Climbing up onto Steps for Limb Mechanism Robot “ASTERISK”

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Abstract: A method for limb mechanism robot “ASTERISK” of climbing up onto steps which are higher than its body is proposed. Basically the robot climbs by wave gait; depending on the step height, the robot dynamically changes its leg stepping sequence. It inclines its body so that its legs can reach up onto the step. When the robot lifts its legs up, it calculates the stability margin by measuring the body orientation with its acceleration sensor. The robot also detects the contact between the feet and step using joint compliance. As the result of experiment, the robot could climb up onto a 230[mm] high step.

Keywords: Six Legged Robot, Climbing Robot, Limb Mechanism Robot, Stability Margin, Joint Compliance

1. INTRODUCTION

For future outdoor application of robots, it will be necessary to develop robots which have both high mobility and high manipulation ability. These operating robots are required to assist human tasks or work in place of humans in dangerous scenarios such as disaster areas, 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, because such areas maybe too dangerous. Construction robots are also required in building sites, because of increase of construction demand or for dangerous material handling such as asbestos removal.

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. However, these mechanisms need to have contact with ground all the time, so it will be difficult to apply these mechanisms to disperse ground. To solve this problem, researches have developed legged robots. For example, “TITAN-VI” which can climb up stairs with its prismatic joints [1, 2], “TITAN-VII” which can climb up a steep slope [3], robots which can climb wall with its sucker mechanisms [4, 5, 6], and robots which can climb up stairs with its compliant legs or its wheeled legs [7, 8, 9]. These robots adapt to non-flat or non-horizontal terrain such as stairs and slopes with its special mechanisms, or their bodies are bigger than the stair size. However, smaller robots will be needed in the future in order to adapt them to narrow and complex scenarios such as disaster areas and building sites.

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 [10]. 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 manipulation ability. We have developed a limb mechanism robot “ASTERISK” which has 6 limbs. So far this robot has realized some operations: omni-directional gait on flat and irregular terrains, climbing stairs, passing through narrow tunnels, and manipulating objects using two neighboring limbs [11].

Our research goal is to provide “ASTERISK” with high mobility and high manipulation ability, which will expand the application fields of “ASTERISK” to areas such as disaster areas and construction sites. In order to enhance the mobility of this robot, the present paper proposes a method of climbing up onto steps which are higher than its body.

2. LIMB MECHANISM ROBOT “ASTERISK”

A limb mechanism robot is a working mobile robot consisting of multiple limbs which can be used as both legs and arms. Depending on tasks and situations, each limb switches two functions: leg function for locomotion and arm function for manipulation. Accordingly the robot can be made lightweight and compact, and can extend both mobility and manipulation ability.

Figure 1 shows limb mechanism robot “ASTERISK” used in this study. This robot has 6 limbs attached to the body radially at even intervals. This arrangement gives the robot homogeneous mobility and manipulation ability in all horizontal directions. As shown in **Figure 2,** each limb consists of 4 rotational joints; thus the robot has 24 DOF. This figure shows the origin of the joint angles, and **Table 1** summarizes 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 (**Figure 3**). The total length of the robot when the limbs are stretched is 840[mm], the height of the body is 78[mm], and the total weight is 4[kg]. In the followings we use term leg (and foot)

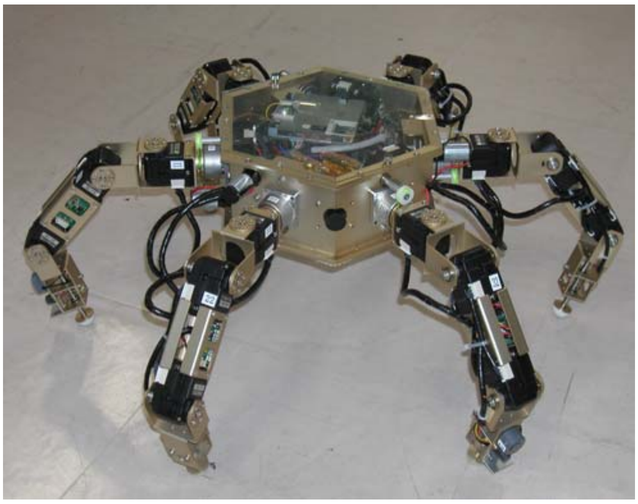

Figure 1: Limb mechanism robot "ASTERISK"

