CLIMBING WITH SNAKE-LIKE ROBOTS

Mark Yim * **Sam Homans** * **Kimon Roufas** *

* *Xerox Palo Alto Research Center, Palo Alto, CA, USA 94304*

Abstract: This paper presents an implementation of a long serial chain robot that can climb stairs in a "snake-biting-its-tail" loop form, climb up ramps using a travelling wave gait and by adding small spikes or cleats, can also climb near vertical porous materials. The gaits are controlled with a *gait control table* which is a simple but powerful way to coordinate the motion of many degrees of freedom. The gaits are implemented on PolyBot G1v4, a self-sufficient modular reconfigurable robot with onboard power, computation, sensors and actuators.

Keywords: modular, self-reconfigurable, robot control, finite state machine

1. INTRODUCTION

Long serial chain robots with many degrees of freedom (DOF) have a variety of applications including inspection robot arms, snake-like locomotion (Hirose and Morishima, 1990; Chirikjian and Burdick, 1995; Klaassen and Paap, 1999) for planetary exploration or search and rescue. While robotic snake-like locomotion over flat terrain has been studied extensively, using the snake form to climb stairs or walls has been less evident. Climbing over obstacles is clearly a useful ability for tasks such as exploration or search and rescue over unstructured terrain and even structured terrain with stairs or curbs etc.

This paper presents two modes of climbing using PolyBot (Yim *et al.*, 2000), a modular reconfigurable robot. Although PolyBot can assume many configurations (arbitrary number of limbs, or loops) this paper will examine only a single serial chain. The first implementation is an extension of a travelling wave style of locomotion extended to climb porous surfaces, such as tree-bark or styrofoam by placing spikes or cleats on the contact points of the robot. The second implementation uses a closed serial chain (a snake biting its tail) to roll up stairs while conforming the surface features.

2. POLYBOT G1V4

PolyBot is a modular reconfigurable robot. Modular reconfigurable robots promise to be extremely versatile, self-repairing and low cost. These systems are made up of many repeated simple modules that can be arranged in many different configurations including snake forms, spider forms, human forms etc. There are several versions of PolyBot as can be seen in (Yim *et al.*, 2000), however this paper uses primarily the G1v4 version in a single serial chain.

2.1 *G1v4*

G1v4 modules have one degree of freedom, carry their own power (two AAA NiMH batteries), their own intelligence (Microchip Technologies PIC 16F877, an 8-bit, 20Mhz RISC processor with about 8K words of memory) and have 4 connection ports or mating plates. A PolyBot G1v4 module is pictured in Figure 1. The actuator is a commercial off the shelf RC hobby servo that has 775 mN-m of torque capability. Each module weighs 124 grams and is approximately 55x58x48mm.

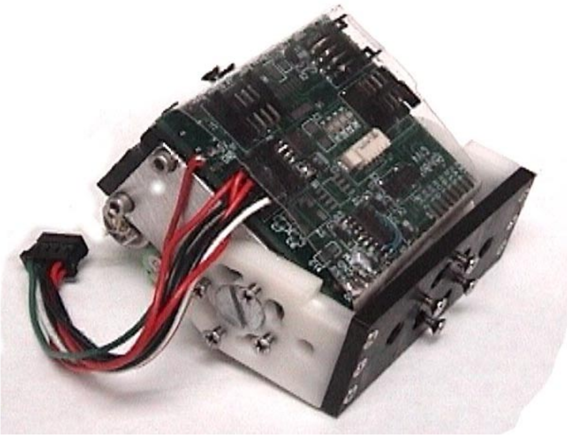

Fig. 1. A G1v4 module

Two modules are attached together by pressing the mating plates together and twisting. An additional cable is attached to one of four connectors on each module for all of the attached modules to pool their power resources and to provide a serial bus. This bus is global running at 19.2kbaud with an 8-bit address space allowing up to 255 modules to communicate on one bus.

Typically, the system is run in a master - slave mode, where a master computer (usually another PIC 16F877) commands all of the modules as slaves.

