4R and 5R Parallel Mechanism Mobile Robots

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***Abstract*— We have proposed a self-reconfigurable parallel robot, which can be configured to 4R and 5R closed kinematic chains. This paper proposes a parallel mechanism mobile robot by mounting it on a crawler mechanism. The combined mobile robot can gain some useful functionalities from the advantage of its parallel mechanism other than just locomotion, such as getting over a bump by control of its center of gravity and carrying an object by making use of its shape. Furthermore, the robot can form three-dimensional structures with other such robots and reach a certain height in which the single one cannot. We have developed two such robots that are self-contained. This paper analyzes the motions of the functionalities and verifies them experimentally using the robots.**

I. INTRODUCTION

The objective of this study is to develop a simple but useful robot. Such a robot is less expensive and more mechanically reliable than a complex robot. A group of such robots could accomplish more than what a single complex robot could do. For an example of such a robot, we have developed a self-reconfigurable parallel robot, which can be configured to 4R or 5R closed kinematic chain [1].

This paper proposes a parallel mechanism mobile robot by mounting the self-reconfigurable parallel robot on a crawler mechanism. The combined robot is still simple and can gain useful functionalities other than just locomotion, such as getting over a bump and carrying an object by making use of its shape. Furthermore, the robot can form three-dimensional structures with other such robots and reach a certain height in which the single one cannot.

Work has been done to make mobile robots more useful. Mobile robots on which one or two serial manipulators are mounted are studied [2] [3] [4]. Several researchers proposed mobile six-DOF parallel manipulators [5] [6] [7]. Each leg of the robot is mounted on a mobile platform, which allows the robot to locomote horizontally. Asama developed a mobile robot equipped with a forklift mechanism that can lift up another such robot [8]. Hirose developed "HELIOS-II", which has a mechanism for carrying an object steadily [9].

The proposed parallel mechanism mobile robot is simple and has the functionalities mentioned above. A group of them would be able to have more functionalities. We have developed two such robots that are self-contained. This paper analyzes the motions of the functionalities and verifies them experimentally using the robots.

II. 4R AND 5R PARALLEL MOBILE ROBOTS

Figure 1 shows our parallel mechanism mobile robot. This robot consists of crawler and parallel mechanisms. The latter is mounted on the former. The parallel mechanism is self-recofigurable as shown in Figure 2 [1]. It can form the 5R and 4R closed kinematic chains (B) and (C) through the open kinematic chain (A). The number of actuators is two, which is equal to the number of DOFs when the robot takes the closed kinematic chains (B) and (C). Therefore, the open kinematic chain (A) is underactuated but we showed that it can be controlled to self-reconfigure to (B) and (C).

For the 4R closed kinematic chain, only one actuator (τ_1 in (C)) drives it and the other actuator (τ_4) drives the one-DOF open link attached to it. By forming the 0 DOF configuration in (D), it can also maintain its shape without consuming power.

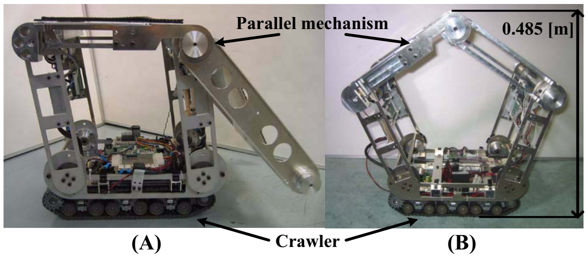


Fig. 1. (A) 4R and (B) 5R parallel mobile robots

The robot can locomote and work with either the 4R or 5R configuration. We also showed that the 5R configuration can roll by itself and proposed a dynamic control algorithm [10], which is useful to recover when the robot falls over (Figure 3). We have developed two such robots. Hereafter, the parallel mechanism mobile robot with the 4R (5R) closed kinematic chain is referred to as the 4R (5R) robot.

Three useful functionalities of the parallel mechanism mobile robot are described next.