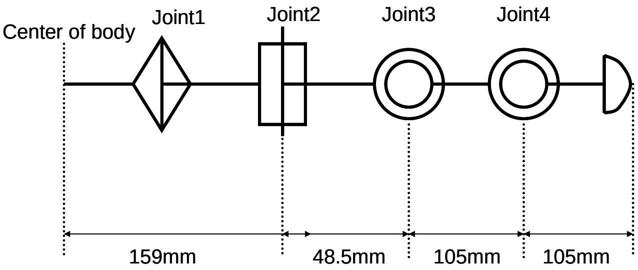

Figure 2: Configuration of limb of "ASTERISK"

Table 1: Range of joint angle of "ASTERISK"

	minimum [deg]	maximum [deg]
joint1	-200	200
joint2	-86.5	86.5
joint3	-118.7	118.7
joint4	-118.7	115.8

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. We improved the first joint module (J1) using harmonic drive system in order to enlarge the range of motor angle and to increase torque. Then the modules can generate enough motor torque to support the robots using three legs. Only if the reference motor angle is commanded, the control unit controls the angle by position control. The current angle can be read out. We can also set arbitrary motor compliance to the module. In the followings we call this actuator module simply "motor".

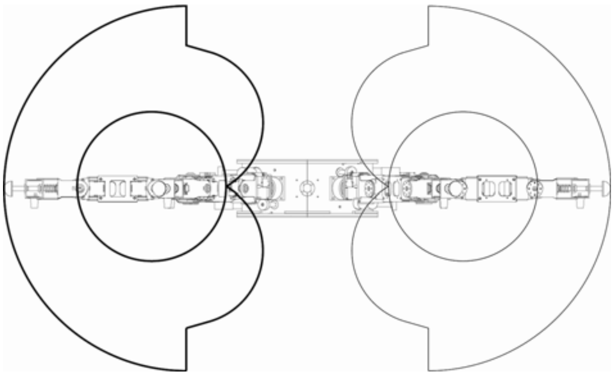

Figure 3: Workspace of limbs

We use the following features of "ASTERISK" for step climbing: large workspace in up and down directions, the compact body which enable the robot to incline aggressively, the acceleration sensor which detects the body inclination, and the motor which can be set arbitrary compliance.

The body height of "ASTERISK" in standard posture is 180[mm]. When the body touches to the ground, it is 80[mm]. When each leg is extended, it is 210[mm].

3. STEP CLIMBING

3.1 Strategy of step climbing

The gait for climbing a high step is based on wave gait. The wave gait is most stable gait of multi-legged robots. The legs move left-right symmetrically about the moving direction, and at least four legs are always supporting the body. Here we define the first two legs close to the step as the "front legs" (**Figure 4**(1)). The second two legs are defined as the "mid legs" (Figure 4(2)), and the third two legs as the "hind legs" (Figure 4(3)). As the assumptions, the height of the step is known by the robot's sensors and initially the robot is near the step.

The flow for climbing a high step is as follows:

1. The robot puts the mid legs forward and supports its body with the mid and hind legs.
2. The robot raises the front legs aside, and inclines its body to match the height of the step. Then the robot raises the front legs without hitting the step (Figure 4(A)).
3. The robot puts the front legs on the step (Figure 4(B)).
4. The robot moves its body forward and upward until the center of gravity comes between the front legs and mid legs (Figure 4(C)).
5. The robot puts the hind legs forward as much as possible.
6. The robot puts the mid legs on the step (Figure 4(D)).
7. The robot moves the body forward and upward until the center of gravity goes beyond the mid legs (Figure 4(E)).
8. If the front or hind legs are stretched to the limit in the process of 7, the robot puts the limited legs forward. Furthermore, where the robot cannot maintain its stability if it raises the right leg and left legs at the same time, the robot puts the legs one by one.

