Design, Fabrication and Testing of a Miniature Wall Climbing Robot Using Smart Robotic Feet

Gregory Wile* and Dean M. Aslam
Micro And Nano Technology Laboratory, Department of Electrical and Computer Engineering, Michigan State University, E. Lansing, MI 48824, USA
*Currently in Mechanical Engineering Department at Case Western Reserve University, Cleveland, OH

ABSTRACT

A miniature wall climbing robot equipped with two smart robotic feet (SRF) is developed and tested. It is controlled autonomously by a PIC16F876 microcontroller and a 6 volt power supply onboard. Each SRF contains a suction cup with a diameter of 40 mm, a vacuum pump, a pressure sensor, and a micro valve. The robot's motion is driven by two servo motors which are electronically linked and synchronized. In addition to climbing vertical walls, it is designed to transition between a floor and a wall, as well as change direction while walking on a surface. Currently, the robot can walk on surfaces ranging from horizontal to an uphill angle of 70 degrees.

Keywords: Robot, wall climber, suction cup, smart robotic foot

1. INTRODUCTION

Autonomous microrobots, equipped with smart sensors, actuators and energy scavenging devices [1-3], are expected to use new walking, rolling, climbing, jumping and flying techniques. Such robots will lead to new future applications in unprecedented areas. However, for current needs in areas such as biomedical, aerospace, environmental and military systems, walking or climbing [4-15] autonomous robots are needed. Object manipulation and surveillance are crucial for many applications, and in many cases, require an ability to climb walls. Therefore, it is necessary to design a small mechanical system to attach to and move on flat and vertical surfaces to collect data and make decisions in different situations. Recently, a smart robot foot based on suction cups and monitoring devices was reported [16], which has been used in wall-climbing robots [14-15] capable of climbing smooth walls. However, the stainless steel body parts of these wall climbers were relatively heavy and, consequently, a tether was used in most cases of testing.

This paper reports the design, fabrication and testing of a miniature, autonomous wall climbing robot, which uses lighter body materials and different walking/climbing mechanisms than those used in robots reported in [14-15]. Consequently, with substantially improved smart robotic feet (SRF), this new robot is faster, lighter and smaller that that reported in [14-15]. The new SRF is equipped with a 40 mm diameter suction cup, a vacuum pump, a pressure sensor and a micro-valve. The entire system operates by control of a single programmable microcontroller, and can be powered by a 6-volt thin cell lithium battery pack mounted onboard, making the robot totally autonomous. The robot has the potential to serve as a base on which to mount data acquisition devices, surveillance equipment, or object-manipulation tools.

2. EXPERIMENTAL

SRF Design and Fabrication

The SRF presented in this paper was re-designed specifically to work in conjunction with this robot. It features a compact size that enables it to be implemented as a single unit, and it can be easily removed or serviced. A completed SRF is shown in Fig. 1. The components include a self-machined mounting block made from polycarbonate that acts as a central connector for the other components. A suction cup with a 40 mm diameter base is secured in a clamp assembly attached to the underside of the mounting block, creating an airtight seal. A diaphragm-type micro-pump measuring only 27.1 mm × 16.9 mm × 28 mm is attached to the top of the mounting block, and provides suction in the cup.

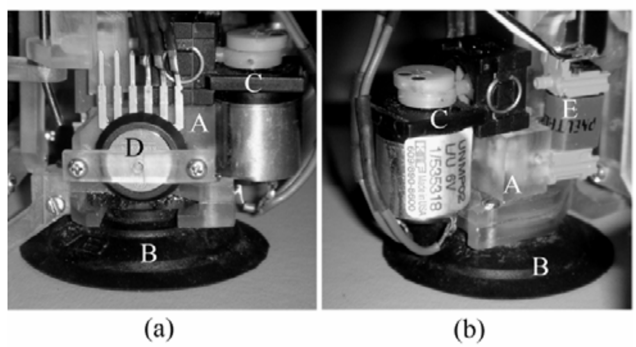


Fig. 1. Two views of the completed SRF. Components include mounting block (A), suction cup (B), micro-pump (C), pressure sensor (D), and micro-valve (E).

