Development of Shape-Variable Hand Unit for Quadruped Tracked Mobile Robot

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***Abstract*— We have devised a novel type of hand unit that is able to vary its shape for a mobile robot with legs which can be used as manipulation arms to perform handling tasks in a tough field for human such as disaster area, construction site, and so on. Two joint motors are attached at the left and right side of the hand unit to open and close according to the shape of target object. The hand unit was designed and its prototypes were fabricated and attached to the front two legs of a quadruped tracked mobile robot. The experimental results by the robot have confirmed that the developed hand unit increases handling ability of the robot as well as keeping original quadruped walking motion.**

***Index Terms*—shape-variable hand unit, quadruped tracked mobile robot, object lifting, quadruped walking**

I. Introduction

In recent years, it is expected that robots perform related works in a tough field for human, for example, rescue activities in a disaster such as earthquake, some tasks in a construction site, and so on. In such cases, the robots need to not only obtain information but also work handling tasks in those areas. Based on this consideration, the authors have developed a quadruped tracked mobile robot [1]. The robot has two tracks and four legs each of which is able to be used as a manipulation arm. The robot is therefore able to move with lifting up and carrying an object using legs and tracks. The tip of a leg has a shape of hemispherical protrusion in order to touch and support ground firmly in its walking. In handling tasks such as lifting, the robot has to grip an object by holding in both sides using two arms. However, it is difficult to grip and handle a sphere-shaped or bar-shaped object due to the shape of the tip.

To solve this problem, we have devised a novel type of hand unit which is able to vary its shape so that the robot performs handling tasks for variety shaped objects to increase the working ability as well as quadruped walking. The hand unit is attached to the end of the leg which is used as manipulation arm.

The following sections describe the quadruped tracked mobile robot developed by the authors, the development of the hand unit, and the experimental results of handling task of variety shaped objects by the robot.

II. Quadruped Tracked Mobile Robot

A. Overview

Fig. 1 shows the quadruped tracked mobile robot, a tracked mobile robot with four legs, which has been developed by the authors. The robot consists of two tracks and four legs. Each two legs are mounted on the side of robot body. Each leg has 4-DOF mechanism and can be used as a manipulator. The robot body has 390 mm in length, 420 mm in width, and 180 mm in height. These dimensions have been determined in order to make lightweight the body so that walking motion by legs is possible. The weight of the robot has become 10 kg.

This robot can move on terrain which has a large gap, as the robot with sub-tracks such as Packbot [2], Kenaf [3], and Quince [4], by using four legs to support the robot body appropriately as shown in Fig. 2(a). This robot also has high climbing ability to a steep slope by assisting the track movement using legs as shown in Fig. 2(b).

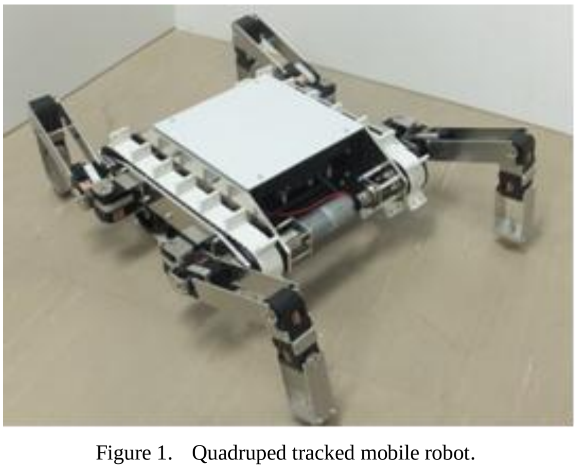

Figure 1. Quadruped tracked mobile robot.

