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A Rubbertuator-Based Structure-Climbing Inspection Robot

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1 Abstract

We describe our progress on the development of ROBIN a ROBotic INspector. ROBIN is a structure-climbing robot designed for man-made environments. It is intended to carry cameras and other sensors onto man-made structures such as bridges, buildings, aircraft and ships for inspection. The robot has two vacuum fixtures connected by a 4 degree-of-freedom articulated mechanism that together allow it to walk across surfaces and will permit transition between adjacent surfaces. ROBIN is novel in several areas. It is the only climbing robot that uses McKibben type pneumatic muscles for movement. It is also novel in its use of a subsumption architecture controller in a climbing robot. ROBIN is one of the few climbing robots that with a mechanism that is capable of transitions between surfaces or from a horizontal surface to a vertical surface below.

2 Introduction

ROBIN, shown in Figure 1, was developed to be a multipurpose structural inspection vehicle that is specialized for man-made environments. It is eventually intended to be the basic component of a larger structural inspection system. As the infrastructures of many nations age, inspection and maintenance of large man-made structures will become increasingly important. This robot and many other climbing robots will become the tools used to safely and efficiently inspect aging infrastructure, such as buildings, bridges, aircraft and ships. An inspection robot is most useful when it can carry sensors into inaccessible or hazardous areas, thereby making the task safer for human inspectors. An inspection robot is also desirable when it performs tests that are too difficult or tedious for human inspectors to handle [1]. The ability to transition between adjoining surfaces is crucial if a structure-climbing robot is to be used to climb complex structures such as bridges or aircraft. Also, it is important for climbing robots to be able to handle a variety of surface types with or without *handholds* for the robot to use. This allows the robot to be a multi-purpose inspection vehicle. We are currently developing ROBIN, so that it may be a low-cost inspection vehicle for man-made environments.

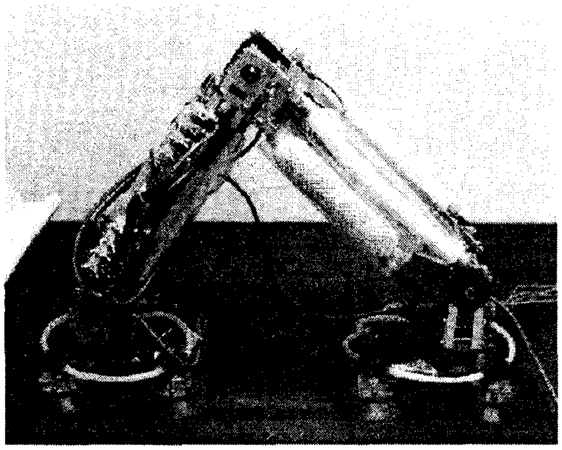

Figure 1: ROBIN

2.1 Previous Climbing Robots

The first developed wall-climbers were planar robots, with minimal range of motion in a third dimension. These robots were confined to move on a planar surface and most of the designs are confined to move on a perfectly flat plane. This critical limitation prevents these robots from being used in all but the simplest environments, where transitions between surfaces are not required and there are no obstacles on the surfaces. The *Sky Washer* [2] was a commercially developed window washing system for skyscrapers. IROW [3] was developed to inspect cylindrical shell walls and bottoms of tanks containing radioactive liquids. Like many other designs, it is connected to power and control systems through an umbilical cord. The *Wall Surface Vehicle* [4] is very similar to the *Sky Washer* [2] in the basic mechanism. It has two degrees of freedom and can be attached to surfaces using vacuum cups or magnetic fixtures. Where the *Sky Washer* was a cartesian mechanism, this robot has a polar mechanism. The *Wall Surface Vehicle* has passive magnetic feet that contain strong permanent magnets, and an electromagnet that is used to *cancel* the permanent magnet field in order to lift a foot. This type of magnetic foot can remain attached to a surface even if there is a power failure. The *Climbing Robot with Continuous Motion* is very similar to the *Sky Washer*. However, it incorporates a special mechanism that allows the robot to maintain continuous translational motion without using wheels, or suction tracks [5]. The robot is intended to be used for welding on ship hulls and other specialized activity where continuous motions are needed.