A pressure sensor, which is mounted on the side of the SRF, monitors the pressure inside the suction cup. Using a current of 45 mA, it was possible to achieve a pressure of approximately 77 torr inside the suction cup. The SRF is also equipped with a 3V micro-valve that is solenoid actuated. When the SRF is ready to be lifted, the valve creates a leak for air to enter the suction cup. Use of the valve enables faster suction cycles, which contributes to a faster walking speed.

Robotic Body Design and Fabrication

The robotic frame is primarily made from machined polycarbonate plastic. Polycarbonate exhibits exceptional strength, thermal and electrical properties, and is light weight. The frame's components are joined with various lengths of stainless steel machine screws, and their kinematics enables various walking motions of the robot. Two Hitec HS-311 servo motors drive the robot's movements, and were selected because of their light weight, high torque, and precise angular positioning capability. One servo (Servo 1) controls the motion of the legs in a vertical plane, while the other servo (Servo 2) controls their motion in a horizontal plane. This was found to be the most convenient setup because it enabled both the height and length of each step to be independently controlled. Figs. 2a and 2b show views of the robot's frame with the servos attached. When standing upright, the robot is 108 mm high, 106 mm wide, and 101 mm long.

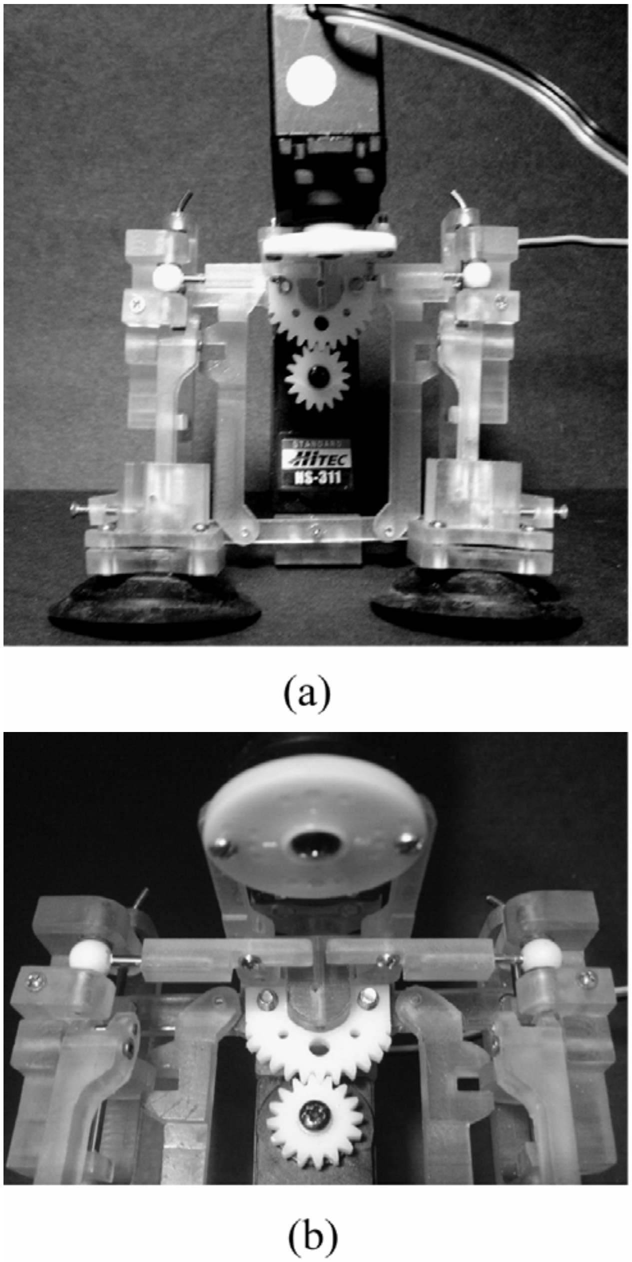


Fig. 2. Front view of the robotic frame and servos (a), and close up view of links under Servo 2.

In addition to walking forward, this robot is designed to transition between two perpendicular surfaces (e.g. from a floor to a vertical wall) by employing a special kinematic mechanism located on each leg assembly. Fig. 3 shows diagrams of the mechanics involved in raising and lowering the robot's legs and transitioning from a horizontal to a vertical surface. Fig. 3a shows a front view of the partial robot frame while it is standing with both feet flat on the surface. Note that the leg assemblies in these diagrams are tilted outward 90 degrees about their respective rods to better show crucial mechanisms in the frame.

