Posture Control of Six-legged Integrated Locomotion and Manipulation Robot

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ABSTRACT

This paper describes the Six-legged Integrated Locomotion and Manipulation Robot with an omni-directional walking mechanism and 4 d.o.f. manipulator. The walking mechanism consists of a parallel link mechanism connecting the two frames with three linear actuators, and this robot has six extendable legs and can move in any direction. The relative position and angle of the two frames are selected arbitrarily in accordance with the length of three actuators. Walking mechanism is composed by combining them with extendable legs. We show the locomotion mechanism and posture control method of this robot in the first half of this paper and the cooperative motion between the locomotion function and manipulation function in the latter half. Walking, inclination control, cooperative motion experiments, were performed with experimental prototype model, and desired movement is attained.

1. INTRODUCTION

In many fields including the construction site, robots have come to be used in place of men. At the construction site, most of the works have been performed by a large number of human workers physically, and mobile machines such as dump-trucks, cranes and bulldozers. The mobile machines with wheels and crawlers assume simple works and their movable environment is limited. If walking robots which can work not only on the plane ground but also on the rough terrain are adopted, the working efficiency will be improved and it will be a countermeasure for a decrease in the labor population. Mobile working robot necessitates two important functions; one is manipulation function, while the other is locomotion function. While working, it is indispensable that two functional parts work cooperatively. Particularly the mobile mechanism plays important parts in the adaptive gait and stable manipulation.

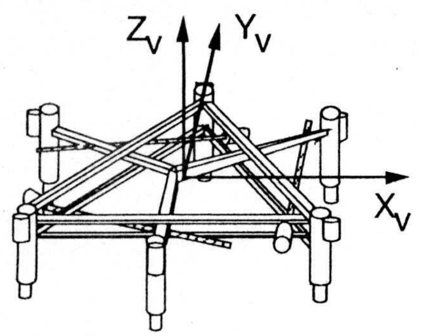
Ground is not always flat and structured: many different levels and obstacles exist. To work under such unstructured environment smoothly, robots need a mobile mechanism that makes it possible to move over the rough terrain as well as plane freely. In the previous research works, many kinds of multi-legged robots have been proposed, a biped[1], a quadruped[2], a hexapod[3-8] type robots for example. The six-legged walking robot can always keep the posture stable with more than three of six legs touching the ground and controlling its center of gravity, while a two-legged and a four-legged walking robot stand with one leg or two legs, and they tend to be unstable. In the other words, the six-legged walking robot has two support polygons and maximum moving speed can be realized with static walk. So a six-legged robot is stabler than a biped and a quadruped walking robot, and is more suitable for working robot on the rough terrain. Though many kinds of six-legged robots have been suggested, mechanisms, gaits and control systems have been studied. We have proposed a six-legged type walking robot[9] with parallel link mechanism[10] connecting two frames. The feathers of this robot are that walking is made by moving the two frames relatively and every three leg are fixed to frames. Though each leg has fewer degrees of freedom than previous six-legged robot [3-8] and the movement is simple, cooperating the relative motion of frames and changing the lengths of the legs, this robot can control the posture arbitrary angle and height. The manipulation function has 4 degrees of freedom and locomotion function has 6 degrees of freedom, thus this working robot is a redundant mechanism with 10 degrees of freedom.

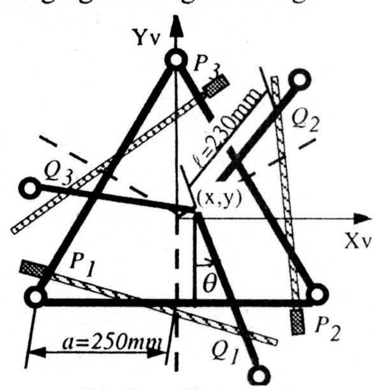
In the first half of this paper we will show an experimental prototype model, and deal with the control method of walking and inclination at the upper surface of the locomotion mechanism. The performance was investigated in terms of moving every direction and passing over steps, and as a result of the experiments, it is confirmed that this new robot can walk in all direction and can easily walk on the gentle slope controlling the inclination of the upper surface[11-12].

In the latter half of this paper, we propose a trajectory following control method by switching the normalizing matrix according to the freedom. The simulation results and the experimental results leads to the availability of the method.

