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Ladder Climbing Control for Limb Mechanism Robot "ASTERISK"

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Abstract— **A ladder climbing motion for limb mechanism robot "ASTERISK" is proposed. This robot has six legs. The upper three legs hold on the upper rung from its both sides alternately, just like pinching it. The lower three legs hold on the lower rung in the same way. Hence the robot can climb the ladder stably. Depending on the posture of the robot, when it lifts up its body, the robot automatically selects the legs supporting the robot's weight and distributes the weight to these legs based on their force margins. The legs which cannot support forces are controlled to always contact with the rungs so that the robot holds the ladder firmly. The advantages of proposed gait and control method are verified by the analysis of the supporting range and the torque, and by experiment on force distribution.**

I. INTRODUCTION

For future outdoor application of robots, it will be necessary to develop robots which have both high mobility and high work ability. These robots are required to assist human tasks or to work in place of humans in dangerous sites such as disaster areas, maintenance fields, building sites, mine fields, etc. For example, it is expected to develop robots for search and rescue in disaster areas in place of human rescuers[1]. Maintenance robots are also required to inspect bridges, tunnels, etc[2].

These fields have rough and complicated terrain compared with indoor fields such as a factory or plant. Wheel or crawler mechanisms are often used as mobile robots because they are easily controlled and they have high energy efficiency compared to legged mechanism[3]. On the other hand, compared with wheels and crawlers, legs do not require continuous ground contact, and the contact points are selectable. It is also possible to change the pose of the robot body without stepping. Because of these advantages, legs have higher terrain adaptability, and legged robots walking on various terrains have been developed. For example, Hirose et al. developed robots which can climb up stairs or a steep slope[4], [5].

If one robot is provided with ability to move in various environments, the application fields of this robot will be expanded. For inspection of exterior walls of buildings and highway overpasses, quadruped wall climbing robots have been developed[6], [7]. Because these robots use sucking discs, they are suitable for moving on flat walls and ceilings. However they are difficult to move on irregular surfaces such as wire gauzes and ladders. As other climbing robots, "WOODY" can climb trees to support forestry works[8], the rock-net climbing robot is designed to investigate detailed rock mass conditions to predict possibilities of landslides[9], and there are some robots which can climb up a ladder[10], [11]. These robots are expected to work in high places in place of humans. Particularly, ladders are used in the human environment such as plants and bridges which require maintenances and inspections regularly. To adapt robots to such complex scenarios, robots which have high mobility and work ability will be needed. In addition, it is important that the robot mechanisms should not be specialized for ladder climbing, because we aim at applying the robots to various environments including flat terrain.

Inspired by some insects and animals which use their limbs effectively for both locomotion and manipulation, Koyachi et al. proposed a "limb mechanism robot" consisting of multiple limbs which can be used as legs and arms [12]. Depending on the task and situation, each limb can perform two different functions: leg function for locomotion or arm function for manipulation. The robot adapts the combination of arm and leg functions to its task or environment. Accordingly the robot can be made lightweight and compact, and can consist of both mobility and work ability. We have developed a limb mechanism robot "ASTERISK" which has six limbs. So far this robot has realized some operations: omni-directional gait on flat and irregular terrains, climbing stairs and high steps, passing through narrow tunnels, manipulating objects using two neighboring limbs, and moving under ceilings[13], [14], [15].

Our final goal is to provide "ASTERISK" with high mobility and high work ability and expand application fields of the robot to tasks in dangerous and inaccessible environments for humans. In the present study, we propose a method for "ASTERISK" of climbing a ladder in order to enhance the mobility of this robot. The method has the following features:

- The robot does not use specialized mechanisms for ladder climbing.
- The upper three legs hold on the upper rung from its both sides alternately, just like pinching it. The lower three legs hold on the lower rung in the same way. Hence the robot can climb the ladder stably.
- Depending on the posture of the robot, when it lifts up its body, the robot automatically selects the legs supporting the robot's weight and distributes the weight to these legs based on their force margins.

