2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Pushing Methods for Working Six-Legged Robots Capable of Locomotion and Manipulation in Three Modes

Kenji Inoue, Kanjiro Ooe, and Suwoong Lee

Abstract—**A working six-legged robot which can switch three modes for locomotion and manipulation was already developed. In its vertical four-leg two-arm mode, lower four legs are used for locomotion and upper two legs for manipulation with its body vertical to the ground. In order to expend capabilities of this robot, a method of pushing a large object in this mode is proposed. The robot holds the object using its upper two legs and body. The robot leans against the object and applies pushing force. Then it walks by moving the outer and inner pairs of the lower four legs alternately. Because of this symmetric walking, the robot can push the object with keeping lateral balance. It can apply large force owing to the effect of its body weight. Because holding the object firmly, the robot can push the object stably without falling down. For comparison, two methods are also analyzed. First the robot simply walks by tripod gait with its body touching the object. Second the robot pushes the object using its upper two legs and walks using its lower four legs in vertical four-leg two-arm mode. Then the merits of the proposed method are clarified. Three methods are experimentally ascertained using the developed robot.**

I. INTRODUCTION

Robots working in dangerous and inaccessible environments for humans are currently under development: maintenance robots of nuclear plants, humanitarian demining robots, and rescue robots for searching disaster victims. Such robots are required to move on complicated, irregular or rugged terrains such as steps, stairs, steep slopes, wild lands and rubbles. They are also required to perform various tasks on site. Hence both high mobility and high ability to work are necessary for these robots. The robots should be also lightweight and compact for high energy efficiency and long operation time. Because legs do not require continuous ground contact and the contact points are selectable in three dimensional space, legs have high terrain adaptability. Legged robots walking on various terrains have been developed[1-12]. Most working mobile robots consist of locomotion mechanisms (wheels, crawlers, legs, etc.) and manipulators. Their locomotion mechanisms and manipulators can be specialized for locomotion and manipulation respectively, but they have problems in flexibility and compact design. Inspired by some insects and animals, Koyachi et al. proposed a “limb mechanism robot” consisting of multiple limbs which can be used as legs and arms[13]. Depending on tasks and situations, each limb switches leg function arm function; the combination of arms and legs are flexible. Accordingly the robot can be made lightweight and compact, and can extend both mobility and ability to work. Takubo et al. developed limb mechanism robot, ASTERISK, which has six limbs. This robot realized omni-directional gait, climbing high steps and ladders, moving under grid-like structure, and manipulating objects using two neighboring limbs[14-17]. In our previous work[18], we developed a working six-legged robot which can switch three modes for locomotion and manipulation. In six-leg mode, the robot walks using six legs fast and stably by omni-directional tripod gait. In horizontal four-leg two-arm mode, four legs are used for locomotion and two legs for manipulation with its body horizontal to the ground. This mode enables low-place manipulation using the two front legs. In vertical four-leg two-arm mode, the robot stands up. Four legs are used for locomotion and two legs for manipulation with its body vertical to the ground. This mode enables high-place manipulation using the two upper legs. In this way this robot has high mobility and manipulation ability.

In order to expend capabilities of this robot, we propose a method of pushing a large object in vertical four-leg two-arm mode. The robot holds the object using its upper two legs and body. The robot leans against the object and applies pushing force. Then it walks by moving the outer and inner pairs of the lower four legs alternately. Because of this symmetric walking, the robot can push the object with keeping lateral balance. It can apply large force owing to the effect of its body weight. Because holding the object firmly, the robot can push the object stably without falling down. For comparison, two methods are also analyzed. First the robot simply walks by tripod gait with its body touching the object. The robot can move fast but cannot apply large force. It is difficult to push the object stably. Second the robot pushes the object using its upper two legs and walks using its lower four legs in vertical four-leg two-arm mode. The robot can apply larger force owing to the effect of its body weight. But it cannot push the object stably and easily falls down. Compared with these methods, the proposed method enables the robot to push a large object stably. Three methods are experimentally ascertained using the developed robot.

Manuscript received September 15, 2009. This work was supported in part by MEXT under Grants-in-Aid for Scientific Research (C) (Project No. 21560256).

Kenji Inoue is with Department of Bio-System Engineering, Yamagata University, Yonezawa, Yamagata, 992-8510 Japan (phone & fax: +81-238-3335; e-mail: inoue@yz.yamagata-u.ac.jp).

Kanjiro Ooe is a graduate student of Department of Bio-System Engineering, Yamagata University.

Suwoong Lee is with Department of Bio-System Engineering, Yamagata University (e-mail: lee@ yz.yamagata-u.ac.jp).

