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Design of Quadruped Walking and Climbing Robot

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***Abstract*—This paper describes an integrated approach for the design of a quadruped robot, called "MRWALLSPECT III(Multifunctional Robot for Wall inSpection version 3)", which walks in planes as well as climb walls with suction pads. Since the robot is expected to be able to move from wall to wall, wall to plane including negotiating convex or concave corners, a comprehensive study is needed to develop the robot. By performing intuitive and geometrical analysis, critical aspects of design such as joint ranges, design of ankles, and location of actuators are discussed. Environmental geometries are classified into several groups, and criteria for design are proposed for each case. The proposed criteria are applied to the actual design of MRWALLSPECT III designed to carry an ultrasonic NDT tool for inspection of the large surface of industrial utilities. By implementing the proposed idea on the robot its effectiveness is experimentally confirmed.**

I. INTRODUCTION

Recently, as one of the prospective applications of the robot, automated NDT(Non-Destructive Testing) technologies arouse the interests of a number of researchers [1]. NDT technology can be applied to large industrial utilities or social infrastructures such as buildings, bridges, oil reservoirs, gas holders etc. Although all of them play quite important roles in our daily life, continuous maintenance activities such as inspection and repair are required because people always face dangerous elements that they possess. However, most of those utilities do not allow workers to easily access them and it is difficult to carry useful instruments to the test points though it is not impossible. On the situations mentioned, the application of robotic technologies can be considered as one of the most preferable solutions. The robot capable of overcoming various unstructured environments and carrying instruments to perform the required tasks can provide more cost-effective solution to the given problem. Among the various forms of the robot, wall climbing robots (at times it is called a wall scanner by NDT researchers) may give us an achievable solutions to the applications and up to now, many researches have been done on the wall climbing robot [2-6]. Although major issues in the design of a wall climbing robot may be the locomotion and the adhesion method, it may not be possible to apply existing criteria since the large industrial utilities are composed of various environmental geometries such as walls,

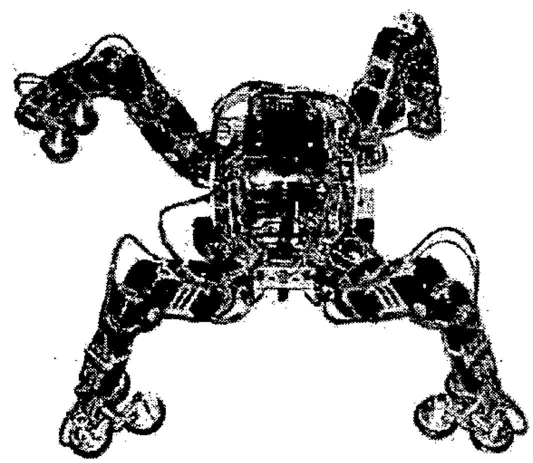


Fig. 1. MRWALLSPECT-III

planes, corner, extrusions etc. In previous researches, few researchers have addressed the wall climbing robots which can overcome various situations such as to move from floor to wall, from wall to ceiling, and to climb over obstacles [2-4]. It is required to perform in-depth studies on the versatile design of a walking and climbing robot. In this report, a comprehensive study on the design of a quadruped wall climbing robot, called MRWALLSPECT-III is performed. As shown in Fig. 1, MRWALLSPECT III under development is for the inspection of industrial utilities such as gas holders, oil reservoirs etc. with ultrasonic NDT instrumentation tools. We begin with classifying environments where the robot moves into four groups such as plain surfaces horizontal or vertical, corners convex or concave, steps, ascending or descending slopes, and critical considerations on the design are discussed. Based on intuitive and geometrical analysis, several criteria for determining joint ranges, location of actuators design of ankle are addressed. Also, employing the criteria, mechanical design of MRWALLSPECT-III is performed.

II. DESIGN CONSIDERATIONS

On the development of a robot, various factors should be taken into account when we choose the mechanism and the size of a robot at the design stage, or when gaits are controlled during operation. In this section, several critical considerations are given for the design of a quadruped walking and climbing robot. The robot, as shown in the design model of Fig. 2, has four legs and three degrees of freedom (abbreviated as DOF from now on) for each leg, where θ_{ij} denote the angle of joint j of leg i. Based on this model, joint ranges, location of actuator and design of ankles are discussed to cope with various characteristic environmental features.