II. LIMB MECHANISM ROBOT "ASTERISK"

A limb mechanism robot is a working mobile robot consisting of multiple limbs which can be used as both

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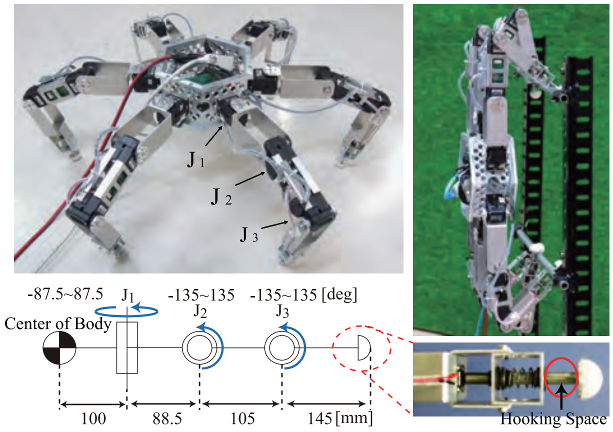

Fig. 1. Limb mechanism robot “ASTERISK”

legs and arms. Depending on tasks and situations, each limb switches two functions: leg function and arm function.

Fig. 1 shows the limb mechanism robot “ASTERISK” used in this study. This robot has six limbs attached to the body radially at even intervals. This arrangement gives the robot homogeneous mobility and work ability in all horizontal directions. Each limb consists of three rotational joints; thus the robot has 18 DOF. This figure shows the origin of the joints, and the ranges of joint angles. The ranges are symmetric on both sides of the body, that allows the same workspace even in up and down directions. The total length of “ASTERISK” when the limbs are stretched is 880[mm], the height of the body is 78[mm], and the total mass is 2.6[kg]. The body height of “ASTERISK” in standard posture is 180[mm] and the width is 500[mm]. In the followings we use term “leg (and foot)” instead of “limb” because this paper only discusses locomotion.

We adopted smart actuator module Dynamixel DX-117 by ROBOTIS as joint actuators. This module contains a servo motor, a reduction gear, a control unit and a communication interface in a compact package. Only if the reference motor angle is commanded, the control unit controls the angle by position control. We can also read out its current angle and set arbitrary motor compliance to it. In the followings we call this actuator module simply “motor”.

We use the following features of “ASTERISK” for ladder climbing: a “U-shape” limb tip (indicated as “hooking space” in Fig. 1) is used to hang on rungs of a ladder, the motor which can be set arbitrary compliance is used to detect the contact between feet and rungs and to calculate the error between commanded position and current position, and six legs attached at even intervals and their large workspace enable the legs to hold the rung alternately and to reach the center of body.

III. LADDER CLIMBING MOTION

A. Prerequisite for Ladder Climbing

Our research goal is to provide “ASTERISK” with high mobility to climb a ladder which is commonly used in human environment. In order not to lose its versatility, we do not use special actuators such as sucking discs and mechanisms which hinder normal walking movement such as hook mechanisms.

An experimental environment used in this research is a ladder composed of metal round bars and placed perpendicularly; the distance between each rung of the ladder is 300[mm], and the diameter of the rung is 12.7[mm] to fit the size of the limb tip. In addition, the “U-shape” limb tip is used to hang on rungs of a ladder as previously stated. This is the simple mechanism and dose not hinder normal walking.

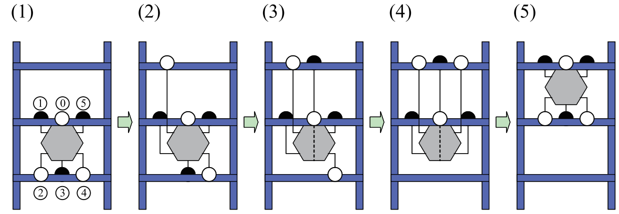

Fig. 2. Gait for ladder climbing

B. Gait for Ladder Climbing

In this section, we describe a gait to climb a ladder. To hold the ladder firmly even when the two swinging legs move to the next rungs, we suggest the ladder climbing gait as follows(**Fig. 2**):

1) Hold the upper rung with upper three legs and hold the lower rung with lower three legs
2) Release left two legs from the current rungs and hang to the next rungs
3) Release mid two legs from the current rungs and hang to the next rungs
4) Release right two legs from the current rungs and hang to the next rungs
5) Move up the body to the next step

In Fig. 2, the white circle shows that the leg is hanging to the rung from front side, and the black circle shows that the leg is hanging to the rung form back side (**Fig. 3**). Hence the robot can hold the rungs firmly. The legs color changes respectively in this flow (5) because the feet turn around the rungs while the body moves to the next step.