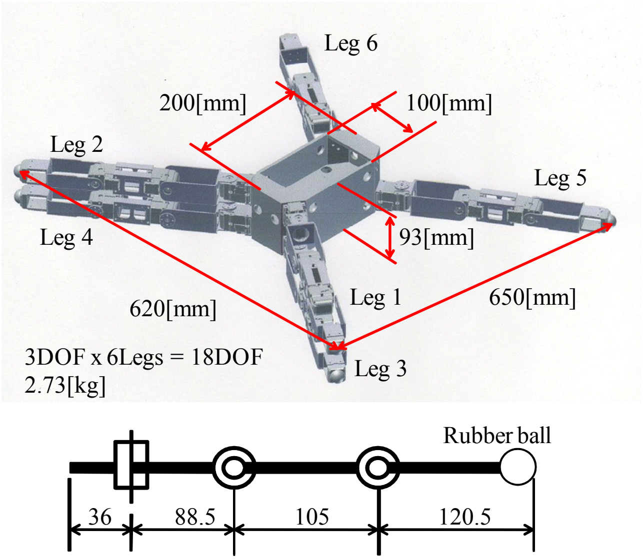


Figure 1: Design of working six-legged robot

II. WORKING SIX-LEGGED ROBOT[18]

A. Design of Robot

Figure 1 shows the design of the developed robot. The distinctive feature of this robot is the arrangement of six legs, which are attached to the chamfered corners of its rectangular solid body. The legs are numbered as shown in this figure. This leg arrangement enables the robot to have three modes for locomotion and manipulation. Each leg has 3 DOF, thus the robot has 18 DOF. A rubber ball is embedded in the tip of each leg to absorb impact at landing and to increase friction force. The robot weighs 2.73[kg].

We adopted smart actuator modules Dynamixel DX-117 and RX-28 by ROBOTIS as joint actuators. Each module contains a servo motor, a reduction gear, a control unit and a communication interface in a compact package. If the reference motor angle is commanded through RS-485, the control unit controls the motor angle by local position feedback control. The resolution of the motor angle is 0.29[deg]. The maximum holding torque of the motor is about 35[kgf cm] for the power supply voltage 14[V]. The modules can generate enough motor torque to support the robot using three legs. The modules are connected serially with each other. In the experiments of this study, we connect 18 modules and an external computer serially with wired RS-485. The reference motor angles are commanded at baud rate 250000[bps] from the external computer to the modules. The sampling time of the external computer is about 20[ms]. The robot uses external power supply of 14[V].

It is also possible to mount a CPU board on the robot's body. This board and the modules communicate with each other by RS-485, and the board communicates with the external computer through wireless LAN. The power can be supplied with batteries[14,18].

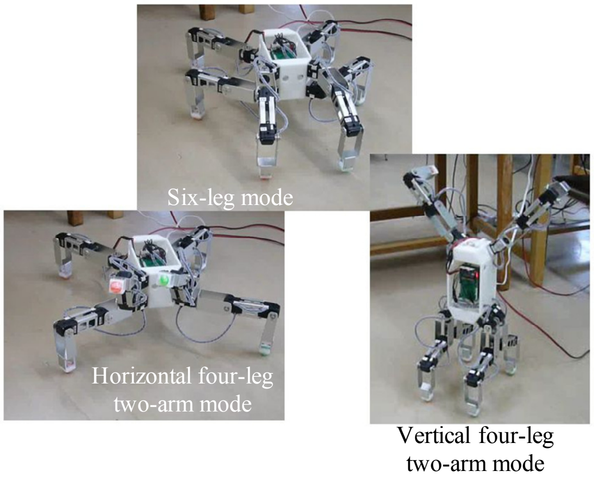


Figure 2: Three modes of robot

B. Three Modes for Locomotion and Manipulation

Figure 2 shows three modes of this robot for locomotion and manipulation.

(a) In six-leg (6L) mode, the robot walks using six legs fast and stably by omni-directional tripod gait.
(b) In horizontal four-leg two-arm (H-4L2A) mode, four legs #3, #4, #5 and #6 are used for locomotion and two legs #1 and #2 for manipulation with the body horizontal to the ground. This mode enables low-place manipulation using the two front legs #1 and #2 while supporting the body using the other four legs stably.
(c) In vertical four-leg two-arm (V-4L2A) mode, the robot stands up. Four legs #1, #2, #3 and #4 are used for locomotion and two legs #5 and #6 for manipulation with its body vertical to the ground. This mode enables high-place manipulation using the upper legs #5 and #6.

Switching these modes gives the robot high mobility and manipulation ability.

III. PUSHING METHODS

A. Pushing by Tripod Gait

The simplest way for the robot of pushing an object is walking by ordinal gait with its body touching the object.