A. Getting over a vertical bump

Figure 4 shows a typical sequence for a crawler robot to get over a vertical bump. The robot raises its front end as shown

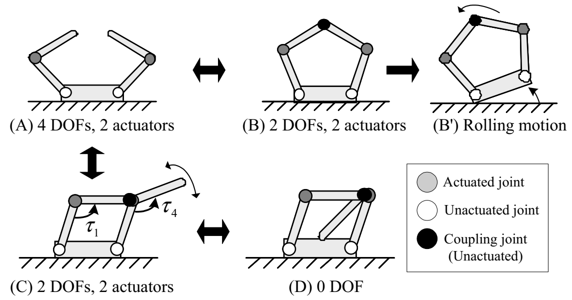


Fig. 2. Self-reconfigurable robot

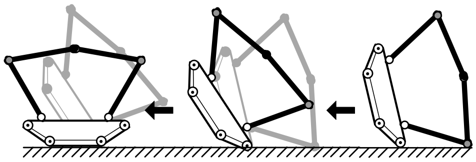


Fig. 3. Recovering motion

in (A). After the bottom of the crawler is on the edge of the bump in (B), the robot moves forward to get over the bump in (C).

In (A), friction is necessary in the vertical direction. Therefore, the crawler requires a large driving force in the horizontal direction. Furthermore, Figure 5 shows a difficult situation due to an overhang.

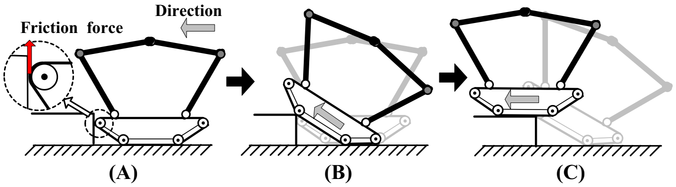


Fig. 4. Sequence of passing over steps

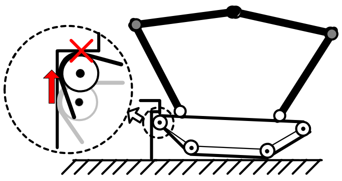


Fig. 5. Difficult situation due to an overhang

This paper presents a new sequence in Figure 4 for the 5R robot to reach (B) without relying on friction. We assume that the crawler is upside-down and trapezoidal, which is often the case. Figure 6 shows the proposed sequence in which the robot raises its front end by making use of its crawler and parallel mechanism. In (A), the robot shifts its COG by changing the shapes of the parallel mechanism first. Acceleration by the crawler enables the robot to raise its front end easily. Section III describes this dynamic motion strategy.

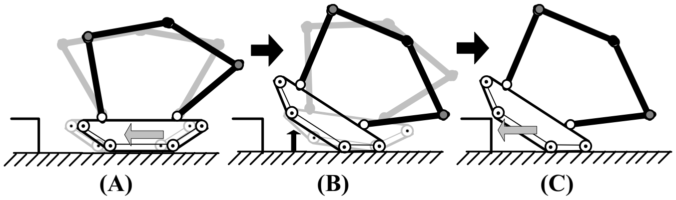


Fig. 6. Sequence of raising front end

B. Going up to a high level

Figure 7 shows a cooperative motion of the 4R and 5R robots. The open link of the 4R robot forms a slope on which the 5R robot goes up. Then the 4R robot elevates the 5R robot. The 5R robot is then able to reach a height in which it cannot reach by itself. Section IV shows a static analysis of this motion to evaluate necessary joint torques of the 4R robot.

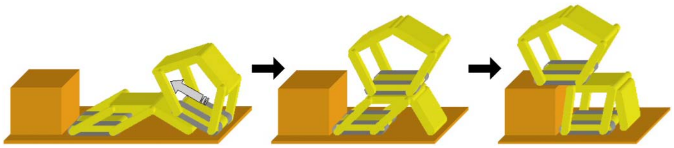


Fig. 7. Going up to a high level

C. Carrying an object

The parallel mechanism of the robot is also useful in carrying an object as shown in Figure 8 (A), (B) and (C). The 5R robot can hold an object in (B) and two robots can cooperatively carry a large object in (C).