Several climbing robots are capable of the crucial ability to make transitions between adjoining planar surfaces. The ability to transfer from floor to wall and from wall to ceiling is crucial for any robot that must inspect a complex environment like a building. The *Nuclear Plant Inspector* was specifically designed to inspect a set of rooms in nuclear reactor buildings [6]. The motions of this robot are similar to those of an inchworm. *NINJA-1* [7] is one of the most complex wall climbing robots ever developed. It has four legs, each with four degrees of freedom, with suction pads on the bottom of each foot. The mechanism of the robot can easily handle uneven surfaces with obstacles. It can transition between surfaces and walk using different postures and walking gaits. The *Tower Painting Robot* [8] was the first climbing robot design based on Rubbertuators, which are rubber, pneumatic actuators. This design used Rubbertuators to form a parallel mechanism with a fixture at each end. The *Tower Painting Robot's* inchworm-like motions are quite similar to the Nuclear Plant Inspector. Unfortunately, this design was never implemented. *ROSTAM-IV* [9] is most similar to the ROBIN design. The three primary differences are the lack of an articulated knee joint, the simple vacuum fixtures used to attach the robot to the surface, and the use of electric motors as actuators. *ROSTAM-IV* can walk across planar surfaces, turn, and perform internal transitions. However, the lack of an articulated knee joint prevents the mechanism from performing external transitions or from stepping over obstacles on the surface. Also, this design used a single vacuum cup on each end fixture to support the robot. While this does support the robot, it is highly sensitive to cracks in the surface and other surface properties.

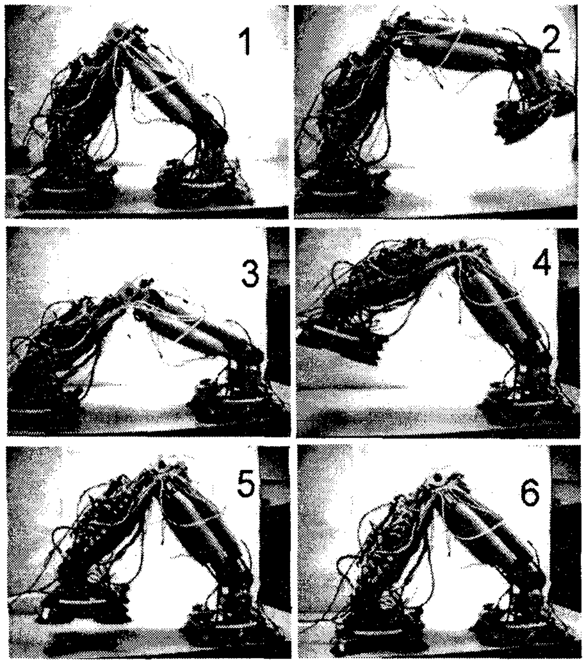

Figure 2: ROBIN Walking Motion Sequence

3 ROBIN: The Robotic Inspector

The basic structure of ROBIN robot is that of a single articulated leg with two feet, one at each end. Figure 2 shows the ROBIN mechanism in action. The robot has four degrees of freedom, and the mechanism is designed so that the robot can walk forward and backward as well as turn. Also, ROBIN can transfer itself from a horizontal surface to a vertical surface, and back. The ability to transition is crucial when inspecting man-made structures. ROBIN's mechanism can perform both internal (floor to wall) and external (roof to outer wall) transitions as well as step over obstacles on a surface while it walks. ROBIN is intended to carry cameras on its back and other contact sensors, like eddy current probes [1] on its feet, but current development focuses on improving the climbing vehicle itself.

3.1 Robot Motions

ROBIN is intended to be a kind of "walking leg" that walks by fixing one foot and stepping to a free foot as depicted by the image sequence in Figure 2. The robot structure can also transition from horizontal to vertical surfaces as shown in Figure 3, although the control software is not yet written for this case.

