Intelligent legged climbing service robot for remote maintenance applications in hazardous environments

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Abstract

Wheeled-tracked vehicles are mainly suitable for relatively flat terrain. Legged-vehicles, on the other hand, have the potential to handle wide variety of terrain. Robug IIs is a legged climbing robot designed to work in relatively unstructured and rough terrain. It has the capability of walking, climbing vertical surfaces and performing autonomous floor to wall transfer. The sensing technique used in Robug IIs is mainly tactile and ultrasonic sensing. A set of reflexive rules has been developed for the robot to react to the uncertainty of the working environment. The robot also has the intelligence to seek and verify its own foot-holds.
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1. Introduction

Large buildings and tall structures often require regular inspection and maintenance in order to ensure the integrity of their construction. Failing to carry out proper maintenance could cause life or damages to property, which could sometimes result in criminal charges. The traditional manual method normally requires the installation of costly scaffoldings or gondolas. Human workers must stand on these scaffoldings or gondolas in mid-air and at high altitude to carry out inspections and repairs. Inevitably, this is a slow and costly maintenance process. Also, in some industries, such as off-shore, nuclear, chemical and power generation industries, inspection by human workers is hazardous and difficult if not impossible. In view of this difficulty, a number of climbing robots have been developed to carry out glass curtain wall cleaning [1–3],

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bridge inspections [4], ship hull inspections [5,6], and painting of large buildings [7]. However, based on experiences of some previous research projects [8–10] in applying climbing robots for remote maintenance applications, it was found that many buildings such as nuclear reactor pressure vessels had very limited access. As a result, a great deal of effort had to be made in order to launch the robots onto the buildings or structures to carry out the required inspection work. This will inevitably slow down the maintenance process and increase the risk of workers who are responsible for installing the robots. A mobile robot which has the capability of walking through a service entrance and then transferring itself onto the vertical surface of the inspected building can save time and reduce risk to human workers who may have to launch the mobile robot in difficult circumstances.

Ninja-I [11,12], a quadruped wall climbing robot, was developed with the capabilities of floor-to-wall transfer. However, its legs were not articulated. As a result, it was not easy to keep the centre of gravity of the robot close to the surface and hence could bring on excessive bending moment on the foot during climbing and transferring between horizontal and vertical surfaces. In addition, the leg structure restricted its reachable range. Ninja-II [13] overcame the aforementioned problems by introducing articulated structure to its legs. However, the robot did not have any gripper on the underside of its body for sitting on the surface during remote operation and hence it did not provide a stable platform for some maintenance operation such as metal cutting which could induce large reaction force to the robot. Besides Ninja series of robot, ROBIN [14], a biped-climbing robot, has attempted to tackle the floor-to-wall transition but no results were shown. Another biped robot, RAMR1 [15–18], was developed by Michigan State University for reconnaissance operations in urban environment. The robot was capable of transferring between orthogonal surfaces. In order to make the robot to work in confined space, RAMR2 [18–20] was developed with its revolute hip joint replaced by a prismatic joint. To increase the reachable range without sacrificing the ability to work in confined space, a new version of RAMR robot was being designed by the University of Utah [21]. The new design provided a hybrid hip joint with discrete prismatic and revolute motion. Despite that these biped climbing robots could perform orthogonal plane

transfer, their climbing mechanism was not very reliable since only one foot was gripping on the surface at any one time when the robot was climbing; a large turning moment could be induced on the gripping foot when the free leg stretches sideways during climbing and this large turning moment could cause the gripping foot to detach from the surface [11]. In addition, the biped structure in general does not provide a stable platform for installing tool package and carrying out maintenance work.

Although a lot of research works has been conducted to develop suitable mechanical mechanisms for climbing, very few have addressed the issue of searching suitable footholds for gripping. For a climbing robot, the ability of finding its own footholds on wall surfaces is essential for remote maintenance applications since the surface condition for this type of applications is generally poor. Ninja robots had partially addressed this issue by developing a "Valve-regulated Multiple" (VM) sucker [11]. The VM sucker was partitioned into a number of smaller chambers and the air flow of each chamber was controlled by a passive mechanical valve. This passive valve would be shut off automatically by excessive air flow caused by air leakage through cracks or any imperfection on the surface. This mechanism could handle very small irregularities and grooves on the wall surface but was not capable of handling large surface defects. For large surface defects, it is necessary for the robot to search for its own suitable footholds.