Tripod gait allows fast and stable six-legged locomotion, because the projection of the center of gravity of the robot on the ground is always kept inside the support polygon. Our robot adopts omni-directional tripod gait[18] as ordinal gait on flat terrain. This method generates the motions of the six legs in real time from the commanded 3-DOF velocity of the robot's body: the 2DOF translational velocity and the angular velocity on the horizontal plane. The robot walks as commanded with keeping the body height from the ground constant. Figure 3 shows the pose of the robot when pushing a large object by tripod gait. This pose is determined so that the front legs may not interfere with the object. We call this method "pushing by tripod gait".

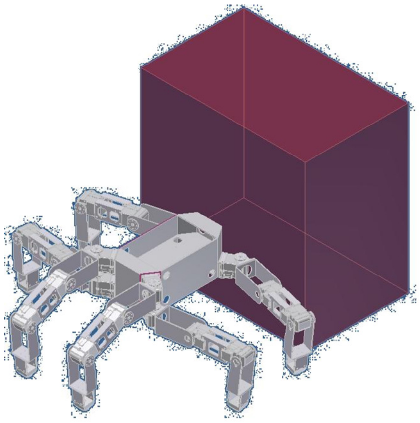


Figure 3: Pushing by tripod gait

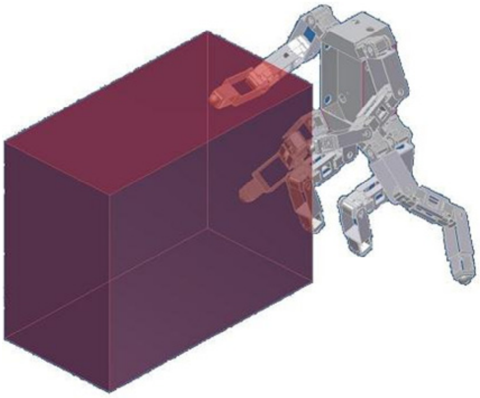


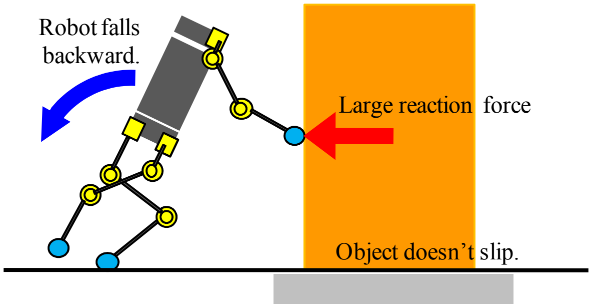
Figure 4: Pushing using upper two legs

Because tripod gait allows fast and stable locomotion, “pushing by tripod gait” is better than the following two methods with respect to speed. But the force applied to the object by this method is smaller than the forces by the following two methods. This is because this method only uses the joint torques to push the object. On the other hand, the following two methods use the effect of its body weight in addition to the joint torques. The robot only touches the object with its body; it does not hold the object. Accordingly the object sometimes leaves the robot. The object is easy to rotate around yaw axis, unless the robot pushes the center of the object.

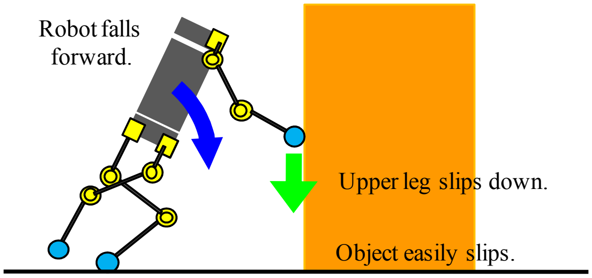
B. Pushing Using Upper Two Legs

One of the ways to increase pushing force is that the robot leans against the object and applies force using the effect of its body weight.

Figure 4 shows the robot pushing an object using its upper two legs in V-4L2A mode. The upper two legs #5 and #6 are used as arms, and they touch the object. While leaning against the object, the robot walks by moving the inner pair of the lower legs #1 and #2 and the outer pair of the lower legs #3 and #4 alternately. We call this method “pushing using upper two legs”.



(a) Large reaction force



(b) Upper leg slip

Figure 5: Problems in pushing using upper two legs

Because of this symmetric walking, the robot can push the object in sagittal direction with keeping lateral balance. The robot uses both the effect of its body weight and the joint torques to push the object. Hence this method can apply larger force to the object than “pushing by tripod gait”.