2.2 *Gait Control Table*

In both climbing instances presented later in this paper, a gait control table (GCT) is used to control the robot (Yim, 1994; Yim, 1993). In these cases, the control is an open loop pattern of motion imposed on the modules (no sensing other than internal joint angle is used). An example is shown in Table 1 where the elements of the table correspond to desired joint angles, shown in degrees, for each of the modules (columns) at each step (rows). At the start, the robot starts with the joint angles corresponding to the first row of the table. Each module then uses closed loop control to move their joint angles at a constant speed to the joint angle in the next step (the next row of the table). Once the desired angle is reached, each module moves to the value in the next step of the table. When the end of the table is reached, the cycle starts over at the top.

Table 1 is the GCT for the snake-like robot in Figure 2 that has a travelling wave of alternating arcs of circles. Each module is numbered from one end of the chain to the other. Since the entries in the table are in joint space, equal values (15 or -15 degrees) in horizontally connected cells make those corresponding modules approximate an arc of a circle. Between the first and second step of the table, there are only three modules which move, module's 1, 5, and 9. The next step has the adjacent modules moving, 2, 6, and 10. At any one time only three modules move. The travelling wave can be seen graphically by the diagonal pattern in the table.

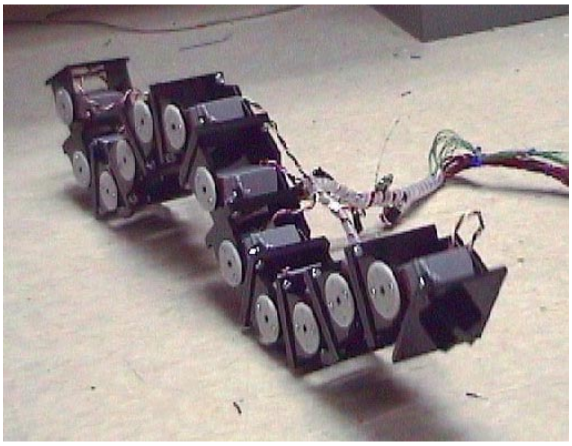

Fig. 2. G1v1 modules using the travelling arc wave gait.

The GCT is a very general method to coordinate the motions of large numbers of modules in a simple fashion.

3. SLOPE/WALL CLIMBING

A significant amount of research on the control and kinematics of undulatory snake-like and inchworm or caterpillar-like locomotion has been studied. These include (Fukushima and Hirose, 1996; Chirikjian and Burdick, 1995; Burdick *et al.*, 1995; Ostrowski and Burdick, 1996; Kelly and Murray, 1995). Some of the standard gaits may be used to climb slopes of varying degrees depending on the ability of the robot to grip the surface. It is useful to first examine how some of these methods might be used to climb up slopes. In particular the PolyBot G2 used a travelling wave gait to traverse up slopes about 30 degrees when the surface was covered with a ribbed rubber mat and the surface contact points of the robot were coated with rubber. This is shown in Figure 3.

Almost any wave form can be used in a travelling wave to result in locomotion. The waveform used in the Figure 3 can be described by Equation 1

$$\mathrm{entry}(i, \mathrm{step}) = A \sin(\omega \mathrm{step} + Ci) \qquad (1)$$

where i is the column of the GCT and step is the row, A is the gain on the wave amplitude, ω is the desired speed of the travelling wave and consequently the speed of the travel of the robot, C is a bias curvature over the whole robot used if the robot needs to raise or lower its head to conform better to climbing up or over something. The combination of the constants A, ω and C

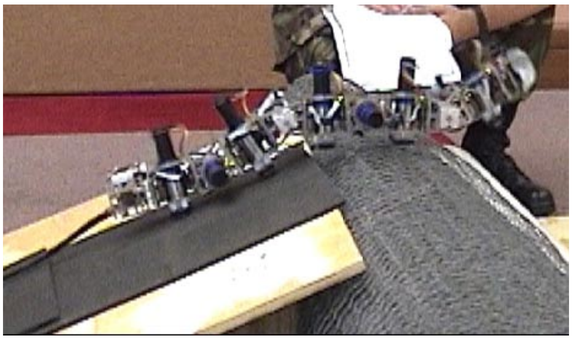

Fig. 3. PolyBot G2 9-module chain climbing a ramp and over chicken wire using the travelling sinusoid wave gait.

is not always straight forward or intuitive. In some instances, for example with large A, the direction of the motion is not always clear. One set of constants which worked for the climbing implemented in Figure 3 and the resulting table is shown in Table 2.