Robug IIs was designed to address the above problems. It had adopted the articulated leg structure with a thoraxial joint to achieve large reachable range and at the same time to keep its body close to the surface to reduce excessive bending moment. It had the ability to walk from the floor to the wall and was also capable of climbing over obstacles and had the intelligence to seek and verify foot-holds. This allowed the robot to work in relatively unstructured environments. In order to provide a stable platform for installing tool package and carrying maintenance tasks, vacuum grippers were attached to the underside of the body in order to allow the robot to sit on the surface during maintenance operation.

This paper will first give a brief description of Robug IIs' system. The rest of the paper will concentrate on describing the control method, the movements and the behaviours used by Robug IIs for wall climbing, climbing over obstacles and floor to wall transfer.
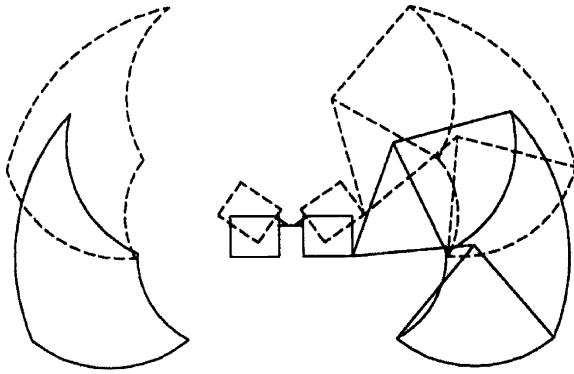
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Fig. 1. Robug IIs workspace.

2. Mechanical system

Robug IIs was a four limb articulated leg robot powered by double acting pneumatic cylinders. Pneumatic actuation is particularly suitable for climbing robots, due to its high force to weight ratio and inherent compliance [25], which allowed an elegant terrain adapting motion. The robot adopted an endoskeletal structure; an internal frame was used to provide the required strength and stiffness for locomotion as well as locations for the joints, whilst the external actuators acted as the prime mover. The advantage of using this structure is that it is more practical for fabrication and maintenance.

The robot consisted of two similar modules. Each module had two mechanical legs and each had a vacuum gripper foot for climbing vertical surfaces. The robot also had three vacuum suckers on its underside. The two modules were joined by a pivot to form a thoraxial joint with a pneumatic cylinder to bend the body. The arrangement increased the effective moving angles of the legs and reduced the stress exerted on the leg-joints (see Fig. 1). This gave the robot the amount of flexibility required for the floor-to-wall transfer.

Each leg had three degrees of freedom and was organised as a spider-like structure (see Figs. 2 and 3). This leg mechanism provided the ability to negotiate and climb over obstacles. It also had the advantage of keeping the body close to the surface, which increased the stability of the robot. An open three bar linkage mechanical structure is used to provide all three degrees of movement of each leg. The anchorage points of the hip and abductor cylinders, and the hip joint were widely separated to reduce stresses on the chassis.
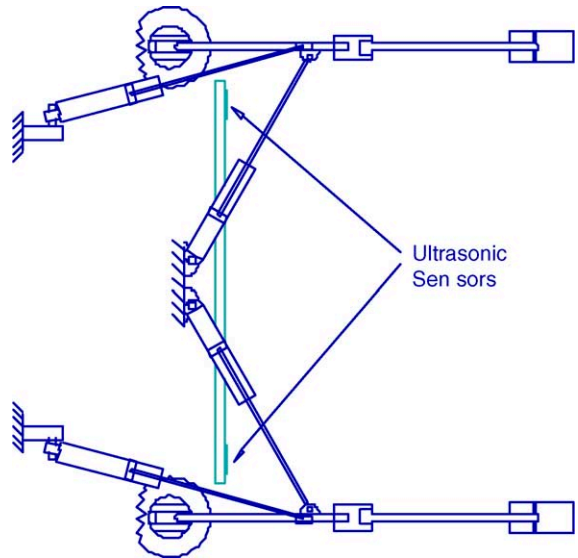