The robot only touches the object with its upper two legs; it does not hold the object. Accordingly the upper legs may leave the object or slip on the object (Figure 5). When the upper legs apply force to the object, the reaction force from the object acts on the upper legs. If this reaction force is large, the upper legs leave the object, and the robot falls backward. Once the upper legs slip down on the object, the robot falls forward. Because the robot leans against the object, it is difficult to recover.

C. Pushing with Holding Object

In order to overcome the demerits of “pushing using upper two legs”, we propose that the robot holds the object using its upper two legs and body firmly in V-4L2A mode.

As shown in Figure 6, the upper two legs #5 and #6 are used as arms. The robot sandwiches the object between these legs and presses its body the object. While leaning against the object, the robot pushes the object using the effect of its body weight. It walks by moving the inner pair of the lower legs #1 and #2 and the outer pairs of the lower legs #3 and #4 alternately. We call this method “pushing with holding object”.

For the same reasons as “pushing using upper two legs”, the robot can push the object in sagittal direction with keeping lateral balance and apply larger force to the object than “pushing by tripod gait”. In addition, because of holding

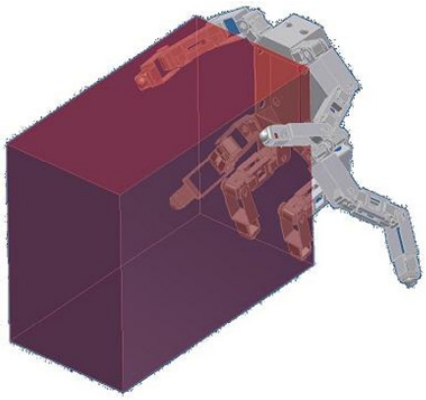


Figure 6: Pushing with holding object

the object firmly with its upper two legs and body, the robot does not leave the object. The robot can push the object stably while maintaining the orientation of the object. By controlling the forces which the upper two legs apply to the object from its both sides, the robot can control the friction forces between these legs and the object. This prevents these legs from slipping down on the object. This slippage is a problem in "pushing using upper two legs". If the robot pulls back the upper two legs and presses the object harder to its body, the friction force between the body and object increases. Hence we can also prevent the body from slipping down on the object. Because the upper two legs hold the object from its both sides, the width of the object is limited.

IV. FORCE ANALYSIS OF PUSHING METHODS IN VERTICAL FOUR-LEG TWO-ARM MODE

A. *Pushing Using Upper Two Legs*

Figure 7 shows the force analysis at the moment when the object gets into motion by "pushing using upper two legs". Here we define the following variables:

f_{x1} : horizontal force acting on support leg from ground
f_{z1} : vertical force acting on support leg from ground
f_{x2} : horizontal force acting on object from upper leg
f_{z2} : vertical force acting on object from upper leg
f_{x3} : horizontal force acting on object from ground
f_{z3} : vertical force acting on object from ground
m : mass of robot
M : mass of object
μ_1 : friction coefficient between ground and support leg
μ_2 : friction coefficient between upper leg and object
μ_3 : friction coefficient between ground and object
g : acceleration of gravity
R : horizontal distance between support leg and center of mass of robot
L : horizontal distance between support leg and near edge of object

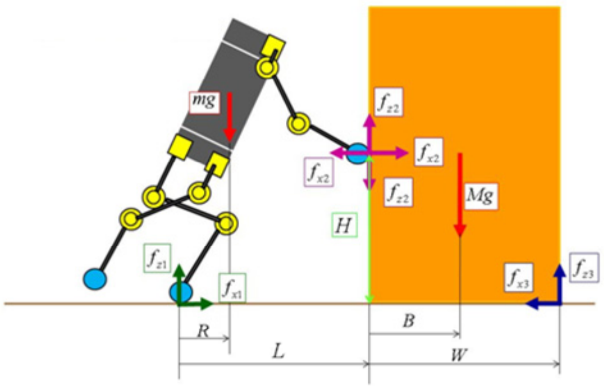


Figure 7: Statics in pushing using upper two legs

H : height of upper leg from ground
W : width of object
B : horizontal distance between near edge of object and center of mass of object

We derive the equilibrium of force:

$$f_{x1} - f_{x2} = 0 \tag{1}$$
$$f_{z1} - f_{z2} - mg = 0 \tag{2}$$
$$f_{x2}H - f_{z2}L - mgR = 0 \tag{3}$$
$$f_{x2} - f_{x3} = 0 \tag{4}$$
$$f_{z2} + f_{z3} - Mg = 0 \tag{5}$$
$$-f_{x2}H - f_{z2}W + Mg(W - B) = 0 \tag{6}$$

The conditions for the robot to be able to push the object are

Support leg does not leave ground: $f_{z1} > 0$ (7)
Upper leg does not leave object: $f_{x2} > 0$ (8)
Object does not leave ground: $f_{z3} > 0$ (9)
Support leg does not slip: $f_{x1} / f_{z1} < \mu_1$ (10)
Upper leg does not slip: $-\mu_2 < f_{z2} / f_{x2} < \mu_2$ (11)
Object slips: $f_{x3} / f_{z3} > \mu_3$ (12)

The unknown variables are six forces $f_{x1}, f_{z1}, f_{x2}, f_{z2}, f_{x3}$ and f_{z3}, and we have six equations (1) to (6). Accordingly all forces are uniquely determined if the geometric relationship between the robot and the object is given.