2. MECHANISM

In order to calculate the posture and the inclination mathematically, we define the coordinate systems as shown in Fig.1-Fig.3. As shown in Fig.1(a), locomotion function consists of a parallel link mechanism, and Σ_v is the vehicle coordinate system fixed on the upper surface. Two frames (Δ-frame, Y-frame) are connected with three linear actuators. The relative position and rotational angle of the two frames are determined arbitrarily according to the lengths of the three ball threads which are controlled independently by the DC motors. To control the relative position and rotational angle(x, y, θ), one of the frames is set at the base. In Fig.1(b), base coordinate system is fixed on the Δ-frame. The lengths of the three actuators (L1, L2, L3) are calculated, once parameters(x, y, θ) are given: For an attitude control, this robot has six extendable legs whose lengths are controlled by the stepping motors. We can control inclination and level of the frame by changing the lengths of legs.

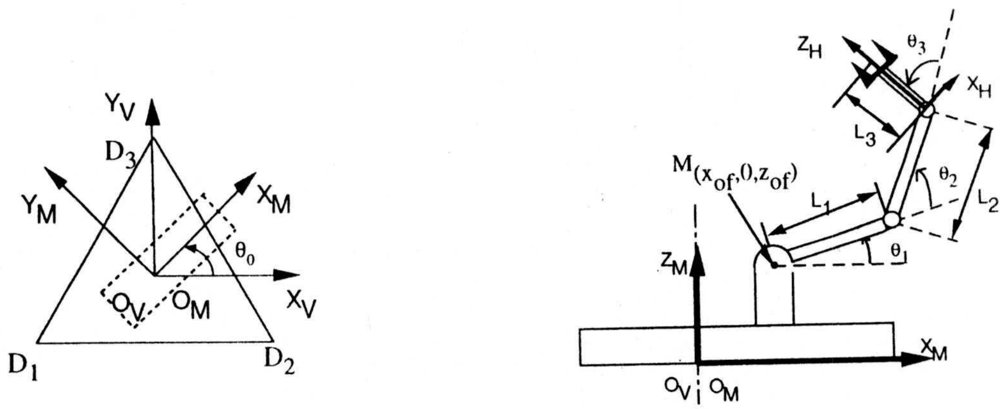




(a) Appearance (b) Coordinate system

Fig.1 Locomotion Mechanism

As shown in Fig.2, manipulation function which has 4 d.o.f. is fixed on the upper surface of Δ-frame. The z-axis of coordinate system Σ_v is consistent with one of manipulator coordinate system Σ_M.



(a) Coordinate system 1 (b) Coordinate system 2

Fig.2 Manipulation Mechanism

Σ_U is the world coordinate system located on the earth, and totally robot system is shown in Fig.3.

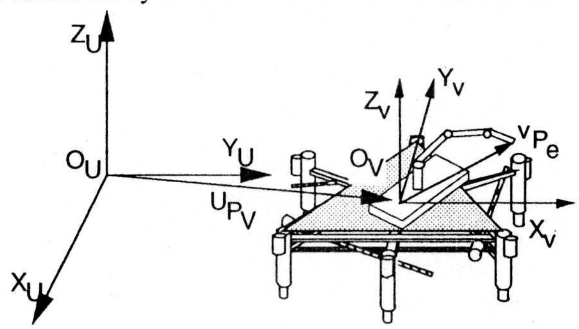


Fig.3 Totally Coordinate System

3. STANDARD GAIT

The robot can walk by the extendable legs attached to the frame. It walks by repeating the following process alternately; lifting one frame at first, sliding it relatively, and putting the legs down. In the walking process, three legs set on one frame are put on the ground, and three legs set on the other frame are lifted above the ground. The inclination of the upper surface is controlled by the three legs put on the ground. It has six degrees of freedom and can move in all directions.

3.1 RELATIVE POSITION CONTROL

This robot has a parallel link mechanism and two frames which can slide relatively by changing length of three linear actuators based on the parameters (x, y, θ). The movable ranges of three parameters (x, y, θ) are limited by three ball threads whose extendable length are limited from 0 mm to 250 mm. There are no other restrictive terms that the actuators interfere with each other. The maximum range of relative position between two frames as θ is constant are shown in Fig.4. As rotation angle θ is getting bigger, the range of relative position is getting larger.