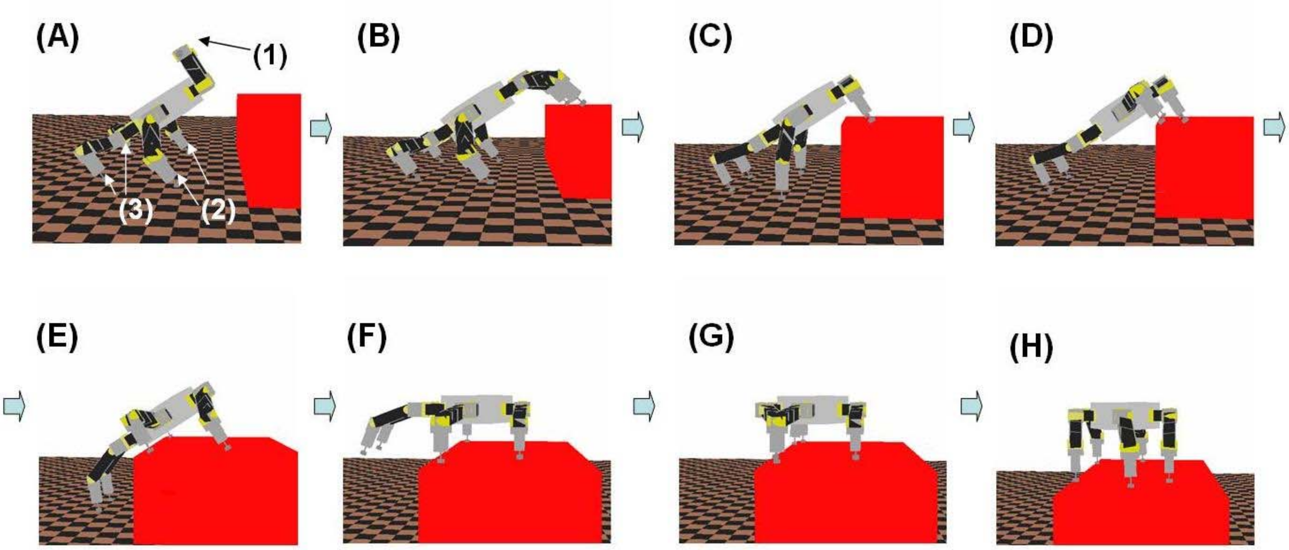

Figure 4: Strategy of step climbing by "ASTERISK"

9. If the center of gravity comes beyond the mid legs, the robot lifts its body above the height of the step and makes its body horizontal (Figure 4(F)).
10. The robot puts the hind legs on the step (Figure 4(G)).
11. The robot puts the mid legs forward and the step climbing is completed (Figure 4(H)).

In this way, this step climbing is based on wave gait where the moving legs are selected from hind to front in order. Depending on the step height, the robot dynamically changes the order of leg stepping in the process of 8.

When the legs are put on the step in this flow (3, 6, 10), the robot confirms the legs are reached to the step by controlling the joint compliance. When the legs are raised (5, 8), the robot judges whether it is possible by calculating the stability margin.

Now we explain these two methods.

3-2 Calculation of Stability Margin

In this research, we use "Normalized Energy Stability Margin" proposed by Hirose [12] to confirm the stability when the robot raises its legs on non-horizontal plane. The "Normalized Energy Stability Margin" is calculated as follows (**Figure 5**):

1. The robot finds the pivot point existing on the straight line connecting the supporting legs when the robot may fall down.
2. It calculates the highest point on the path of center of gravity when we assume that the body rotates around the pivot point.