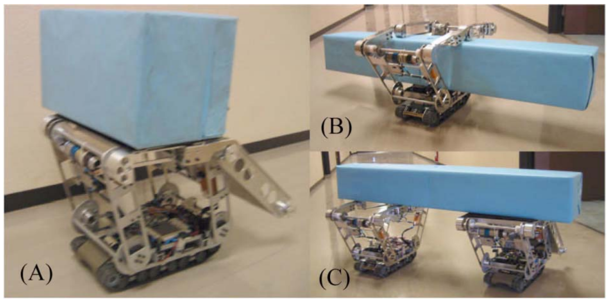


Fig. 8. Carrying objects

III. GETTING OVER A BUMP

A. Analysis of raising the front end

To raise the front end, the robot needs to move from (A) to (B) in Figure 9. In (B) the edge R of the crawler is on the ground. For static stability in (B), the COG of the robot needs to be in the region (b') of (B).

First consider the question whether or not the robot can move from (A) to (B) statically. If the COG is in the region (b) of (A), the robot can move to (B). However, if it is in the region (c') of (B) when the robot reaches (B), the robot falls over as shown in (C). To avoid this, the COG must be in the intersection of (b) and (b)' as shown in (D) or the robot must quickly shift its COG from (b) to (b') until it reaches (B). The area of the intersection (b) and (b') is often small.

Acceleration by the crawler is a better way. If the ZMP, instead of the COG is in the region (b) of (A), the robot can move from (A) to (B). Therefore the COG can be anywhere in the region (b') of (D). The area of (b') is much larger than that of the intersection of (b) and (b').

Let i be the link number and $i = 0$ represents the crawler. The ZMP of the robot x_{zmp}, shown in 9 (E), is given by

$$x_{zmp} = \frac{\sum_{i=0}^{4} m_i\{x_i(\ddot{z}_i + g) - z_i\ddot{x}_i\} - \sum_{i=0}^{4} I_i\dot{\omega}_i}{\sum_{i=0}^{4} m_i(\ddot{z}_i + g)} \tag{1}$$

where m_i and I_i are the mass and the inertia moment of link i, respectively, (x_i, z_i) are the x and z coordinates of the COG of link i, ω_i is the angular velocity of link i, and g is the acceleration of gravity.

For simplicity, assume that the parallel mechanism has no relative motion to the crawler which moves only horizontally. Then the accelerations of the links are equal to that of the crawler.

$$\ddot{x}_1 = \ddot{x}_2 = \ddot{x}_3 = \ddot{x}_4 = \ddot{x}_0, \tag{2}$$

$$\ddot{z}_1 = \ddot{z}_2 = \ddot{z}_3 = \ddot{z}_4 = \ddot{z}_0 = 0, \tag{3}$$

$$\dot{\omega}_i = 0. \tag{4}$$

Therefore, Eq. (1) is simplified as

$$x_{zmp} = x_G - \frac{z_G}{g}\ddot{x}_0 \tag{5}$$

where

$$x_G = \frac{1}{M}\sum_{i=0}^{4} m_i x_i,\ y_G = \frac{1}{M}\sum_{i=0}^{4} m_i y_i \ : M = \sum_{i=0}^{4} m_i, \tag{6}$$

and $\ddot{x}_0$ is the acceleration of the crawler which can be given. To start to move from (A) to (B),

$$x_{zmp} > x_t, \tag{7}$$

where x_t is the x coordinate of the bottom edge of the crawler.

B. Experiment of raising the front end

We verify this ZMP analysis experimentally. According to Eqs. (5) and (7), given $\ddot{x}_0$ and z_G, the robot starts to move from (A) to (B) when

$$x_G = x_t + \frac{z_G}{g}\ddot{x}_0 \tag{8}$$

We set z_G = 0.11, 0.12, 0.13, 0.14 and 0.15, and the acceleration of the crawler $\ddot{x}_0 = -6.85\,m/s^2$. Table I shows physical parameters of each link and the crawler. $x_t = 0.2$m.

Figure 10 shows experimental results of the COGs $(x_G\ z_G)$ of the robot with which it starts to move. The solid line is the line of Eq. (8). The experimental results show that the ZMP analysis is valid.