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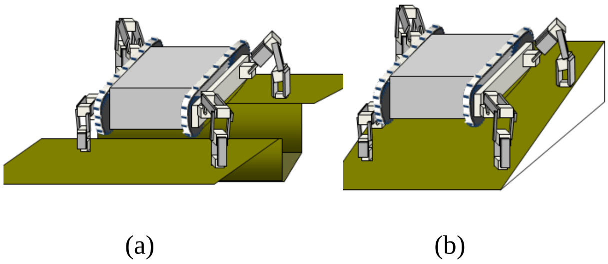

Figure 2. Movement of the robot: (a) moving over a large gap, (b) climbing a steep slope.

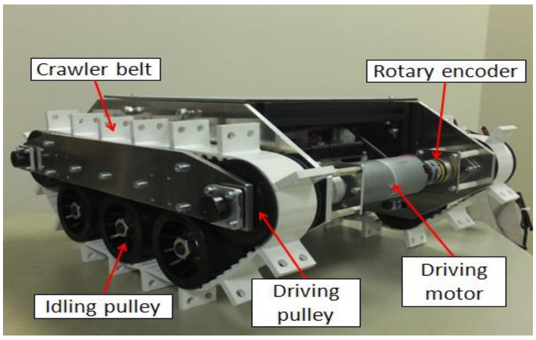

Figure 4. Overview of track unit.

B. Design

In addition to the high mobility, another advantage of this type of robot is that the robot is able to perform some useful tasks at a disaster area such as removal of rubble objects by acting the legs as manipulators. Fig. 3(a) and Fig. 3(b) illustrate several examples of the advantage. If there is a small obstacle such as stone on the pathway of the robot in its movement, the robot will be able to remove the object using one leg as shown in Fig. 3(a). The robot is also able to carry a large object using two legs and move it to the destination as shown in Fig. 3(b).

C. Track Mechanisms

Fig. 4 shows an overview of the track unit. Two tracks are attached at both sides of the robot body. Each track consists of a belt with attachments and five pulleys. One pulley which is at the most front or rear side acts as a driving pulley; a DC geared motor Tsukasa TG-85R-SU is directly connected to it. The other four pulleys act as idling pulley; a rotary encoder Omron E6A2-CW3C is attached to the idler pulley at the most opposite rear or front side to the driving pulley. The two driving pulleys for the left and right tracks are located diagonally to balance the body: the right track has a driving pulley at the rear side and the left track has it at the front side. Because the locations of the motor and encoder are quite symmetric, the robot is able to run straight stably. The deceleration ratio of the gear is 1/85.3, the rotational speed of the motor at the time of no load is 15620 rpm, and driving pulley is 57.3mm in diameter. The maximum velocity of the robot in track movement is therefore estimated approximately 500 mm/s even though it will depend on road surface.

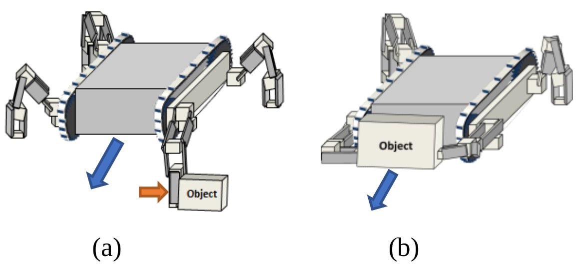

Figure 3. Motions for tasks: (a) removing a small obstacle on the pathway, (b) carrying a box object.

D. Leg Mechanisms

Fig. 5 shows the mechanism of a leg. The leg has four joints: two yaw joints (J_1, J_4) and two roll joints (J_2, J_3). In walking motion, the robot uses the leg as 3-DOF mechanism by fixing the angle of J_4. On the other hand, it is necessary to use the joint J_4 as a 4-DOF manipulator when the robot performs a manipulation task such as carrying an object shown in Fig. 3(b). Each length of five links has been determined as l_1=45, l_2=42, l_3=150, l_4=68, and l_5=95 mm in order that the robot is able to manipulate a front object as well as walk.

As joint actuators, two servo motors Kondo KRS-6003HV have been used for the joints J1 and J2, and Kondo KRS-4034HV for the joints J3 and J4. The former one has 6.57 Nm and the latter one has 4.09 Nm as the maximum torques. These have been selected based on a statics analysis of necessary torques in hybrid locomotion such as running over a gap [1].