We consider the case that the vertical force f_{z2} acting on the object from the upper leg equals zero: the upper leg does not slip. Then the conditions for the robot to be able to push the object are simplified into:

$$R / H < \mu_1 \tag{13}$$
$$(W - B) / H > \mu_3 \tag{14}$$

From Equation (13), the support leg slips when the height H of the upper leg from the ground is too low. From Equation (14), the object does not slip when H is too high. Hence the optimal height of the upper leg from the ground exists to push the object.

B. *Pushing with Holding Object*

Figure 8 shows the force analysis at the moment when the

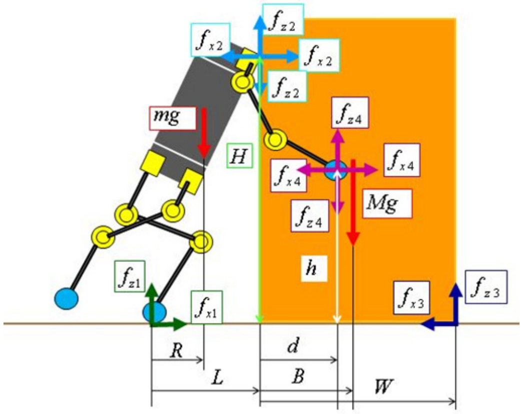


Figure 8: Statics in pushing with holding object

object gets into motion by "pushing with holding object". Here we redefine the following variables in the preceding section:

f_{x2} : horizontal force acting on object from body
f_{z2} : vertical force acting on object from body
H : height of body's contact point from ground

We define the following new variables:

f_{x4} : horizontal force acting on object side from upper leg
f_{z4} : vertical force acting on object side from upper leg
d : horizontal distance between near edge of object and upper leg
h : height of upper leg from ground

Then we derive the equilibrium of force:

$$f_{x1} - f_{x2} - f_{x4} = 0 \quad (15)$$
$$f_{z1} - f_{z2} - f_{z4} - mg = 0 \quad (16)$$
$$f_{x2}H - f_{z2}L + f_{x4}h - f_{z4}(L + d) - mgR = 0 \quad (17)$$
$$f_{x2} + f_{x4} - f_{x3} = 0 \quad (18)$$
$$f_{z2} + f_{z4} + f_{z3} - Mg = 0 \quad (19)$$
$$-f_{x2}H - f_{z2}W - f_{x4}h - f_{z4}(W - d) + Mg(W - B) = 0 \quad (20)$$

The conditions for the robot to be able to push the object are

Body does not leave object: $f_{x2} > 0$ (21)
Body does not slip: $-\mu_2 < f_{z2} / f_{x2} < \mu_2$ (22)
Robot pushes object: $F = f_{x2} + f_{x4} > 0$ (23)

in addition to (7), (9), (10) and (12). The total pushing force which the robot applies to the object is expressed by F. It is the sum of two horizontal forces f_{x2} and f_{z4}. By increasing the forces which the upper two legs apply to the both sides of the object, the robot can give sufficient friction force between the upper legs and the object. Thus we assume that the upper legs do not slip.

The unknown variables are eight forces f_{x1}, f_{z1}, f_{x2}, f_{z2}, f_{x3}, f_{z3}, f_{x4} and f_{z4}, and we have six equations (15) to (20). We choose f_{x2} and f_{x4} as parameters in the following analysis. Then the other forces are calculated using these equations from the given f_{x2} and f_{x4}.