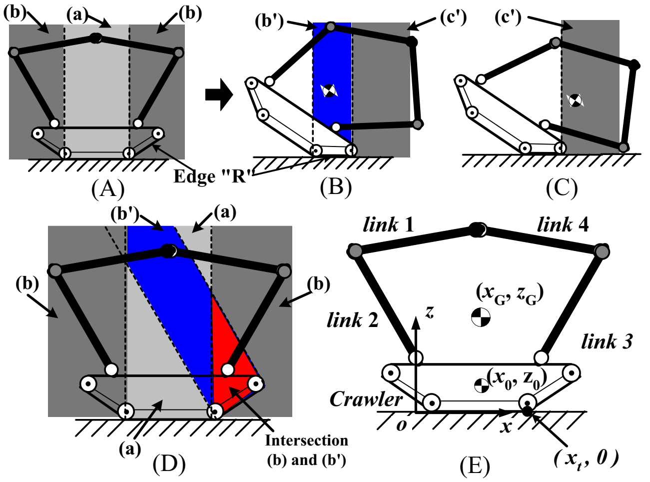


Fig. 9. Condition for the wheelie motion

TABLE I

PHYSICAL PARAMETERS OF EACH LINK

l_1	0.25 m	l_{c1}	0.125 m	m_1	1.01 kg
l_2	0.25 m	l_{c2}	0.175 m	m_2	1.37 kg
l_3	0.25 m	l_{c3}	0.175 m	m_3	1.37 kg
l_4	0.25 m	l_{c4}	0.097 m	m_4	1.08 kg
l_0	0.25 m	l_{c0}	0.125 m	m_0	3.47 kg

C. Experiment of getting over a bump

We experimentally verify that the 5R robot can get over a bump 0.1m high by raising its front end dynamically. Figure 11 shows snapshots of the robot. The robot can raise its front end and get over the bump.

IV. THE MOTION OF GOING UP TO A HIGH LEVEL

A. Static force analysis

This section analyzes the statics of the 4R robot elevating another robot as described in Section II-B. This analysis is necessary to see if the 4R robot can actually elevate the 5R robot of 8.3kg within the maximum joint torque of its actuators which is 13.5Nm.

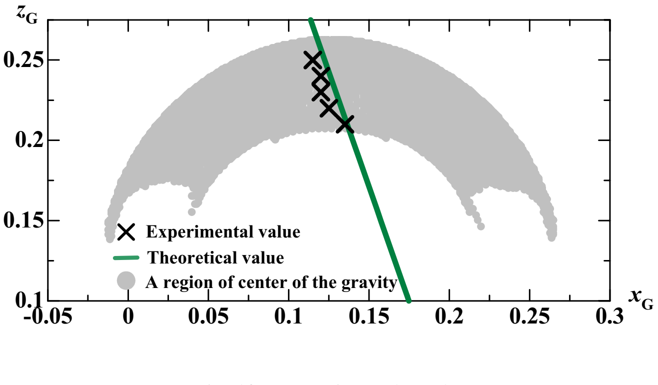


Fig. 10. Experimental result

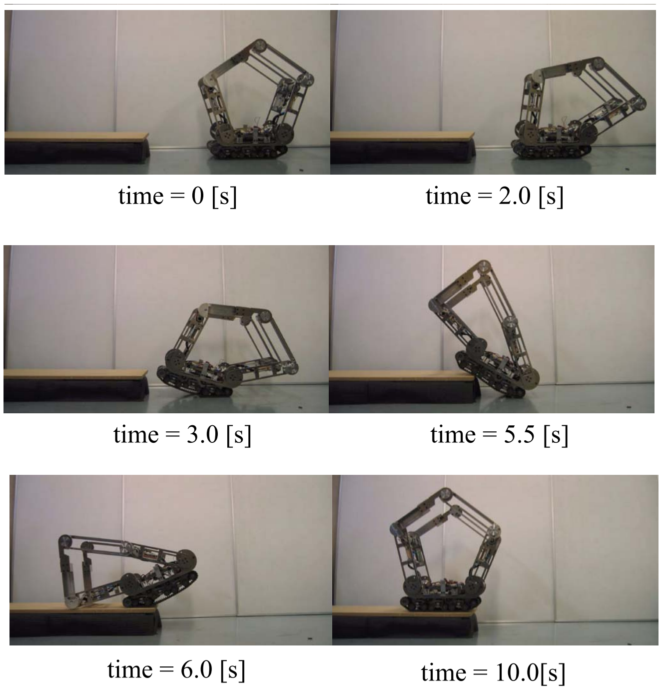

time = 0 [s]
time = 2.0 [s]
time = 3.0 [s]
time = 5.5 [s]
time = 6.0 [s]
time = 10.0[s]

Fig. 11. Snapshots of the getting over experiment

When link 4 is in contact with the ground as shown in Figure 12 (A) and (B), two actuators of the 4R robot can be used to elevate a robot. link 4 loses contact with the ground at a certain angle of θ_2. In such a situation, only one actuator τ_1 elevates a robot.