C. Workspace of Legs

Fig. 3 shows the workspace of the robot on condition that the upper three legs or the lower three legs are the same height.

The crossover area of the upper and lower legs is only near the center of the body. Therefore, movements to transfer each leg to the next rungs (the flow from (2) to (4) in the gait) are performed around the rung lateral to the body. Although the robot can climb the ladder whose step size is up to 340[mm], we use the ladder which is mentioned in section III-A.

D. Analysis of Holding Ability

1) Advantage of Proposed Gait: In the following section, we analyzed an advantage of proposed gait by calculating the range where feet can support the force while the body moves to the next step. The distance between the neighboring rungs is changed. We defined the distance between the ladder and

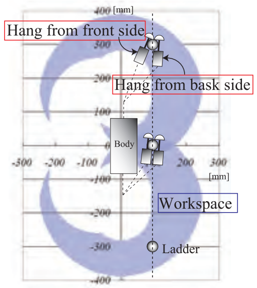

Fig. 3. Workspace of legs and side view of gait

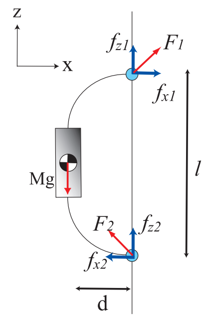

Fig. 4. Force analysis

the body as 100[mm] which is almost limit of the workspace as shown in Fig. 3.

First, we calculated force directions added to each foot by following equations when the robot holds the ladder as shown in **Fig. 4**. This equations are defined by following parameters:

- Distance between the neighboring rungs: l
- Distance between the ladder and the body: d = 100[mm]
- Force acting on the upper legs from the upper rung: $F_1 = \{f_{x1}, f_{z1}\}$
- Force acting on the lower legs from the lower rung: $F_2 = \{f_{x2}, f_{z2}\}$
- Ratio of the force f_{z1} to f_{z2}: α

Note that "z" direction is vertical and M is the mass of the robot in the figure.

$$f_{x_1} - f_{x_2} = 0 \quad (1)$$
$$f_{z_1} + f_{z_2} = Mg \quad (2)$$
$$l f_{x_1} = dMg \quad (3)$$
$$f_{z_1} : f_{z_2} = \alpha : 1 - \alpha \quad (4)$$

We analyzed the force range by varying l. As a result of this analysis, F_1 is in the 20.3 to 73.3[deg] range and F_2 is in the -73.3 to -20.3[deg] range when α is varied in the 0.9 to 0.1 range. This angle is defined z direction as 0[deg] and given in clockwise.

Second, we calculated the direction of each foot while the body moves to the next step, and the range where the upper or lower three feet can always support.We assumed that the supporting range of each foot is 180[deg] from its foot direction as shown in **Fig. 5**.

As a result of this analysis, when all legs hang on rungs from one side, the longer the distance between each rung, the smaller the angle range(**Table I,II**). The values in this table show the angle range where the upper or lower three feet can always support the force while the body moves to the next step when the distance between each rung is l. Table I shows the angle range when all legs hang on from one side, and Table II shows the angle range when legs hang on from both sides alternately.

Taking account of the results of force directions (F_1 and F_2), when all legs are hang on from one side (Table I), there is a risk that legs slip on rungs and the body falls down to the ground because the angle range is so small and the supporting range actually may not be 180[deg] even if the

TABLE I
ANGLE RANGE FOR LEGS TO SUPPORT ROBOT'S WEIGHT WHEN THEY HANG ON RUNGS FROM ONE SIDE

l [mm]	Upper Legs [deg]	Lower Legs [deg]
250	2.2 $\sim$ 119.8	- 109.8 $\sim$ -2.3
300	2.3 $\sim$ 88.5	-86.7 $\sim$ -2.3
340	2.3 $\sim$ 69.3	-67.5 $\sim$ -2.3

TABLE II
ANGLE RANGE FOR LEGS TO SUPPORT ROBOT'S WEIGHT WHEN THEY HANG ON RUNGS FROM BOTH SIDES

l [mm]	Upper Legs [deg]	Lower Legs [deg]
250	2.2 $\sim$ 187.5	-265.7 $\sim$ -2.3
300	-1.7 $\sim$ 178.3	-242.6 $\sim$ -2.3
340	-0.5 $\sim$ 179.5	-216.3 $\sim$ -2.3

force acting on each rung is within the angle range. On the other hand, when legs hang on from both sides alternately (Table II), legs can support the force in a wide range, and it is expected to support more stable by acting internal force on rungs with three legs.

