StickyBricks: An Adhesion-Based Modular Self-Reconfigurable Robotic System

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***Abstract*—The field of modular robotics depends predominantly on the scale and reliability of both actuation and inter-module connection. This paper presents StickyBricks, a unique modular robotic system comprised of 30mm cubes with adhesive belts around their perimeter. Design and construction of the system is addressed and the dynamics of a multiple belt-drive system and the unique motion constraints imposed by such a system are examined. Several methods of adhesion are discussed, and a future view incorporating gecko-inspired dry adhesives and 3D locomotion is addressed.**

I. INTRODUCTION

THE idea of fine-grained modular self-reconfigurable robots is compelling. One can imagine large numbers of tiny robotic modules working together to create larger, more powerful robots. In contrast to large, expensive and complex robots, self-reconfigurable systems present the idea of a system of identical modules which can be programmed to arrange themselves in multiple configurations for multiple tasks.

Mark Yim [3] describes three benefits of modular self-reconfigurable robots: reliability, versatility, and cost. While large robots created for a specific task are often suited only to that task, reconfigurable robots are able to adapt to different tasks in different environments. Large custom-made robots are always expensive and often unreliable, while small modules can be mass-produced for vast cost savings.

An important benefit of a massively parallel homogeneous robot system is the ability to self-repair an internal failure. In the event of a hardware malfunction, surrounding modules would be able to move the offending part to a passive location, or eject it completely from the system. Effective self-repairing robots have not been demonstrated, but improved modular hyper-redundant systems are a clear path toward this goal.

Most of the existing designs are based on homogeneous modules; systems of identical components which connect with each other to form lattice-like assemblies. Current designs feature either modules which push and pull their neighbors [2][9] or which rotate around each other [1][3][12][13]. Since 1990, many modular self-reconfigurable systems have been built. For a catalog of designs, see [11].

A primary point of failure of existing designs lies in the reliability of the inter-module connections, which are either mechanical or magnetic. The goal for the StickyBricks project is to explore the feasibility of using adhesion to connect modules to one another. We accomplish this by wrapping each module with an adhesive belt. Figures 1 and 2 show the design of a StickyBrick module.

The StickyBricks systems is two-dimensional, and from above, operates much like the familiar sliding puzzle games [10], with each module moving along its neighbors.

Fig. 1. Top view of two connected StickyBricks.

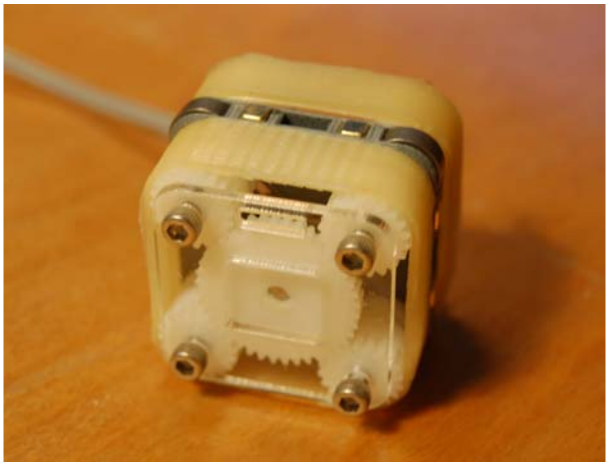

Fig. 2. Bottom view of a single module.

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II. MECHANICS

Each StickyBrick module is basically a tiny motor connected by a gear train to a pair of adhesive, circumferential belts. Transparent top and bottom plates sandwich four rollers that carry the belts and mesh with a pinion gear connected to the motor. A center plate carries the motor and has magnets and steel blocks mounted on its perimeter. The assembly is held together by four bolts that act as axles for the rollers.