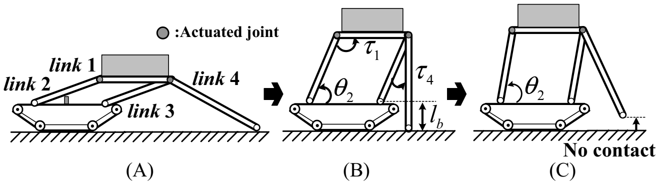


Fig. 12. The elevating sequence

To simplify the analysis, we assume that COG of a robot elevated is at the center of link 1 and that the COG of each link is at its geometrical center (see Figure 13). Normally the friction between a crawler and the ground is sufficient. Therefore we assume that the crawler of the 4R robot is stationary on the ground.

Notations are as follows:

$f_{xi},\ i = 1, 2, 3$: force exerted by joint i in the x direction,
$f_{zi},\ i = 1, 2, 3$: that in the z direction,
L_d: mass of a robot elevated,
μ_s: coefficient of static friction between link 4 and the ground,
N: reaction force from the ground,
θ_t: the angle between link 4 and the ground.

For joint 4, f_{x4j} and f_{z4j}, $j = 1, 3$, and 4, are the forces on link j exerted by joint 4 in the x and z directions, respectively(see Figure 13 (C)).

The force equilibrium equation of link 1 is given by

$$f_{x1} + f_{x41} = 0 \tag{9}$$

$$-m_1 g - L_d g + f_{z1} + f_{z41} = 0 \tag{10}$$

The moment equilibrium equation of link 1 about the COG of $link1$ is

$$(-f_{z1} + f_{z41})\frac{l_1}{2} + \tau_1 = 0 \tag{11}$$

The force and moment equilibrium equations of link 2 through link 4 are given in Appendix.

The force equilibrium equation of joint 4, shown in Figure 13 (C), is given by

$$\begin{pmatrix} f_{x41} \\ f_{z41} \end{pmatrix} + \begin{pmatrix} f_{x43} \\ f_{z43} \end{pmatrix} + \begin{pmatrix} f_{x44} \\ f_{z44} \end{pmatrix} = \mathbf{0} \tag{12}$$

The number of these constraints is 14. There are 15 unknowns, which are forces in the x direction
$f_{x1},\ f_{x2},\ f_{x3},\ f_{x41},\ f_{x43},\ f_{x44},$
forces in the z direction:
$f_{z1},\ f_{z2},\ f_{z3},\ f_{z41},\ f_{z43},\ f_{z44},$
the reaction force from the ground: N, and joint torques : τ_1 and τ_4.

When link 4 is not in contact with the ground as shown in Figure 12 (C),

$$N = 0 \tag{13}$$

Therefore τ_1 is determined uniquely. When link 4 is in contact with the ground, however, there are more unknowns than constraints, which means that τ_1 and τ_4 can be selected. In this paper for simplicity

$$\tau_1 = \tau_4 \tag{14}$$

Eq. (9) through (14) and Eq. (16) through (24) can be rewritten in vector-matrix form as

$$\boldsymbol{U} \begin{pmatrix} \boldsymbol{f} \\ N \\ \boldsymbol{\tau} \end{pmatrix} = \boldsymbol{p} \in R^{15\times 1}, \tag{15}$$

where

$\boldsymbol{U} \in R^{15\times 15}$,
$\boldsymbol{f} = (\boldsymbol{f}_x \quad \boldsymbol{f}_z)^T \in R^{12\times 1}$,
$\boldsymbol{f}_x = (f_{x1} \quad f_{x2} \quad f_{x3} \quad f_{x41} \quad f_{x43} \quad f_{x44})^T$,
$\boldsymbol{f}_z = (f_{z1} \quad f_{z2} \quad f_{z3} \quad f_{z41} \quad f_{z43} \quad f_{z44})^T$,
$\boldsymbol{\tau} = (\tau_1 \quad \tau_4)^T \in R^{2\times 1}$,
$\boldsymbol{p} = (\mathbf{0}\ \ (m_1 + L_d)g\ \ m_2 g\ \ m_3 g\ \ m_4 g\ \ \mathbf{0})^T \in R^{15\times 1}$.