2) Torque Required to Climb a Ladder: We also analyzed joint torques from the force F_1 and F_2 required to move up the body to the next step by varying α. In order to hang on the ladder stably with no rotation for the robot, at least the left and right upper two legs and the mid lower leg must hang on the rungs and support the forces. Therefore, as a serious condition, we defined that left upper and right upper legs always support F_1 evenly and mid lower leg always support F_2.

As a result, the maximum torques required to move up the body when α is varied in the 0.9 to 0.1 range are as follows:

- The second joints J_2 of upper two legs: 18.9 - 8.4 [kgf cm]
- The third joints J_3 of upper two legs: 15.7 - 3.9 [kgf cm]
- The second joint J_2 of mid lower leg: 19.1 - 40.2 [kgf cm]
- The third joint J_3 of mid lower leg: 11.4 - 31.4 [kgf cm]

The joint numbers are shown in Fig. 1 and the maximum torque of Dynamixel DX-117 is 37 [kgf cm]. The results show that it is possible to support F_1 and F_2, and afford to hold the rung from both sides by exerting internal force as long as α is not close to zero.

IV. FORCE DISTRIBUTION FOR LADDER CLIMBING

A. Outline

When the robot actually climbs the ladder, there is a problem that loads of legs are unbalanced by only controlling leg positions because of the errors of its calibration, assumed environment, and so on. In addition, when legs hold the rung from both sides, the size of the rungs may cause problems that legs exert too much force on the rungs or legs do not completely contact with the rungs. Furthermore, each foot direction changes while the body moves up because the robot can use only two degree-of-freedom (the second and the third joints) for moving up the body. In this section, we describe the control method to solve these problems.

The outline of this control is as follows. First, we calculate the supporting range where each foot can support the force from its current angles. Second, we calculate the force margin of each foot to support the force in vertical direction. The robot automatically selects the legs which support the force of gravity and balances the loads of the legs depending on the force margin. In addition, it is necessary to repeat this calculation in real time because the directions of all legs change while the body moves.

B. Calculation of Force Margin

We define the force directions acting on each leg from the rung "$f_{x1}, f_{x2}, f_{z1}, f_{z2}$" by calculating equations (1)-(3) in section III-D.1. f_{x1}, f_{x2} are the force which support the rotation around "y" axis of the robot and can be determined, and f_{z1}, f_{z2} are the forces in vertical direction which can not be determined but these are always in "+z" direction. We can distribute f_{z1}, f_{z2} to the legs.

In the followings the suffix "i" represents the number of each leg ($i = 0, ..., 5$). Now, we define the vertical direction to the current foot direction as supporting direction, which support the force the best. We calculate "s_{d_xi},s_{d_zi}" which are the values of x and z axial component of the supporting direction (unit vector) as shown in Fig. 5.

Then we check whether each leg can support the forces of x and z direction. In the following calculation, the value "1" of "s_{xi}" and "s_{zi}" means that the leg can support the force, and the value "0" means that the leg can not support the force. If the signs of s_{d_xi} and f_{x1} or f_{x2} are equal, we set the value "s_{xi}" as "1". If not, we set the value as "0". With regard to z direction, if s_{d_zi} is bigger than b_1, we set the value "s_{zi}" as "1". If s_{d_zi} is between b_1 and b_2, s_{zi} decreases from "1" to "0" linearly, and if s_{d_zi} is smaller than b_2, we set the value s_{zi} as "0" (**Fig. 6**). This is to vary the force margin continuously so that the foot can support the force evenly around the center of "Supporting Range" and can not support much force near the end of it. Here, b_1 and b_2 are thresholds to determine the supporting range.

The motor of each joint can be read out its current position and set arbitrary compliance against the external force. If external force acts on the motor, it causes a position error between its commanded position and its current position depending on its compliance. Therefore, the same position errors mean the same forces are acting on the legs if we set the same compliance to motors. In the followings we use this position errors of each foot in place of the forces.