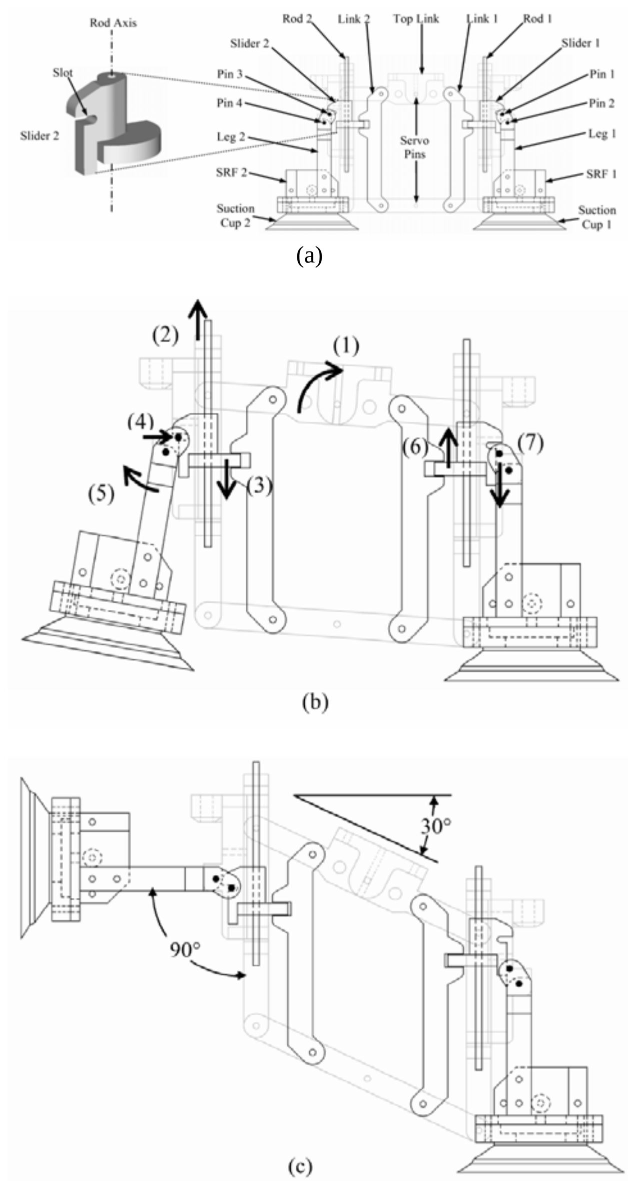
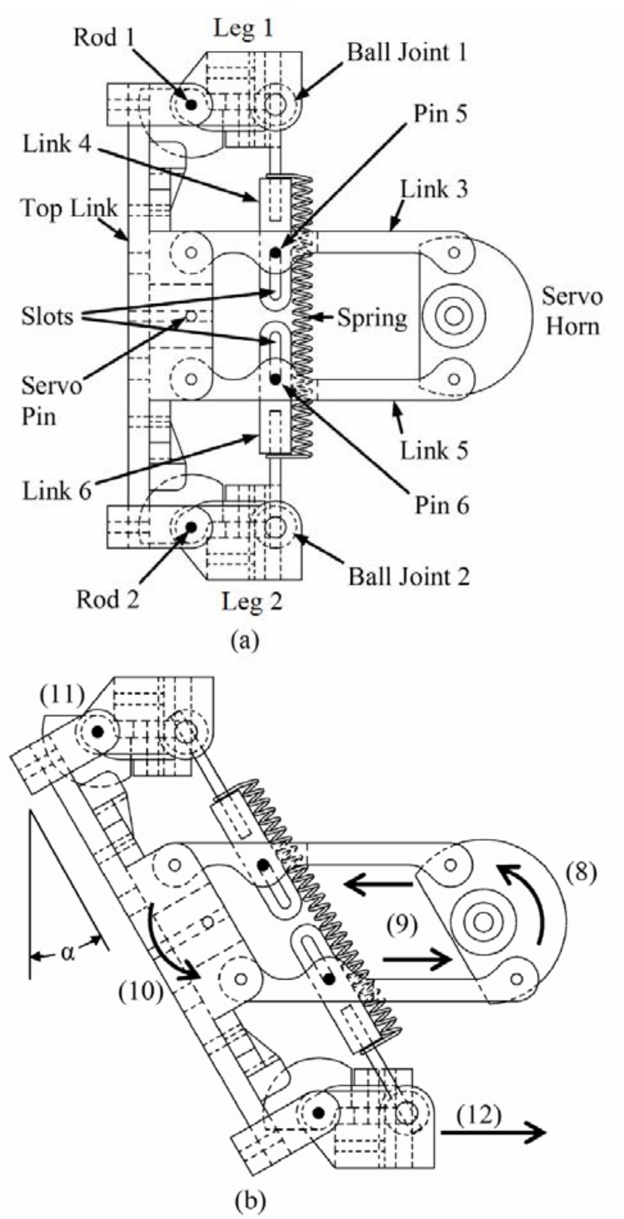