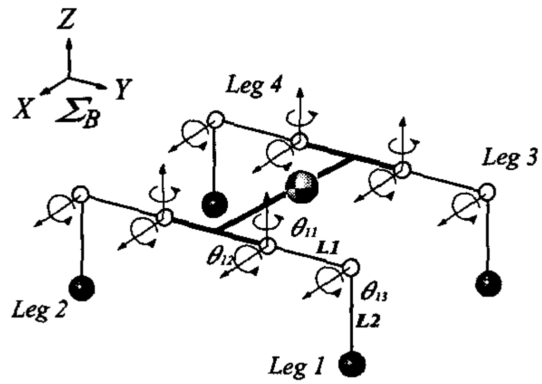


Fig. 2. Design model of quadruped walking and climbing robot

A. Determination of Joint Ranges

In this section, we begin with classifying the working environments into several groups. Then, the required joint angles to negotiate environmental conditions are determined. In fact, since the robot is assumed to have a general kinematic structure as shown in Fig. 2, joint ranges is one of the most critical issues in the design. As preliminary steps for analysis, following assumptions are set in advance.

Assumption 1: The length of thigh L_1 and tibia L_2 of legs are equal to L. According to the basic kinematic structure of the robot shown in Fig. 2 the leg mechanisms of the robot can be considered as that of a serial manipulator. Employing *Manipulability* [7] as the optimizing function, the length of thigh L_1 and that of tibia L_2 are determined to be equal.

Thus, for each leg the inverse kinematics can be computed as follows.

$$\theta_{i1} = \arctan 2(p_y, p_x) \qquad (1)$$

$$\theta_{i2} = \arctan 2(p_z, p_y) + \arctan 2(\kappa, p_y^2 + p_z^2) \qquad (2)$$

$$\theta_{i3} = -\arctan 2(\kappa, p_y^2 + p_z^2 - 2L^2) \qquad (3)$$

where

$$\kappa = \sqrt{(p_y^2 + p_z^2 + 2L^2)^2 - 2[(p_y^2 + p_z^2)^2 + 2L^4]}$$

and p_x, p_y, and p_z denote the positions of the ankle.

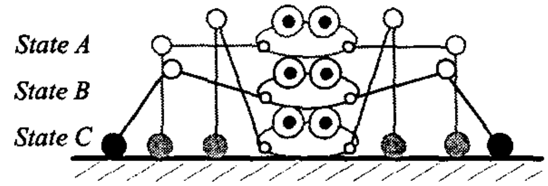


Fig. 3. Plain surface

Assumption 2: The robot always keeps its body parallel to the surface during locomotion. It is acceptable since the robot does not change the orientation of the body for easiness of gait planning and control.

Assumption 3: Assuming that H_o is the height of the step and H_r is the height between the bottom of robot body and the first joint, an obstacle and a wall can be discriminated according to

1) $H_o < L - H_r$: the step is considered as an obstacle that the robot can go over.
2) $H_o \geq L - H_r$: the step is regarded as a kind of wall to climb on.

Depending on this discrimination, the patterns of locomotion is changed.

Assumption 4: The range of the first joint angle is constrained to be $0° \leq \theta_{i1} \leq 90°$ because all the workspace required can be accessed with these joint ranges.

1) Plain surface: Plain surface corresponds to surfaces without obstacles as shown in Fig. 3. During walking on a plain surface the posture of the robot is represented as A, B and C as illustrated in Fig. 3. Here, the state A means the stand–up phase and the state C denotes the sit-down phase. All the other postures exist in between two extreme phases, phase A and C, typically such as the state B. Thus, considering H_r we can derive the joint ranges for moving a plain surface using Eq. (3) as follows.

$$0° \leq \theta_{i2} \leq \varphi$$
$$-90° - \varphi \leq \theta_{i3} \leq -90°$$

where,

$$\varphi = \arctan 2\left(L - H_r, \sqrt{2LH_r - H_r^2}\right)$$

2) Obstacle: According to the assumption 3, $H_0 < L - H_r$ in the case of the obstacle. Fig.4 shows the schematic scene of walking over an obstacle represented as a step. Procedures to go over an obstacle is successively described from step 1 to step 4. In the step 3, the relations between joint angles and the maximum height $L - H_r$ of the obstacle are obtained. When the robot posture is in the step 3, front legs and rear legs coincide with the state A and C of Fig. 3, respectively. Consequently, it can be addressed that the joint ranges to go over the obstacle have the same as that of of the plain surface.