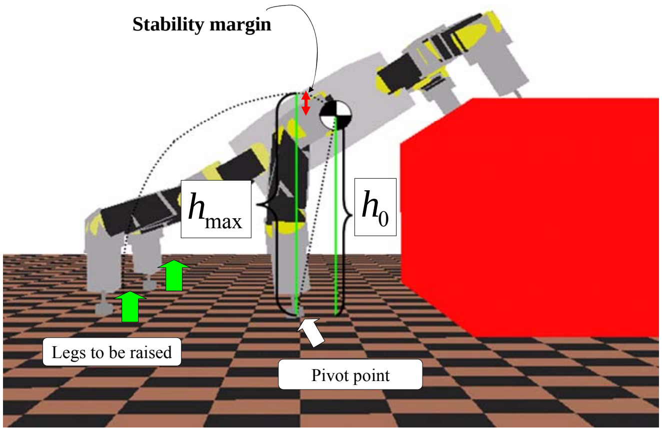

Figure 5: Normalized energy stability margin

3. It calculates the difference of the highest point $h_{\max}$ and the current height of center of gravity h_0. This is the "Normalized Energy Stability Margin".

The body inclination angle needed in this calculation is detected by the acceleration sensor which is equipped in the robot's body.

3-3 Detection of foot contact using joint compliance

Here we explain the method of detecting foot contact on the step.

The motor of "ASTERISK" can command reference joint angle, read current angle, and set arbitrary joint compliance. Hence we can harden or soften the leg joints. As shown in **Figure 6**, we can detect whether the foot touches to the step or not using this feature [13].

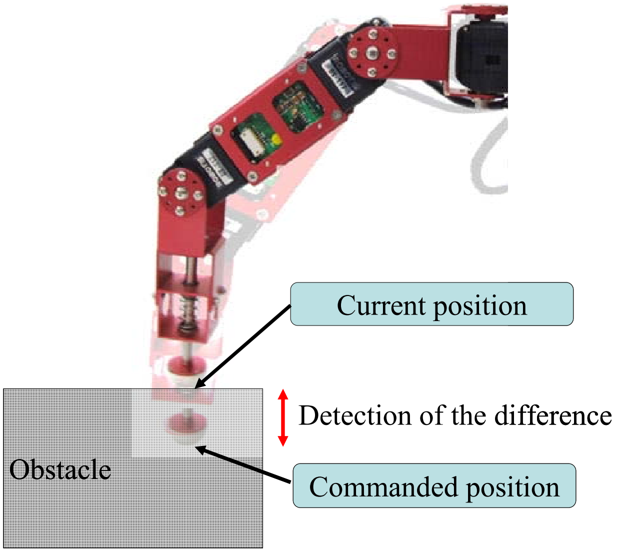

Figure 6: Foot contact detection using joint compliance

1. The robot sets the joint compliance soft before it lowers its legs.
2. The robot lowers the leg.
3. It reads the current angles and calculates the current position of the foot by forward kinematics.
4. It calculates the difference between the commanded and current foot positions.
5. If this difference is large, the foot contact is detected. If the difference is small, the robot returns to the 2nd process.
6. After the robot can detect the foot contact, it set the reference joint angles as the current angles, and sets the joint compliance hard.

This detection process enables the robot to climb steps when some errors of the step height exist, and also the step's surface is rough.

4. ANALYSIS OF CLIMABLE STEP HEIGHT

We analyzed the maximum height of steps which "ASTERISK" can climb up.

In the strategy shown in the section 3-1, the robot moves its center of gravity from the state where the center of gravity is between the mid legs on the step and the hind legs on the ground (strategy 6) to the state where the center of gravity is between the mid and front legs on the step (strategy 7). Accordingly the robot can lift up its body on the step if it achieves the posture shown in **Figure 7**: the hind legs are on the ground and the center of gravity is between the mid and front legs on the step. This posture is defined by the following parameter:

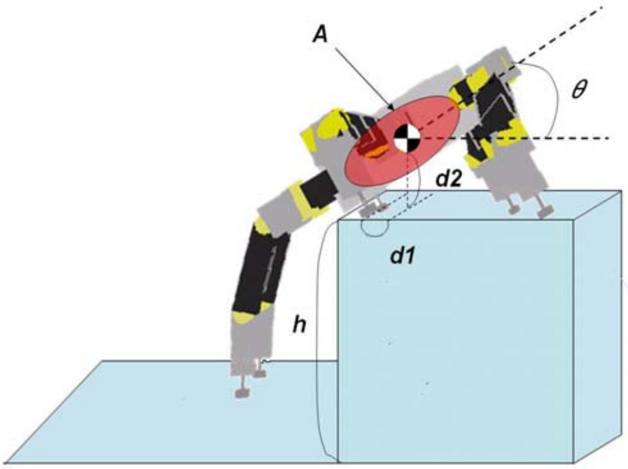

Figure 7: Analysis of climbable step height

- The height of the step : h [mm]
- The inclination of the body : θ [deg]
- The distance from the center of gravity to the mid legs on the step : d_1 [mm]
- The height of the center of gravity from the step : d_2 [mm]