Fig. 3. Various stages of raising a leg. Listing of various parts (a), relative motions of parts (b), and completely raised leg configuration (c).

Servo 1 (not shown) is attached to the back side of the frame between the two servo pivot pins, and drives the vertical motion of the legs. In 3b, Servo 1 rotates the Top Link (1), causing the assembly of Leg 2 to move upwards (2). The geometry of the frame causes Link 2 to move downwards relative to Rod 2, in turn moving Slider 2 downward along Rod 2 (3). Pin 3 engages the slot in Slider 2 (4), rotating Leg 2 about Pin 4 (5). Leg 1 remains stationary while SRF 1 is suctioned to the flat surface. Link 1 moves Slider 1 upwards along Rod 1 (6), and Pin 1 moves downward relative to Slider 1 along its vertical edge (7). When the Top Link is rotated to a maximum angle of 30 degrees (Fig. 3c), Leg 2 is at an angle of 90 degrees relative to Leg 1. At this point SRF 2 is ready to suction to a vertical wall. After SRF 2 is stuck to the wall and SRF 1 is released from suction with the floor, Servo 1 raises Leg 1. At this stage the mechanism works in reverse, rotating the rest of the robot backwards 90 degrees to allow SRF 1 to meet the wall surface.



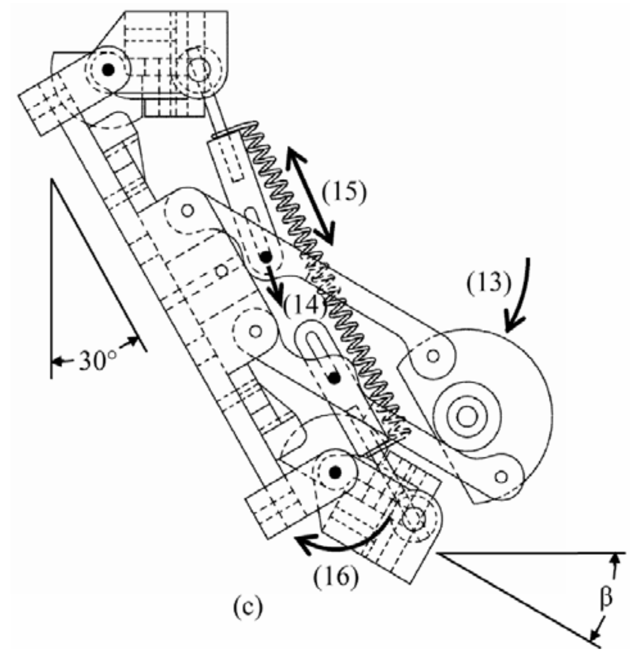


Fig. 4. Various stages of moving a leg forward and turning. Listing of various parts (a), relative motions of parts (b) and (c).