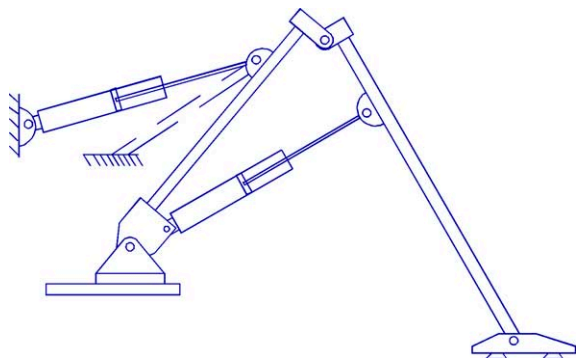Fig. 2. Plan View of the structure of the two front legs.

Fig. 3. Elevation view of the leg structure.

The gripper foot was attached to the leg by a ball joint, this provided the gripper foot with the flexibility required to align itself with uneven surfaces. These gripper feet and the base suckers were driven by compressed-air ejector pump and could provide a pull-off force corresponding to 80% atmospheric pressure.

3. Control system

Each leg was controlled by an on-board dedicated microcontroller board. These controller boards provided position, force and compliant control modes. An
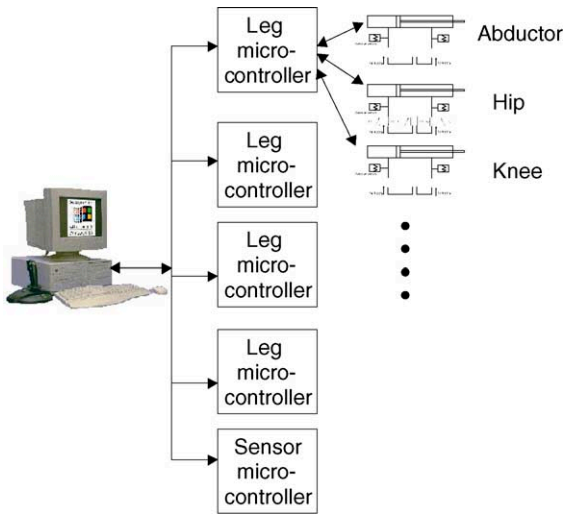
Fig. 4. Computer control system.

Fig. 5. The valve arrangement for cylinder control.

additional board was used to provide sensor information from the robot. A supervisory computer at the user end provided the human–machine interface, path planning and functions necessary for co-ordinated motion. A master–slave configuration (see Fig. 4) via a serial link was used to network the supervisory computer and all the leg controllers. A specially designed protocol was used for passing commands and information between the Supervisory computer and the robot. All the important commands were arranged as absolute commands. The repetition of the same command did not affect the final movement.

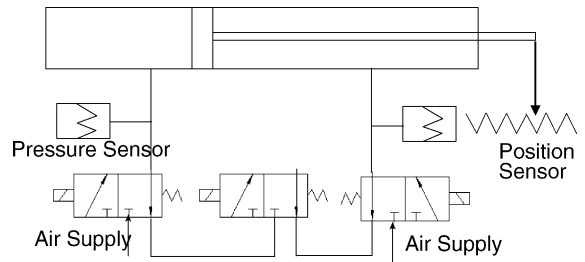Each pneumatic cylinder was controlled by three electrically controlled valves, which can allow air to be

in both sides of the piston simultaneously (see Fig. 5). Pulse width modulation method was used to drive the cylinder. Since pneumatic action system is non-linear in nature [22,23], a fuzzy logic controller (FLC) has been developed to improve its performance. The fuzzy controller consisted of four primary components, a control rule base, a decision-making inference engine and fuzzification and defuzzification interfaces. The structure of the fuzzy controller is illustrated in Fig. 6. The fuzzification interface quantised the system input variables onto approximate linguistic measures defined by fuzzy sets having the membership functions shown in Fig. 7. The system variables to be observed were defined as e (cylinder position error) and Δe (cylinder position error difference)

$$e(k) \overset{\Delta}{=} p_T(k) - p_A(k)$$

$$\Delta e(k) \overset{\Delta}{=} e_0(k) - e_0(k-1)$$

where $p_T(k)$ was the target cylinder position and $p_A(k)$ was the measured cylinder position at the kth sampling