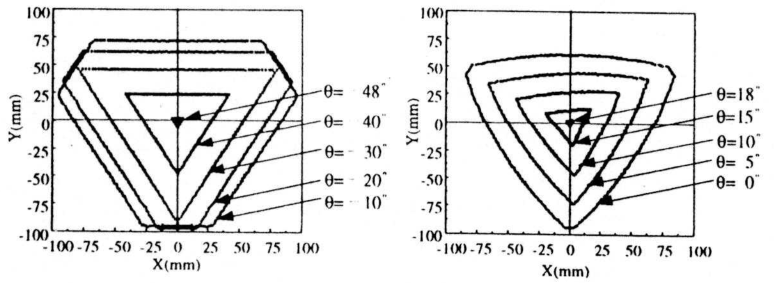


Fig.4 Range of the Relative Motion between Two Frames

3.2 WALKING

This robot can walk by changing support frame and swing frame alternatively. As steady-state locomotion, walking speed depends on the step length (length of relative motion of two frames) and the swing phase time T'. The duty factor β of this robot is constant and maximum value of β is 0.5. So the walking speed V_{max} is shown in equation (1).

$$V_{max}=\{(1-\beta)/\beta\}\, s/T' = s/T' \qquad \cdots (1)$$

As the direction of relative motion comes up to equation (2), the maximum walking speed 130mm/min. and step length S:160mm are realized.

$$\theta_w(°) = 30 + 60n \qquad (n = \pm 1, \pm 2, \pm 3) \qquad \cdots (2)$$

This robot can turn around the arbitrary point. As the center of turning agrees with the center of the Δ-frame, this robot can pivot on the spot and the turning radius is the smallest. At this case, the range of the rotation angle is $-48° \leqq \theta \leqq 18°$ and the maximum rotation speed is realized 150° /min.

3.3 Overcome the Ditch

There are many type of area on which foot can stand, ditches, sunken places ,obstacles , for example. In Fig.5, we show the width of a ditch which this walking robot can overcome, in case the ditch lies perpendicularly to the direction of walking. As shown in Fig.5 the width depends on the relative rotation angle θ and walking direction θ_w. As θ is constant, the width changes periodically with the value of θ_w. To overcome the wide ditch, robot must pivot and change walking direction in advance.

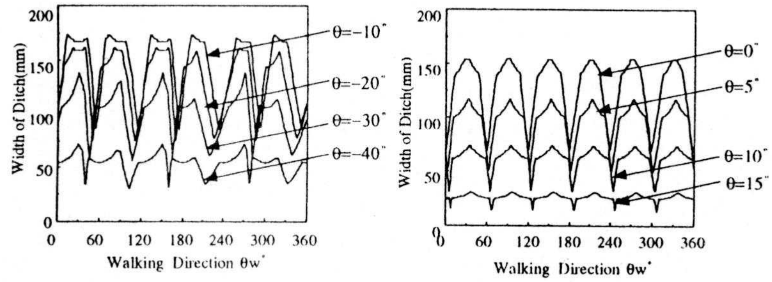


Fig.5 Width of the Ditch

4. INCLINATION CONTROL OF THE LOCOMOTION FUNCTION

4.1 SIGNIFICANCE OF THE POSTURE CONTROL

Roughness of the ground influences the posture of the robot. In other words, the posture of the upper surface depends on the leg lengths of the robot. The positions of the legs must be controlled in the three-dimensional space to walk on the rough terrain. So some legged robots whose each leg has three degrees of freedom have been studied, but control systems of them tend to be complicated. Therefore, we suggest a simple mechanism consisted of parallel link mechanism as mentioned above. Because each leg of this robot has only one degree of freedom. When this robot works on the rough terrain, manipulation, inclination, and walking must be controlled cooperatively. The posture of the upper part depends on that of the lower part. Inclination control of the upper surface is indispensable in case of conveying the load. Here we study on the inclination control method.