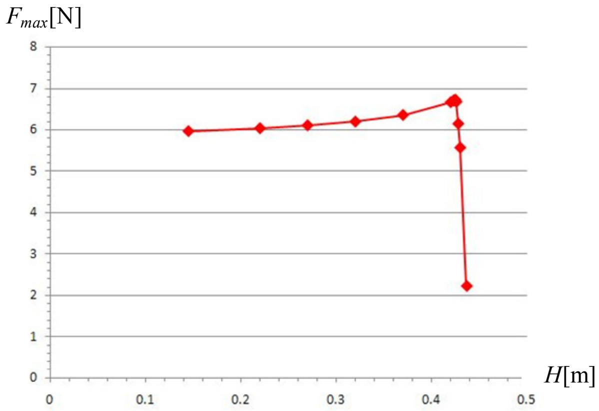


Figure 9: Relationship between maximum pushing force F_{max} and height H of body's contact point in pushing with holding object

For different height H of the body's contact point, we analyze the range of two horizontal forces (f_{x2}, f_{x4}) which satisfies the conditions for the robot to be able to push the object. Then the maximum value F_{max} of the total pushing force F for the height H is obtained. The parameters except H[m] are set as

m =2.73[kg], M =1.62[kg], $\mu_1 = \mu_2 = \mu_3$ =0.20,
W =0.75[m], B =0.325[m],
$L = \sqrt{(0.438)^2 - H^2}$ [m]
R =L/3.571[m], d =L/1.316[m], h =H/1.4[m]

These values and ratios are the same as those in the experiments.

Figure 9 shows the analytical results of the relationship between the maximum pushing force F_{max}[N] and the height H[m] of the body's contact point. When H=0.425[m], F_{max} is the maximum value 6.73[N]. Higher or lower H reduces F_{max}. Hence the optimal height of the body's contact point exists to push the object. This is the same as "pushing using upper two legs".

Figure 10 shows the analytical results of the range of horizontal forces (f_{x2}, f_{x4}) which satisfies the conditions. f_{x2} is pushing force of the body, and f_{x4} is pushing force of the upper leg. When f_{x2} and f_{x4} are positive, both the body and the upper leg push the object. Thus the robot pushes the object efficiently. When f_{x2} is positive and f_{x4} is negative, the robot pulls back the upper leg and presses the object harder to the body. This is for preventing the body from slipping on the object. We need additional positive force f_{x2} of the body to cancel the negative force f_{x4} of the upper leg. Accordingly this case is not efficient. From Figure 10, f_{x2} and f_{x4} can be positive when the height H of the body's contact point is 0.42[m]. Hence the robot can push the object efficiently at this height. As H becomes lower (0.32[m] and

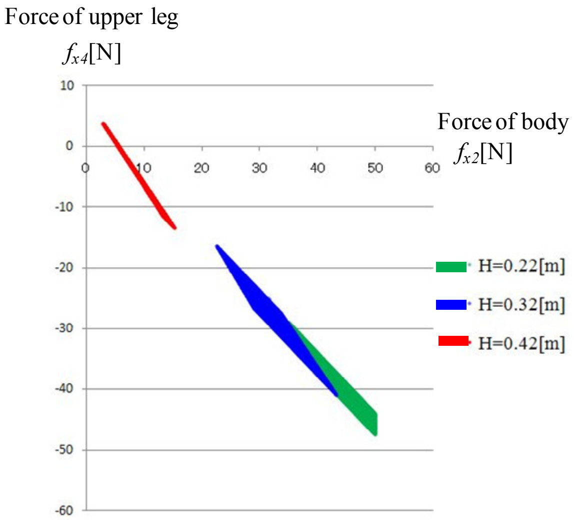


Figure 10: Horizontal forces (f_{x2}, f_{x4}) which satisfies conditions for robot to be able to push object

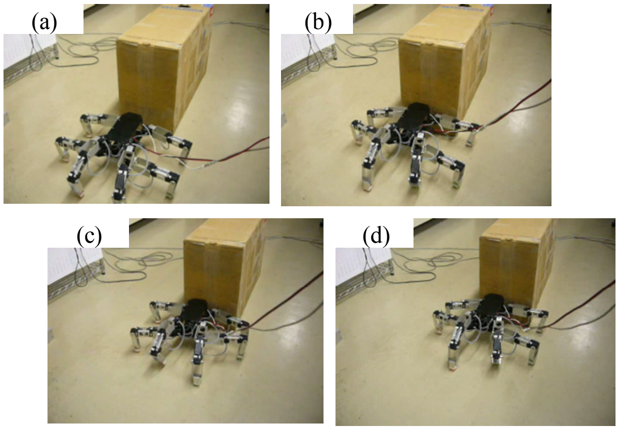


Figure 11: Experiment of pushing by tripod gait

0.22[m]), f_{x4} is negative and decreases. Thus the robot cannot push the object efficiently.

V. EXPERIMENTS

A. Pushing by Tripod Gait

The object used in the experiments of section A, B, and C is a cardboard box: 0.480[m] in height, 0.285[m] in width, 0.750[m] in length and 1.62[kg].

Figure 11 shows the robot pushing this object by tripod gait. Its step length is 0.1[m]. The robot sometimes leaves the object. The first links of the front legs #5 and #6 touch the object. Accordingly it is difficult to push the object stably with keeping the desired orientation of the object.

