A Self-contained Wall Climbing Robot with Closed Link Mechanism

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A self-contained wall climbing robot, called MRWALLSPECT (Multi-functional Robot for WALL inSPECTion) II, is developed. It is designed for scanning external surfaces of gas or oil tanks with small curvature in order to find defects. The robot contains all the components for navigation in itself without any external tether cable. Although it takes the basic structure of the sliding body mechanism, the robot has its original characteristic features in the kinematic design with closed link mechanism, which is enabled by adopting a simple and robust gait pattern mimicking a biological system. By employing the proposed link mechanism, the number of actuators is reduced and high force-to-weight ratio is achieved. This paper describes its mechanism design and the overall features including hardware and software components. Also, the preliminary results of experiments are given for evaluating its performances.

Key Words : Self-Contained, Wall-Climbing, MRWALLSPECT II

1. Introduction

Robotic inspection technologies can be applied to various utilities such as underground pipelines, buildings, bridges, oil reservoirs, gas holders, and ships (Choi, 2000 ; Ryew, 1999 ; Baik, 2001). Since all of utilities play quite important roles in our daily life, people always experience dangerous situations caused by them and thus, continuous activities of maintenance such as inspection and repair are required. However, most of the utilities do not allow workers to easily access them and it is difficult to carry useful instruments to the test points. To cope with these situations, the researchers have proposed various solutions employing robotic technologies. Among the proposed robots, the robot capable of climbing vertical surfaces and carrying instrument to perform the required tasks provides a cost-effective solution to the given problem.

Up to now, various types of experimental robots have been developed. Two major issues in the design of the wall-climbing robot are the locomotion and the adhesion method. With respect to the adhesion method, the robots are largely classified into three categories such as magnetic, vacuum pad and propulsion type. The magnetic type (Schempf, 1995 ; Hirose, 1995) is heavy and used only for the ferromagnetic surface. The vacuum pad type (Yano, 1997 ; Yano, 1998 ; Oomichi, 1992 ; Fukuda, 1992 ; Pack, 1997 ; Backes, 1997 ; Luk, 1991) is light and easy to control. The propulsion type (Nishi, 1991) is used in very restricted environments.

Most of previous wall-climbing robots utilize a number of actuators as they are generally composed of complex mechanisms for driving and adhesion. Thus, their weights increase accordingly, which has negative effects on the whole system. A wall-climbing robot should not only be light but also have large payload so that it may reduce excessive adhesion forces and carry instruments during navigation. However, the previous robots

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could not sufficiently satisfy those requirements.

MRWALLSPECT II which can make most of elementary motions required to navigate on the wall such as translation and rotation, is a totally self-contained system (Ryu, 2001) since it has its own source of electricity, compressed air and communication device etc. The robot can perform given tasks without any external supply of energy or compressed air. Communications between the robot and the operator station are performed via wireless LAN and RF channel, and thus there is no physical wire connection to the robot. In this paper, focusing on its original kinematic construction, its hardware components and software for control are described with preliminary test results.

This paper is organized as follows. Section 2 describes its motivations and ideas. The kinematic construction and mechanism of MRWALL-SPECT-II are described in Section 3. In Section 4 we address hardware construction and software structure of the overall system. The gait control algorithm is described in Section 5. Section 6 introduces experimental results, and we conclude with summary in section 7.

2. Motivations and Basic Ideas

As shown in Fig. 1, the proposed robot has two legs with one trunk (or it may be considered to be two symmetrical legs and one extra leg, depending on the role of the trunk). The legs and the trunk are actuated with single motor, respectively and thus, it uses three actuators totally.

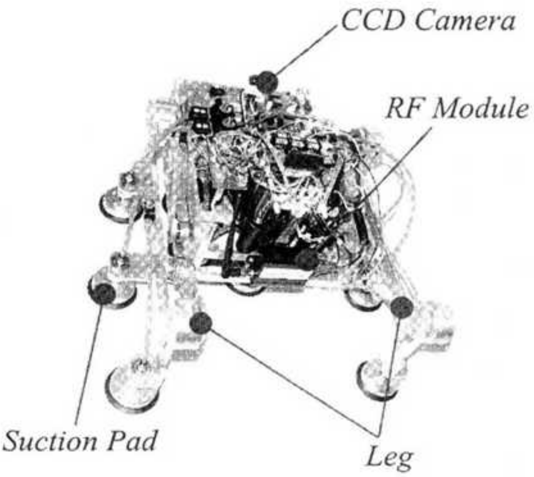


Fig. 1 MRWALLSPECT-II

MRWALLSPECT II is motivated from observations on the motions of animals such as those of apes with long limbs. Apes use their limbs and trunk as well as legs on walking. In this case legs play less important role in locomotion than the human.