3.1 *Caterpillar Climbing*

For climbing vertical porous materials, the travelling wave gaits above turn out to be inappropriate. The approach used in this paper is to place spikes on every fourth module which will make contact with the terrain. These spikes dig into the surface that it is climbing. They are angled slightly downward so they don't enter the surface perpendularly. This helps to keep the spikes from slipping out. Many of the standard serpentine gaits will not work for climbing with spikes depending on the approach and departure motion of the points of contact near the surface.

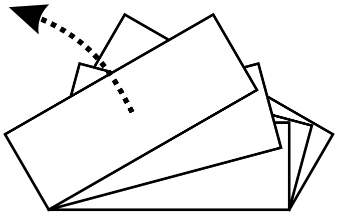

Fig. 4. Illustration of a foot making contact using a travelling arc gait.

Figure 4 shows the motion of the foot as it contacts the surface for the travelling arc gait. Since the wave form is arcs of circles, the motion of modules near contact with the ground is similar to a wheel rolling on the ground. This means that if spikes were added, they would have a rotational component to their movement which may not be optimal. The spikes may jam in the surface material, or the material may be gouged out, reducing the ability to grip the surface with the corresponding loss of surface integrity.

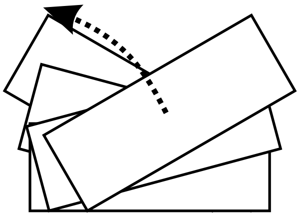

Fig. 5. Illustration of a foot making contact using travelling sinusoid gait, note the bottom scrapes to the right while the robot moves to the left.

Figure 5 shows the motion of the foot as it contacts the surface for the travelling sinusoid gait. As the foot makes contact with the ground, it scrapes backwards on the ground since the other ground contact points do not move at the same speed. Here the spike's gouging or jamming effect would be even worse for climbing than the travelling arc method.

Fig. 6. A caterpillar climbing a tree. The rear feet move first progressing up.

A more desireable motion is for the spikes to approach the surface along the axis of the spike and to depart in the same line. To attain this motion, a gait similar to the way a caterpillar climbs is used as in Figure 6. A caterpillar first moves its rear feet upward to grab a surface, then the next pair move to grab the surface. Each foot pair moves in turn from rear to front. These independent leg motions are implemented with the gait control table in Table 3.

This motion results in foot contact motion that is illustrated by Figure 7. Here a group of modules form a "hump" which disengages the spike from the porous material. This hump then moves the spike forward to re-engage the material at a higher position.

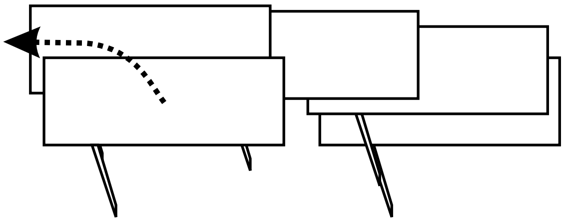

Fig. 7. Illustration of a foot making contact using caterpillar gait.

The images in Figure 8 show the robot climbing a ceiling tile grating, a rigid plastic grid. This method should easily be extended to climb chain-link fences and other porous materials such as soft wood or bark.

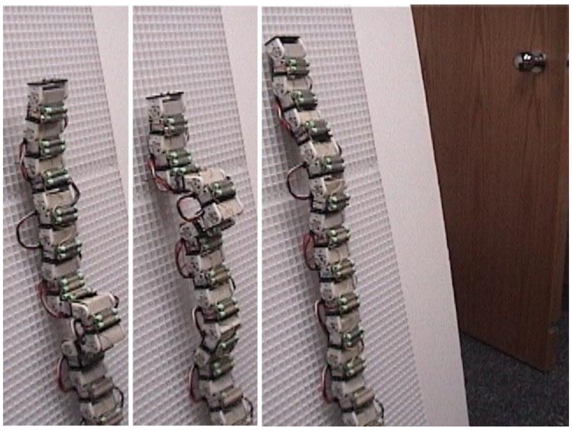

Fig. 8. The caterpillar gait. Note the moving foot (the hump) moves from the bottom to the top of the robot.