B. Pushing Using Upper Two Legs

Figure 12 shows the robot pushing the object using the upper two legs. Its step length is 0.1[m]. Because the upper legs apply force to right and left ends of the object, the robot can push it straight. Once the upper legs slipped down on the object, the robot fell forward. If the object did not slip, the upper legs left the object by the reaction force, and the robot fell backward. Thus it is difficult to keep the robot's balance.

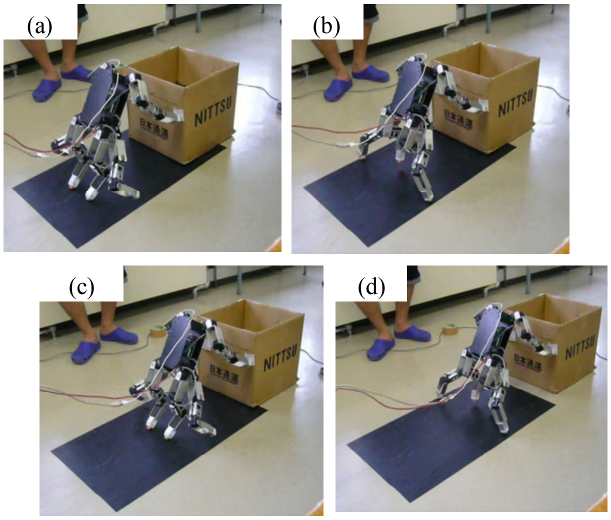


Figure 12: Experiment of pushing using upper two legs

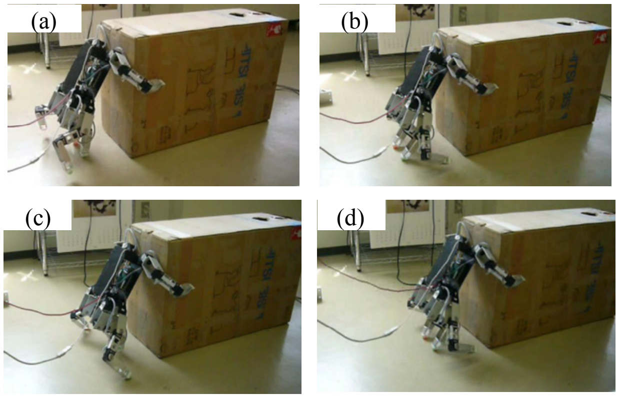


Figure 13: Experiment of pushing with holding object

C. Pushing with Holding Object

Figure 13 shows the robot pushing the object with holding it using the upper two legs and the body. Its step length is 0.1[m]. The height H of the body's contact point is 0.42[m]. Because the robot holds the object, the robot can push the object straight as desired. The upper legs and the body do not slip on the object. Accordingly this method allows stable pushing.

D. Comparison of Travelling Distance

Because "pushing using two upper legs" cannot keep the robot's balance, we compare the travelling distance by "pushing by tripod gait and that by "pushing with holding object". The used object is a cardboard box: 0.215[m] x 0.410[m] x 0.265[m], and 0.628[kg]. We change the weight M[kg] of the object by adding some weights, and measure the travelling distance D[m].

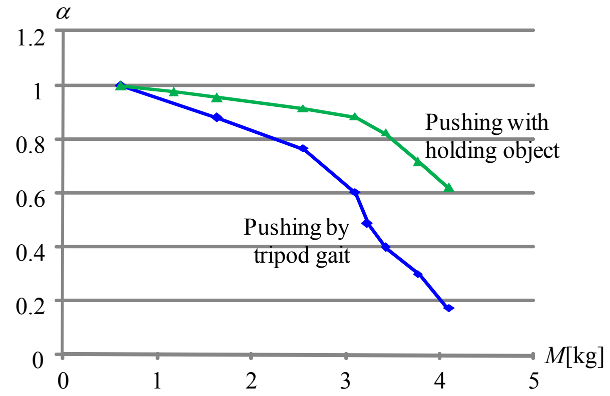


Figure 14: Relationship between object's weight M and ratio α of travelling distance

Figure 14 shows the experimental result. The vertical axis is the ratio $\alpha = D/D_0$, where D_0 is the travelling distance at no additional weights (the cardboard box only). From this result, the robot can push the object of 4.11[kg] by both methods. But the ratio α at this weight by "pushing by tripod gait" is 16.7[%]. It means that the robot almost slips and cannot push the object efficiently. The ratio α at this weight by "pushing with holding object" is 61.9[%], which is much larger than α by "pushing by tripod gait". When the ratio α is 90[%], the robot can push the object of about 2.7[kg] and 1.5[kg] by "pushing with holding object" and "pushing by tripod gait", respectively. The former is almost double the latter. Accordingly "pushing with holding object" enables the robot to push larger objects more efficiently than "pushing by tripod gait".