The linkages associated with moving the robot's legs in a horizontal plane are shown in the top portion of Fig. 2b. Fig. 4 shows diagrams of the top view of the robot. The linkages attached beneath Servo 2 move the robot's legs forward and backward as well as turn them about a vertical axis. The horizontal servo, which is not shown in the drawing, is mounted on top of the frame, linked between the servo pin and the central hole of the servo horn. When the robot is ready to move Leg 2 forward (Fig. 4b), Servo 2 rotates in a counterclockwise direction, looking from above (8). Links 3 and 5 translate as shown (9), rotating the Top Link counterclockwise (10). In this stage of movement, the SRF on Leg 1 is suctioned to the surface (not shown), and keeps Leg 1 stationary throughout this process. As a result, the entire Top Link rotates about Rod 1 (11), in turn translating Leg 2 forward (12). Links 4 and 6 are secured in Legs 1 and 2, respectively, with ball joints. They are also attached to Links 3 and 5, respectively, by means of pin and slot connections.

The spring, which is stretched between opposite ends of Links 4 and 6, keep them firmly pressed against Pins 5 and 6, respectively. The primary purpose of Links 4 and 6 are to keep Legs 1 and 2 facing forward and parallel to each other while the Top Link rotates. When the angle of rotation α reaches 30 degrees, a mechanical stop in the assembly of Leg 1 prevents further rotation of the Top Link relative to Leg 1. In Fig. 4c, further rotation of the horizontal servo causes Links 3 and 5 to rotate clockwise (13) while the Top Link remains fixed. Because Link 4 is restrained by Ball Joint 1, Pin 5 is allowed to slide along the slot in Link 4 (14), while Pin 6 continues pushing Link 6 outward. The spring extends in length (15), and Leg 2 rotates about Rod 2 (16) through the angle β.

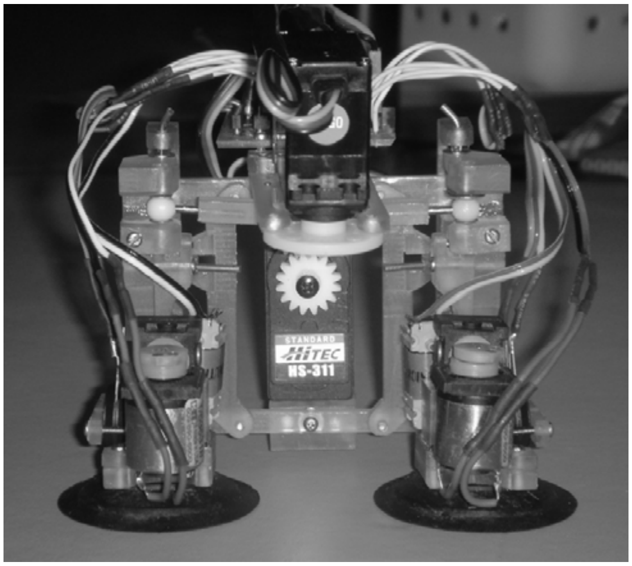


Fig. 5. Front view of completed robot.

Control

The robot (Fig. 5) was designed such that both servo motors and both SRFs can be controlled by a single, central circuit board. This configuration was chosen to minimize the number of electronic components, reduce the total weight of the control system, and to make the overall design more compact. The controller and associated electronic components are mounted on a printed circuit board attached to the Top Link behind Servo 2, as shown in Fig. 6. The circuit diagram of the board is shown in Fig. 7.

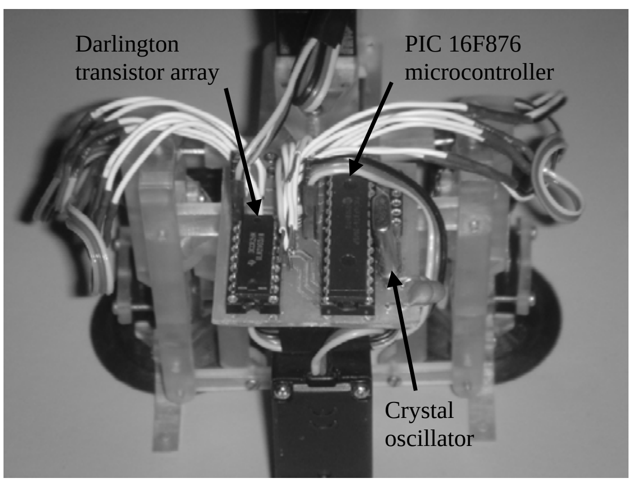


Fig. 6. Rear view of robot, showing printed circuit board and electronics.