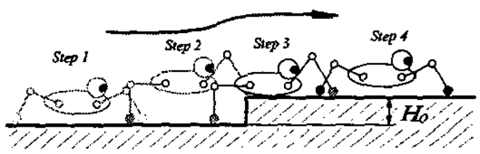


Fig. 4. Obstacle

3) Ascending and descending slope: When a walking robot moves up or down on the slope, tumbling of the body and slipping of the legs should be avoided. However, in the case of the walking and climbing robot with suction pads, these problems may be neglected because the legs always have adhesive forces between the ground and the legs. Assuming that the robot might not tumble and slip, the range of joint angles used in the slope is considered to be the same as plain surface, and the maximum angle of inclination is determined as shown in Fig. 5. If λ is the maximum distance between supporting points, it is equal to $x_f + 2L$. Also d_{slope} is equal to $L - H_r$. Consequently, the relationship between a maximum angle of inclination and the distance of supporting points can be calculated as follows.

$$\gamma_{max} = 2\tan^{-1}\left[2\frac{L-H_r}{x_f+2L}\right] \tag{4}$$

where x_f is the length of the body of the robot. From Eq.

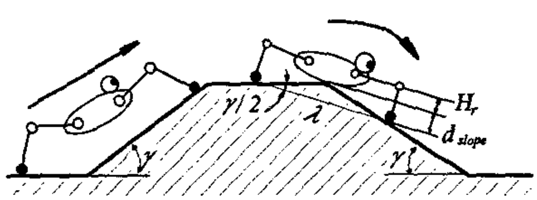


Fig. 5. Ascending or descending slope

(4), we can say that ascending slope is the case $\gamma < \gamma_{max}$, and the case of $\gamma \geq \gamma_{max}$ is included in the environment of a concave or convex corner.

4) Convex and concave corner: Transfer from a plain to a plain or a plain to a wall via a corner is one of the key functions of the walking and climbing robot. These situations can be classified into two groups, one is the convex corner and the other is the concave corner, and mathematical joint conditions can be derived. As shown in Fig. 6, in the case of transfer via a convex corner, the suitable joint conditions can be written by

$$\begin{aligned} -\sin^{-1}\left(\frac{2H_r+x_f}{4L}\right) \leq\ & \theta_{i2} \leq \varphi \\ -90^\circ - \varphi \leq\ & \theta_{i3} \leq -90^\circ \end{aligned}$$

Fig.7 describes the procedures of walking from a plain to the vertical wall through a concave corner, especially step

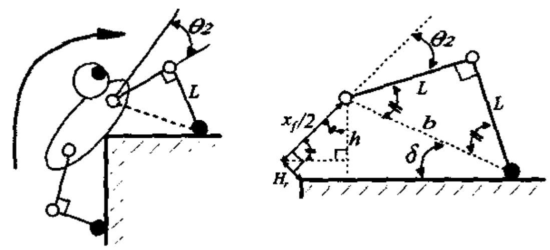


Fig. 6. Convex corner : $\delta = \sin^{-1}(\frac{h}{b})$

2 and 3. According to these steps, the joint ranges can be determined as follows.

$$\begin{aligned} 0^\circ \leq\ & \theta_{i2} \leq 90^\circ \\ -90^\circ - \varphi \leq\ & \theta_{i3} \leq -90^\circ \end{aligned}$$