3.2 Pneumatic Muscles

Rubbertuators, which are flexible pneumatic actuators, are the muscles of ROBIN. These actuators are

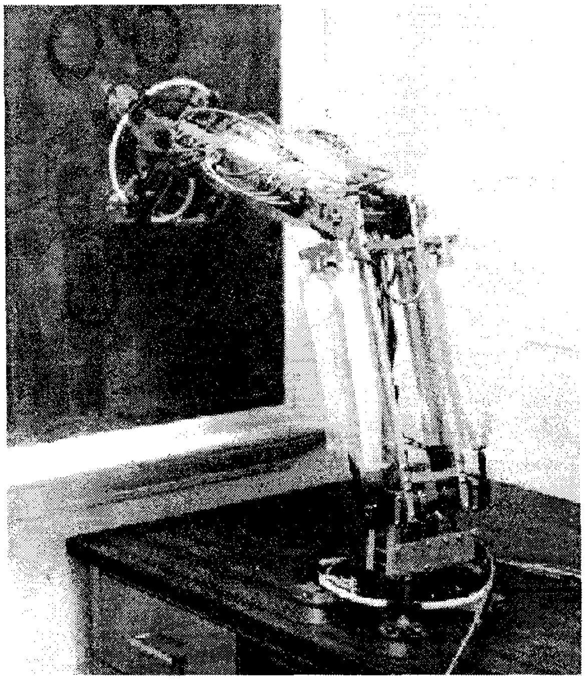

Figure 3: ROBIN Mechanism in Transition Pose

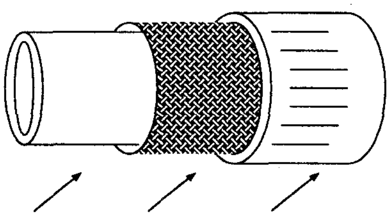

Figure 4: Structure of a Rubbertuator

lightweight, strong and are one of the technologies that enabled us to develop ROBIN. The rubbertuators on ROBIN are controlled by an extremely simple on-off valve system. Joint position is fed back from optical encoders to a stiffness control system, and pressure sensors feed back the rubbertuator pressures. As illustrated in Figure 4 a Rubbertuator is made from a rubber tube surrounded by a fiber sheath, with fittings at each end. As the tube is inflated and increases in diameter, the fiber sheath maintains nearly a constant volume and forces the Rubbertuator to contract in length. The Rubbertuators on ROBIN weigh about 300g each but exert almost 300Kgf when contracting under full pressure.

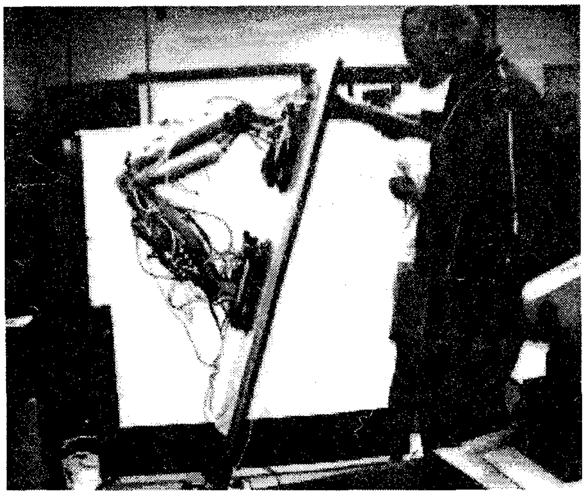

Figure 5: ROBIN Hanging Out on a Wall

3.3 Vacuum Feet

The vacuum fixtures, or feet, of the robot are responsible for providing a strong hold on the traversed surface at any angle or orientation. Multiple suction cups were used to make the fixture less sensitive to surface cracks. The five cups are placed like the pips on a die. The cups were arranged to achieve a minimal footprint area, while leaving enough space between the cup contact circles for the spreading that occurs when the cup is firmly seated on a surface. Figure 5 shows the robot hanging on a wall supporting its own weight.