We set the position of mid legs from the edge of the step to 10 [mm].

We analyzed by varying these parameters in the following ranges:

- h : 0~280 [mm]
- θ : 0~50 [deg]
- d_1 : 0~30 [mm]
- d_2 : changed so that the body can not contact the step for the given θ and d_1

We solved inverse kinematics for a group of these parameters. When there is a solution of inverse kinematics, the robot can realize the posture for the parameters.

The results of this analysis are shown in **Figure 8**. This figure represents the movable area $A\,[mm^2]$ of the center of gravity position (d_1, d_2) when the step height is h [mm] and the inclination angle of the body is θ [deg]. If the area A is large, the robot can realize the posture shown Figure 7 for various center of gravity positions.

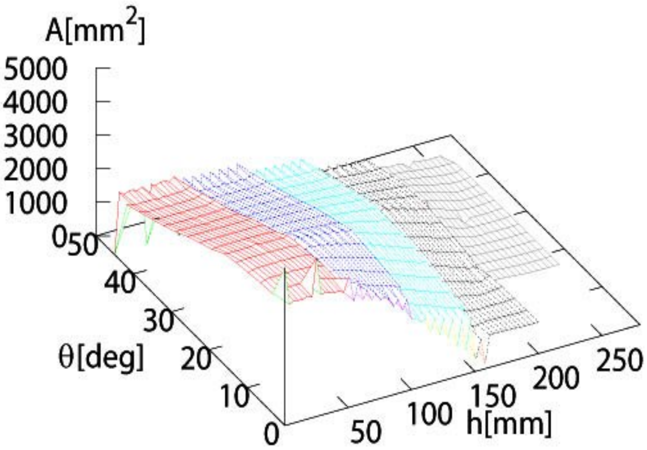

Figure 8: Results of climbable step height

We find that the robot can move its center of gravity in wide range when it inclines its body. And the area A decrease suddenly when the θ become 45 [deg]. This is because there are no solutions of inverse kinematics owing to the limitations of some joint angles. As the results of analysis, the highest step which "ASTERISK" can climb up is 261 [mm], but actually the robot may not climb up such a high step because of the weight of itself, the error of the joint angles, the requirement of enough stability margin.

5. EXPERIMENT

We experimented on how much height of the step "ASTERISK" can climb up.

We determined the inclination angle of the body as the angle which gives the largest area of A when the step height is h. This is because it allows path of the body easily during the process of the climbing movement. In this experiment, we changed the step height from 140 [mm] which is the bottom height of the robot's body to 240 [mm] every 20 [mm], and examined how many times the robot rearranged the position of the legs until it put the hind legs on the step after putting the mid legs on the step. **Figure 9** shows the initial state of this experiment.

Figure 10 shows the climbing motion of the "ASTERISK" when the step height is 200 [mm]. The numbers in the Figure 10 correspond to the numbers of the strategy in the section 3-1. **Table 2** shows the experimental result of the times of leg rearrangement. We count one time when the robot displaces its right and left legs at the same time, and count two times when it displaces its legs one by one because of little stability margin.

When the step height was 240 [mm], the robot could not climb up the step. This is because its legs almost stretched up to its limit, the body could move so little that the times of legs rearrangement increased, thus it took to climb up the step more than two minutes. Therefore, the robot actually could climb up onto 230 [mm] step.