We calculate the force margin of each leg "f_{mi}" by following equations.

$$f_{mi} = s_{zi} \times \sqrt{r^2 - e_{xi}^2} \tag{5}$$

The "r" is the parameter which shows the maximum permissible error of the foot. First, we consider a circle with radius r and multiply s_{zi} to its z axis. Then, we define the value of z axis of the ellipse as the f_{mi} when its value of x axis is the position error "e_{xi}" (**Fig. 7**).

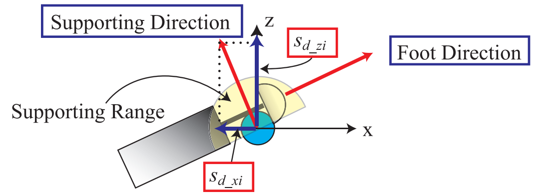

Fig. 5. Supporting direction

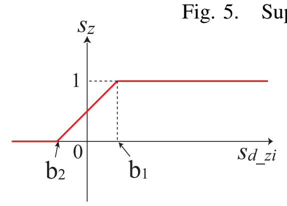

Fig. 6. Definition of s_z

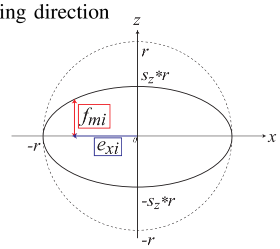

Fig. 7. Definition of f_{mi}

C. Control Method

In this section, we explain the flow of the force distribution control. We control the robot to automatically select the supporting legs from s_{xi} and s_{zi} defined in section IV-B by calculating the current positions of each leg, and to distribute forces so that loads of the legs are balanced equally. Furthermore, we control the legs which can not support forces to always contact with the rungs so that the robot does not fall down even when the external force suddenly acts to the robot.

The flow of the control is as follows.

1) Calculate f_{x1} and f_{x2}
2) Read out current angles of all joints
3) Calculate s_{d_xi} and s_{d_zi} of each leg defined in section IV-B
4) Calculate s_{xi} and s_{zi} of all legs, and select the supporting legs of each x and z direction
5) Calculate current positions of each foot p_{xi} and p_{zi} from current angles of each joint, the position errors e_{xi} and e_{zi} between current positions and commanded positions p_{d_xi} and p_{d_zi}, and count up e_{zi} as "$e_z sum$"
6) Calculate f_{mi} of the leg when its s_{zi} is bigger than "0" from its e_{xi}
7) Calculate the average position "p_{ave_x}" and "p_{ave_z}" of the supporting legs when its s_{xi} is "1" or its s_{zi} is bigger than "0"
8) Calculate command positions by following equations
   • Command position in z direction when s_{zi} is bigger than "0"

$$\begin{aligned} p_{d\_zi}(t+dt) &= p_{d\_zi}(t) + d_{move} \\ &+K_{1z}\left(\frac{f_{mi}}{\sum_i f_{mi}} e_z sum - e_{zi}\right) \end{aligned} \tag{6}$$

   • Command position in z direction when s_{zi} is "0"

$$\begin{aligned} p_{d\_zi}(t+dt) &= p_{d\_zi}(t) + d_{move} \\ &+K_{2z}(0 - e_{zi}) + K_{3z}(p_{ave\_z} - p_{zi}) \end{aligned} \tag{7}$$

   • Command position in x direction when s_{xi} is "1"

$$p_{d\_xi}(t+dt) = p_{d\_xi}(t) + K_{1x}(d - p_{xi}) \tag{8}$$

   • Command position in x direction when s_{xi} is "0"

$$\begin{aligned} p_{d\_xi}(t+dt) &= p_{d\_xi}(t) \\ &+K_{2x}(0 - e_{xi}) + K_{3x}(p_{ave\_x} - p_{xi}) \end{aligned} \tag{9}$$

Here, "$K_{1x}, K_{1z}, K_{2x}, K_{2z}, K_{3x}, K_{3z}$" are feedback gains, and "d_{move}" is the moving distance of the body in one sampling period.