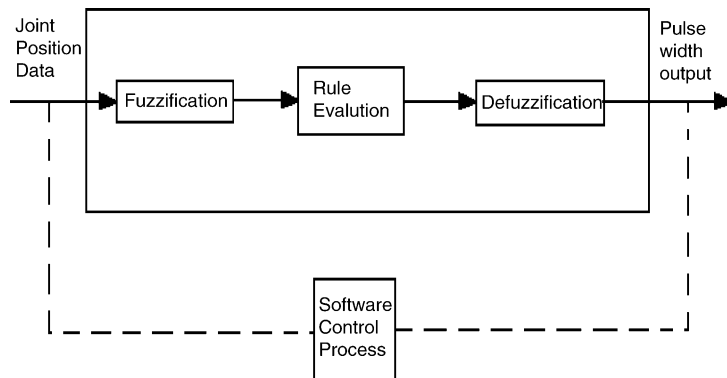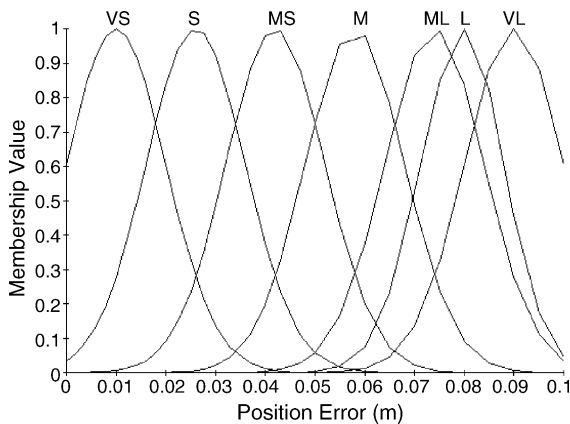Fig. 6. Structure of the fuzzy controller.

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Fig. 7. Fuzzy error sets.

Fig. 8. Fuzzy set shape definition variables.

instant. The following linguistic variables were used as labels of the fuzzy sets: VS, Very Small; S, Small; MS, Medium Small; M, Medium; ML, Medium Large; L, Large; VL, Very Large.

The fuzzy rule set was designed to manage the mark-space ratio in a pulse width modulation control algorithm according to the position error and position error difference. The control rules are defined in a knowledge base and are represented in linguistic form in Table 1, which has e (cylinder position error) down the left hand column and Δe (cylinder position error difference) along the top row. The first element in Table 1 states 'IF ⟨position error⟩ is Very Small AND ⟨change in position error⟩ is Very Small THEN ⟨pulse width⟩ is Very Small. The control rules are processed within the fuzzy inference engine, which generates a resultant output fuzzy set.

The defuzzification interface used the centre-of-area method to compute a singleton control value for imple-
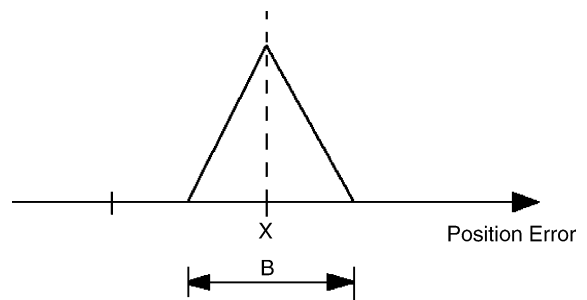
mentation from the output fuzzy set; this method was used as it produces a gradually changing control output.

Although it is simple to program a fuzzy system using simple rules and membership functions, the tuning of the system performance is a largely subjective process and as a result the design of fuzzy logic controllers is mostly a trial-and-error procedure with extensive tuning of the relational. However, it is possible to automatically improve the performance of the system by using genetically inspired learning strategies now commonly referred to as Genetic Algorithms (GAs) [24]. GAs are particularly good for optimising fuzzy sets as they can explore a search space in many directions simultaneously while avoiding local minima.