A 16F876 microcontroller controls the robot's main functions and decision making. The microcontroller is responsible for the robot's locomotion via the servos, as well as the operation of the components on the SRFs. Fig. 8 shows the sequence of actions that the microcontroller is programmed to take when the robot walks in a straight-line path.

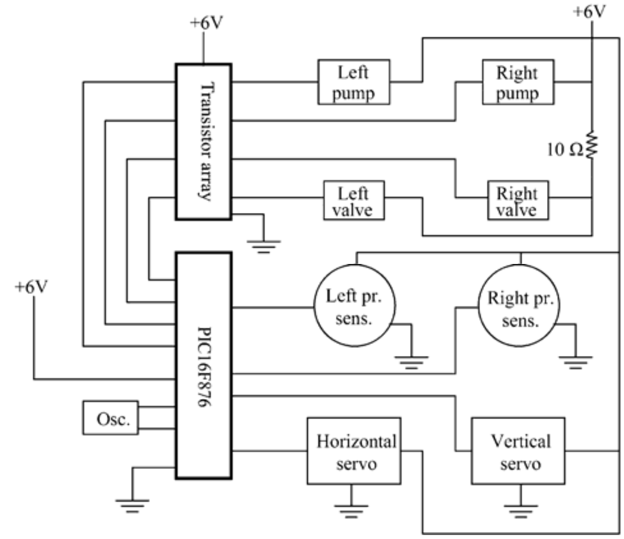


Fig. 7. Circuit diagram of the PCB.

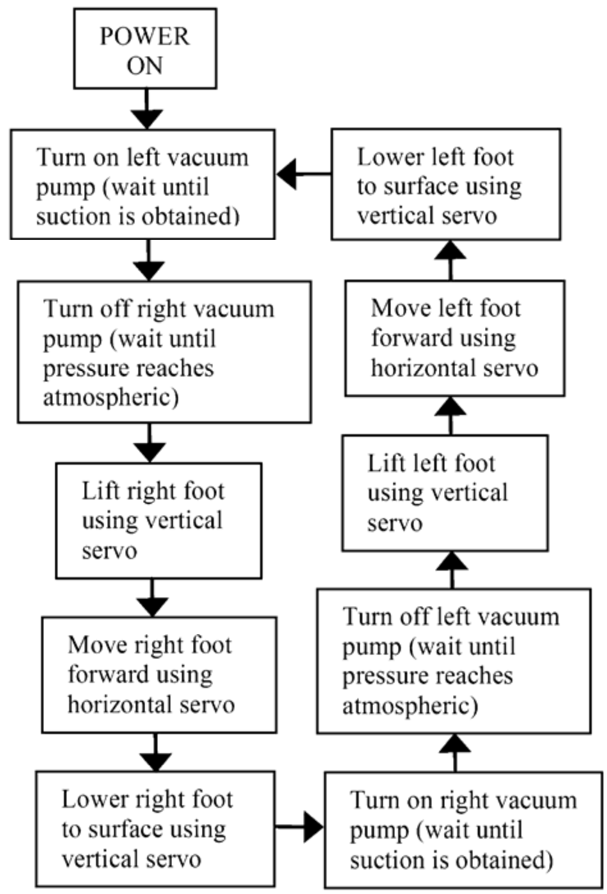


Fig. 8. Flow diagram for straight-line walking motion of robot.

The clock used with the controller is a 20 MHz crystal oscillator. A ULN2003A Darlington transistor array is used to power the vacuum pumps and the solenoid valves on the SRFs. Each pressure sensor supplies a signal voltage that varies linearly with pressure to a 10-bit analog-to-digital converter embedded in the microcontroller. The servo motors are powered directly from the 6V supply, and are controlled by a pulsed signal from outputs of the microcontroller.

An important consideration taken into account while programming the robot was how to determine if a foot is properly suctioned to the surface. In order for the robot to walk or climb safely, it must have a large enough pressure differential between the inside and outside of the suction cup. The pressure inside each cup is monitored with a pressure sensor located on the SRF. During the walking cycle, the robot is programmed to release a foot only when the opposite foot has achieved sufficient suction to the surface. In this way, at least one foot is securely stuck to the surface at all times.