Assuming that U is non-singular, the joint torques $\boldsymbol{\tau}$ can be obtained.

First we determine the angle θ_2 at which link 4 loses contact with the ground, assuming that the 4R robot elevates a robot of up to 12kg, 1.5 times as heavy as the 5R robot. Figure 14 shows the joint torque τ_1 as a function of θ_2 when $N = 0$. The angle of θ_2 should be greater than 73deg so that $|\tau_1|$ is less than the maximum joint torque 13.5Nm. This condition is met if link 4 is longer than 0.329m.

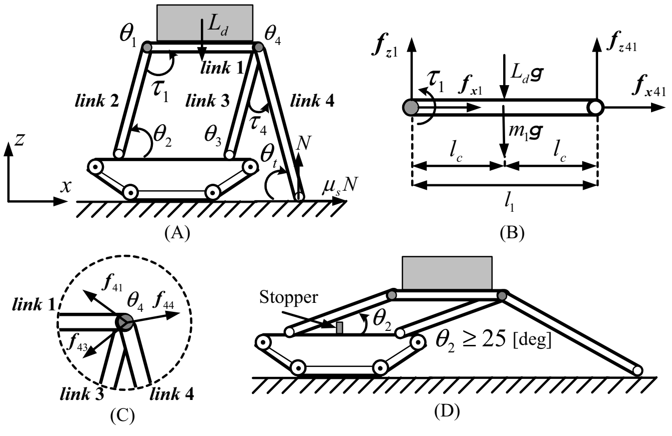


Fig. 13. Parameter of the 4R robot

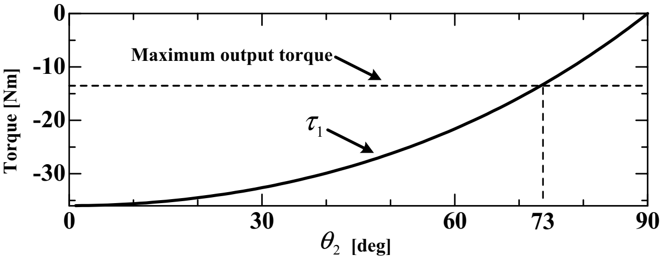


Fig. 14. Necessary joint torque to elevate 12 kg robot

Figures 15 shows necessary joint torques of $\tau_1(=\tau_4)$ for $\mu_s = 0.1, 0.5$, and 1.0 when link 4 is in contact with the ground. In (A) the mass of a robot elevated is $L_d = 8.3$kg and in (B) $L_d = 12.0$kg. The stopper, shown in Figure 13 (D), limits the range of θ_2 as $\theta_2 \geq 25$deg. Figure 15 (A) shows that the 4R robot can elevate the 5R robot of 8.3 kg if $\mu_s \leq 1.0$, while (B) shows that it can elevate a 12 kg robot only when $\mu_s \leq 0.1$. Installing a small wheel to the end of link 4 can easily reduce μ_s.

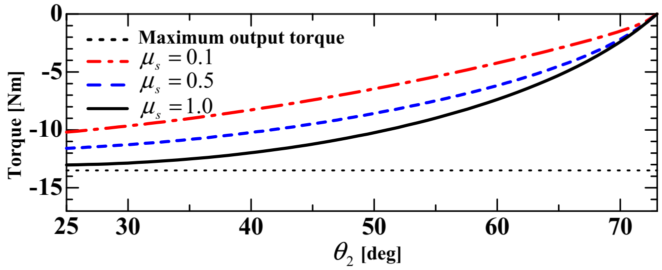
B. Experiment

We verify experimentally that the 5R robot can reach 0.4m height with the assistance of the 4R robot. Figure 16 shows the experimental result.