4 Control System

A network of microcontrollers is used for low-level control of ROBIN. Each joint of the mechanism and each fixture is controlled by a set of microcontroller boards shown in the physical layer of Figure 8. The microcontroller board is a generic design that allows the same board be used for vacuum system control and for pneumatic joint control. This network of microcontrollers is connected to a host PC that runs the subsumption architecture controller. Low level algorithms like pressure and stiffness control run on the microcontroller network.

4.1 Pressure Control

Traditionally, Rubbertuators [10] have been controlled by very large, heavy, and expensive servo valves. This posed a major problem for applying Rubbertuators in a mobile, climbing robot, where weight is often a primary concern. Using such valves would defeat the great strength to weight advantage offered by Rubbertuators. On-off type solenoid valves offered a lightweight, low-cost alternative to the solenoid valves, but introduced a more complex control problem. Using solenoid

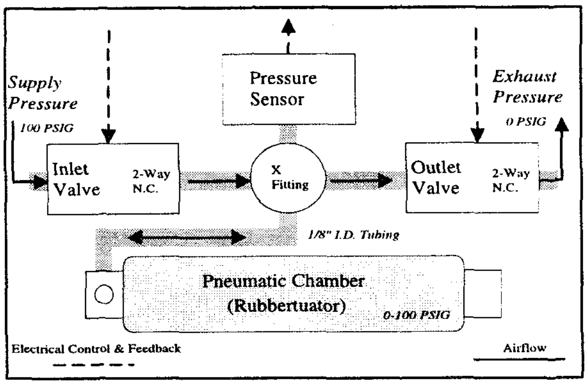

Figure 6: Single Rubbertuator Pneumatic Circuit

valves, the cost of the pneumatic system and the weight is less than 40% of the lightest commercially available servo valves that were found. A diagram of the pneumatic circuit for a single Rubbertuator is shown in Figure 6. There are eight such circuits on the robot to control the four joints. The inlet valve V_i inflates the Rubbertuator causing it to contract, while the outlet valve V_o exhausts to atmosphere causing the Rubbertuator to relax. Rubbertuator pressure is fed back to the control computers from a pressure sensor. The inlet and outlet valves were selected to have very short response times less than 10 msec, due to the desire to use them in a pulsed or bang-bang control system.

There are three possible control actions: increase pressure (inlet valve on), maintain pressure (both valves off), decrease pressure (outlet valve on). The rate of pressure change is a nonlinear function of the relative values of inlet, outlet and internal pressure and valve flow parameters. Additionally there is some minimal leakage in the pneumatic system that works as a disturbance to the control system. With this simple valve system, only bang-bang pressure control has been successful. The inlet valve is opened if the pressure is below the target pressure zone and the outlet valve is opened if the pressure is above the target zone. There is a small hysteresis region where both valves are closed to prevent the excessive oscillations of the bang-bang controllers near the pressure setpoints. The valves selected have extremely small flow rates and are a major limitation on system performance.

4.2 Joint Stiffness Control

The stiffness controller is built on top of the pressure controllers and is responsible for maintaining a minimum stiffness that will satisfy the constraint that the chains connecting the rubbertuators to the robot joints must not slip off the sprockets. When inflated, the Rubbertuator acts like a nonlinear air spring, and varying the pressure in the tube varies the spring constant and contraction rate(ϵ). The length of a contracted rubbertuator is $(1-\epsilon)L_o$, where L_o is the maximum length. The manufacturer lists an equation that describes the contraction force of the Rubbertuator [10]:

$$F_{rub}(P,\epsilon) = P\left[a(1-\epsilon)^2 - b\right] D_o^2 \qquad (1)$$

Where P is pressure, ϵ is contraction rate, a, b are parameters of the rubbertuator type and D_o is the original diameter of the Rubbertuator. Some properties that can be observed from this model are that force is linear in pressure P and nonlinear in contraction rate ϵ. This does equation not model actuator hysteresis which arises in part from friction between the fiber cords in the cover and friction between the fiber cover and the rubber tube. A pair of rubbertuators is used to make a revolute joint as shown in figure 7. They work as a flexor-extensor pair, much like animal muscles. The stiffness of the joint comes from the pulling forces of the two rubbertuators that move the joint. Each rubbertuator only exerts force in the direction of contraction. This stiffness is independent for each side of the joint and thus, each direction of rotation.