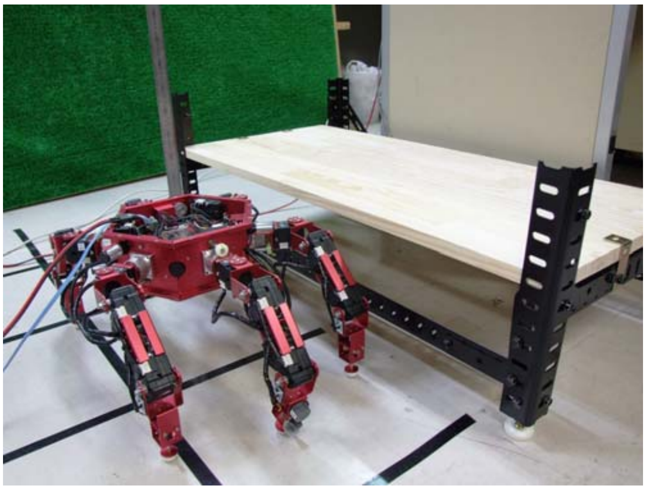

Figure 9: Experimental environment

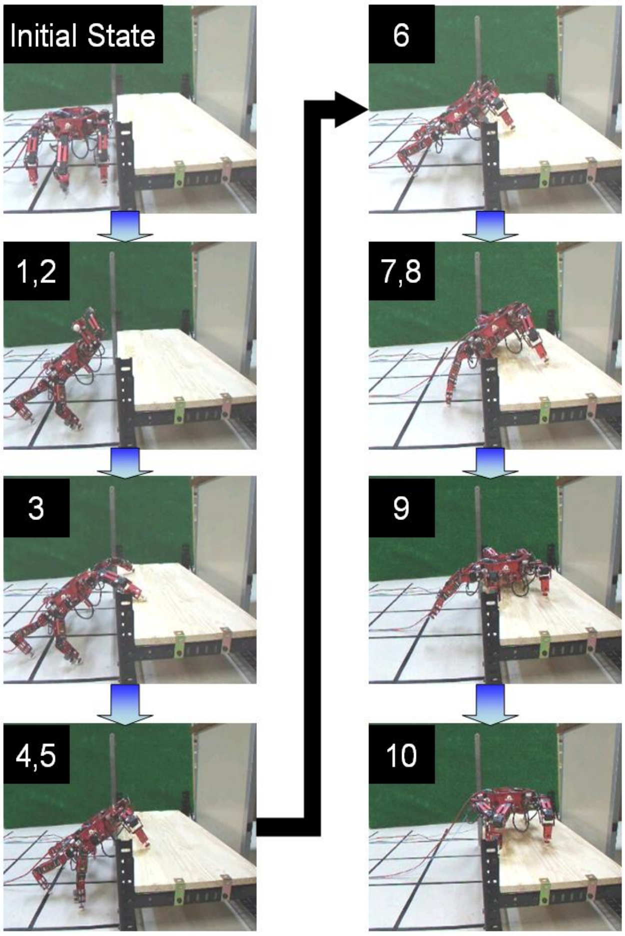

Figure 10: Climbing up onto 200 mm step for "ASTERISK"

Figure 11 shows one of the results of foot contact detection when the mid leg was put on the step. The horizontal axis represents the time and vertical axis represents the foot position error in vertical direction. The increase of the position error shows the foot begin to touch the step, and we judged the contact when the error become more than 7 [mm] in this experiment.

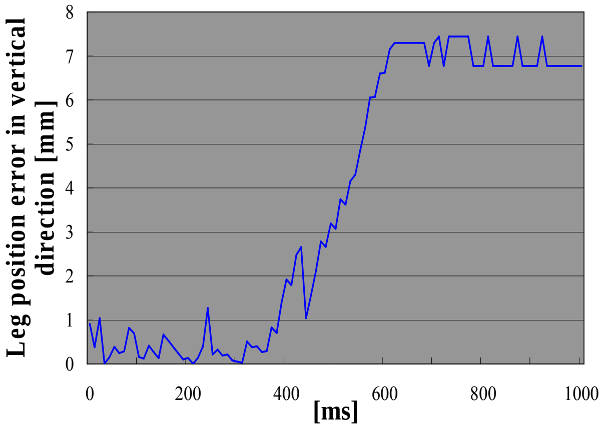

Figure 11: Detection of foot contact

Table 2: Experimental result of step climbing

Step height h [mm]	Body angle θ [deg]	Times of leg rearrangement
140	24	2
160	28	4
180	31	4
200	33	4
220	37	6
230	39	10
240	41	more than 16