E. Control System

Fig.6 shows the control system for the robot. The system consists of track and legs control units. Through an interface system on a remote PC, which acts as a host for the control units, an operator can send commands to the robot and receive status from the robot by wireless communication.

For these control units, we have embedded two microcomputer boards in the robot: Arduino Due and Arduino Uno. Arduino Due is used for the main control board of the robot. After this board receives control commands from the remote PC, it passes motion commands for legs to Arduino Uno with serial communication, and, according to robot motion commands, sends PWM signals to motor driver circuit for track control. Arduino Uno manages legs motion corresponding to the command received from Arduino Due. It plans legs motion, calculates joint angles at each time according to the motion, and sends appropriate control pulses to 16 RC servo motors for four legs.

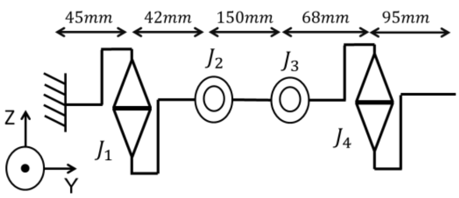

Figure 5. Mechanism of a leg.

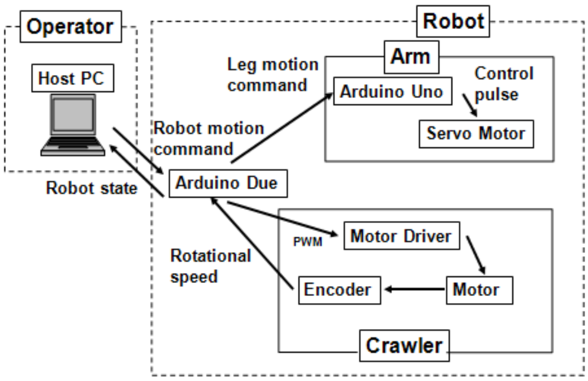

Figure 6. Control system.

III. SHAPE-VARIABLE HAND UNIT

A. Mechanism

Fig. 7 shows the mechanism of the hand unit devised in this study. In order to enable the robot to grip variety shaped objects as well as walk by four legs, the hand unit needs to have not only wide palm but also let the tip of the leg touch the ground firmly. Therefore, we have devised a mechanism in which the shape of the tip of the leg can be changed as such [5] and [6]. Two joint motors are attached at the left and right sides so that the hand can be opened and closed.

By this mechanism, the robot is able to open the hand according to the shape of target object in a handling task. Besides, the robot is able to walk using four legs in original way by fully opening the hand along the link of leg.

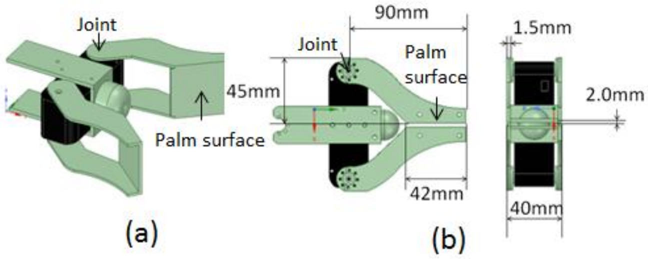

Figure 7. Shape-variable hand unit: (a) overview, (b) lateral views.

B. Design

We have used a CAD software "Design Spark Mechanical" by RS Components Inc. [7]. This software enables us to confirm assemblage of parts visually and whole motion by moving joints on display before fabrication. In addition, it is able to convert 3D CAD data into 2D CAD data for cutting easily.

The thickness of the side part of hand is made 1.5 mm and the length between joint and tip of each hand is 90 mm. The size of palm surface, which makes contact with an object, is designed 40 mm in width, 42 mm in length, and 2 mm in thickness.

These sizes were determined so that the hand is fully opened in walking and the palm surface and tip of the leg become straight when it opens 90 degrees to come in contact with a face of an object stably.