4.2 INCLINATION CONTROL WITH THREE LEGS

To determine the position and inclination of the upper surface in the three-dimensional space, we determine the coordinates of the three points on the upper surface. In order to calculate the posture and the inclination mathematically, we define the coordinate systems as shown in Fig.6. Σ_U is the world coordinate system located on the earth, Σ_v is the base coordinate system fixed on the upper surface. (β, γ) are Z-Y-X Euler angles, β is a rotation angle around the axis Yf , γ is a rotation angle around the axis Xf. So the equation of the upper surface becomes as equation (3),

$$s\beta c\gamma x - s\gamma y + c\beta c\gamma z = 0 \qquad \cdots (3)$$

Let the direction, where the inclination of the upper surface is the largest, be η, and the maximum angle be ξ, as shown in Fig.9. The unit vector of the direction η becomes ($\cos\eta$, $\sin\eta$) and the relation between (η, ξ) and (β, γ) is written as follows:

$$\frac{\partial y}{\partial x} = \frac{\tan\gamma}{c\beta} s\eta - \tan\beta c\eta \qquad \cdots (4)$$

Differentiating ξ with η , the direction η is determined, as follows

$$\frac{\partial}{\partial\eta}\left(\frac{\partial y}{\partial x}\right) = \frac{\tan\gamma}{c\beta} c\eta + \tan\beta s\eta = 0 \qquad \cdots (5)$$

$$\tan\eta = -\frac{\tan\gamma}{s\beta} \qquad \cdots (6)$$

From the equation (4) and (6), the relation between (η, ξ , β,) and the Euler angle is written as follows:

$$\tan\xi = -\frac{\tan\beta}{\cos\eta} \qquad \cdots (7)$$

Experimental results are shown in Fig.7 This robot has six elastic legs and each legs is controlled by a stepping motor. After calculating length of legs to change, inclining motion is performed and each leg is expanded by a speed which are proportioned to its displacement. From the experimental results, the error between the desired inclination and present value of the inclinometers are reduced up to 0.1° by controlling the lengths of legs. The experiments were successful.

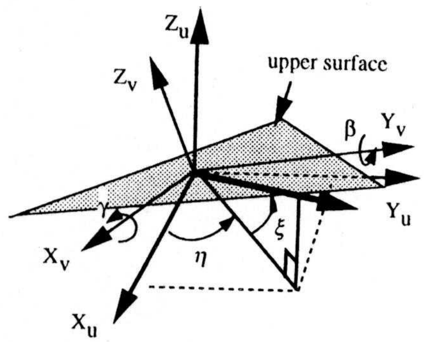


Fig 6 Inclination Coordinate System

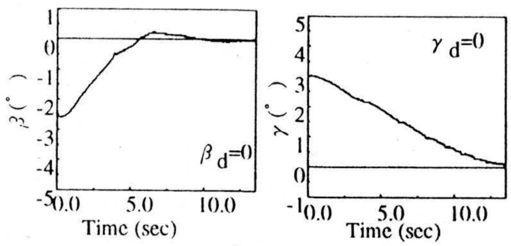


Fig .7 Inclination Contrlol $(\eta_d, \gamma_d)=(0,0)$

5. WALKING WITH LEVELING CONTROL

We performed walking experiments with leveling control of the upper surface on the slope of 10 degrees. Walking experiment on the slope is shown in Fig.8. On the whole, we could keep the level and got fairy good result.