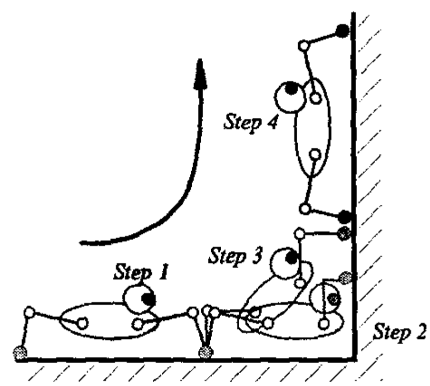


Fig. 7. Concave corner

B. Location of actuators

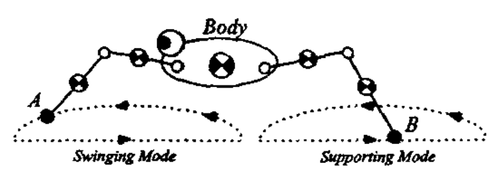
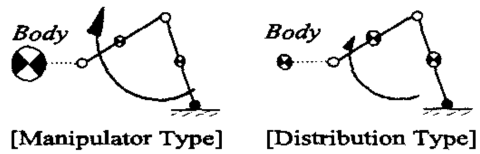
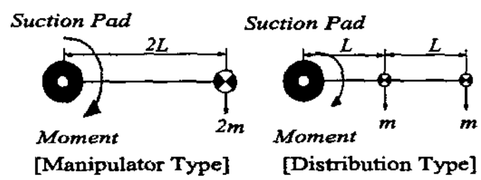


Fig. 8. Supporting and swing mode

In the case of conventional quadruped walking robots, the mass of the leg is relatively small compared with that of the body because all the actuators are located in the body to ensure fast motion of the leg by reducing the weight of the leg [2]. It may be called as the inverse pyramid type of mass distribution from the body to the leg. Normally, as shown in Fig. 8, the trajectories of legs consist of the supporting mode and the swinging mode. During the swinging mode, the body of a robot becomes the rotation center of the tip of the leg. On



(a)



(b)

Fig. 9. Location of Actuators

the other hand, during the supporting mode, the point B becomes the rotation center of the body of the robot. As shown in Fig. 9(a), in the conventional quadruped walking robot, the supporting mode is in need of more energy than the swinging mode because the body of the robot possessing the most of the mass should be driven. The energy consumption of the walking robot are different between the supporting mode and the swinging mode, and considering the efficiency of energy, the decreasing mass distribution for a quadruped walking robot is not suitable for the walking and climbing robot since it is focused on the swinging mode. Also, the suction pad employed to adhere to the wall is vulnerable to the shear force by the torsional moment, and thus, as depicted in Fig. 9(b) most of the mass should be distributed in the legs rather than the body. That is, the pyramid type of mass distribution is desirable for a compact and robust walking and climbing robot.

C. Design of ankle

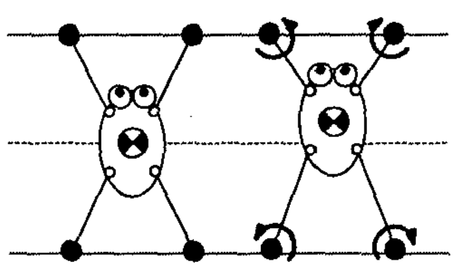


Fig. 10. Torsional moment in ankle

A walking and climbing robot, though it has thee–DOF mechanisms for legs, possesses feet having surface contact with suction pads. Thus, as shown in Fig. 10, torsional moments always exist on each ankle during walking as well as climbing, which may break the adhesion of the suction pad as explained. To prevent the effect of the torsional moment on the robot, a moment–free ankle mechanism is desirable in the case of a walking and climbing robot.

