

# **Modular Robots- Enhancement in Robotic Technology by the development of Segmented Reconfigurable High-Utility Robots**

**Rustam Sengupta & Ankit Gupta**

Faculty of Engineering, DEL,

Dayalbagh, Agra-282005

[rustam@thesenguptas.net](mailto:rustam@thesenguptas.net)

[ankit81@epatra.com](mailto:ankit81@epatra.com)

## **Abstract**

Conventional Robots have always been thought to be humanoid in form or as advanced computerised machines working on the shop floor. This has been so because the tasks given to the robot have been predefined and the terrain predictable and helpful. But in cases where both mission and geography are unknown, their ability to change in shape could be of very great value, since they could adapt to constantly varying tasks and systems. Modular reconfigurable robots- experimentally made by interconnecting multiple, simple, similar units- can perform such shape shifting. Imagine a robot made up of a chain of simple hinge joints. It could shape itself into a loop and move by rolling like a self-propelled tank tread; then break open the loop to form a serpentine configuration and slither under and over obstacles; and then rearrange its modules to “morph” into a multilegged spider, able to stride over rocks and bumpy terrain. Such type of high utility robots are being developed in many research labs around the world, one already in the experimental stage is the one at Xerox Palo Alto Research Center (PARC), in California. It is postulated that systems of this kind would be useful for remote autonomous operations, particularly in hostile environs such as under the sea, at a scene of natural disaster and on other planets. This paper tries to externalise the development in design and technology of such modular robots, and also highlight their various applications.

## Introduction

**Modular Self-reconfigurable (MSR) robotics** is a new technology with the potential to significantly expand the domain of robot applications. The key characteristic of MSR robots is their ability to change configuration automatically, enabling them to adapt their shape to suit multiple, changing tasks. The underlying design philosophy is to build complicated systems from a varying number of basic units, or modules. Modular reconfigurable robots are built from tens to hundreds, and potentially millions of modules. Instead of designing a new and different mechanical robot for each task, many copies of one simple module are built. The module can't do much by itself, but when connected together a system that can do complicated things can be obtained. In fact, a modular robot can even reconfigure itself -- change its shape by moving its modules around -- to meet the demands of different tasks or different working environments. Modules have degrees of freedom and share standard connection interfaces allowing them to attach and detach from one another. This makes them capable of re-arranging their positions and connections within the robot, to transform the overall configuration. These are like cells in a human body; are few in types but many in number. Such robots are n-modular systems (where n is the number of module types.) An n-modular system holds three promises: versatility, robustness, and low cost. Its versatility stems from the many ways the modules can be connected. The same set of modules could be connect to form a robot with few long thin arms and a long reach or one with shorter arms that could lift heavy objects. For a typical system with hundred of modules, there are usually millions of possible configurations, with can be applied to various tasks. But to put together a useful system, solutions must be found to the complexities of programming great many coupled but independent robotic units. The more the modules are added the tougher the programming gets tougher. Self-reconfiguration introduces a difficult planning problem as the number of modules (and degrees of freedom) in a robot increases. A practical solution would automatically generate a sequence of module operations necessary to transform one configuration into another. This involves planning for the connectivity changes and motion trajectories of every module, while taking account of restrictive motion constraints. Adding to the difficulty is the fact that even though all MSR robots share the same design and operating principles, particular module hardware designs result in strikingly different approaches to reconfiguration. To date, few solutions have been proposed, and no practical algorithms exist yet for some categories of MSR robots. Other problems include controlling and coordinating modules to work together effectively and not collide or otherwise interfere with each other. The system should also be able to repair itself and shed crippled units. Besides, economic conditions dictates that the cost should be low that is the modules can be mass-produced.

## Development of Reconfigurable Robots

Modular, self-reconfigurable robots show the promise of great versatility, robustness and low cost. This paper presents examples and issues in realizing those promises.

Modular Robotics can be broadly charted out to have clearly defined generations or developmental stages. The initial development of modular robotics can be attributed to have one of its origins in the Xerox Palo Alto Research Centre or XeroxPARC. Their modular Robot was named the PolyBot its features as well as characteristics have been constantly enhanced in the subsequent generations.

### **Predecessor to PolyBot : The PolyPod**

PolyPod was a bi-unit modular robot. This meant that the robot was built up of exactly two types of modules that were repeated many times. This repetition made manufacturing easier and cheaper. Dynamic reconfigurability allowed the robot to be highly versatile, reconfiguring itself to whatever shape best suits the current task.