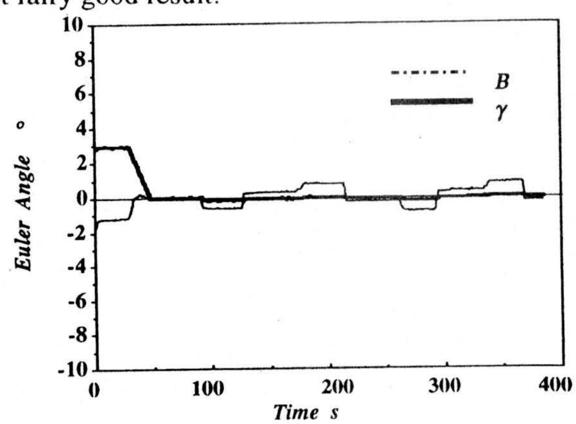


Fig.8 Leveling Walk on the Slope

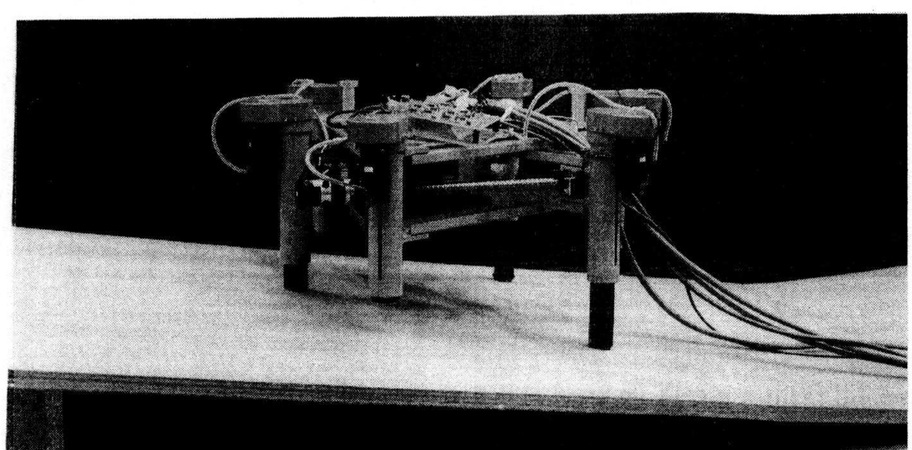


Fig.9 Leveling Walk Experiment

6. Cooperative Motion

As mentioned above, this robot has 10 degrees of freedom and totally has redundant degrees of freedom. So even if given the position of the operating point, the each position of the joints cannot be determined as one value. In this chapter we formulate the method of determining the joint variables with pseudo-inverse matrix and refer to the trajectory control by using manipulability measure as evaluation criteria.

6.1 Formulation

The operating point ${}^{U}r_{e}$ based on the coordinate system Σ_{U} is expressed as equation (8). The 10 control parameters are presented as equation (9). $\{{}^{U}x_{0}, {}^{U}y_{0}, {}^{U}z_{0}\}$ are the elements of parallel moving vector , $\{\alpha, \beta, \gamma\}$ is the Euler angles and $\{\theta_0, \theta_1, \theta_2, \theta_3\}$ are the joint variables of the arm.

$$
{}^{U}r_{e} = \begin{bmatrix} {}^{U}x_{vo} \\ {}^{U}y_{vo} \\ {}^{U}z_{vo} \end{bmatrix} + \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix} \begin{bmatrix} c\theta_0\{L_1 c\theta_1 + L_2 c\theta_{12} + L_3 c\theta_{123} + X_1\} \\ s\theta_0\{L_1 c\theta_1 + L_2 c\theta_{12} + L_3 c\theta_{123} + X_1\} \\ L_1 s\theta_1 + L_2 s\theta_{12} + L_3 s\theta_{123} + Z_1 \end{bmatrix} \quad \cdots (8)
$$

$$
q = \left[{}^{U}x_{v0}, {}^{U}y_{v0}, {}^{U}z_{v0}, \alpha, \beta, \gamma, \theta_0, \theta_1, \theta_2, \theta_3 \right]^T \quad \cdots (9)
$$

The relation between the velocities of operating point and joint is written in (10). $J(q)$ is the Jacobian matrix. $\dot{q}$ is joint velocity vector as (11).

$$
{}^{U}\dot{r}_{e} = J(q)\dot{q} \qquad J : 3 \times 10 matrix \quad \cdots (10)
$$

$$
\dot{q} = \left[{}^{U}\dot{x}_{V}, {}^{U}\dot{y}_{V}, {}^{U}\dot{z}_{V}, \dot{\alpha}, \dot{\beta}, \dot{\gamma}, \dot{\theta}_0, \dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3 \right]^T \quad \cdots (11)
$$

Since $J(q)$ is not a regular matrix, solitary $\dot{q}$ cannot be solved. But generalized solution is expressed as (12) with pseudo-inverse matrix associated with minimization of determinant of $({}^{U}\dot{r}_{e} - J(q)\dot{q})$.

$$
\dot{q}_d = J^{+}(q)^{U}\dot{r}_{ed} + \left(I - J^{+}(q)J(q)\right)k(t) \quad \cdots (12)
$$

The second term in equation (12) shows the redundancy of the system. We define the redundant term with manipulability measure[13] as evaluation criteria $V(q)$. Generally $V(q)$ is defined as equation (13), this value is an evaluation criteria which indicates how easily the position or posture of the end of robot arm are manipulated.