C. Fabrication

The designed 2D CAD data of parts of the hand unit were read by ORIGINALMIND Inc. CNC software USBCNCV3 [8] and cutting of parts was performed by KitMill RD420 [9]. We used A2017 duralumin board for the side surface of the hand and A5052 aluminum board for the palm surface. A rubber for slip resistance was also attached to the palm surface.

Two fabricated hands have been attached to each end of the front two legs. Fig. 8 shows the overview of the robot with hands. As mentioned above, this robot has four 4-DOF legs at the left and right sides of the body; two legs are attached to the front and rear part of each side.

In a handling task by the robot, the hand is opened properly corresponding to the shape of target object as shown in Fig. 9, in which the opening angle is 30 degrees. In leg-walking, the hand is fully opened to expose the tip of the leg as shown in Fig. 10, in which the opening angle is 120 degrees. The opening angle of the hand becomes 0 degree when the both palm surfaces touch each other and is represented by the rotation angle of the joint of hand unit from this shape. The computation of the angle is described in the next section. KONDO KRS-4034HV servo motors [10] are used for the joints. The weight of one fabricated hand is 205 g.

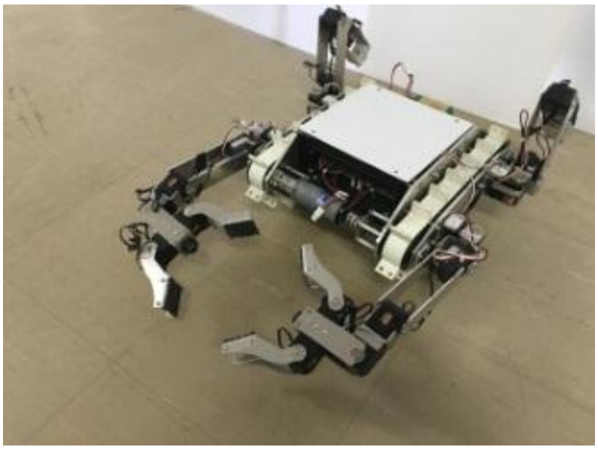

Figure 8. Quadruped tracked mobile robot equipped with the shape-variable hand unit.

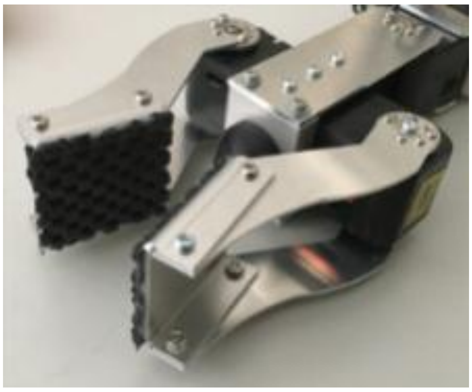

Figure 9. The hand unit in which the opening angle is 30 degrees.

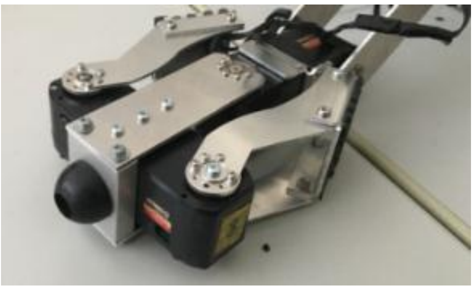

Figure 10. The hand unit when fully opened: the opening angle is 120 degrees.

IV. Hand Opening Angle

The robot is able to handle sphere-shaped objects using the developed hand. However, in order to do grasp them properly, the hand has to be opened by proper angle according to the curvature of surface of the object. Here we consider how to compute opening angle of the hand to the size of object.