III. MRWALLSPECT III

By applying the proposed ideas, a walking and climbing robot, called MRWALLSPECT III illustrated in Fig. 11 has been developed. MRWALLSPECT III has four legs with three–DOF active joints and a passive ankle joint for each leg. The active joints are actuated by three geared

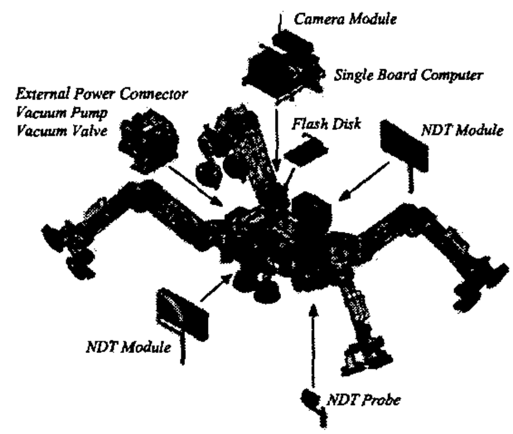


Fig. 11. Schematic of MRWALLSPECT–III

DC motors, respectively. The ankle joint of the robot that is a passive spherical joint as shown in Fig. 12 has the joint ranges of roll, pitch and yaw such as $\pm 22°$, $\pm 31°$ and $-16.5° \sim 95°$ respectively. On determining the joint

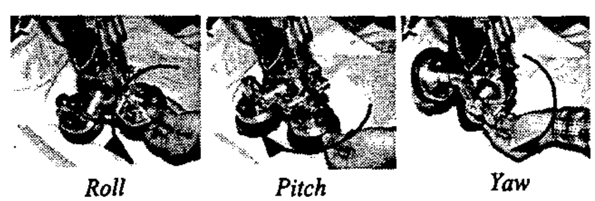


Fig. 12. Ankle with passive joint

ranges we applied the proposed scheme. The joint ranges for each environmental condition have been calculated as listed in Table. I. Based on these results, the specification of the joint ranges to cope with all the environmental conditions are determined as follows.

$$\begin{aligned} 0° \leq \theta_{i1} \leq 90° \\ -20° \leq \theta_{i2} \leq 90° \\ -145° \leq \theta_{i3} \leq -90° \end{aligned} \tag{5}$$

TABLE I
JOINT RANGES($L = 225mm$, $H_r = 40mm$, $x_f = 226mm$)

environment	range
plain surface	$0^\circ \le \theta_{i2} \le 55^\circ$ $-145^\circ \le \theta_{i3} \le -90^\circ$
obstacle	$0^\circ \le \theta_{i2} \le 90^\circ$ $-145^\circ \le \theta_{i3} \le -90^\circ$
ascent and descent	$\gamma_{max} = 30^\circ$
concave	$0^\circ \le \theta_{i2} \le 90^\circ$ $-145^\circ \le \theta_{i3} \le -90^\circ$
convex	$-20^\circ \le \theta_{i2} \le 55^\circ$ $-145^\circ \le \theta_{i3} \le -90^\circ$

In this robot, three suction pads are attached symmetrically on each ankle and six ones are on the bottom of the body. Thus, totally eighteen suction pads are quipped for adhesion on the wall and the vacuum for suction is generated by four vacuum pumps connected in parallel. Also, in order to make smooth transition from adhesion to detachment, a two–way–three–port–valves is employed to prevents the vacuum from being locked down. MRWALL-SPECT III contains two controllers. One is an embedded controller using a single board computer(Pentium-III 850MHz with IDE type flash disk, several DIO channels, DA channels, and wireless LAN module) and RTLinux is ported as the operating system. The other controller is used to drive the one–DOF CCD camera unit for visual inspection and the ultrasonic NDT module. The motor in the visual inspection module is driven by 50Hz PWM signal generated by FPGA(EPM7128SLC84-15). The NDT module mounted on robot processes the raw data obtained by the ultrasonic probe and sends the results via the main controller to the operator. The visual information of the camera module is transferred to the operator via RF transmission unit. The power of the robot is supplied with a tether cable, although all the other communication is transmitted through wireless LAN. In the open space, it can be controlled far from 300 meters away. In the design