$$
V(q) = \sqrt{\det\left(J(q)J^{T}(q)\right)} \quad \cdots (13)
$$

Setting the $k(t)$ as (14)-(16), the value $V(q)$ becomes bigger controlling the robot with (12).

$$
k = k_p \xi(t) \quad \cdots (14)
$$

$$
\xi = [\xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6, \xi_7, \xi_8]^T \quad \cdots (15)
$$

$$
\xi_l = \partial V(q) / \partial q_l \quad \cdots (16)
$$

To deal with the velocity and angular velocity in the same dimension, we define the normalizing matrix as equation (17)(18).

$$T_v = diag\left(\frac{1}{{}^{U}r_{V1\max}}, \frac{1}{{}^{U}r_{V2\max}}, \frac{1}{{}^{U}r_{V3\max}}\right) \quad \cdots (17)$$

$$T_q = diag\left(\frac{1}{\dot{q}_{1\max}}, \frac{1}{\dot{q}_{2\max}} \cdots \frac{1}{\dot{q}_{10\max}}\right) \quad \cdots (18)$$

With this normalizing matrix, equation (12) is translated as (19). $\hat{J}(q)$ is the Jacobian matrix between normalized joint velocity vectors.

$$\dot{q}_d = T_q^{-1}\hat{J}^{+}(q)T_v{}^{u}\dot{r}_{ed} + T_q^{-1}\left(I - \hat{J}^{+}(q)\hat{J}(q)\right)\xi(t)k_p \quad \cdots (19)$$

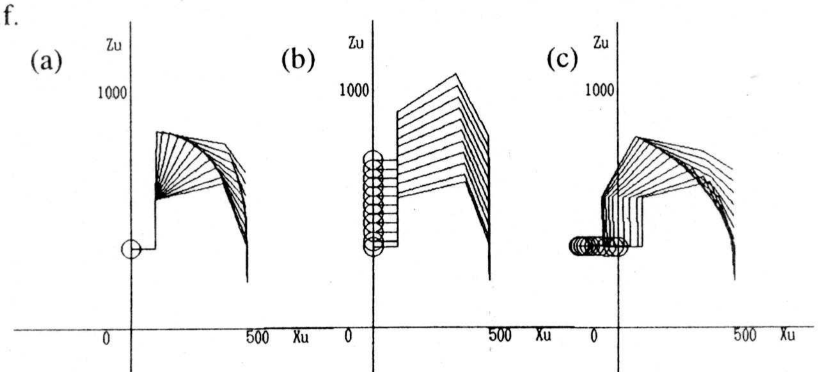
Robot is controlled according to the equation (19), switching the normalizing matrix corresponding to the freedom.[14]

6.2 Relation between Freedom and Posture

Though this robot has ten control parameters as equation (9), the ground situation or the work situation sometimes lead to restrict some of freedom. In such cases, by defining the terms corresponding to the restricted parameters of the normalizing matrix to 0, we can control the robot with same equation (19). Generally, the degrees of freedom is getting greater, the manipulability measure is getting greater.

If the trajectory control is practiced according to the equation (19), the motion of the robot is differ in the case of different degrees of freedom. As mentioned above, the degrees of freedom can be selected by changing the normalizing matrix.

In Fig.10, the simulation of trajectory control is shown and (a) is 4 d.o.f, (b) is 5 d.o.f. (c) is 10 d.o.f.



(a)4 d.o.f $\quad T_q = diag\left(0,0,0,0,0,0,\frac{1}{0.1},\frac{1}{0.1},\frac{1}{0.1},\frac{1}{0.1}\right)$

(b)5 d.o.f $\quad T_q = diag\left(0,0,\frac{1}{50},0,0,0,\frac{1}{0.1},\frac{1}{0.1},\frac{1}{0.1},\frac{1}{0.1}\right)$