In coding the Genetic Algorithm, there must be some defined protocols that enable the GA to understand information regarding the fitness function that is being optimised. Consideration must be given to both the encoding of the membership functions within the GA and the methods by which the GA controls the shape of the fuzzy sets.

The membership functions of the fuzzy sets used were represented by two coefficients defining the function peak position (x) and size of the base (B) (see Fig. 8) then the GA only needed to be coded with these two parameters in order to make adjustments to the fuzzy sets. Therefore the 'chromosomes' of the GA only represented the disparity between the proposed fuzzy sets and the fuzzy sets from the previous generation. For the first generation, adjustments were made at random on the initial fuzzy sets. The following generations evolved a resultant fuzzy set from the previous generation, which had been selected by weighted-random analysis of the fitness levels.

The factors to be considered in evaluating the population fitness levels were the time to reach target posi-

Table 1
The fuzzy PD rule table

e_0	Δe_0						
	VS	S	MS	M	ML	L	VL
VS	VS	VS	VS	VS	S	MS	M
S	VS	S	S	S	MS	M	ML
MS	VS	S	S	MS	M	ML	L
M	VS	S	MS	M	ML	L	VL
ML	NM	MS	M	ML	L	L	VL
L	MS	M	ML	L	L	L	VL
VL	M	ML	L	VL	VL	VL	VL

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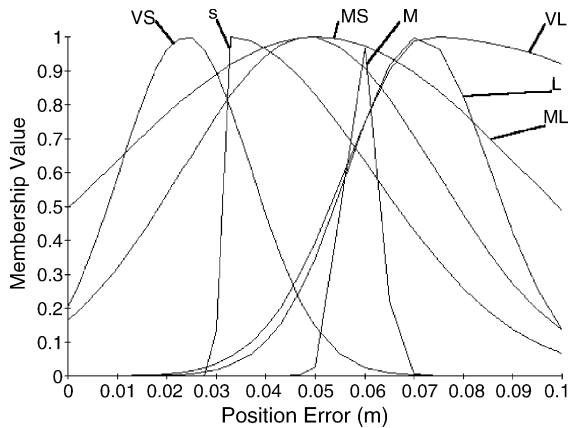
Fig. 9. The membership functions after GA optimisation.

Fig. 11. Cylinder response with PD controller.

tion, the settling time and the precision required. In the event of the system exhibiting such qualities as slow response time or excessive overshoots the chromosome fitness value could be reduced, lowering the probability of that chromosome reproducing and evolving the attributes into the next generation. This method tailors the learning process to eliminate characteristics that are not permitted to exist within the system.

For tuning the fuzzy controller, a population size of 50 classifiers was used, each 32 bits long (4 bits for each fuzzy set). The GA was allowed to run for 100 generations. These parameters were found to be adequate through experience of using the system. The resulting GA-generated optimal fuzzy membership functions are shown in Fig. 9. The response of the fuzzy PD controller is displayed in Fig. 10. As compared with the perfor-
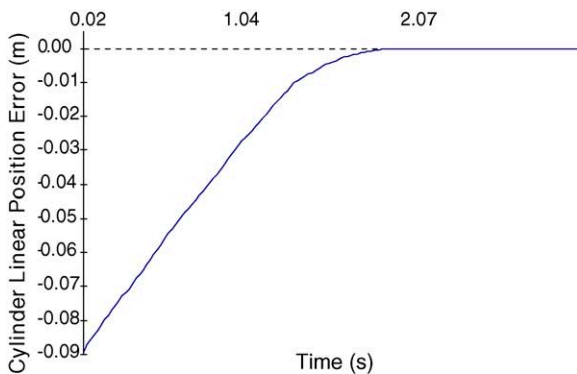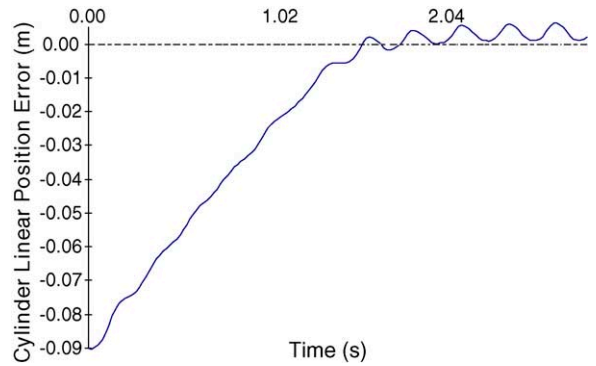
mance of a standard PD controller (see Fig. 11), the fuzzy controller can increase the accuracy of the system to $+/-0.3$ mm (0.2% of the rod extension range). In addition, the small oscillations occurred in the standard PD control method has also been eliminated (see Fig. 11).