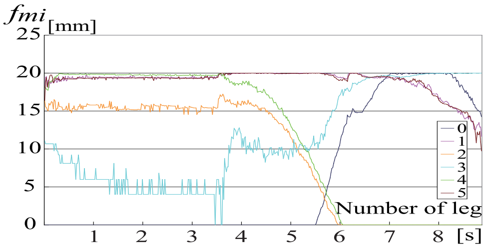

Fig. 8. f_{mi} of each leg

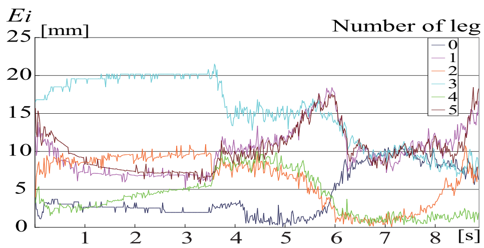

Fig. 9. E_i of each leg

9) Calculate command angles of all joints from these command positions by solving inverse kinematics.

The third term on the right-hand side of the equation (6) is the term to distribute $e_z sum$ depending on f_{mi}. "$\frac{f_{mi}}{\sum_i f_{mi}} e_z sum$" is the desired error of the reference leg, and the next command position is commanded so that e_{zi} gets closer to this. With regard to legs which can not support forces (s_{xi} or s_{zi} of the leg is "0"), we realize that legs always contact with the rung and do not exert too much force on it by not only bringing the foot position close to the average position of the supporting leg but also reducing the position error close to zero. And we define the desired position in x direction of legs of $s_{xi} = 1$ as d=100[mm] which is almost limit of the workspace.

D. Experimental Results

We conducted an experiment on the robot to move up its body to the next step with the control stated in section IV-C. Here, we defined parameters as follows: $K_{1x}, K_{1z} = 0.1$, $K_{2x}, K_{2z} = 0.5$, $K_{3x}, K_{3z} = 0.1$, r = 20[mm], and sampling time "dt" is 17.6[ms] in this experiment. First 200 sampling times, we set the d_{move} as 0[mm] to balance and converge the forces on the spot, then we set the d_{move} as -1[mm] to climb up the ladder.

Fig. 8-9 show the experimental result. Numbers in the figure represent each leg: we number in counterclockwise and define the mid upper leg as number "0" as shown in Fig. 2.

Fig. 8 shows a graph of f_{mi} calculated with s_{zi} and s_{xi} at each time. Fig. 9 shows a graph of "$E_i = \sqrt{e_{xi}^2 + e_{zi}^2}$" that represent magnitudes of position errors acting on each leg.

In Fig. 9, we can see that E_3 is bigger than others and E_1, E_2, E_4, E_5 converge around 5[mm] at first 200 sampling times (about 3.5 second). This is because s_{zi} of number 1,2,3,4,5 legs are bigger than "0" and $e_z sum$ are distributed to these legs at the initial posture. However E_3 is bigger than others even if we reduce e_{z3} close to zero for the reason that

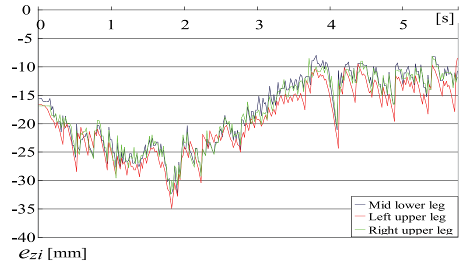

Fig. 10. Experimental result of position error of each leg

only this leg support f_{x2}.

Then the directions of each foot changed while the body moved up. We can see that E_2, E_4 get smaller and E_0 gets bigger at 5 to 7 seconds. This is because s_{z2}, s_{z4} reduce to zero and s_{z0} increases over "0" as the feet change their directions. In this part, only number 1,3,5 legs can support the force and their position error E_1, E_3, E_5 increase temporarily, however errors do not change suddenly because their f_{mi} change continuously. These results show that the robot could balance the loads acting on its legs depending on its foot directions.

E. Comparison with Another Method

1) Control Method: Finally, we show the advantage of proposed method by comparing the result of the method we already proposed.

In this method, we defined the supporting legs as the left and right upper legs and the mid lower leg, and keep the other legs from contacting with rungs in order not to exert internal forces, then control the three supporting legs to balance their loads.

We defined the mid lower leg as a reference leg, and control this leg to follow the reference position to move the body; the position of the lower rung against the body. On the other hand, we control the left and right upper legs to cause the same error respectively as the position error of the mid lower leg multiplied by a ratio which determines how much force the upper legs support compared to the lower leg.