### **The PolyBot**

PolyBot is a modular, self-reconfigurable system that is being used to explore the hardware reality of a robot with a large number of interchangeable modules. Three generations of PolyBot have been built over the last three years, which include ever increasing levels of functionality and integration. PolyBot has shown versatility, by demonstrating locomotion over a variety of terrain and manipulating a variety of objects. PolyBot is the first robot to demonstrate sequentially two topologically distinct locomotion modes by self-reconfiguration. PolyBot has raised issues regarding software scalability and hardware dependency and as the design evolves the issues of low cost and robustness are being addressed while exploring the potential of modular, self-reconfigurable robots.

### **Generation 1**

The first generation of PolyBot has the basic ideas shared in all the generations of repeated modules being about 5 cm on a side. The modules are built up from simple hobby RC servos, power and computation are supplied offboard. The modules are manually screwed together, so they do not self-reconfigure. The G1 modules showed the first instance of simple reconfiguration for locomotion in 1997.

#### *PolyBot G1 Design:*

There are two structural parts to each module, made from laser cut plastic sheet. Various plastics were tested (acrylic and ABS) and finally delrin for the g1v3 version was selected. The modules were screwed to their neighbors with bolts in the four corners. Each face was square so that modules could be attached at 90 degree increments allowing motion all in-plane or out of plane if desired. The two parts were rotated relative to each other by a standard hobby servo. Servos from FMA direct(S355M) which have an output torque of 114 oz-in and fit well in the form factor were employed. Power (6V) and control signals were provided offboard in this version. The current required could be up to 500mA per module. Using a 68HC11 microcontroller to generate the PWM servo control signals and interpret a higher level joint angle commands sent to it from a PC by RS232. A later solution was to use the miniSSC, a serial servo controller. Note, that external control and power makes cabling and a wire harness a painful necessity. The design was

fairly straight forward to construct from off the shelf parts and laser cutting is available from many plastics shops.

#### *Uses and Characteristic Features:*

The modular configurable robots by virtue of using sensor to conform to the terrain can flow over obstacles and even climb stairs. Since it is not rolling like the wheel to can make tricky and sharp turns. This is exhibited by the various gaits of the robot. The snake like gait excels at travelling over or through obstacles; a linear set of modules can stretch longer distances than can a non-linear form so as to cross small ditches or go down steps. Using a snake configuration and up to 32 modules, polybot has been seen to experimentally overcome a variety of obstacles, including crawling through 10cm aluminium pipes, up 30 degree ramps, over loose debris and wooden pallets.

**First Loop to Snake Reconfiguration** - PolyBot demonstrated two topologically distinct locomotion modes sequentially by self-reconfiguration. This action was the first two steps of this visualization from 1995. The reconfiguration did not require docking, the system had to simply disconnect one connection port. The significance, however, is not diminished as an existence proof that multiple tasks can be accomplished through closed-chain reconfiguration.

**Locomotion in tubes** - Using a snake-like undulating travelling wave gait, the robot climbed into and out of a 4" diameter ducting pipe. This was part of locomotion through a general rubble pile of wooden pallets.

**4-legged spider** - For uneven and uncertain or rocky terrain a 4-legged spider configuration was employed. A 4-legged spider configuration walks somewhat like a person on crutches, two legs moving at a time. This gait was actually more like a shuffle. Two legs moved at a time; the front and back reach forward while the sides balance the robot, then the front and leg balance while placing the side legs forward.

**Snake-like turning** - Two clear certain obstacles certain freedom of movement was essential this was provided by the polybot by exhibiting a characteristic snake like turning action hence there were some initial tests on gaits that turn. After several tries, it turns out the most effective way for short to medium length chains is to form arcs of circles over the whole robot.

**Multilegged Walking Platform** - To build a multilegged walking platform with up to 12 legs, one-, two-, and three-module legs are attached to the bottom of a rectangular plate. When the walking platform is turned upside down, the correlation between locomotion and manipulation is revealed; the legs become fingers that can move balls, boxes, paper and other objects. Using an inchworm-like gait, Polybot G1v4 (version 4) has climbed nearly vertical porous materials ( like tree or ceiling tile ) by using a short spike attached to the bottom of some modules. The robot lifts the rearmost spike and inserts it at a higher point than the next-nearest spike and so on, in a wave travelling from tail to its head. A similar method is used to climb vertical chain-link fences, but with hooks instead of spikes attached to the modules. Besides to make it more versatile, modular robots can be made to mimic human body parts like the hand and the foot.

## **Generation 2**

The second generation of PolyBot is actually just a stepping stone to get to the third generation of PolyBot. The largest functional difference is that G2 modules have the ability to automatically attach and detach from each other, making the system self-reconfigurable. In addition to the ability to reconfigure, these modules are much stronger and carry much more computational power.