Although Robug was mainly a sensory-based robot and used its reflexive behaviours (see Section 4 for detail) to handle unstructured environments, the proposed fuzzy control method with GA tuning did help to improve its walking and climbing performance. Firstly, it provided a smooth control for the legs and body movements since it could eliminate the small oscillations occurred in the standard PD control method. Secondly, with the improved position accuracy, it enabled the robot to make the maximum strike for each of its walking or climbing steps. Based on authors' experience, the proposed control method could actually reduce 15% of the time required by the Robug to reach its target location. In addition, as each leg had sufficient strength to carry sensors, the improved accuracy allowed the robot to use its leg as a scanning probe to look for structure defects.

4. Behaviours

Robug IIs was designed to work in relatively unstructured environment. In order to accommodate the uncertainty in the working environment, Robug IIs was designed as a sensory-based control robot rather than a pure position control robot. The sensing technique used in Robug IIs was mainly tactile sensing.

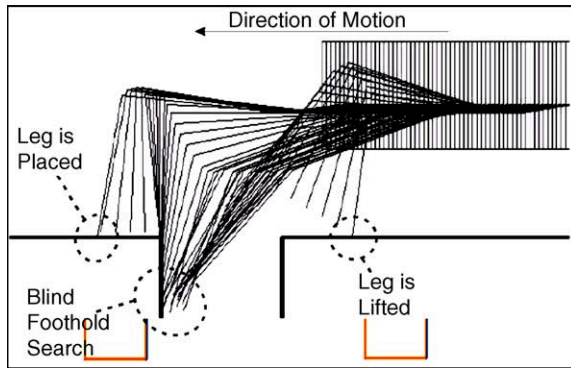Fig. 10. Cylinder response with Fuzzy Logic PD controller.

Fig. 12. Blind foothold search and obstacle avoidance.

Each leg was equipped with pressure sensors and potentiometers to provide force and position information of the leg. The leg could be used to feel for obstacles and the level of the surface. The compliant control of the leg allowed the robot to perform tactile sensing without damaging the building structure. The vacuum sensors at the feet and base suckers gave the measurements of gripping force on the surface. Ultrasonic sensors were also installed at the front of the robot for measuring distance of the object.

In order to allow the robot to handle the uncertainty in unstructured environments, a set of rules were developed to define the behaviours of the robot for reacting to the sensory information fed back from the environment.

These rules are listed as follow:

1. No leg will move unless the robot has at least three suckers gripping firmly on the surface. This rule prevents the robot from falling when it is climbing a wall.
2. A reflex action for searching foothold is build into the leg controller (see Fig. 12). This arrangement provides a fast searching movement. The reflex action allows the leg to search for a foot-hold in front. It also provides an oscillating movement, which can be used to remove loose material on the surface. This facility will increase the chance of finding gripping surface.
3. No two legs will be allowed to apply force in the opposite directions. This prevents any damage to the chassis caused by excessive force since each cylinder can exert 500 N force.

4. Always use minimum force for searching foothold and negotiating object. This rule ensures the robot will not cause any damage to the climbing structure.
5. Since the robot is capable of walking, climbing and floor-to-wall transfer, the gravity force exerted on each joint can vary significantly when the robot is lifting the body. A simple compensation scheme is used to overcome the gravity force where additional pressure can be added gradually by increasing the additional force demand variable in the leg controller.
6. The robot will adjust the position of the legs to spread out the force exerted on each leg.

The above rules form the basic behaviours of the robot. They provide the local autonomy to each limb. Other high level of strategies can be added to provide the task oriented applications.