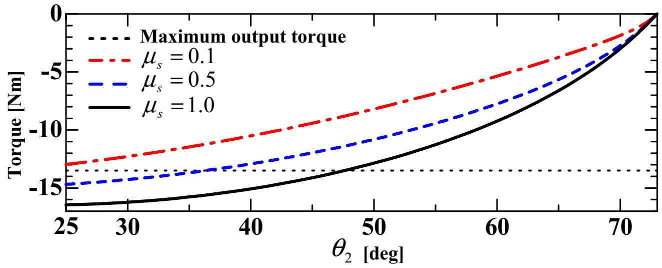
V. CONCLUSION

This paper proposed 4R and 5R parallel mechanism mobile robots. We verify that the 5R robot can get over a bump 0.1m high by controlling its center of gravity and acceleration by its crawler mechanism. We also verify that the 4R robot can elevate the 5R robot to a level 0.4m high.

A group of them could do more. For example, a group of the 4R and 5R robots could form three-dimensional structure, as shown in Figure 17. "Quadlator", a quadruped robot developed in our laboratory for whole body manipulation [11], could gain its workspace in three-dimensional space.



(A) $L_d = 8.3$ [kg]



(B) $\boldsymbol{L_d} = 12.0$ [kg]

Fig. 15. Necessary joint torque $\tau_1(=\tau_4)$ to elevate a robot

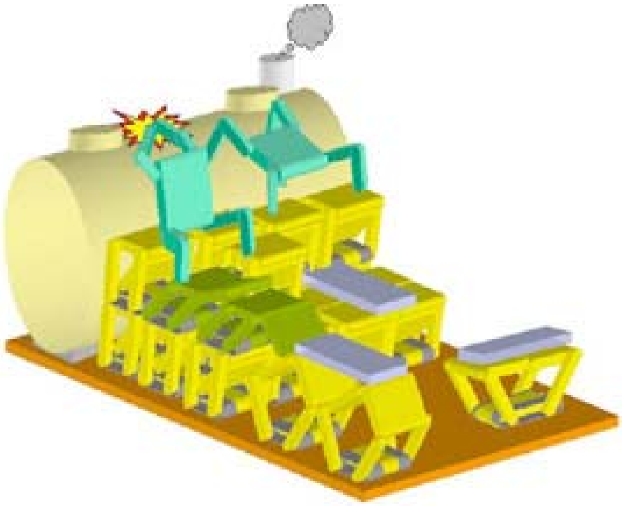


Fig. 17. Forming three-dimensional structure and cooperating with Quadlator

APPENDIX

We derive force and moments balance equations of link 2 through link 4.

The force and moments balance equations of link 2 can be described as:

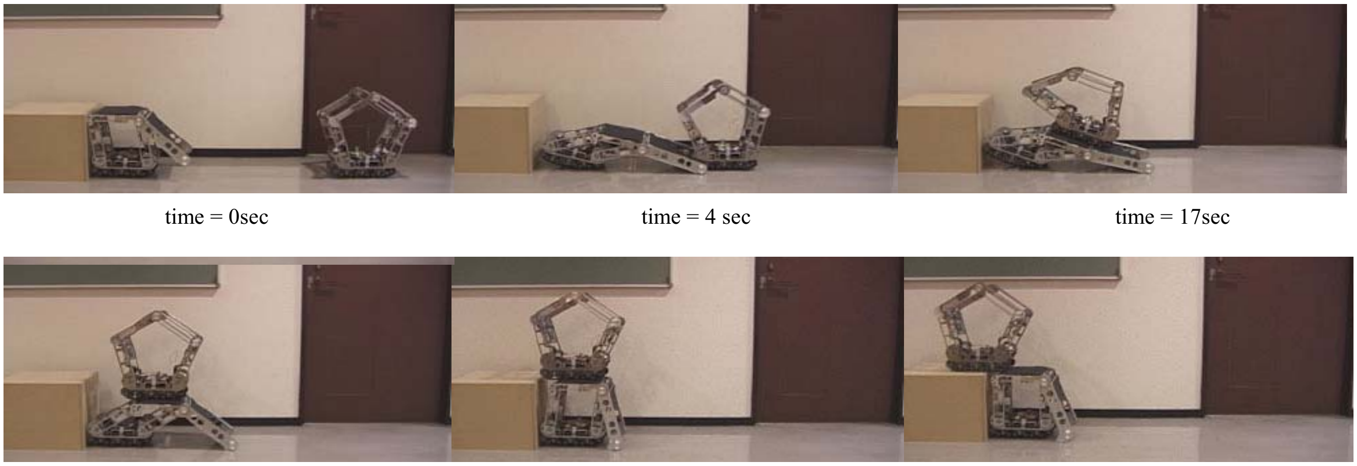
$$-f_{x1} + f_{x2} = 0 \tag{16}$$

$$-m_2 g - f_{z1} + f_{z2} = 0 \tag{17}$$

$$\{(f_{x1} + f_{x2})s_2 - (f_{z1} + f_{z2})c_2\}\frac{l_2}{2} - \tau_1 = 0. \tag{18}$$

