Modular Reconfigurable Robots in Space Applications

Mark Yim. Kimon Roufas, David Duff, Ying Zhang, Sam Homans

Xerox Palo Alto Research Center (PARC)
3333 Coyote Hill RD
Palo Alto CA, 94304
yim@parc.xerox.com

Abstract

Robots used for tasks in space have strict requirements. Modular reconfigurable robots have a variety of attributes that are advantageous for these conditions including the ability to serve as many tools at once saving weight, packing into compressed forms saving space and having large redundancy to increase robustness. Self-reconfigurable systems can also self-repair as well as automatically adapt to changing conditions or ones that were not anticipated. PolyBot may serve well in the space manipulation and surface mobility class of space applications.

1 Introduction

Modular reconfigurable (MR) robots are those systems that are made up of many modules that can be rearranged. We are particularly interested in those systems that have many modules and only a few types. In addition, systems that can reconfigure themselves have extra properties that make them desirable. Self-reconfigurable modular reconfigurable systems include [1-6].

1.1 Space requirements

There are a variety of tasks that articulated robots can do in space including: space manipulation (servicing equipment in space) surface mobility (planetary exploration) robotic colonies (outposts that are either self-sustaining, or preparatory for human colonies)[7]. In addition, articulated robots may perform scientific experiments that include sample and return of planetary atmosphere or terrain, testing the composition of the atmosphere or rocks or other tests using arbitrary scientific equipment.

There are three characteristics that may prove advantageous to space missions. 1) **Compactness and Lightness**; the cost of sending equipment into space is coupled with the size and weight. 2) **Robustness**, missions often have only one attempt to succeed (at great cost). 3) **Versatility and adaptability**, in exploration, the environments are inherently unknown, adaptability increases the chance of success.

MR systems made up of repeated, regularly shaped modules can be more easily packed into a space. Since the systems can be arranged into different forms, the same robotic system can be used to perform a large variety of tasks. Rather than sending many specialized tools, one MR system can suffice for most [8].

MR systems also have large redundancy and so may be more robust. There are very many repeated modules so there are many replacements for a failing module. The problem is that as the number of modules increases, the redundancy increases, but the probability of one module failing also increases. The system must have control strategies that exploit a graceful degradation that is robust to a number of failing components. This will have advantages over systems that may fail catastrophically.

MR systems have been shown to be versatile simply by the variety and number of basic locomotion [9,10] and manipulation modes[11].

2 PolyBot Hardware

PolyBot is a modular reconfigurable robot system composed of two types of modules about 5 cm on a side, one called a *segment* and one called a *node*. The segment module has 1 DOF and 2 connection ports. The node module is rigid with no internal DOF and 6 connection ports. So far, experiments with these systems have concentrated on addressing the versatility issue. Future generations will address the promises of robustness and low cost.

There are two generations of PolyBot implemented and a third one in design. Generation 1 is referred to as G1 and Generation 2, G2. The primary differentiator between the two is that G1 is manually configurable and G2 has the ability to automatically reconfigure.

2.1 Generation One (G1)

The G1 module structure is laser cut plastic and is essentially cube shaped. It has one DOF rotating two opposing plates of the cube using commercial off the shelf hobby RC servos as the main drive over +/- 90 degree range.

There are four versions of G1. The first three versions (G1v1, G1v2, and G1v3 being the last) are quick prototypes with modules bolted together along with offboard computation and power. These versions are approximately 7x7x7 centimeters. Gary Haith at NASA Ames used G1v3 as the basis for their Snakebot experiments [12]. Other researchers will be able to use the G1v3 design as it is available for research use by the research community.

Figure 1: A G1v4 module with a communications cable attached. Two of four connection plates are visible. Two AAA batteries are mounted on the backside.

The latest (4th) version, G1v4, carries its own batteries and computational resources, and is approximately 5x5x4. Figure 1 shows G1v4 with 4 connection ports. It needs no nodes as the each module has more than two connection ports. Manually pressing together two ports then twisting, lock the modules together. A short cable installed between each module establishes an RS232 communications bus connecting a PIC 16F877 (a small 8-bit microcontroller) on each module.