In a typical locomotion pattern illustrated in Figs. 2 and 3, the ape uses the limbs as one of legs and carries out biped-like walking. During the motion their body and limbs are utilized such that the limbs leave the body while the body may close to the ground. The body is raised, lowered or attached to the ground according to the locomotion sequences. The legs just play the role of an auxiliary device of the trunk. In this work, we actively employ these observations in the design of a wall climbing robot. The idea becomes effective by developing a simple gait pattern mimicking the locomotion of the ape. To obtain the forward motion in the proposed mechanism, two lateral legs (or limbs according to Figs. 2 and 3) simultaneously step forward and adhere to the wall while lifting the trunk and producing the forward motion of the robot's trunk. After the trunk is laid on and adheres to the wall with the suction pads, the legs detach from the wall and start to step forward again by moving in space. By successively repeating the aforementioned sequences, the forward motion of the robot illustrated in Fig. 2 is produced. As illustrated in Fig. 3, the rotation is accomplished by turning

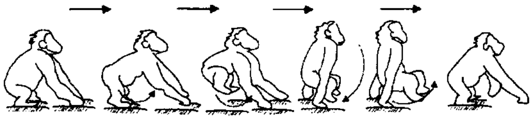


Fig. 2 Illustrated Gait Pattern (translation)

Fig. 3 Illustrated Gait Pattern (turning)

its whole body while attaching its trunk on the wall.

In general wall climbing robots carry on two basic types of motions such as "LIFT UP" and "MOVE". "LIFT UP" is necessary to detach or attach the pad on the wall (whatever types of adhesion method are utilized) and thus, at least two independent sets of actuators are required to perform required motions. In the proposed robot, however, these movements are realized with just single set of actuators. It is a quite advantageous feature because it reduces the weight of the system and enables to build a lightweight and compact robot. Ruggedness in the hardware and the software of the system are improved because a complicated control system is not necessary anymore. Just velocity control is enough for moving the robot. Also since the idea is realized by using closed kinematic chains, the robot has relatively large payload compared to the others with kinematically open loop mechanisms.

3. Mechanism Design

In this section, kinematic features of MRW-ALLSPECT II are comprehensively addressed. As shown in Fig. 1, the proposed robot has a trunk and two symmetrical legs located on both sides of the trunk. Each leg is composed of planar closed kinematic chains driven by an actuator and both of them moves synchronously.

Figure 4 illustrates the kinematic diagram of the proposed closed link mechanism for the leg. It is just an one-degree-of-freedom mechanism because it basically takes the form of a modified parallel four bar linkage. Applying Kutzbach's equation (Shigley, 1997) to the mechanism proves its mobility such as

$$\begin{aligned} m &= 3(n-1)-2j_1-j_2 \\ &= 3\times(8-1)-2\times10=1 \end{aligned} \tag{1}$$

where m denotes mobility, n is the number of link, means one-degree-of-freedom joint and j_2 represents two-degree-of-freedom joint, respectively. After simple calculations the total degree of freedom of the leg mechanism can be verified to be one. Now, let us explain how the mechanism depicted in Fig. 4 works. In the mechanism, the rectangles virtually connecting the points, $A_0A_1A_3A_2$, $A_0A_1A_7A_5$ and $A_5A_7A_9A_8$ are chosen to be parallelograms, respectively. Thus links A_2A_3, A_8A_9 and the virtual link connecting A_5A_7 only execute translation without rotation while the actuat or located at A_4 rotates. The trajectory of A_9, called coupler curve, is generated by the motion of the coupler $A_6A_7A_9$ with the rotation of the actuator located at A_4. Thus, the trajectory of A_8 just copies that of A_9. The coupler curve varies depending on the selection of linkage dimensions, whereas the linkage dimensions can also be synthesized for the specific coupler curve. Thus, if an adequate coupler curve is determined to be capable of imitating the gait pattern shown in Fig. 2, the desired gait pattern may be realized with the rotation of the actuator located in A_4. In this paper, a semicircular curve is employed as shown in Fig. 4. For the semicircular coupler trajectory the feet of lateral legs track the semicircular trajectory relative to the trunk as the actuator in A_4 rotates while the trunk is fixed. Because A_8 just copies the motion of A_9, the link A_8A_9 follows the semicircular trajectory without rotating as the actuator at A_4 rotates. However, when the ground link is changed from the trunk to the leg the trunk moves relative to the legs. Translational motion illustrated in Fig. 2 is accomplished by changing the role of the ground link and by switching suction patterns between states when legs adhere to the wall, and the trunk does, respectively. The former state is named leg-grounded state and the latter is body-grounded state for convenience.