The opening angle to the radius of the sphere object, r, is calculated as follows. Fig. 11 shows the computation model for it. A or B shows the center of rotation axis for the right or left joint respectively. The origin of coordinate, O, is set to the center of the line between A and B. C or D shows the contacting point of the right or left palm to the surface of the object. E shows the position of the center of palm when opening angle of the hand is 0 degree; the hand closes by touching both palms each other. The opening angle θ is then the angle between the lines AC and AE. The lengths of AC and AO are 82 mm and 41 mm respectively. The angle between the line AC and the palm surface is 30 degrees. S shows the center of the object.

In this condition, the length of the line AS, x, is given by the cosine theorem;

$$x = \sqrt{r^2 + |\mathrm{AC}|^2 - 2r|\mathrm{AC}|\cos(2\pi/3)} \quad (1)$$

From this, the angle φ between the lines AC and AS is given by

$$\varphi = \cos^{-1}\left(\frac{|\mathrm{AC}|^2 + x^2 - r^2}{2|\mathrm{AC}|x}\right), \quad (2)$$

and the angle ϕ between the lines AO and AS is given by

$$\phi = \cos^{-1}\left(\frac{|\mathrm{AO}|}{x}\right). \quad (3)$$

The opening angle θ is then obtained by

$$\theta = \varphi + \phi - (\pi/3) \quad (4)$$

Because |AC|=|AE|.

Based on this, the opening angle θ to the radius of the sphere object, r, was calculated. Fig. 12 shows the result. The black solid line shows the opening angle. We can see the angle is almost corresponding to the value of $\tan^{-1}(r/100)$, which is plotted by red dashed line; the maximum error to the opening angle was about 0.5 degrees.

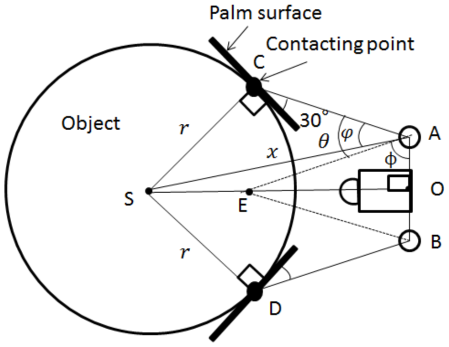

Figure 11. Computation model for the opening angle of the hand unit.

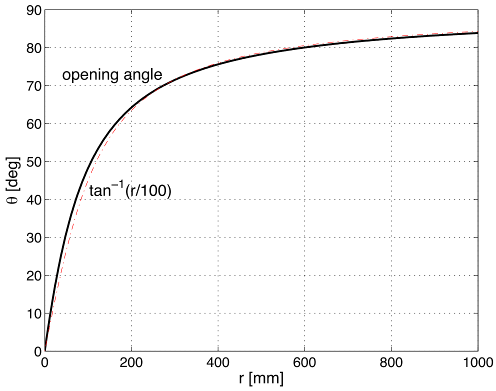

Figure 12. Computed opening angle to the radius of object.

V. Experiments

Several experiments were employed to confirm handling ability of developed hand mechanism and walking motion as the same way to original mechanism. As the handling task, grasping and lifting up box-shaped, sphere-shaped, and ellipsoid-shaped objects, and pulling out a long pipe object were examined.

A. *Lifting up Box-shaped Object*

In this experiment, an object of rectangular parallelepiped which has 210 mm in length, 220 mm in width, 160 mm in height, and 150 g in weight was used. The robot which is located in front of the object grasps it using two front legs, lifts it up, and moves it to the top of the robot's body. We have compared the motions when using the developed hand unit and not using it. The result when the hand unit is used is shown in Fig. 13. The hand was opened 90 degrees to grasp lateral surface of the object firmly.

As the result, the robot was able to lift the object up stably by using the developed hand unit. On the other hand, the handling motion was not performed stably when not using the hand unit; the object was rotated after lifting due to gripping by the tip of hemispherical protrusion.