#### *Polybot G2 Module Design:*

G2 is made of just two types of cube shaped modules: a segment that has just a hinge joint between two hermaphroditic connection plates, and a node, which doesn't move but has six connection plates. Most of the functions depend on the hinged segment, which produces the

robots movements, whereas the nodes job is to provide branches to other chain of segments. Structurally, each segment is roughly the size of a cube about 5cm on a side and has one motor that rotates the hinge. The two connection plates on either sides of the hinge join it to the other modules both electrically as well as physically. The MicroMo gear motor, although heavy is quite powerful delivering up to 5.6Nm of torque at 60 RPM and the stainless steel sheet structure has a range of motion of +90 to -90 degrees. The two connection plates on either side of the module are identical, hermaphroditic and have a 4 way rotational symmetry. Any two connection plates may be attached together at 90 degree increments. Four grooved pins enter four holes and are grabbed by a latching mechanism that is released by a shape memory alloy actuator. Each face has a 4 times redundant custom made hermaphroditic electric connectors to enable power and communications to be passed from module to module.

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, Each module communicates over a semi-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.

The G2 has two kinds of sensors; position sensors to determine the angle between the two connection plates, and proximity sensors. The first are Hall effect sensors, which measure voltage induced by magnetic flux to determine the motor's angle with a resolution of 0.45 degrees. These also serve for commutation and are built into the segment's 30-W brushless DC motors, which can generate 4.5 newton-meter of torque. The proximity sensors are infra-red detectors and emitters mounted on the connection plates. They serve primarily to aid in docking two modules but can also be used to help the robot maneuver in tight places.

#### *Characteristic Features:*

**Fully Automatic Docking** - Here for the first time in the G2 modules docking and undocking was fully autonomously. Guidance was aided by a light intensity based measurements. Shape Memory Alloys latch and unlatch the modules.

**Deployable Video Camera** – The robot has a video camera attached to it which increases its ability of better job performance. It can provide information to a user who is controlling the robot remotely. PolyBot is also capable of detaching and deploying the camera - ideal for reconnaissance of denied areas.

### **Conro System**

In the Conro system, built at the Information Sciences Institute at the University of Southern California, in Marina del Rey every module is like every other, with two small hobby servomotors that actuates right angled hinged joints controlled by an 8-bit microcontroller. The modules communicate with their neighbours through an infra-red interface. Rather than hermaphroditic connection plates, Conro's modules have three male connectors at one end and one female connector at the other. A system like this will easily form a tree structure as well as a structure with a single loop.

### **Generation 3**

The third generation of PolyBot is currently under construction. Much of the mechanical hardware for 180 segments and 20 nodes has been built. Electronics have been designed and prototyped and software is in development. The goals for this large batch of modules are to demonstrate locomotion with large configurations and reconfiguration between configurations.

The target form factor for G3 was a 5 centimeter cube. The G3 module is actually a bit smaller at 50 x 50 x 45mm. The main drive was custom designed and built. It uses a modified Maxon 32mm diameter brushless pancake motor as the source with a 3.75:1 planetary gear stage between the motor and the size 8 100:1 harmonic output stage. This new main drive weighs only 70 grams compared to G2's 300 grams bringing the total module weight down from 450 grams to about 200 grams. The G3 drive should deliver 1 Nm of torque and the machined aluminum frame has a range of motion of +90 to -90 degrees. In addition, an actuated roller ratchet will provide 10-15 Nm of braking in either direction.

The two connection plates on either side of the module are identical, hermaphroditic and have a 4 way rotational symmetry. That is, any two connection plates may be attached together at 90 degree increments. To connect the plates four grooved pins enter four holes on the opposing plate and are grabbed by a latching mechanism that can be later released by a shape memory alloy actuator. Each face has 4 times redundant custom made hermaphroditic electric connectors to enable power and communications to be passed from module to module. Each face also has four IR LEDs and sensors for face to face docking during reconfiguration and rudimentary module-to-module communication. This communication is used during initialization by the robot to discover its configuration.

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. Each module communicates over a local bus within chains of segments using the (controller area network) CANbus standard. The six sided nodes will have switching and routing capability to pass messages from segment chain to segment chain.

In G3, the sensing includes the hall-effect sensors built into the brushless DC motors serving both for commutation as well as joint position with a resolution of 0.04 degrees, an absolute joint angle sensor (custom potentiometer), four accelerometers (one redundant, but can frequently be used for joint angle sensing) for measuring orientation relative to gravity and potentially contact bumps, contact whiskers, and low resolution force sensors on the interface pins. In addition, due to the placement of the IR components on the G3 interface plates, these components may also be used for proximity sensing.

## Three Types of Reconfigurable Robots

Robots that can change shape can be classified in terms of how they do so, They are built for chain, lattice, or mobile configurations. The chain kind make themselves over by attaching and detaching chains of modules to and from themselves, with each chain attached to rest of the the modules at one or more points. Nothing ever moves off on its own. The chains may be used as arms for manipulating objects, legs for locomoting, or short tentacles for both locomotion as well as manipulation. Xerox Palo Alto Research Centre (PARC) is focusing on this class, which has found to be the most versatile. A chain robot has already demonstrated locomotion by rolling like a tank tread, climbing stairs, slithering like a snake, climbing like a caterpillar, and walking like a spider.