5. Walking and climbing movement

The movement of the robot can be grouped into two main types: (1) normal climbing or walking, (2) climbing over obstacle or floor to wall transfer.

During the normal climbing or walking, the thoraxial actuator will be fully extended so that the two mechanical modules are level with each other. Base suckers are used to assist climbing and walking. In this mode, the movement of the robot can be divided into four basic steps: (1) move the legs to follow a pre-planned trajectory, (2) get the legs to grip onto the surface, (3) move the body to follow a pre-planned trajectory and (4) get the base vacuum sucker to grip onto the surface. When the base suckers are firmly attached on the wall, all four legs can move at the same time for fast operation.

Considering the case when the robot is moving forward, the following movements are implemented:

1. The robot starts at the rest position as shown in Fig. 13a.
2. The robot releases all the gripper feet suckers.
3. All four legs will follow a pre-defined trajectory (see Fig. 13b).
4. Each leg starts searching for a gripping surface until a secure grip is verified. The attitude after gripping on the surface is shown in Fig. 13c.
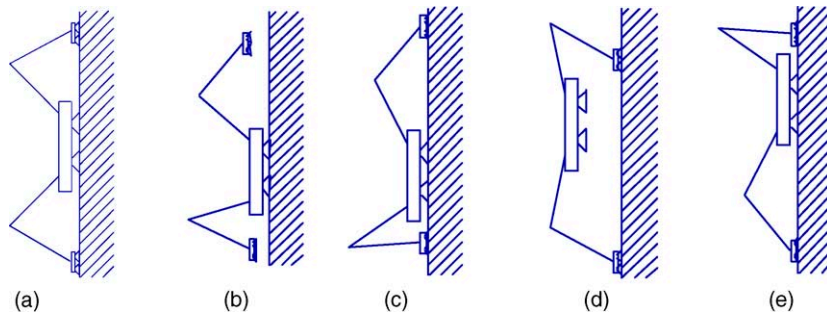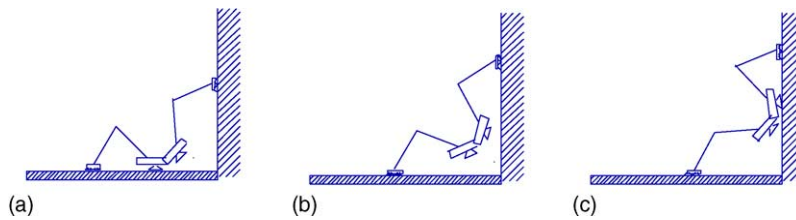
Fig. 13. Robug IIs wall climbing sequence.

Fig. 14. Robug IIs floor-to-wall transfer sequence.

5. The robot then releases its belly sucker and levers its body up and follows a pre-planned trajectory as shown in Fig. 13d.
6. The robot starts searching for a gripping surface until a secure grip is verified at the base suckers. The position after the body gripping on the surface is shown in Fig. 13e.

In the case of turning, the front leg on the near side of the turning direction and the rear leg on the off side will move outward. The remaining legs will move inward. The robot will then lift the body and turn to the required direction.

For climbing obstacles or floor-to-wall transfer motions, the robot will use its thoraxial actuator to control the bending angle of the body. This increases the effective angle that the leg can travel and hence enhance the flexibility of the robot for climbing over sharp angled objects or slopes. The base suckers are not normally used in this kind of movement and only one leg is moving at any one time.

When the robot is performing a floor-to-wall transfer operation, a sequence of movements is executed as follow:

1. The robot will walk toward the wall until a full walking pace is not possible. Ultrasonic distance sensors are used to measure the distance. The robot will walk with its front legs spread when it is close to the wall.
2. The robot releases the front feet and front base sucker. It then bends the body up according to slope of the wall.
3. The front legs starts searching for a secure grip on the wall (see Fig. 14a).
4. The robot then releases its rear base sucker and then lift its body up (see Fig. 14b).
5. Each leg will release its gripper feet sucker and search for a secure grip in turn.
6. It lifts its body up and follows a planned trajectory (see Fig. 14c).
7. Step 5 and 6 are repeated until the rear legs are just reaching the floor.
8. The robot will straighten the spine cylinder and the move its body toward the wall until a secure grip is obtained at the base suckers.
9. It then moves its rear legs in a high gait to transfer onto the wall.