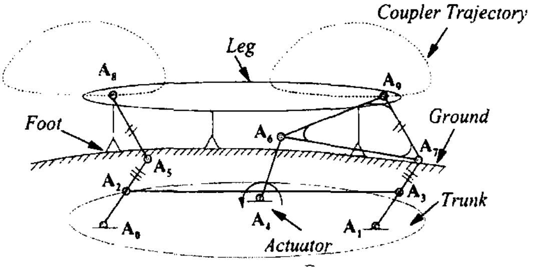


Fig. 4 Kinematic design of leg

On turning the robot to change its moving direction, it is simply carried out by rotating its trunk during body-grounded state. Though turning is impossible on leg-grounded state, it may not be a problem because positing the robot is not so much crucial in the proposed applications. Consequently, generation of required motions in the proposed mechanism is realized by using only two set of independent actuators.

Employing the techniques usually applied in kinematic analysis (Shigley, 1997), principal dimensions of the linkages are calculated. The lengths of linkages are determined by synthesizing a linkage to generate a path through precision points. To generate the gait pattern illustrated in Fig. 2, we set the coupler curve as a semicircular curve with the diameter of 60 mm shown in Fig. 5.

The actual dimension of the coupler curve is not so much important because only ratios or relative dimensions of the links are determined through synthesis procedures. Real dimensions of the linkage can be amplified or reduced with the ratios according to requirements of the tasks. In the linkage illustrated in Fig. 4, whole dimensions are able to be determined if those of a four-bar linkage represented with $A_1-A_4-A_6-A_9-A_7$ are as explained. If dimensions of A_1A_7 and A_9A_7 are known, those of A_0A_5, and A_8A_5 are, too. Thus, the synthesis of the linkage is reduced to that of the four bar linkage and it is required to design a four-bar linkage whose coupler point A_9 traces a specified semicircular trajectory. In addition the shape of coupler trajectory is not necessarily to be a complete semicircle. It just needs to have a flat interval with a curved one and the point A_9 just travels by way of several important via-points on the curve, called precision points. From these procedures the ratios among the links are determined as follows (we are not going to describe kinematic synthesis procedures since it can be found in a number of textbooks in kinematics).

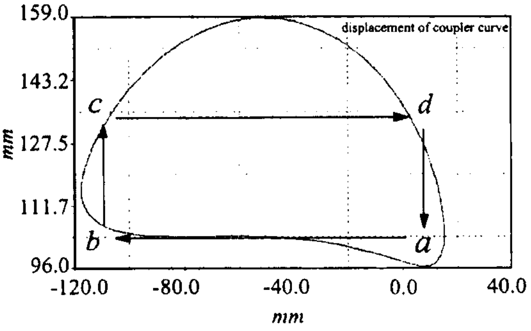


Fig. 5 Coupler trajectory

$$\frac{3.56}{Z_1}=\frac{1}{Z_2}=\frac{3.73}{Z_3}=\frac{1.32}{Z_4}=\frac{2.46}{Z_5}=\frac{1.63}{Z_6} \tag{2}$$

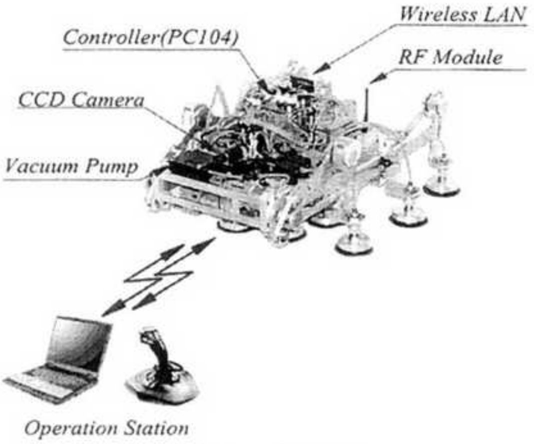
where Z_1, Z_2, Z_3, Z_4, Z_5 and Z_6 represent A_1A_4, A_1A_4, A_4A_6, A_6A_7, A_1A_7, A_6A_9 and A_7A_9 respectively. If one of the dimension is given to be an absolute value, for example Z_1, the others are determined from Eq. (2) accordingly. Fig. 5 shows the coupler curve generated when $Z_1=268$ mm. Even though the coupler curve deviates from the specified semicircle a little shown in Fig. 5, it does not cause substantial problem on the overall gait pattern.