We developed the stiffness controller by calibrating the equlibrium pressure for each joint position. A file containing a position and an associated pressure for each rubbertuator was generated by a sampling program. This data is used to calculate a best-fit polynomial curve for each rubbertuator which is used to generate a normalized table of encoder positions and pressure values. This table is downloaded from the host computer to each joint's associated microcontroller. The stiffness controller then sets the minimum desired pressure values for each encoder position thereby enabling a minimum chain-tensioning stiffness for each side of the joint. A stiffness command is defined as an additional pressure value added to the current minimum, chain-tensioning pressure for the rubbertuator. By increasing the stiffness of one side of a joint it is moved to a position where the forces from the two rubbertuators and the environemnt are balanced. New chain-tensioning pressures are continually reloaded as the joint moves through its range due to the additional stiffness from commands. There is no feedback of actual stiffness, so the control of stiffness is open loop.

5 Behavior System

ROBIN utilizes a behavior-based architecture using subsumption for arbitration [11]. Unlike most behavior systems, sensor data bandwidth is conserved by constructing behaviors such that they require minimal information. Figure 8 details the behavior architecture that comprises the system.

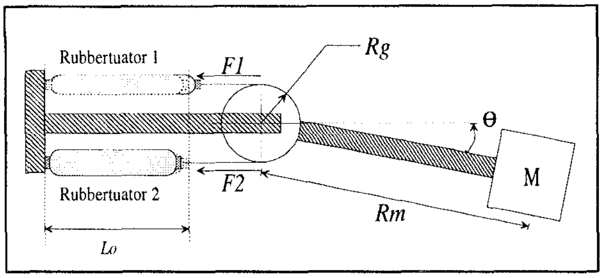

Figure 7: Rubbertuator Joint

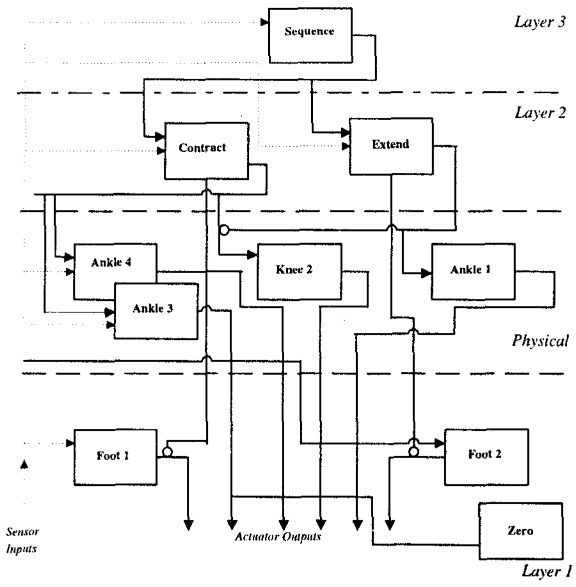

Figure 8: Behavior-Based Control System

5.1 Level 1

Level one contains the *Foot behaviors* which are basic to the system in order to maintain surface suction and locomotion. The foot behaviors respond to infrared sensor detection of a surface by enabling the vacuum pump for that foot. This low-level behavior may be subsumed by higher-level behaviors in order to walk.