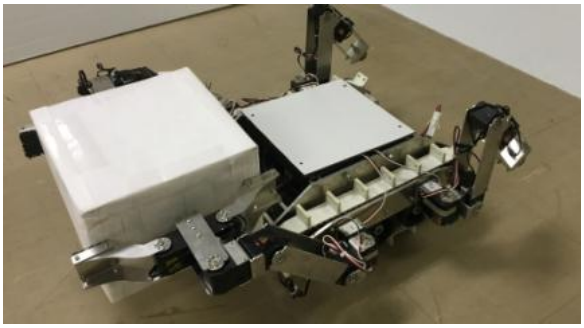

Figure 13. Lifting a box-shaped object using developed hand units.

B. Lifting up Sphere-shaped Object by Two Arms

Two sphere-shaped objects which have different sizes were selected as target objects. One object is placed on the floor and the robot grasps it from left and right sides using front two arms so that the center of palm touches to the surface of the object.

Two balls which have 160 mm and 210 mm in diameter were selected as the target objects. The opening angle to the radius of the sphere object was calculated as described in Section III; it was 42.6 degrees for 160 mm, and 49.4 degrees for 210 mm.

Fig. 14 shows an overview of the robot motion when it grasps and lifts up the object which has 160 mm in diameter and 140 g in weight. Fig. 15 shows an overview of the robot motion when it grasps and lifts up the object which has 210 mm in diameter and 270 g in weight. In both experiments, the robot was able to lift the object up stably.

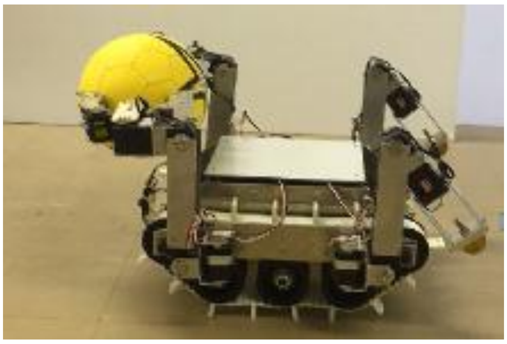

Figure 14. Lifting a sphere-shaped object which has 160 mm in diameter.

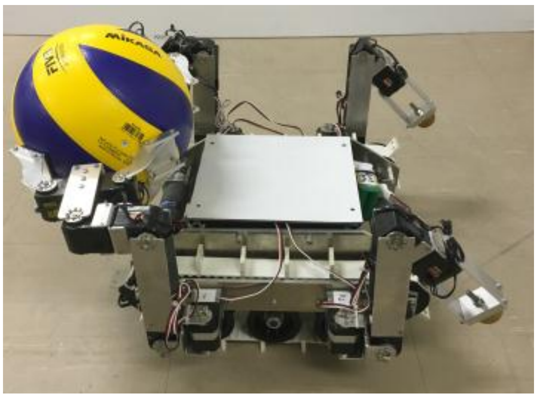

Figure 15. Lifting a sphere-shaped object which has 210 mm in diameter.

The handling tasks of sphere-shaped object by two robotic arms, which has not been able to perform by the arms in original mechanism, were successfully performed by the developed hand mechanism.

C. Lifting up Ellipsoid-shaped Object by Two Arms

We also considered an ellipsoid-shaped object as another type of object which is not box-shaped nor sphere-shaped object. Lifting task of a football which has 110 mm in width, 125 mm in height, and 145 g in weight was examined.

Fig. 16 shows an overview of the robot motion when it grasps and lifts up the object which is placed horizontally to the robot. Fig. 17 shows the result when the object is placed vertically to the robot. In both cases, the robot was able to lift this type of object up stably.

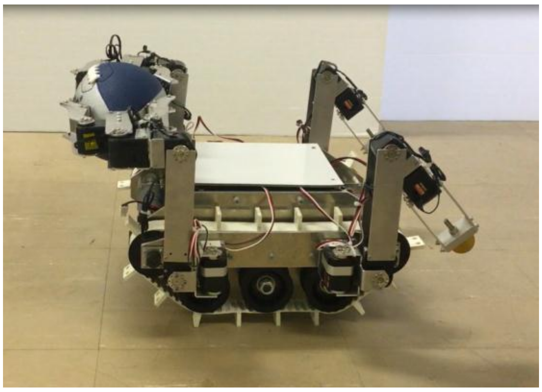

Figure 16. Lifting an ellipsoid-shaped object placed horizontally.