Therefore, we use following equations instead of equations (6),(7).

- Command position in z direction of the mid lower leg

$$p_{d\_z3}(t+dt) = p_{d\_z3}(t) + K_1(\hat{p_{d\_z3}} - p_{z3}) \quad (10)$$

- Command position in z direction of the left and right upper legs ($i = 1, 5$)

$$\begin{aligned} p_{d\_zi}(t+dt) &= p_{d\_zi}(t) \\ &+ K_2\{K_3(\hat{p_{d\_z3}} - p_{z3}) - (p_{d\_zi} - p_{zi})\} \end{aligned} \quad (11)$$

Here, "$\hat{p_{d\_z3}}$" is the ideal position of the mid lower leg, "K_1, K_2" are feedback gains, and "K_3" is the ratio of forces which each leg supports. With regard to x direction, we use the same equations as (8).

2) Experimental Results: We conducted an experiment on the robot to move up its body to the next step by reducing the "$\hat{p_{d\_z3}}$" at a constant speed 0.067[m/s]. We defined feedback gains as follows: $K_1 = 0.1$,$K_2 = 0.1$,$K_3 = 1.2$.

Fig. 10 shows a graph of position errors of each legs in z direction e_{zi} while the body moves up. We can see

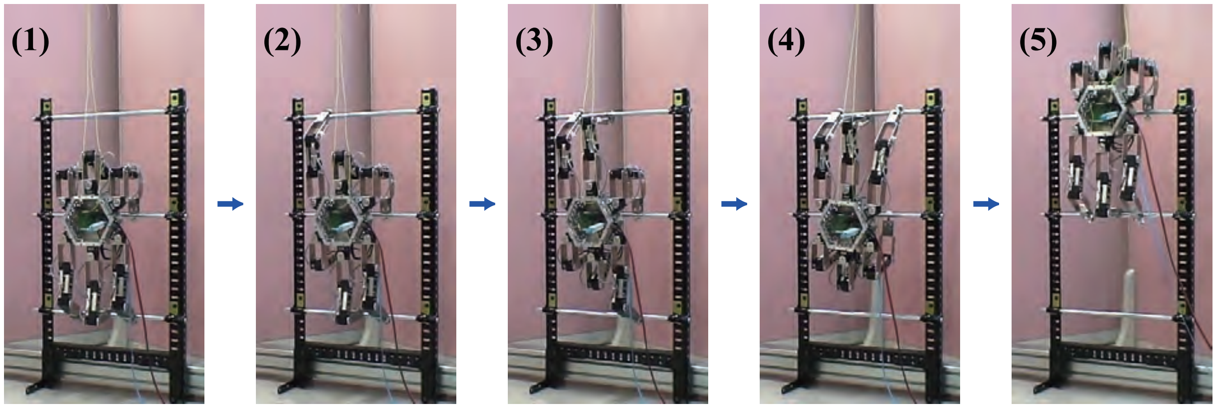

Fig. 11. Ladder climbing motion

that the three position errors changed equally by distributing the loads in z direction. However, the maximum error reached about 35[mm], and this error is quite bigger than the maximum error of proposed method (about 20[mm]) as shown in Fig. 9, because the robot used only three supporting legs in this experiment. In addition, the magnitudes of position errors $E_i = \sqrt{e_{xi}^2 + e_{zi}^2}$ reached 45[mm] because we considered only the position error in z direction in this experiment.

These two experimental results show that the proposed control method enables the robot to reduce the loads of the legs by distributing the load among the supporting legs.

Fig. 11 shows an appearance of ladder climbing motion. The numbers of this figure correspond to the numbers in Fig. 2.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we proposed a method to climb a ladder stably for limb mechanism robot "ASTERISK":

- A gait for ladder climbing to hold each rung alternately with six legs
- A control method for moving up the body to distribute loads acting on each leg depending on the posture

We also verified the advantages of these methods by analyzing the supporting range and the torque for the gait, and by comparing a proposed method and a previous method for the force distribution control.

However, we used a "U-shape" limb tip which limits the size of rungs. Therefore, in the future, we will improve these methods to climb a ladder more stably without such a mechanism by adding one joint on the foot. This will also enable the robot to cover more complex fields such as a inclined or horizontal ladder.

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