5.2 Level 2

Level 2 comprises those behaviors that locomote ROBIN by sending the necessary stiffness commmands to the specified controller joints. These behaviors are encompassed in the *Extend* and *Contract behaviors*. The *Extend behavior* is triggered by the *Sequence behavior* to run or reset its state. It has inputs from the ankle and knee encoders. It sends the specified stiffness pressures to the ankle and knee joint controllers in order to lift the free foot, extend the knee, and lower the free foot. The *Contract behavior* is also triggered by the *Sequence behavior*. It sends the specified stiffness pressures to the ankle and knee joint controllers in order to lift the free foot, close the knee, and lower the free foot. Goal positions are implemented by a rule-based position control algorithm that *successively approximates* the necessary stiffness values to attain the desired position. It calculates a window of encoder positions around our goal which determine when to increase or decrease our approximation. If the current position is above the goal window, we send a stiffness command to the joint opposite the desired direction and decrease our approximate stiffness. If the current position is below the goal window, we send a stiffness in the desired direction of rotation to the joint controller and increase the approximated stiffness. When we are inside the goal window, we output the approximated stiffness value. This method of successive approximations eventually settles to a stiffness that sustains a position inside the goal window.

5.3 Level 3

Level 3 has the highest priority of all behaviors and contains the *Sequence behavior.* This behavior monitors the vacuums and knee position to determine what state ROBIN is currently in. It then signals the appropriate behavior to run. This behavior is necessary mainly because of hardware limitations. ROBIN has no vacuumm sensors for surface suction detection, yet. Therefore, we use timeouts generated in this behavior to control the subsumption of the vacuums for stepping.

6 Evaluation

Figure 9 shows the sequence of robot motion commands and joint position responses for straight walking on a horizontal surface. The figure describes the motion of each joint through two steps compared with its desired position. Solid lines indicate the desired joint angle with dashed lines indicating the actual joint angles. Note that these goal angles are only valid when the corresponding controlling behavior is running. The step begins at two seconds with Extend moving towards its goal angle of 15 degrees. This is achieved at 18 seconds which causes Extend to begin opening the knee to the desired angle of 80 degrees. Achieving this goal leads to an open, extended free fixture which Extend then lowers to the surface by changing the desired joint one goal to 45 degrees. This goal causes the foot sensor to detect a surface and enable the vacuum which, in turn, signals the Sequence behavior to disable Extend and enable Contract. Contract immediately begins moving joints three and four toward their desired positions of 37 and -46 degrees, respectively. This is achieved at 38 seconds causing Contract to close the

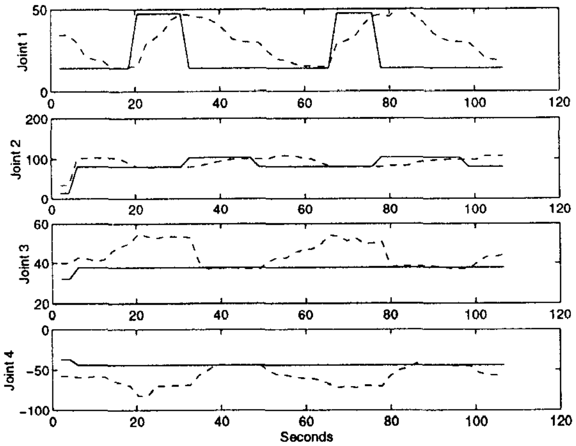

Figure 9: Joint Stepping Sequence

knee. The desired position of joints three and four is such that they do not move after the knee has contracted. The process is completed at 44 seconds and resets the state of each behavior for the next step.

7 Future Work

The robot currently walks on flat and inclined surfaces up to about 30 degrees from vertical. We are also developing more behaviors for the robot to handle transitions from horizontal to vertical surfaces and back. These will be higher-level behaviors that subsume the normal extend and contract behaviors used in straight walking. Hardware refinements such as larger valve ports will allow more responsive conrtrol. We also plan to add vacuum sensors to the feet to confirm that suction is achieved before releasing for the next motion. With these additions ROBIN will be on its way to being a useful robotic inspection vehicle.

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