As individual StickyBricks are only 30mm square, very little torque is required to move them along the edge of an assembly. The torque generated by electric motors scales down poorly, however, and advances in dry adhesive technology would increase the force necessary to peel the adhesive belt from the connected assembly. Required actuator torque is specified by:

$$\tau_a \geq W_{SB} + F_p \tag{1}$$

where:

τ_a	Actuator torque
W_{SB}	Weight of one StickyBrick
F_p	Adhesive peel force

A circumferential belt is nothing new. Whether a tank or an office robot, tread drive systems are common and versatile. Most of these systems provide locomotion for a vehicle on a horizontal plane with the tread contacting the ground surface. StickyBricks, in contrast, uses its circumferential belt on its side, connecting with neighboring modules to reconfigure. Without the familiar force of gravity providing preload to the leading edge of the drive belt, however, a module would tend to spin in place when powered, even with a highly adhesive belt. To address this issue, we embed tiny Neodymium magnets and steel blocks into the center plate of each module. The magnets provide a preload force so that the belts of neighboring modules remain in contact, but they do not provide any actuation themselves.

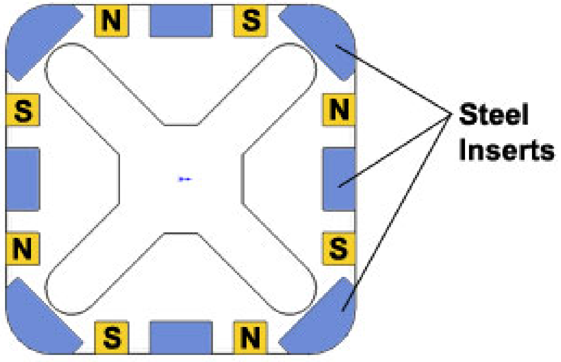


Fig. 3. Top section view of the center body, showing alternating magnet polarities and steel inserts.

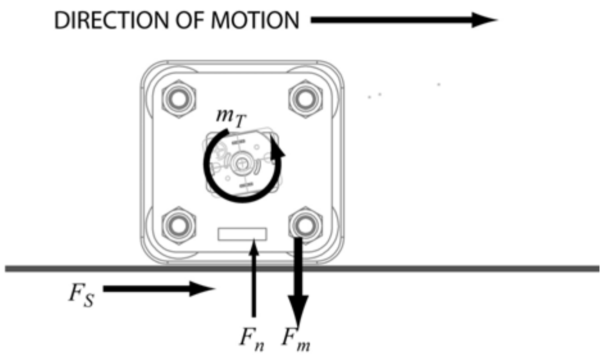


Fig. 4. Force distribution on a moving StickyBrick.

III. CONSTRUCTION

StickyBricks were designed and built iteratively, with the benefit of two manufacturing tools in our lab: a precision 40W laser cutter and a Stratasys Fused Deposition Modeling (FDM) machine. The speed at which prototypes could be constructed contributed significantly to the design, allowing changes to be made quickly, and improving the design by enabling immediate, repeated experimentation.

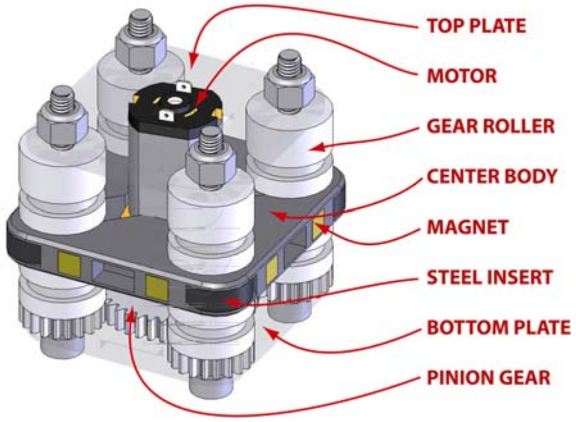


Fig. 5. Illustration showing the component parts of a single module with belt removed.

The two body plates are constructed out of .06” extruded acrylic sheet, and the five gear rollers were built using ABS plastic on the FDM machine. The bolts and nylon locking nuts are 18-8 stainless steel and thin discs of .010” thick electrical grade Teflon® PTFE act as bearings to reduce friction between the gears and body plates.