In Fig. 5 the interval from *a* to *b* represents leg-grounded state and that from *c* to *d* corresponds to body-grounded state. The intervals from *c* to *b* and from *d* to *a* represent switching phases between body-grounded state and leg-grounded state, respectively. Switching from the pads of legs to those of the trunk occurs during the phase from *b* to *c* and from legs to the trunk does from *d* to *a*. Rotation of the robot is only possible during the interval from *c* to *d*, that is body-grounded state.

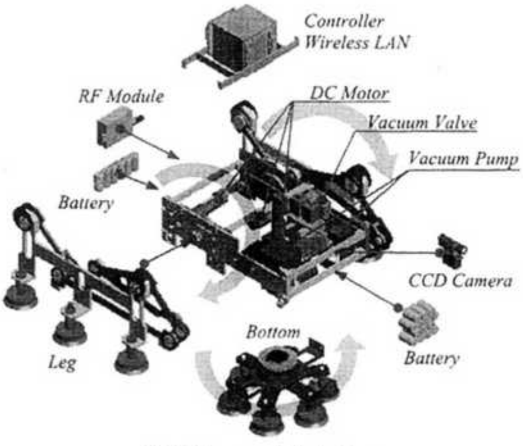
4. MRWALLSPECT II

4.1 Hardware construction

The overall system consists of two parts, the wall-climbing robot, and the operator station as illustrated in Fig. 6. The specifications of MRWALLSPECT II are listed Table 1. In the proposed robot three geared DC servo motors for are equipped in the trunk, that is two motors translational motion and the other for rotational one. Each has an encoder for sensing the position and velocity of the links. The robot is teleoperated from the operator station using the



(a) Overall system



(b) Disassembled view

Fig. 6 System layout

Table 1 Specifications of MRWALLSPECT-II

items	specification
weight	20 kg
Maximum speed	50 cm/min
size	540 mm × 400 mm × 220 mm
geared DC motor	20 watt (86 : 1)
vacuum pump	vacuum 800 mbar, flow rate 330 L/h
solenoid valve	2 way 3 port
battery	24[V], 3[A] (1.2 volt 20 cells connected in series)
controller	PC104 (Cyrix 233GX)
wireless LAN	PCMCIA type
vacuum sensor	2 EA
CCD camera	1 EA (RF module)
suction pad	12 EA

joystick that sends commands to the embedded controller in the robot via wireless LAN. In the open space, it can be controlled far from 300 meters away. We used UDP (User Datagram Protocol) protocol to communicate between the wall-climbing robot and the operator.

The wall-climbing robot has two controllers. One is an embedded controller with PC104 (Cyrix 233GX, 64 Mbytes RAM) that integrates IDE type flash disk (500 Mbytes), several DIO channels, PWM (Pulse Width Modulation) generator, and wireless LAN(PCMCIA) module. In this controller, Real Time Linux is ported as the operating system. The other controller driven by 50 Hz PWM signal generated by FPGA (EPM7128SLC84-15) is used to drive CCD camera. The camera module has single rotational degree-of-freedom with the range of 180°.

MRWALLSPECT II is equipped with a battery module to perform the self-contained operation. The battery module consists of 20 cells (1.2 volt) connected in series (Ni-Hydrogen battery, 72 watt). Because MRWALLSPECT II requires approximately 4.5 ampere continuous current, approximately 30 minute operation is possible if the battery is charged once. Twelve suction pads are equipped for adhesion and the vacuum for the suction pad is generated by two vacuum pumps connected in parallel. Also, to accomplish the smooth adhesion and detachment, two vacuum valves (2-way 3-port) and vacuum sensors are used. These devices prevent the vacuum from being locked down.