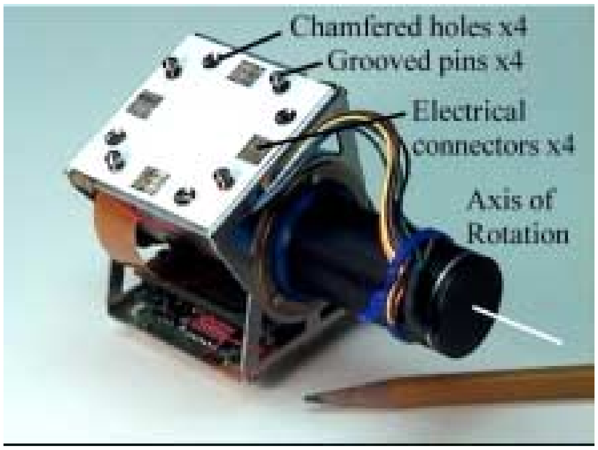

Figure 2: One G1 module showing the connection plate with 4 pins, 4 mating chamfered holes and 4 hermaphroditic electrical connector sets.

2.2 Generation Two (G2)

The segment of the second generation of PolyBot (G2) is shown in Figure 2. It can be divided into three subsystems: 1) structure and actuation, 2) sensing, computation and communication, and 3) connection plate..

2.2.1 Structure and Actuation

The structure is similar to G1 but made of laser-cut stainless steel sheet weighing 416 gms. A brushless DC motor with gear reduction sits in the middle of the segment on the axis of rotation and can generate 4.5 Nm of peak torque. The motor protrudes outside the 5cm cube desired size limit. The gear reduction consumes the most space. In the next generation, G3, a form of harmonic drive may reduce the gearbox size allowing the motor to sit within the 5cm cube.

2.2.2 Sensing, Computation and Communication

Each module contains a Motorola PowerPC 555 embedded processor with 1 megabyte of external RAM.

This is a relatively powerful processor to have on every module and its full processing power has not yet been utilized. The final goal of full autonomy may require the use of these processors and memory.

Hall-effect sensors built into the brushless DC motors serve both for commutation as well as joint position with a resolution of 0.45 degrees. Infrared emitters and detectors, mounted on the connection plate, serve primarily to aid docking but can also be used as proximity sensors. It is planned to include other proximity, tactile, force/torque sensing and possibly a low-resolution CMOS chip-camera on each module in G3.

Each module communicates over a global bus using the (controller area network) CANbus standard. Two CANbuses on each module allows the chaining of multiple module groups to communicate without running into bus address space limitations.

2.2.3 Connection Plate

Each segment has two connection plates. The connection plate serves two purposes; to physically connect and to electrically connect two modules together. Both power and communications are passed from module to module.

PolyBot allows two connection plates to mate in 90 degree increments allowing two modules to act together in-plane or out-of-plane. This multi-way attachment requires the electrical connectors to be both hermaphroditic as well as 4 times redundant.

These connectors were custom made as no commercial hermaphroditic connectors could be found with large enough current capacity and high enough density (1mm pitch). The connection plate consists of 4 grooved pins along with 4 chamfered holes as shown in Figure 2. An SMA actuator rotates a latching plate that catches the 4 grooves in the pins from a mating connection plate.

Each connection plate has 2 photo-diodes and 4 LED’s that are sequenced to allow the determination of the relative 6 DOF position and orientation of a mating plate. This aids in the closed loop docking of two modules and their connection plates [13].

2.2.4 Node

The node is a rigid cube made of 6 connection plates (one for each face). It serves two purposes; one is to allow for non-serial chains/parallel structures, the other is to house higher power computation and power supplies. G2 has high power requirements and was designed to run tethered to a power supply.

3 PolyBot Software

Programming the closed-loop motion and reconfiguration of systems with large numbers of modules can be difficult. The locomotion shown in this article uses a precomputed gait control table. This is essentially a simplified finite state machine for each module with a prescribed sequence of behaviors for each module. It has been shown that gait control tables are an effective way to control large numbers of modules [14].

In one demonstration, PolyBot G2 was tested over an obstacle course while under semi-teleoperated control, one module contains a set of gait control tables which were downloaded dynamically to the modules to perform such actions as turning, reversing direction, altering the speed and amplitude of the sinusoid gait and changing from loop gait to snake gait.

The current architecture for G2 and the future G3 design uses a Massively Distributed Control Network (MDCN) which will extend the CANbus protocol to 100,000’s of nodes using Internet-like mechanisms. On top of this communication layer an Attributes and Services model will be used to coordinate and synchronize data over multiple processes and processors [15].

4 PolyBot Capabilities

PolyBot has demonstrated a variety of capabilities including a variety of locomotion and manipulation tasks and the ability to reconfigure between several different configurations.