The motor is a 298:1 gear motor made by Sanyo, and is driven by a 5v regulated power supply. Specifications for the motor are provided in Table 1. For experimentation, the motor is simply wired to a reversing switch to allow a single StickyBrick to move forward and backward. Early testing confirms that the motor provides far more power than necessary for moving a single StickyBrick along the edge of an assembly.

TABLE I
SANYO 12G-A4S MOTOR SPECIFICATIONS

Specification	Quantity
No Load Speed	62 rpm
Starting Torque	3300 gf-cm
Weight	8.7 g
Size	10 x 12 x 29 mm
Noise	< 55 dB
Voltage	5 V
200 g-cm load current	95 mA
Gear Reduction	297:1

The adhesive drive belt was manufacutured with Vytaflex 20® urethane rubber compound. Three piece circular belt molds were built using FDM, and the urethane was poured by hand and allowed to set overnight. Each belt features a longitudinal rib that fits in a slot in the rollers to maintain alignment.

Our intent is to realize the low cost promises of simple robotic modules. The motor, nuts and bolts are the only items that are purchased, everything else is made in our lab from inexpensive materials. This puts the total cost of manufacturing a single StickyBrick module around US$20. If we start a 3D print job in the evening, there will be parts for eight StickyBricks ready when we come in in the morning.

IV. MOTION CONSTRAINTS

In order to experiment with belt-drive locomotion, a fixed system is assumed, with one or more modules moving along the perimeter of the system. Motion along a linear edge of the system is straightforward, but the singularities involved in concave and convex transitions demand analysis.

Without experimentation, it is unclear exactly how a StickyBrick will handle a convexity (figure 2), but there are no forces present to cause it to detach from the structure or reverse direction. A concavity is another matter. Upon approaching a concavity, a StickyBrick will adhere to the perpendicular surface (figure 3) and will attempt to continue and detach from the previous surface. To accomplish the transition, it will be necessary for the shear force of the belt against the new surface to be greater than the adhesion force normal to the previous surface.

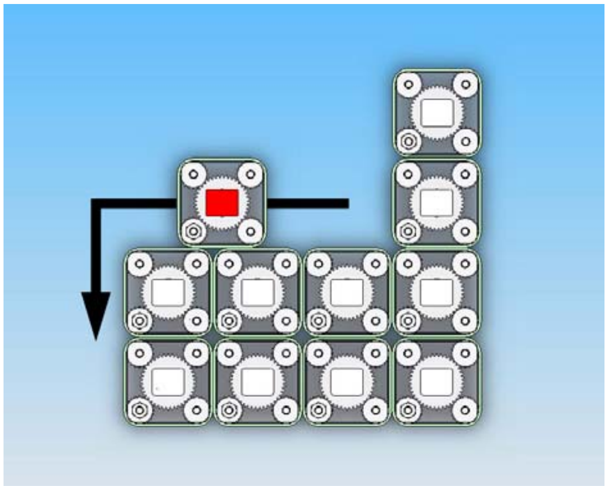


Fig. 6. Navigating a concavity.

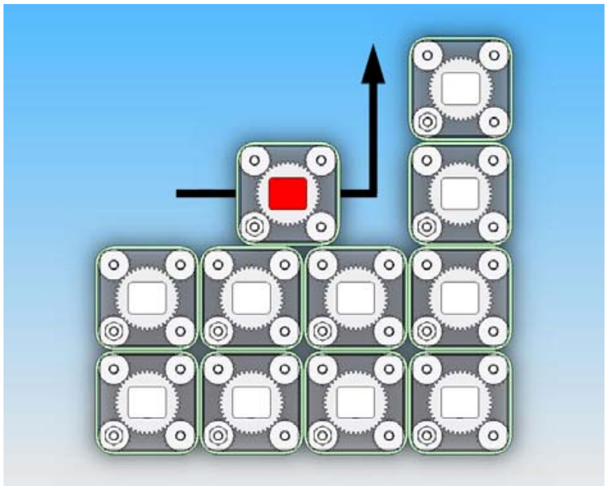
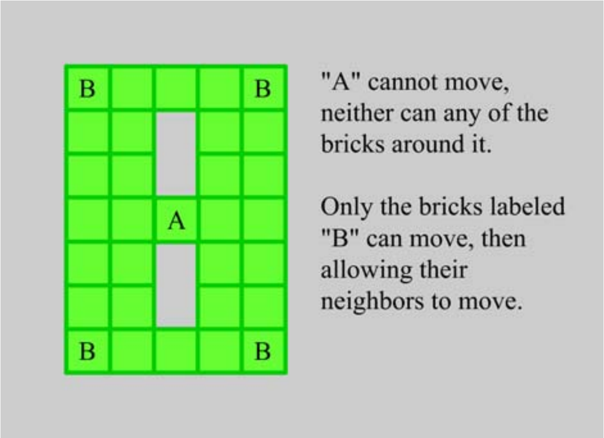