4.2 Software for control

Figure 7 shows the software structure for the control system. The software consists of two parts, that is, server and client similar to those of the hardware. The server program is run on the embedded hardware with PC104 and the client program that is the user interface program is installed in the computer of the operating station. To overcome the time delay in the teleoperation

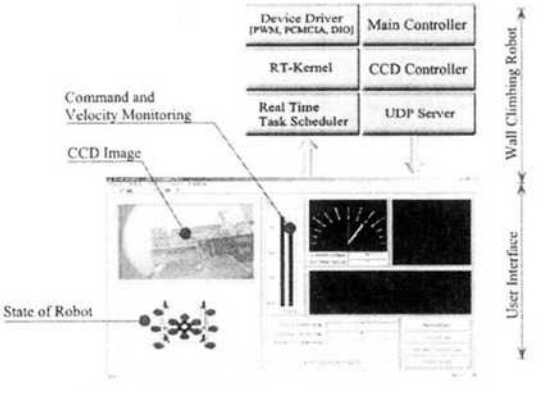


Fig. 7 Software structure

and the system down due to the unsteady socket in communication in the realtime operating system, the control program is separated into the real-time scheduler and the server program. Also the character devices are used to communicate between these programs. Along with the server program, a telnet server is run on the PC104. The control program in PC104 consists of the user space and the kernel space. The user space provides several functions for user interface such as monitoring and the kernel space function includes schedulers, driver programs for various data acquisition boards, respectively. Windows NT is used as the operating system on the computer of the operating station. Information for controlling the robot in the operating station e.g. CCD image, the direction of navigation and current velocity is displayed in the terminal of the operator station using the user interface program.

5. Control

The control of the proposed robot is mainly focused on how to smoothly switch between leg-grounded state and body-grounded state. During translation, the suction pads of the legs moves along the circumferential interval in the semicircular trajectory and close to the wall by rotating the driving actuators. After contact with the wall the vacuum sensors detect whether the vacuum of the legs is established, and the suction pads of the trunk are released. Then, the rotation of the motors toward the ongoing direction causes the trunk to be translated forward and consequently the suction pads of the trunk have contact with wall again. By successively repeating these sequences, the forward motion of the robot is produced. Although the robot translates by rotating the actuator, the actuator has two different velocity profiles during one cycle of rotation. When the robot is in leg-grounded state its trunk translates while the legs are attached to the wall and the velocity is kept slow because the mass of the trunk is relatively heavy. On the contrary during body-grounded state the legs is required to move as fast as possible in order to increase the moving speed. The velocity of the robot is planned and controlled according to this strategy. Figure 8 shows the velocity profiles of the actuator for the driving link, where the slope of the graph represents the velocity of the actuator. It can be noted that the velocity in leg-grounded state is 10 rad/sec and 20 rad/sec in body-grounded state.

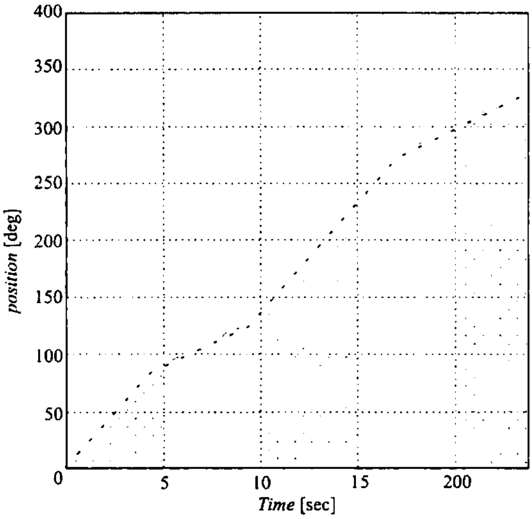
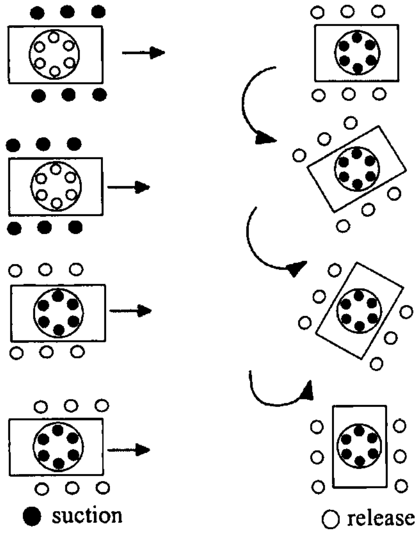


Fig. 8 Position control of leg

The rotation, different from the translation, can be accomplished only when the trunk is attached to the wall and the legs are released, that is body-grounded state. In this state, the actuator for rotation attached in the trunk turn the whole body of the robot because the suction pad of the trunk is attached to the wall and both legs are detached. As illustrated in Fig. 9 the states of suction pads switch alternatively between leg-grounded state and body-grounded state during the motions. There are overlapped periods of suction between two states as depicted in Fig. 10. It is to avoid the unexpected detachment of the robot from the wall during the switching period of suction and to enhance the safety of the robot against external disturbances.