4.1 Loop configuration

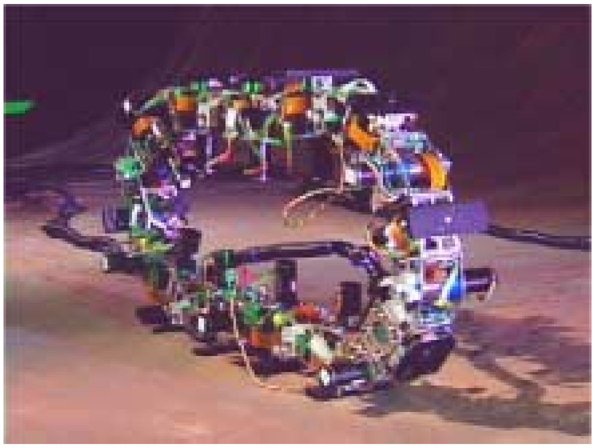

Figure 3: A loop of 23 G2 modules using rolling track locomotion.

Figure 3 shows the G2 modules in a loop configuration that rolls like a tread. Just as a wheeled style of locomotion tends to be more energy efficient than legged ones, this gait is the most efficient gait we have tried. Some initial tests with 10 G1v4 modules mounted with common off the shelf batteries led to about 0.5 kilometer (about 2000 body lengths) travel on one charge. It is expected that further optimizing the motion as well as improving the battery technology would drastically increase the range.

This gait is well suited to moving on straight, flat terrain and even climbing, some structures, however it is susceptible to tipping over if moving laterally across a slope.

4.2 Snake configuration

Figure 4: A snake-like sinusoid gait. The travelling wave causes forward locomotion.

One of the first configurations attempted is the snake or linear concatenation of modules as shown in Figure 4. This configuration is easily extended to an arbitrary number of modules without complicating the control.

Essentially, these motions are achieved by propagating a waveform traveling down the length of the chain. Almost any waveform will result in some locomotion. Figure 4 shows G2 with a joint-space sinusoid waveform. Using a G1 based design NASA Ames developed a sidewinder snake gait that uses lateral motion as well as other gaits.

4.3 High Mechanical Advantage

By using closed chain configurations of PolyBot, the system can be brought into configurations in which the Jacobian of the robot's motion relative to its joint space becomes singular. In these positions the system has very large mechanical advantage. Using this in conjunction with a locking mechanism large forces may be applied over large distances [16].

4.4 Reconfiguration

Figure 5: A four-legged spider-like configuration with G1 modules.

PolyBot has demonstrated reconfiguration going from a loop form to a snake form to a spider form shown in Figures 5. The loop to a snake is relatively easy as the robot simply detaches at one point (like falling apart). The snake to the spider is more difficult as the two ends of the snake dock with a point at the center of the robot forming a figure-8. It then detaches at the top and bottom of the figure-8 forming 4 legs. The automatic docking process uses IR emitters and detectors to guide the docking process [13}.

5 PolyBot Space Applications

Since PolyBot is very general in its construction, it could essentially be used in any application where an articulated robot could be used. However, we will focus on two, space manipulation and surface mobility.

5.1 Space manipulation

This task is well suited for PolyBot since space is relatively “clean” and gravity free. The system does not need to worry about dirt or dust or mud interfering with the connection mechanisms. For single open chain snake-like robots, the robot’s own weight is one of the major limitations in what it can do. Gravity-free environments greatly increase the torque-limited range of motion for these configurations.

The general versatility of the system should lead to cost savings as mentioned earlier as well as increased capability. Since most of the operations in space are happening for the first time, unexpected needs may arise. MR robots can be reconfigured to suit the need. For example, if a longer reach on a robot is needed for a space station maintenance operation, more modules may appended in a long chain. If more torque or force is needed to manipulate a satellite in space but not more reach, the robot may be reconfigured into many parallel arms.

Aspects of manipulation in space that need to be addressed include inverse kinematics algorithms, applying large forces and torques where needed and for large space structures traversing over the structure.

Inverse Kinematics For hyper-redundant arms that MR systems can form, inverse kinematics is one of the interesting problems. There are a variety of solutions to this problem. Many involve fitting the robot to a “back-bone” curve [17]. Other solutions that have been applied to PolyBot include a brute force constrained optimization technique that incorporate both joint constraints as well as torque constraints [18] as well as a method based on dextrous workspaces formed by sub-chains [19]. The latter solution is relatively fast and easily made computationally distributed.

Large forces and torques By exploiting the large mechanical advantage formed near singularities as described earlier, the system can apply large forces to arbitrary positions. The internal forces and the modules own weight under gravity are some of the main limitations of using the high mechanical advantage method. Here weightlessness in space is clearly advantageous.