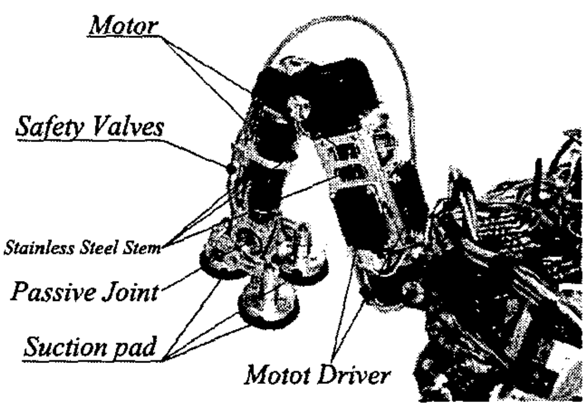


Fig. 13. Leg mechanism

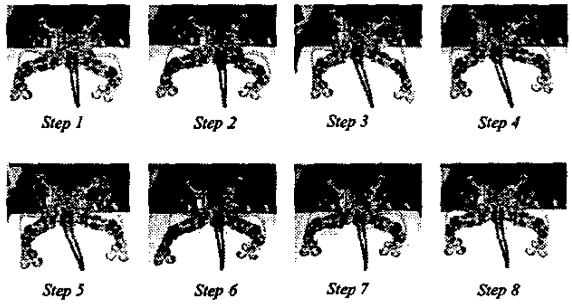


Fig. 14. Static walking using crawl gait

of the legs, the proposed scheme is employed. As shown in Fig. 13, two DC motor including driving circuits are embedded in the leg mechanism to assure the pyramid type of mass distribution. On the contrary, to enhance the strength of the leg against the bending or twist forces, the thigh and tibia of the robot are reinforced with four pairs of stainless stick. Also, the wiring, one of the most serious problem in the robot system, is accomplished through the inside of the leg. Consequently, all the components except control signals are contained in the legs like a module to provide the easiness of maintenance.

IV. PRELIMINARY EXPERIMENTS

In the first of experiments, the crawl gait [8] was tested. A simple PD control scheme was applied and the positions were measured. The stroke of leg is about $20mm$ and maximum walking velocity is about $50cm/min$. Fig.14 shows the successive scenes of crawl gait.

In the second, the walking over an obstacle and climbing over the convex / concave corner were tested. As

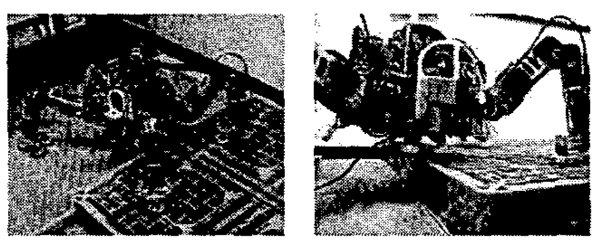


Fig. 15. Moving on step

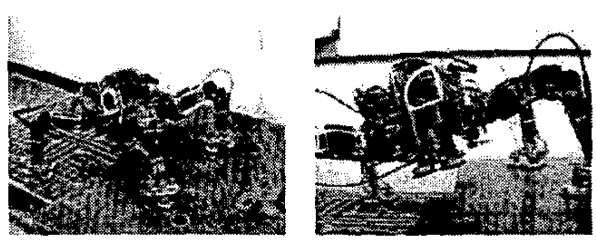


Fig. 16. Overcoming convex corner

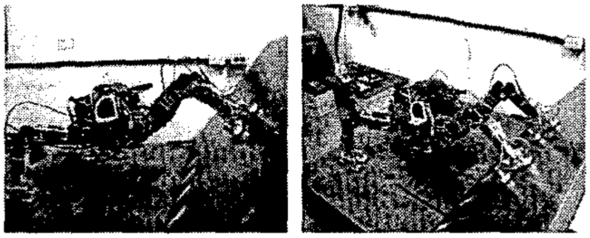


Fig. 17. Transfer from plain surface to wall

shown in Figs 15, 16 and 17, the robot could cope with these environments.

V. Conclusion

In this paper, we presented a quadruped walking and climbing robot. Its design criterion and mechanism structure were introduced. It is a semi-stand alone system for scanning external surfaces of gas tanks or buildings and inspecting defects with NDT tools during navigation. MRWALLSPECT III has better capability for overcoming various environments than most of previous quadruped walking robots or wall climbing robots because of its terrain adaptability. As future researches, gait planning for the various environmental conditions are under development.

VI. ACKNOWLEDGMENTS

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