4. STAIRCLIMBING

For small robots like PolyBot with modules about 5cm's on a side, normal stairs have about 17cm's high steps and can pose as a significant obstacle. While a chain of modules can theoretically climb stairs using the same snake-like gaits described above, practically, the actuator limitations make this difficult.

The torque limit for one G1v4 module will allow it to support 3 modules in a cantilever fashion. This would allow the top module to reach about 16cm high. There are methods to minimize the lever arm required to lift modules to a vertical position (Nilsson, 1997), however to gain enough height to not only reach the top of a step but to gain a foothold as well as progress up the step is difficult. It is not immediately apparent how to apply the travelling wave gait with these methods to achieve forward progress up stairs.

Closed chains (like a snake biting its tail) on the other hand allow modules to divide the torque requirements between multiple modules exploiting the closed chain constraint. In addition, a gait is straight forward since progress can be achieved by rolling up the stairs.

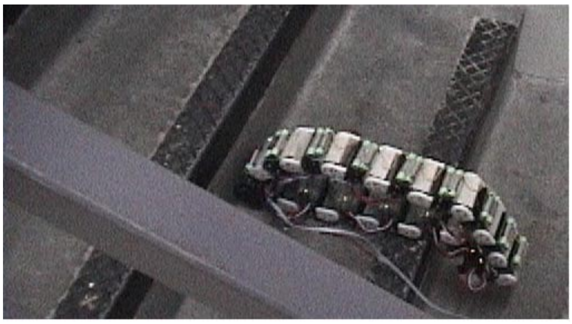

Fig. 9. Stair climbing in the loop form, on one step.

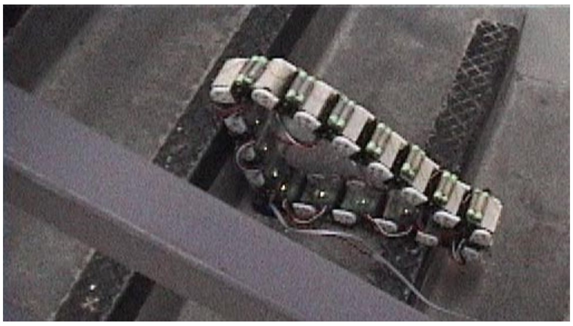

Fig. 10. Stair climbing in the loop form, reaching the next step.

Fig. 11. Stair climbing in the loop form, climbing up the next step.

In Figures 9- 11, a loop of 17 modules can be seen climbing over the corner of a step. While the GCT could have been implemented in a distributed fashion among the computers on each module, instead a cable supplies commands from a GCT residing on a laptop (not shown). These modules contain their own power and have the ability to climb many flights of steps on one charge, however it has only been tested on one flight (approximately 10 steps) so far due to cable length limits.

Part of the GCT for climbing stairs is shown in Table 4. A dash in an entry in the table indicates that the servo runs in a compliant mode. Since the robot has an additional closed chain constraint, errors in position under a stiff position control might cause excessive control efforts as servos fight each other.

Since there are no environment sensors on this version, the system is not exactly complying to the shape of the stairs. The motion is mostly prescribed, taking the shape of the stairs without sensing them. As such, the table grew to be large as the pattern of motion did not happen to coincide with the pattern of stairs. In the table it takes 9 steps (rows) of the GCT to climb one physical step of the stairs. After 18 steps (rows) the pattern has shifted in the table by one module (column). Thus it takes $18x17 = 306$ steps before the cycle repeats. It is likely that a slightly different pattern of motion may have resulted in a much smaller table.

5. CONCLUSIONS AND FUTURE WORK

In this paper, two instances of climbing using a snake-like robot are presented, one climbing porous surfaces, the other climbing stairs in a snake-biting-its-tail form.