Traversing space structures Supporting large space structures either by helping to construct or by maintenance, robot systems have been proposed to traverse the structure by docking and undocking into ports that are situated regularly over the structure. The robots would use these ports somewhat like a rock climber uses hand-holds. Since docking is one of the innate abilities for modular reconfigurable systems like PolyBot, it should be straightforward to unify the docking ports so that both the robot and the structures use the same physical and possibly electrical configurations.

5.2 Surface Mobility

Another promising application is surface mobility for planetary exploration. The versatility of the MR systems allows it to be able to traverse a very wide range of terrain and overcome a large variety of obstacles.

5.2.1 Climbing over obstacles

One type of obstacle is a step. The size of the step relative to the size of the robot is one way to measure the difficulty of the obstacle. For example, normal human stairs are roughly 20 cm high, and a human maybe 200 cm tall which translates to an obstacle 0.1 body lengths.

Figure 6: A loop configuration conforming to terrain as it climbs stairs,

Moving down stairs in an uncontrolled fashion is a relatively easy thing to do. The snake-like configurations achieved this with some control by having some compliance within the system to somewhat take the shape of the terrain as it traversed it. Climbing up stairs is more difficult given the actuator limits of serial chains. Figure 6 shows the loop configuration climbing stairs. In this case, the robot again takes the shape of the terrain (each step) as it climbs. Having a closed chain allows a parallel effort relaxing some of the actuation requirements. The steps are roughly 0.5 body lengths for the given configuration.

5.2.2 Climbing porous surfaces

By adding short spikes to the bottom of some modules, the G1v4 modules were able to climb porous surfaces as shown in Figure 7. The spikes grab onto porous material (like a chain-link fence, a tree or a ceiling tile as in the figure), then climb up in a similar way that caterpillars or inchworms climb.

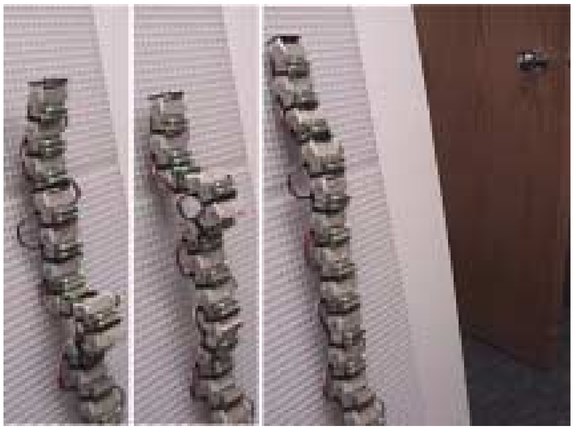

Figure 7: Caterpillar locomotion climbing a near vertical porous material (ceiling tile)

5.2.3 Constrained motion

The snake form is particularly well suited for locomotion through highly constrained environments. In very rocky terrain such as found at the bottom of a rockslide, locomotion may be difficult. These areas may also provide particularly interesting areas for geologists. The G1 PolyBot prototypes were shown to be able to maneuver through a pile of wooden pallets and even through a 10cm diameter aluminum tube (just 1.4 times the body width).

5.2.4 Other considerations

One of the issues that MR systems must overcome is dealing with environmental hardening. If the system is to reconfigure, the connection ports must be robust to dust and dirt and other contaminants. Self-wiping connectors and proper sheathing of the modules are some steps toward this.

While it is clear that the rolling track or loop gait is very much more power efficient than others, it still may not be efficient enough. Some NASA studies indicate travel up to 10 kilometers for some tasks and 100’s kilometers for others [7]. Portable and renewable power continues to be a major development area.

5.3 Digging

Using the high mechanical advantage from parallel systems and the ratcheting mechanism, Polybot can be used for digging or moving rocks. Digging or uncovering layers of a planetary or cometary surfaces could be of key interest to planetary geologists. If this functionality is scaled up (either through larger modules, larger number of modules, or with longer term operation) it may also be useful in the preparation of terrain for the establishment of bases.[7]

6 Summary and Conclusions

PolyBot is a modular reconfigurable robot that can self-reconfigure. Several versions of the hardware have been developed and experimented with. The experiments have shown that PolyBot has many characteristics that are well suited to do many of the tasks that are required for space exploration including space manipulation and surface mobility. PolyBot can use energy efficient modes of locomotion as well as modes that can overcome large obstacles or squeeze into tight places.

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