6. Conclusion

Robug IIs with its insect-like structure and articulated limbs had the mechanical capability to han-
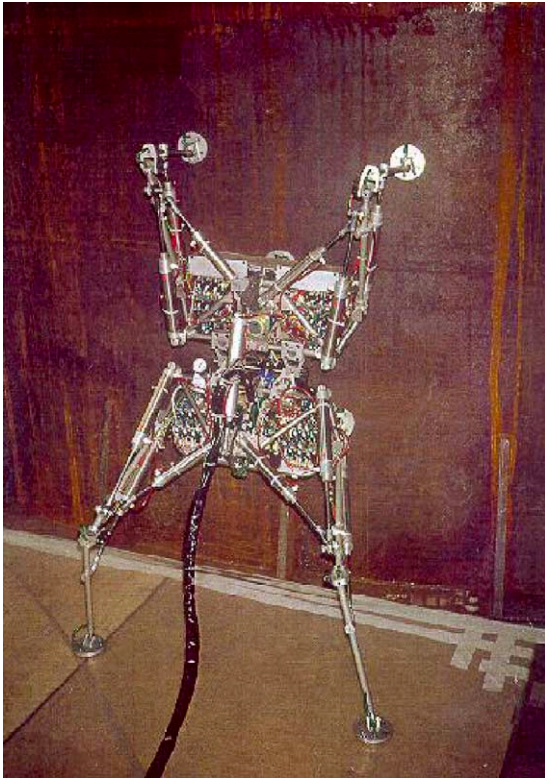
Fig. 15. Robug IIs performing an automatic floor-to-wall transfer.

Fig. 16. Robug IIs climbing a Magnox nuclear reactor pressure vessel.

dle wide variety of the terrain. Pneumatic actuators were used to power the robot in order to reduce the weight of the robot and yet provide enough strength for carrying tools. In order to overcome the deficiency of the standard PID control method in controlling non-linear pneumatic actuators, a Fuzzy control method with GA tuning was developed. The proposed method provided smooth and accurate motions for the robot and hence enhanced the walking and climbing performance. In addition, the improved accuracy also allowed the use of the robot leg as a scanning probe for inspecting structure defects. The reflexive behaviours facilitated the robot to work in relatively unstructured environment. This kind of autonomy had certainly simplified the operation procedures of the robot. The capability of performing automatic floor-to-wall transfer was vital for applications where access to the structure being inspected is limited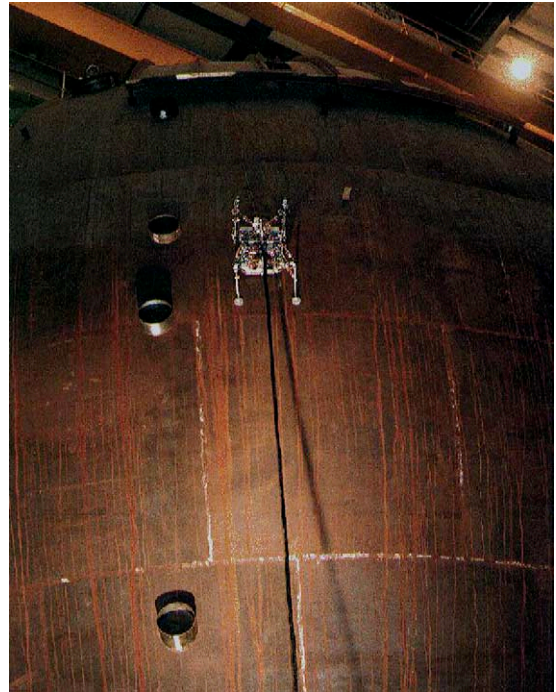. The robot was tested on a real-scale model of a Magnox nuclear reactor pressure vessel and the result has confirmed the usefulness of the robot (see Figs. 15 and 16).

Further work in navigation system is being carried out to enhance the autonomy of the robot. Since the robot is capable of walking and climbing, the navigation problem is no longer restricted in 2-D space. The robot has to determine whether it should walk round the obstacles or climb over them.

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