Robot testing

The robot was first tested on a horizontal smooth plastic surface, as shown in Fig. 9. Following the walking sequence shown in Fig. 8, the robot was programmed to continuously take steps in a straight-line path. Some trouble was noted when the robot attempted to place a foot down onto the horizontal surface.

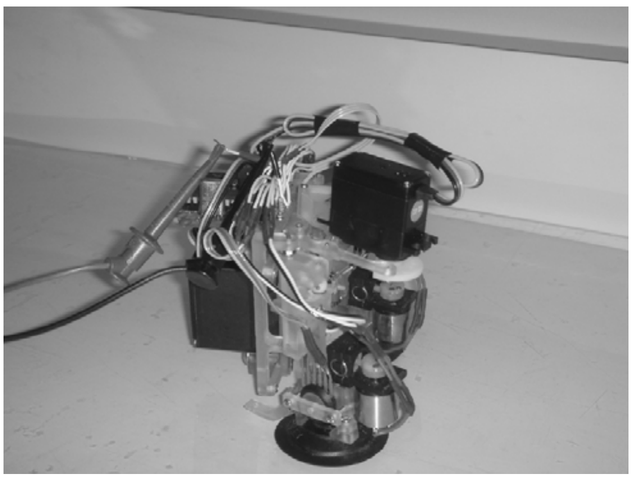


Fig. 9. Robot walking on a horizontal plastic surface.

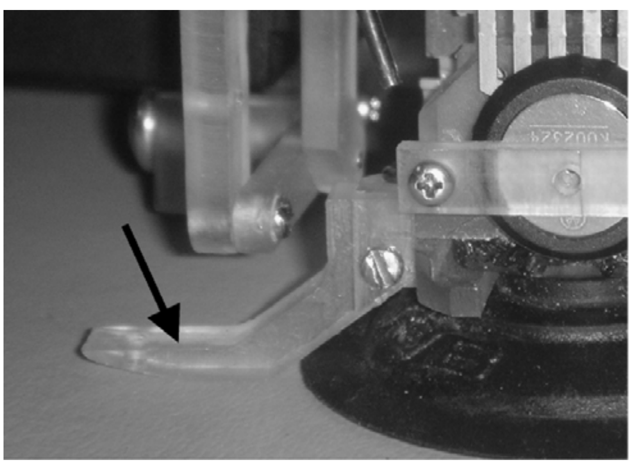


Fig. 10. Additional brace added to rear of SRF.

Due to the swinging motion of the leg as it was raised and lowered, the back edge of the suction cup contacted the surface before it was completely lowered. The friction between the edge of the cup and the surface prevented the foot from finishing its rearward swing and creating an air tight seal. To remedy this problem, a small polycarbonate guard was fabricated and attached to the back of each SRF (Fig. 10). The reduced friction of the guard allowed the cup to lower completely to the flat surface, dramatically improving the walking performance of the robot.

The surface was then inclined at different angles while the robot walked. Fig. 11 shows a sequence of photos displaying various stages of the walking cycle of the robot on an inclined wall. In Fig. 11a, both SRFs are initially suctioned to the surface. In 11b, the right foot is lifted (notice its upward rotation).