The porous surface climbing was implemented climbing a near vertical portion of egg-crate. We expect the same method should easily extend to climbing chain-link fences and possibly soft wood if the spikes are sharp enough.

In an unknown environment in which the robot is running autonomously, such as for planetary exploration, humans will not be there to add spikes to a robot. It is possible to design a module with retracting spikes so that the spikes do not interfere with other tasks. For other tasks such as search and rescue or covert surveillance or access to denied areas, a human may be able to configure the robot as needed.

The stair climbing was implemented with an open loop gait so it was tailored to climb stairs of a given geometry. The next version of PolyBot G1v4 will have contact sensors so that the robot may sense the terrain and react to it accordingly. We expect that by the time of this publication, we will have demonstrated a robust stair climbing robot that will climb stairs of varying geometry and conform to a large range of terrain. Essentially, the robot forms a loop that conforms to the shape of the stairs, climbing the stairs will result.

Acknowledgements

This research was supported in part by the Defense Advanced Research Projects Agency (DARPA) under contract #MDA972-98-C-0009. The authors would also like to acknowledge the help of David Duff and Ying Zhang for aid in the design of the modules and controllers.

REFERENCES

Burdick, J.W., J. Radford and G.S. Chirikjian (1995). Sidewinding locomotion gait for hyper-redundant robots. *Advanced Robotics* **9**(3), 195–216.

Chirikjian, G.S. and J.W. Burdick (1995). The kinematics of hyper-redundant robot locomotion. *IEEE Transactions on Robotics and Automation* **11**(6), 781–793.

Fukushima, E.F. and S. Hirose (1996). Efficient steering control formulation for the articulated body mobile robot kr-ii. *Autonomous Robots* **3**(1), 7–18.

Hirose, S. and A. Morishima (1990). Design and control of a mobile robot with an articulated body. *Intl. J. of Robotics Research* **9**(2), 99–114.

Kelly, S.D. and R.M. Murray (1995). Geometric phases and locomotion. *J. of Robotic Systems* **12**(6), 417–431.

Klaassen, B. and K.L. Paap (1999). Gmd-snake2: a snake-like robot driven by wheels and a method for motion control. In: *International Conference on Robotics and Automation.* IEEE. Detroit, Michigan, USA. pp. 3014–3019.

Nilsson, M. (1997). Snake robot free climbing. In: *International Conference on Robotics and Automation.* IEEE. Albuquerque, New Mexico, USA. pp. 3415–3420.

Ostrowski, J. and J. Burdick (1996). Gait kinematics for a serpentine robot. In: *International Conference on Robotics and Automation.* IEEE. Minneapolis, Minnesota, USA. pp. 1294–1299.

Yim, M. (1993). A reconfigurable modular robot with many modes of locomotion. In: *International Conference on Advanced Mechatronics.* JSME. Tokyo, Japan. pp. 283–288.

Yim, M. (1994). Locomotion with a unit-modular reconfigurable robot. PhD thesis. Stanford. Reprinted as Stanford CS Tech. Report STAN-CS-TR-95-1536.

Yim, M., D.G. Duff and K.D. Roufas (2000). Polybot: A modular reconfigurable robot. In: *International Conference on Robotics and Automation.* IEEE. San Francisco, California, USA. pp. 514–520.

Table 1. Gait control table for a travelling arc motion

	Module ID's											
	1	2	3	4	5	6	7	8	9	10	11	12
step 1	15	15	15	15	-15	-15	-15	-15	15	15	15	15
step 2	-15	15	15	15	15	-15	-15	-15	-15	15	15	15
step 3	-15	-15	15	15	15	15	-15	-15	-15	-15	15	15
step 4	-15	-15	-15	15	15	15	15	-15	-15	-15	-15	15
step 5	-15	-15	-15	-15	15	15	15	15	-15	-15	-15	-15
step 6	15	-15	-15	-15	-15	15	15	15	15	-15	-15	-15
step 7	15	15	-15	-15	-15	-15	15	15	15	15	-15	-15
step 8	15	15	15	-15	-15	-15	-15	15	15	15	15	-15

Table 2. Gait control table for travelling sinusoid wave gait.