Fig. 7. Navigating a concavity.

A serious limitation of a belt-drive system for modular robotics is its inherent 2D nature. While true of the current StickyBrick design, one can imagine a design in which the two belts are independently actuated, allowing for differential drive steering and the ability to move in three dimensions.

The nature of belt-drive locomotion is very different from a standard “box on wheels” mobile cube. Since the side of a StickyBrick opposite the drive side is always moving in an opposite direction from travel, a StickyBrick module can carry no payload, or piggyback other modules. In contrast to most other modular systems [2][3][9] which rely on an assembly of modules (a meta-module) to move, StickyBricks move in a necessarily independent fashion.



"A" cannot move, neither can any of the bricks around it.

Only the bricks labeled "B" can move, then allowing their neighbors to move.

Fig. 8. Motion constraints for a module with a circumferential belt.

The continuous belt rotation creates many situations in which an individual module cannot move, as shown in figure 8. Although this restricts motion planning, it also may serve to strengthen the lattice-like assembly of modules. In general, an assembly of StickyBricks must begin to reconfigure at the corners, as any brick attached on two of its opposite edges is free to move.

V. Adhesion

The success of the StickyBrick system will depend on the adhesion properties of the individual modules to one another. We have conducted initial force measurements on several polymers to determine their suitability for use as drive belts. Three forces will be measured for each material's adhesion to itself: adhesion force along the normal, shear force, and peel force. To enable belt-drive locomotion, a successful belt material will have a low peel force, and high shear force. To enable transitions at concavities, the material's shear adhesion will need to be significantly higher than its normal adhesion.

A long-term goal of this project is to take advantage of the dry adhesion methods currently being researched. It has been shown [5] that geckos, with billions of micro and nano-fibers on their toes take advantage of Van der Waals forces to strongly and temporarily adhere to various surfaces. Work has been done to create synthetic gecko-inspired fibers [6] but they are not yet flexible, reliable, or durable. Additionally, preliminary structures built from nanofibers have shown good adhesion properties to other materials, but poor adhesion to the same material.

In the absence of feasible dry adhesive materials, various polymers are being tested including polydimethyl siloxane (PDMS) and several durometers of Vytaflex urethane rubber.

A drawback of an adhesion based system for inter-module connection is the possibility of environmental contamination. The StickyBricks system will be tested in a clean environment, with the hope that next-generation dry adhesives will enable testing to move to real-world environments.

VI. Planning

Motion planning for a modular robotic system is rarely straightforward, but the unique motion constraints imposed by the StickyBricks' circumferential belt simplifies the task. Since only modules on the perimeter of an assembly (or on the perimeter of an interior void) are able to move, planning a reconfiguration or gait is much simpler than in a compressible unit system such as [2].

We have begun to implement a planning simulation based on the *Directed Growth* algorithm presented in [14]. Individual modules know only their position and the complete desired configuration. If they inhabit a cell that should be vacant, they begin a walk around the outside of the assembly in a direction determined by the current *seed* module, which propagates a hormone alerting other modules that it is missing a neighbor. The first seed module is picked at random, but then the next seed modules are selected from the neighbors of the previous seed. This process greatly speeds reconfiguration, since many modules can be moving at the same time toward target cells that are closely spaced.