6. Preliminary Experiments

To confirm the effectiveness of the proposed robot several experiments were carried out in the experimental configuration shown in Fig. 11. In



(a) (b)

Fig. 9 Suction pattern in translation and rotation: (a) Translation, (b) Rotation

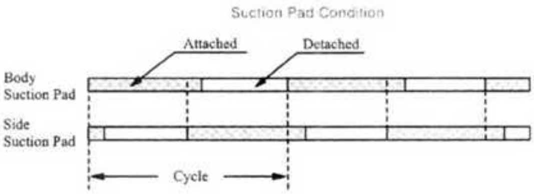


Fig. 10 Timing of switching

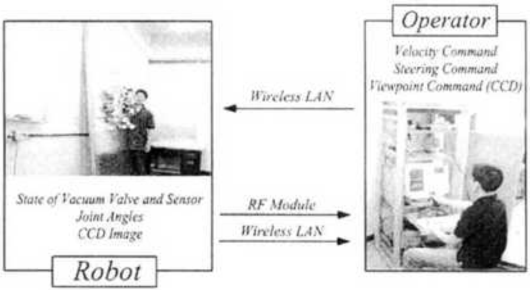


Fig. 11 Experimental setup

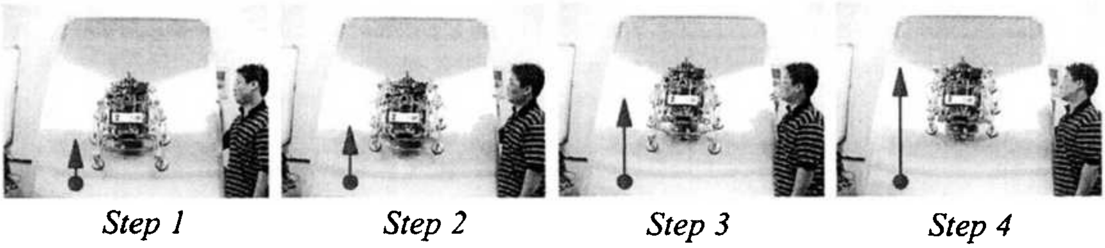


Fig. 12 Translational motion

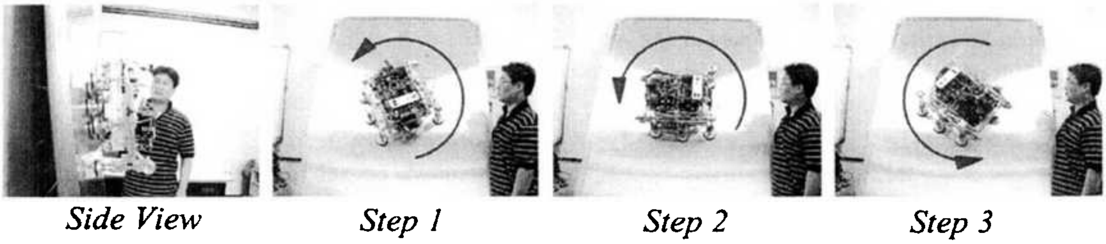


Fig. 13 Rotational motion could

the case of the forward motion, the normal speed of the robot was measured about 35 cm/min (Max. 50 cm/min) when the robot was on the horizontal plane as well as vertical wall. Fig. 12 shows the successive scenes of translation on the wall. Fig. 13 shows the rotation motion on wall and the range of rotation was approximately ±90°. In the side view of the robot shown in Fig. 13, it can be observed that the legs are detached from the wall during the rotation.

7. Conclusion

In this paper, we presented a self-contained wall-climbing robot, called MRWALLSPECT-II. The robot make most of elementary motions such as translation and rotation. Though the proposed robot does not has sufficient mobility on moving over a surface with small curvature, it can be applied a lot of inspection services with other instrumentation tools such as NDT (NonDestructive Testing) sensors. In this report the adhesion method of the robot was not discussed sufficiently. According to the preliminary expreiment, the proposed robot displayed stable adhesion in aluminium plate or concrete walls with fine surfaces, though off-the-shelf suction pads are employed, but it may be in trouble with severely corrupted surfaces. In the next stage of the research we are planning to devise a new adhesion mechanism and implement a ultrasonic testing sensor on the robot to inspect the cracks of the utilities.

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