These equations of link 3 are

$$f_{x3} + f_{x43} = 0 \tag{19}$$



time = 0sec time = 4 sec time = 17sec

time = 30sec time = 40sec time = 50 sec

Fig. 16. Snapshots of the experimental result

$$-m_3 g + f_{z3} + f_{z43} = 0 \tag{20}$$

$$\{(f_{x3} - f_{x43})s_2 - (f_{z3} - f_{z43})c_2\}\frac{l_3}{2} - \tau_4 = 0. \tag{21}$$

These equations of link 4 are

$$f_{x44} + \mu_s N = 0 \tag{22}$$

$$-m_4 g + f_{z44} + N = 0 \tag{23}$$

$$\{(\mu_s N - f_{x44})s_t + (N - f_{z44})c_t\}\frac{l_4}{2} + \tau_4 = 0, \tag{24}$$

where c_2 and s_2 stand for $\cos\theta_2$ and $\sin\theta_2$, and c_t and s_t stand for $\cos\theta_t$ and $\sin\theta_t$, respectively.

REFERENCES

[1] O. MORI and T. OMATA : Coupling of Two 2-Link Robots with a Passive Joint for Reconfigurable Planar Parallel Robot, 2002 IEEE International Conference on Robotics and Automation, pp.4120-4125, 2002.

[2] O. Khatib, K. Yokoi, K. Chang, D. Ruspini, R. Holmberg and A. Casal : Vehicle/Arm Coordination and Multiple Mobile Manipulator Decentralized Cooperation, Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 546-553, 1996.

[3] O. Brock, O. Khatib and S. Viji : Task-Consistent Obstacle Avoidance and Motion Behavior for Mobile Manipulation, 2002 IEEE International Conference on Robotics and Automation, pp.388-393, 2002.

[4] K. Kosuge, M. Sato and N. Kazamura : Mobile Robot Helper, Proc. of 2000 IEEE International Conference on Robotics and Automation, pp.583-588, 2000.

[5] L. W. Tsai and F. Tahmasebi : Synthesis and Analysis of a New Class of Six-DOF Parallel Mini-Manipulators, Journal of Robotic Systems, vol.10, No.5, pp.561-580, 1993.

[6] M. Shoham, R. Ben-Horin and S. Djerassi : Kinematics, Dynamics and Construction of a Planarly Actuated Parallel Robot, Robotics and Computer Integrated Manufacturing, Vol.14, No.2, pp.163-172, 1998.

[7] S. Shoval and M. Shoham : Sensory Redundant Parallel Mobile Mechanism, Proc. of 2001 IEEE International Conference on Robotics and Automation, pp.2273-2278, 2001.

[8] H. Asama, M. Sato, N. Goto, H. Kaetsu, A. Matsumoto, I. Endo : Mutual Transportation of Cooperative Mobile Robots Using Forklift Mechanisms, Proc. of 1996 IEEE International Conference on Robotics and Automation, pp.1754-1759, 1996.

[9] S. Hirose, S. Aoki and J. Miyake : Terrain Adaptive Quadru-Track Vehicle HELIOS-II, Proc. 20th Int.Symp. on Industrial Robots, pp.235-243, 1989.

[10] T. YAMAWAKI, O. MORI and T. OMATA : Nonholonomic Dynamic Rolling Control of Reconfigurable 5R Closed Kinematic Chain Robot with Passive Joints, Proc. of 2003 IEEE International Conference on Robotics and Automation, pp.4054-4059, 2003.

[11] T. OMATA, K. TSUKAGOSHI and O. MORI: Whole Quadrupted Manipulation, Proc. of 2002 IEEE International Conference on Robotics and Automation, pp.2028-2033, 2002.