	Module ID's											
	1	2	3	4	5	6	7	8	9	10	11	12
step 1	0	9.9	9.9	0.0	-9.9	-9.9	0.0	9.9	9.9	0.0	-9.9	-9.9
step 2	8.1	11.1	3.0	-8.1	-11	-3.0	8.1	11.1	3.0	-8.1	-11	-3.0
step 3	11.5	5.7	-5.7	-12	-5.7	5.7	11.5	5.7	-5.7	-12	-5.7	5.7
step 4	8.1	-3.0	-11	-8.1	3.0	11.1	8.1	-3.0	-11	-8.1	3.0	11.1
step 5	0.0	-9.9	-9.9	0.0	9.9	9.9	0.0	-9.9	-9.9	0.0	9.9	9.9
step 6	-8.1	-11	-3.0	8.1	11.1	3.0	-8.1	-11	-3.0	8.1	11.1	3.0
step 7	-12	-5.7	5.7	11.5	5.7	-5.7	-12	-5.7	5.7	11.5	5.7	-5.7
step 8	-8.1	3.0	11.1	8.1	-3.0	-11	-8.1	3.0	11.1	8.1	-3.0	-11

Table 3. Gait control table for the caterpillar gait.

	Module ID's											
	1	2	3	4	5	6	7	8	9	10	11	12
step 1	10	-10	-10	10	10	-10	-10	10	10	-10	-10	10
step 2	10	-10	-10	10	10	-10	-10	10	90	-60	-90	60
step 3	10	-10	-10	10	10	-10	-10	10	85	-85	-85	85
step 4	10	-10	-10	10	90	-60	-90	60	0	0	-35	35
step 5	10	-10	-10	10	85	-85	-85	85	10	-10	-10	10
step 6	90	-60	-90	60	0	0	-35	35	10	-10	-10	10
step 7	85	-85	-85	85	10	-10	-10	10	10	-10	-10	10

Table 4. Gait control table for travelling sinusoid wave motion

	Module ID's																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
step 1	0	0	-	-	-	45	0	0	-	0	0	0	-20	-90	-45	-	0
step 2	0	0	-	-	55	55	0	0	-	0	0	-90	-30	0	0	0	-
step 3	0	-	-	-10	55	55	0	0	-	0	-90	-20	0	0	-	0	-
step 4	-	-	0	-10	75	35	-	0	-	-90	0	0	-	-	-	0	-
step 5	-	0	0	-10	85	0	-	-90	-90	0	0	-30	-	-	0	0	-
step 6	0	0	0	-10	85	-10	-90	-90	0	0	-	-	-	-	-	-	-90
step 7	0	0	0	0	85	-80	-90	0	0	-45	-	0	0	-	-	0	-
step 8	0	0	0	10	-60	-90	0	0	-	-	0	0	-	-	0	0	-
step 9	0	0	0	0	-90	-80	0	0	-	-	0	-	-	0	0	0	-
step 10	0	0	0	-20	-90	-45	-	0	0	0	-	-	-	45	0	0	-
step 11	0	0	-90	-30	0	0	0	-	0	0	-	-	55	55	0	0	-
step 12	0	-90	-20	0	0	-	0	-	0	-	-	-10	55	55	0	0	-
step 13	-90	0	0	-	-	-	0	-	-	-	0	-10	75	35	-	0	-
step 14	0	0	-30	-	-	0	0	-	-	0	0	-10	85	0	-	-90	-90
step 15	0	-	-	-	-	-	-	-90	0	0	0	-10	85	-10	-90	-90	0
step 16	-45	-	0	0	-	-	0	-	0	0	0	0	85	-80	-90	0	0
step 17	-	0	0	-	-	0	0	-	0	0	0	10	-60	-90	0	0	-
step 18	-	0	-	-	0	0	0	-	0	0	0	0	-90	-80	0	0	-
step 19	0	-	-	-	45	0	0	-	0	0	0	-20	-90	-45	-	0	0
step ...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...