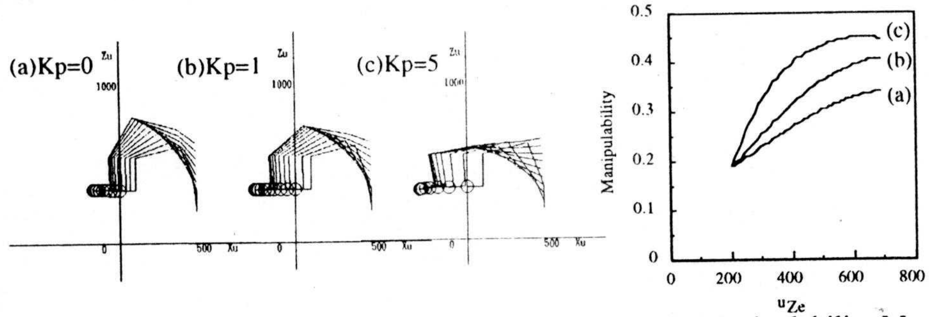
(c)10d.o.f $\quad T_q = diag\left(\frac{1}{50},\frac{1}{50},\frac{1}{5},\frac{1}{0.017},\frac{1}{0.017},\frac{1}{0.017},\frac{1}{0.1},\frac{1}{0.1},\frac{1}{0.1},\frac{1}{0.1}\right)$

Fig.10 Different Motion between Different Freedom

As shown in Fig 10, the influences of the freedom is confirmed.

6.3 Effect of the Redundancy Term

The second term in equation (12) shows the redundancy of the system. In this paragraph, we compare the differences which is produced by the different kp.In Fig.11, the simulation of trajectory control is shown and (a):kp=0, (b)kp=1 (c)kp=5. As shown in Fig.11, as the proportionality constant getting large, the manipulability measure is getting large.



(a) Simulation (b) Manipulability Measure

$$T_v = diag\left(\frac{1}{100}, \frac{1}{100}, \frac{1}{100}\right) \qquad T_q = diag\left(\frac{1}{50}, \frac{1}{50}, \frac{1}{5}, \frac{1}{0.017}, \frac{1}{0.017}, \frac{1}{0.017}, \frac{1}{0.1}, \frac{1}{0.1}, \frac{1}{0.1}, \frac{1}{0.1}\right)$$

Fig.10 Different Motion Caused by the Redundant Term

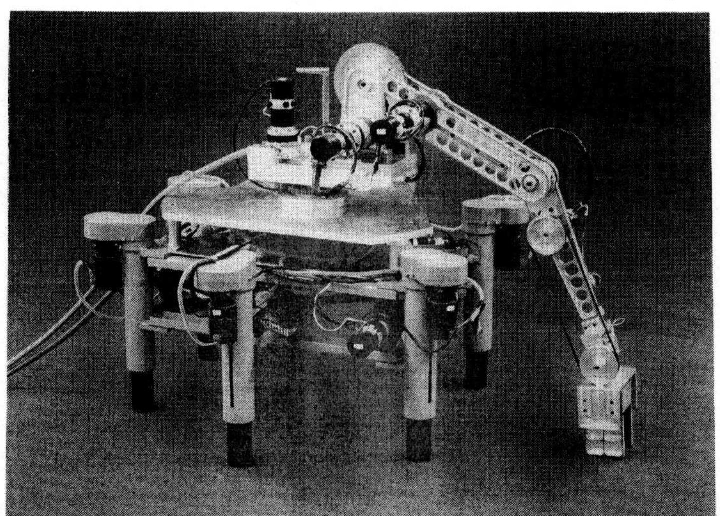


Fig.11 Six-legged Integrated Locomotion and Manipulation Robot

7. Conclusion

A Six-legged Integrated Locomotion and Manipulation Robot with an omni-directional walking mechanism and 4 d.o.f. manipulator was proposed. Legged walking mechanism that can move on the rough terrain freely is useful. Ground is not always flat and there exist many different levels and obstacles, it is important for the robot to change the inclination of the its base. Three types of experiments of legged mechanism, translational walking, rotational walking and inclination control were performed. As the result of the experiments, it was confirmed that the robot can walk on the gentle slope and has high performance of passing over obstacles with steps of different levels. As total degrees of freedom of this system is redundant, the position of the joints cannot be determined solitary. To determine the joint variables we formulated the system and proposed the technique, and simulated trajectory control according to the equation (19). As the result of the experiments with prototype robot, the trajectory control is succeeded, and it is confirmed that the technique is available for the redundant robot. We intend to make further studies on practical applications of control redundant labor robot considering many ground or work situations .

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