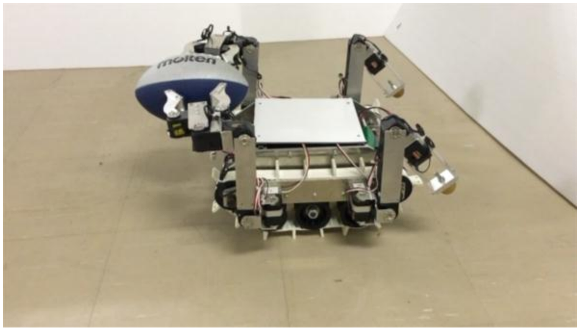

Figure 17. Lifting an ellipsoid-shaped object placed vertically.

D. Picking up Sphere-shaped Object by Single Arm

Picking up a sphere-shaped object was performed by single manipulation arm with the hand unit. Two kinds of ball which has 160 mm in diameter and 140 g in weight and 97 mm in diameter and 185 g in weight were used in this experiment.

Fig. 18 shows an overview of the robot motion when it grasps and picks up a sphere-shaped object which has 160 mm in diameter using single arm. This object is actually same to the one which is used in the experiment shown in Fig. 14. Even though it is very large to handle by single arm, the robot was able to pick it up successfully.

Fig. 19 shows an overview of the robot motion when it grasps and picks up a baseball which has 97 mm in diameter. Computed opening angle of the hand unit was

30.5 degrees. In this experiment, the robot was also able to lift the object up stably.

This type of handling task has never been possible by the arm in original mechanism. Using the hand unit presented in this study, the robot was able to expand the kind of handling task.

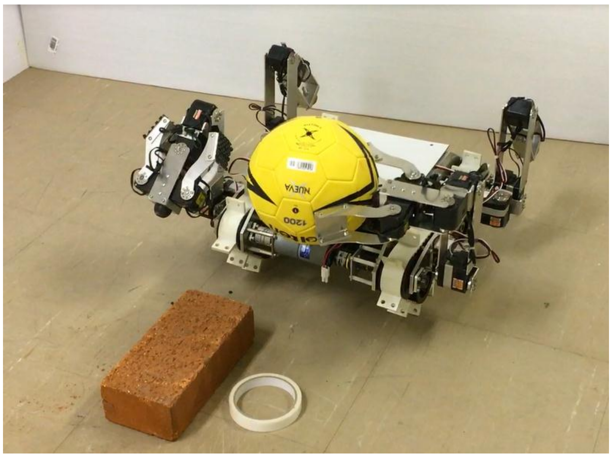

Figure 18. Picking up a sphere-shaped object which has 160 mm in diameter by single arm with the hand unit.

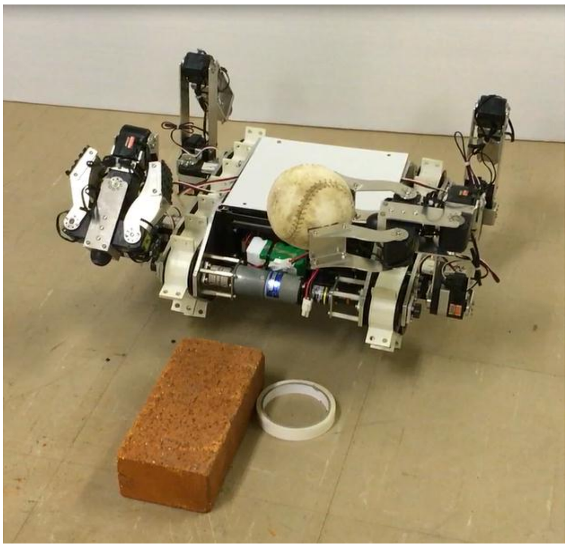

Figure 19. Picking up a sphere-shaped object which has 97 mm in diameter by single arm with the hand unit.