Lattice robots change shape by moving into positions on a virtual grid, or lattice. They are like pawns moving on a chess board, except that this board has three dimensions. As with chain robots all modules remain attached to the robot. Planning and control issues become less complex when the modules have to move only to the neighbouring positions within a lattice instead of any arbitrary position. The robot needs to only deal with what is occupying the limited number of neighbouring positions in the lattice: for example, four positions for a module that moves on a flat square grid. With its less demanding programming, this class currently has the most research groups working on it, including ones at Dartmouth University, in Hanover, N.H.; Cem Usal at Carnegie Mellon University, in Pittsburgh; and Greg Chirikjian at John Hopkins University in Baltimore, Md.

Mobile self-configurable robots change shape by having modules detach themselves from the main body and move independently. They then link up at new locations to form new configurations. This type of configuration is less explored than other two because the difficulty of reconfiguration tends to outweigh the gains in functionality.

## Programming Perplexities

Programming the movements of n-modular systems is a struggle. As the number of modules grows, the complexity of many of the computational tasks explodes. At the same time though, because each module has its own computer, the computational resources increase but only linearly. Further complications accrue from increases in the number of module types, the distributed nature of resources, constraints posed by torque limits of the motor, failing modules, and limited communication bandwidth. To keep confusion at bay, three control techniques are being used: gait control tables, unusual messaging method, and a hierarchical organization.

A gait control table stores precomputed motions for reference. Simple open-loop control instructions coupled with the mechanics of the configuration suffice many of the capabilities demonstrated so far, including the snake, loop, and spider gaits. Most often one module contains the gait control tables which are downloaded by other modules as and when required.

An alternative to gait control tables is the message passing method developed by the University of Southern California's Information Sciences Institute. The novel technique is modelled in the way a single hormone may produce a variety of responses throughout the body. Rather than specific instructions sent to each module, a single message flows through module to module. It is modified by some of them as it passes through them and therefore sends dissimilar messages to and

produces different effects on other modules. The state of module to which the message is passed—the joint angle for instance dictates whether and how the message is altered. The same message could change the motor angle in the first, not change in the next and deleting itself in the third.

Another way of simplifying programming, which is well suited to chain type robots, is to divide the robot into hierarchical portions, rather as a finger, hand and arm form a hierarchy within the body. Such an organisation simplifies programming. Because the motion of the modules between the smaller virtual modules matters less.

## Conclusion

Modular robots should have the most impact on those tasks which need versatility. Explorations of distant planets could be just the thing. Its inherently unknown aspects demands that the system adapt to unknown situations. Urban search and rescue in buildings badly damaged by an earthquake or a bomb is another promising application. The first two generations of Modular Robots have shown some of the versatility possible with these systems, most notably is the use of self-configurability to adapt to changes in the environment or the task. Newer generation robots are being constructed to explore other issues. To solve the complexities arising with sophisticated new robotic designs, engineers are looking forward to biology and see how nature solves the same problems of control, self-repair and efficiency.

## *References:*

1. ***“Modular Robots: Change shape to Conquer Task and Terrain”*** *IEEE Spectrum*- Feb 2002
2. ***“Modular Robotics”*** Xerox Palo Alto Research Centre (Xerox PARC)
3. ***“Massively Distributed Control Nets for Modular Self-Reconfigurable Robots”***, Y. Zhang, M. Yim, K. Roufas, C. Eldershaw, accepted to 2002 AAAI Spring Symposium on Intelligent Distributed and Embedded Systems.
4. ***“Reconfiguration Planning for Modular Self-Reconfigurable Robots”*** , A. Casal, PhD Thesis, Stanford, 2002
5. ***“Evolution of PolyBot: A Modular Reconfigurable Robot***, D. Duff, M. Yim, K. Roufas, *Proc. of the Harmonic Drive International Symposium, Nagano, Japan, Nov. 2001, and Proc. of COE/Super-Mechano-Systems Workshop, Tokyo, Japan, Nov. 2001*
6. ***“Modular Reconfigurable Robots in Space Applications”***, M. Yim, K. Roufas, D. Duff, Y. Zhang, S. Homans, *10th Intl. Conf. on Advanced Robotics Budapest, Hungary, Aug. 2001*
7. ***“Modular Reconfigurable Robots, An Approach To Urban Search and Rescue”***, M. Yim, D. Duff, K. Roufas, *1st Intl. Workshop on Human-friendly Welfare Robotics Systems, Taejeon, Korea, Jan. 2000*