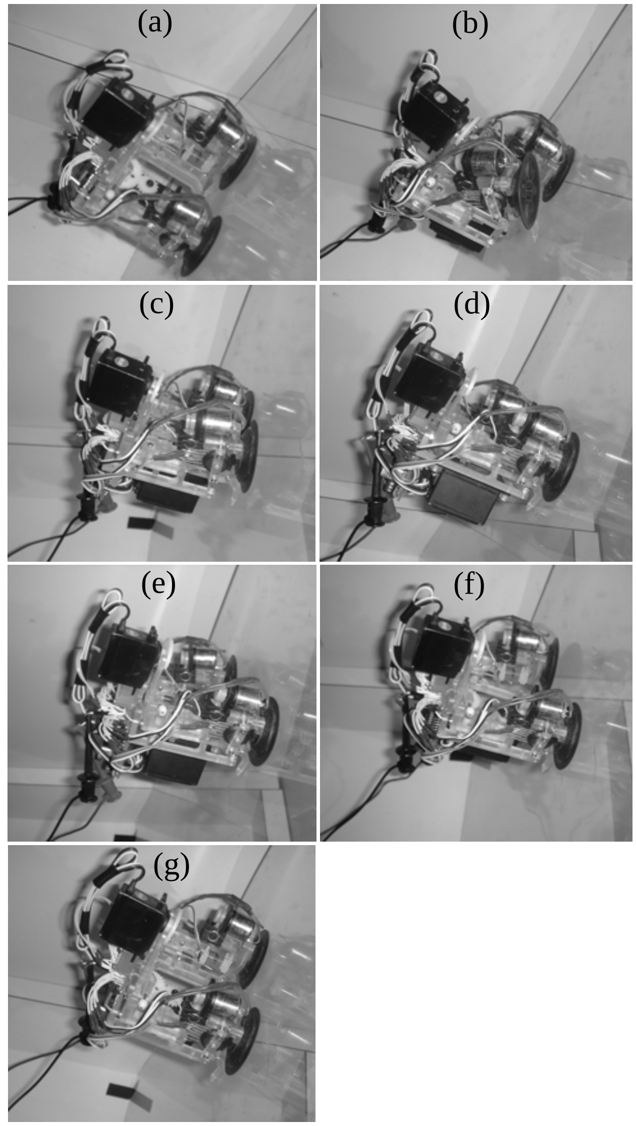


Fig. 11. Sequential views of the robot climbing a 70-degree inclined plastic surface.

Figs. 11c and 11d show the robot moving the right foot forward and setting it down to make suction with the surface. The robot then lifts the left foot (11e), moves it forward (11f), and sets it down to make suction with the surface (11g) to complete one full step cycle. The performance of the robot remained consistent at angles up to 70 degrees, at which point the suction cups failed to adhere to the surface without assistance. It was noted that as the angle of the surface increased, the length of the robot's step decreased. This was likely caused by the greater moment caused by the weight of the robot about its feet, resulting in slight deformations in the frame. To reduce the weight of the body, a lighter servo was used. In addition to its lighter weight, the new servo (model HS-225BB) features a smaller size and greater torque than the original servo. Because this model draws more current, however, only Servo 2 was replaced with this model in an effort to conserve battery power.

3. RESULTS AND DISCUSSION

A recurrent problem when running the robot was the deformation of the polycarbonate frame as it moved. Due to the complexity of the frame design, space tolerances in the multiple joints connecting the members tended to magnify the deformations. Ideally, the robot should be able to walk without the aid of braces mounted behind the suction cups. In the finished robot, however, these braces were found to be necessary, and they improved the robot's walking capability on horizontal and inclined surfaces. When ascending a near-vertical wall, the moment caused by the weight of the body created deformations in the frame that prevented the cups from squarely contacting the wall and creating suction. Another significant issue noted was the deformations of the suction cups themselves when supporting the robot's weight. One possible remedy for this is to add small braces around the perimeter of the suction cups similar to the guard added to the back of each SRF. This would help hold the standing leg perpendicular to the surface, as well as guide the lowering foot squarely by preventing the cup's edge from catching the surface prematurely.

Work is still being done to improve the robot's climbing capability on smooth surfaces of all orientations. Further areas of testing will determine performance qualities including maximum walking speed of the robot at various wall angles, maximum load-carrying capacity, and total current consumption as a function of time. In the future, a touch, light, or other suitable sensor will be added to the front of the robot to detect the presence of a perpendicular wall. Eventually, a CMOS camera may be mounted on the body to monitor the robot's surroundings, including surface features, texture, or obstacles.

4. CONCLUSIONS

A miniature wall climbing robot equipped with two smart robotic feet has been designed and tested. Each SRF contains a suction cup with a diameter of 40 mm, a vacuum pump, a pressure sensor, and a micro valve. The robot is currently capable of walking on a horizontal smooth surface and an inclined surface that is angled up to 70 degrees. Two servo motors are used to drive the robot's motion, and are controlled by a PIC16F876 microcontroller.

5. ACKNOWLEDGEMENT

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