E. Pulling out a Pipe Object

Pulling out a pipe object in rubble was performed by single manipulation arm with the hand unit. A polyvinyl chloride pipe was used. Its diameter was 20 mm, length was 290 mm, and weight was 85 g. Several wood bricks were used as rubble and the object was put inside them.

Fig. 20 shows an overview of the motion. The robot approached the hand of the left manipulation arm to the object, grasped it using the hand unit (the top panel of Fig. 20), and pulled it out (the bottom panel of Fig. 20).

This result demonstrated that the handling ability increased using developed hand unit because this robot had originally never been able to perform this task.

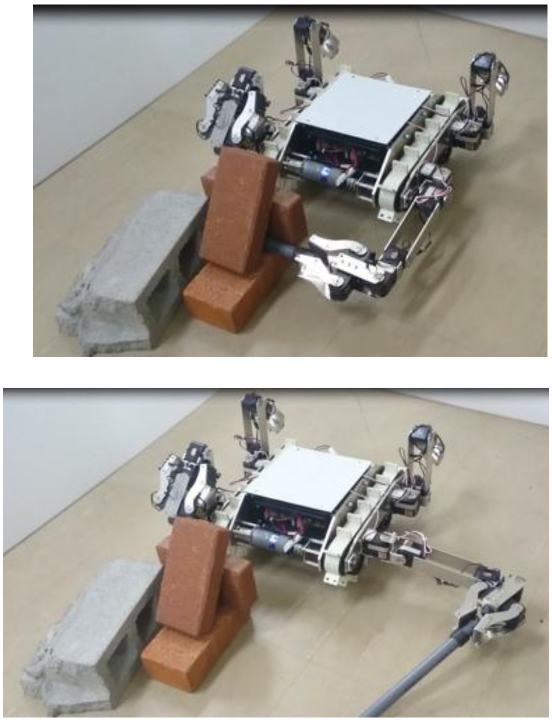

Figure 20. Pulling out a long pipe by the use of developed hand unit.

F. Quadruped Walking

Static crawl walking was performed by four legs in which each hand was fully opened to expose the tip of the leg same as original way. Fig. 21 shows an overview of the walking motion. As the result, the robot was able to walk smoothly without hand touching to the ground as the same way before attaching the hand units.

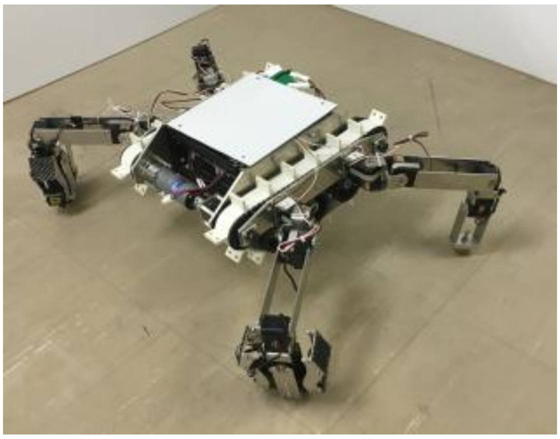

Figure 21. Quadruped walking.

VI. Conclusions

This study developed a shape-variable hand unit to attach to the end of the leg which can be used as a manipulation arm for handling task. The hand unit was designed and its prototypes were fabricated and attached to the front two legs of a quadruped tracked mobile robot. The experimental results by the robot have confirmed that the developed hand unit increases handling ability of the robot as well as keeping original quadruped walking motion.

This hand unit presented in this study is very useful for handling of variable shape of object; thus, the robot will be able to perform variety of tasks such as removal of rubble in a dangerous place for human, carrying and bringing back an important object in a disaster area, an assemble work at a construction site, and so on.

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