VII. Results and Current Work

Our prototype modules are robust and efficient, and hold together well in a lattice assembly. The motors have a balance of speed and torque, moving the modules even when fitted with highly adhesive belts and at speeds around 10cm/s. The modules move reliably along a line of other StickyBricks and also traverse any ferromagnetic surface well. When we add a second magnet to the module, convex corners can be negotiated.

Fig. 9. The StickyBrick on the right is traversing the StickyBrick on the left, which is attached to a steel surface.

Without manual reconfiguration of the magnets, the modules cannot traverse along the edge of a line of identical StickyBricks and also successfully negotiate a convex corner. In the current design, the preload force provided by the magnet creates a singularity condition when the forces of two opposing magnets meet along an edge.

While keeping an eye toward simpler solutions, we are experimenting with two methods of magnetic force actuation in order to achieve the desired behavior. The first makes use of a mechanical linkage, using the rotational force of the drive motor to swing a preload magnet into place whenever the module is moving. Since the magnetic preload force is not required when the modules are at rest, this solution would effectively add the appropriate preload force on either edge of the drive side when the module requires it, but then retract it when the motor shuts off.

The second method we are looking at involves replacing the permanent magnets with tiny electromagnets, also actuated whenever the module is in motion. A significant drawback to using electromagnets is their high power consumption. Since we intend to scale StickyBricks down in size, the poor scaling of electromagnetic strength with a change in size is also a consideration.

We are experimenting with several different belt materials. As we alter the stiffness of the belts, we see that the modules exhibit different behaviors in certain scenarios. Stiffer belts reduce the amount of preload needed, for instance, and more flexible belts allow for the traversal of more irregular terrain.

VIII. FUTURE WORK

An obvious drawback of the current StickyBrick design is its two-dimensional nature. A 3D StickyBrick is currently under development. By using dual belts, we can achieve a differential drive mechanism, allowing the belt to turn in place. By adding additional adhesive panels on the two non-drive sides of the “StickyCube,” a stable lattice assembly can be maintained while still allowing for motion. It may be possible to design the additional adhesive panels to be retractable, allowing for the StickyCube to traverse channels only one module wide.

Research is also underway into better materials for the drive belt. Current research into gecko-inspired dry adhesives shows promise, and Sitti’s group [8] is working on the manufacture of microfibers using PDMS. The flexibility of PDMS may make it a suitable material for the belt.

To prepare StickyBricks for further experimentaition, it will be beneficial to remove the tether and provide on-board power. One 700mAh AAA rechargeable NiMH battery will fit next to the motor and provide enough power for up to an hour of experimentation. In addition, simple sensors will help to coordinate motion and planning among the modules. Infrared emitters and detectors mounted along the edges of each module would provide simple communication to keep modules aligned on a grid, and the current crop of Zigbee wireless transmitters could provide for communication to a host PC.

Scaling the modules down in size is a tempting proposition but involves several design challenges. Smaller geared motors are available but become quickly more expensive and less powerful as they’re scaled down. The pitch of the current geartrain is at the limit of the resolution our FDM can produce, so manufactured gears would need to be substituted. These constraints don’t even take into account the power density issues involved in scaling battery systems or electromagnets. This is not to imply that the StickyBricks system cannot be scaled down, just that it is not as straightforward as simply reducing the size of each individual component.

IX. CONCLUSION

The StickyBricks system is an experimental self-reconfigurable robotic system. We have presented the mathematical basis for its design along with details of its construction. Motion of each module in the system is heavily constrained, but appropriate planning enables both targeted reconfiguration and locomotion. The StickyBricks system is novel both for its single-actuator simplicity and extremely low cost per module. Currently, the system is in an iterative stage of design and several important research questions are being examined. We are working to make the system more reliable and better able to traverse varying terrain.

Work on StickyBricks is by no means complete. We have designed and built several prototypes which address questions about feasibility, and more prototypes are necessary to examine other questions that have been raised in the process. We have demonstrated a small robotic module that can locomote using an adhesive belt on its perimeter, and outlined the next steps for development of a successful modular reconfigurable system.

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