6. CONCLUSIONS

We proposed a method of climbing a high step for limb mechanism robot "ASTERISK", and achieved climbing up onto 230 [mm] step. The height of "ASTERISK" is 180 [mm] in its standard posture and 210[mm] when each legs is extended. Accordingly the robot achieved climbing up onto high steps which are higher than its body.

In the near future, we will improve the step climbing algorithm so that "ASTERISK" can climb up onto higher steps. We will also detect the distance from the step and the step height using range sensors.

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REFERENCES

[1] Shigeo Hirose, Kan Yoneda, Kazuhiro Arai, Tomoyoshi Ibe: "Design of Prismatic Quadruped Walking Vehicle TITAN VI", Proceedings of the 5th International Conference on Advanced Robotics, pp.723-728, 1991.

[2] Shigeo Hirose, Kan Yoneda, Kazuhiro Arai, Tomoyoshi Ibe: "Design of Quadruped Walking Vehicle for dynamic walking and stair climbing", Proceedings of the 7th International Conference on Advanced Robotics, pp.107-124, 1995.

[3] Shigeo Hirose, Kan Yoneda, Hideyuki Tsukagoshi: "TITAN VII: Quadruped Walking and Manipulating Robot on a Steep Slope", Proceedings of the 1997 IEEE International Conference on Robotics and Automation, 1997.

[4] Taehun Kang, Hyungseok Kim, Taeyoung Son, Hyoukryeol Choi: "Design of Quadruped Walking and Climbing Robot", Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003.

[5] Hyungseok Kim, Taehun Kang, Vo Gia Loc and Hyouk Ryeol Choi: "Gait Planning of Quadruped Walking and Climbing Robot for Locomotion 3D Environment", Proceedings of the 2005 International Conference on Robotics and Automation, 2005.

[6] Shigeo Hirose, Kazuyoshi Kawabe: "Ceiling Walking of Quadruped Wall Climbing Robot NINJA-II", Proceedings of the 1st International Conference on Climbing and Walking Robots, 1998.

[7] S. Talebi, M. Buehler, E.Papadopoulos: "Towards Dynamic Step Climbing For A Quadruped Robot with Compliant Legs", Proceedings of the 3rd International Conference on Climbing and Walking Robots, 2000.

[8] E. A. Moore, M. Buehler: "Stable Stair Climbing in a Simple Hexapod Robot", Proceedings of the 4th International Conference on Climbing and Walking Robots, 2001.

[9] K. H. Low, W. K. Loh, Heng Wang, Jorge Angeles: "Motion Study of an Omni-Directional Rover for Step Climbing", Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005.

[10] N. Koyachi, et al.: "Control of Walk and Manipulation by A Hexapod with Integrated Limb Mechanism: MELMANTIS-1", Proceedings of the 2002 IEEE International Conference on Robotics and Automation, pp.3533-3558, 2002.

[11] Tomohito Takubo, Tatsuo Arai, Kenji Inoue, Hikaru Ochi, Takeshi Konishi, Taisuke Tsurutani, Yasuo Hayashibara, Eiji Koyanagi: "Development of Limb Mechanism Robot", the 36th International Symposium on Robotics, 2005.

[12] Shigeo Hirose, Hideyuki Tsukagoshi, Kan Yoneda: "Normalized Energy Stability Margin: Generalized Stability Criterion for Walking Vehicles", Proceedings of the 1st International Conference on Climbing and Walking Robots, 1998.

[13] Taisuke Tsurutani, Kenji Inoue, Tomohito Takubo, Tatsuo Arai: "Locomotion of Limb Mechanism Robot Hanging from Grid Ceiling Using Force Sensor and Joint Compliance", the 4th SICE System Integration Division Annual Conference (SI2005), 2005. (*In Japanese*)