYqokZlRcKw

[8] http://www.youtube.com/watch?v=ya9znkzJIcE