VI. CONCLUSION

We proposed a method for our working six-legged robot of pushing a large object in V-4L2A mode. The robot holds the object using its upper two legs and body. While leaning against the object, the robot walks by moving the outer and inner pairs of the lower four legs alternately. The features of this method are summarized:

(a) The robot can apply large force owing of the effect of its body weight.

(b) The robot can push the object in sagittal direction with keeping lateral balance because of symmetric walking.

(c) The robot can push the object stably without falling down and can maintain the orientation of the object because it holds the object firmly.

(d) The width of the object is limited.

We derived the conditions for the robot to be able to an object and analyzed the ability of pushing. It is ascertained by experiments that the robot can push large objects efficiently.

The robot has another mode: H-4L2A mode. But the robot cannot walk symmetrically in this mode. That impairs the lateral balance of the robot and causes the object to rotate about yaw axis. H-4L2A mode cannot apply so large force as V-4L2A mode, because the robot does not lean against the object. For these reasons, we did not consider H-4L2A mode in this paper.

In future works we will attach an attitude sensor to the body and force sensors to the feet of the robot. Then we will propose a control method of pushing using these sensors.

REFERENCES

[1] R. Hodoshima, et al.: "Development of TITAN XI: a Quadruped Walking Robot to Work on Slopes", Proc. 2004 IEEE/RSJ IROS, pp.792-797, 2004.
[2] T. Kang, et al.: "Realtime Perception with Infrared Scanner for Navigation of Quadruped Walking and Climbing Robot", Proc. 2004 IEEE/RSJ IROS, pp.2550-2555, 2004.
[3] T. Kang, et al.: "Design of Quadruped Walking and Climbing Robot", Proc. 2003 IEEE/RSJ IROS, pp.619-624, 2003.
[4] E. Karalarli, et al.: "Intelligent Gait Synthesizer for Hexapod Walking Rescue Robots", Proc. 2004 IEEE ICRA, pp.2177-2182, 2004.
[5] J. M. Morrey, et al.: "Highly Mobile and Robust Small Quadruped Robots", Proc. 2003 IEEE/RSJ IROS, pp.82-87, 2003.
[6] T. J. Allen, et al.: "Abstracted Biological Principles Applied with Reduced Actuation Improve Mobility of Legged Vehicles", Proc. 2003 IEEE/RSJ IROS2003, pp.1370-1375, 2003.
[7] A. Konno, et al.: "An Adaptive Gait for Quadruped Robots to Walk on a Slope", Proc. 2003 IEEE/RSJ IROS, pp.589-594, 2003.
[8] U. Saranli, et al.: "Back Flips with a Hexapedal Robot", Proc. 2002 IEEE ICRA, pp.2209-2215, 2002.
[9] S. Bai, et al.: "Path Generation of Walking Machines in 3D Terrain", Proc.2002 IEEE ICRA, pp.2216-2221, 2002.
[10] E. Z. Moore, et al.: "Reliable Stair Climbing in the Simple Hexapod RHex", Proc. 2002 IEEE ICRA, pp.2222-2227, 2002.
[11] H. Kimura, et al.: "Three-Dimensional Adaptive Dynamic Walking of a Quadruped - Rolling Motion Feedback to CPGs Controlling Pitching Motion", Proc. 2002 IEEE ICRA, pp.2228-2233, 2002.
[12] K. Kato, et al.: "Development of the Quadruped Walking Robot, TITANIX (Mechanical Design Concept and Application for the Humanitarian Demining Robot), Advanced Robotics, 15, 2, pp.191-204 2001.
[13] N. Koyachi, et al.: "Mechanical Design of Hexapods with Integrated Limb Mechanism: MELMANTIS-1 and MELMANTIS-2", Proc. 8th ICAR, 1997.
[14] T. Takubo, et al.: "Integrated Limb Mechanism Robot ASTERISK", Journal of Robotics and Mechatronics, Vol.18, No.2, pp.203-214, 2006.
[15] K. Inoue, et al.: "Omni-directional Gait of Limb Mechanism Robot Hanging from Grid-Like Structure", Proc. 2006 IEEE/RSJ IROS, pp.1732-1737, 2006.
[16] S. Fujii, et al.: "Climbing up onto Steps for Limb Mechanism Robot ASTERISK", Proc. 23rd ISARC, pp.225-230, 2006.
[17] S. Fujii, et al.: "Ladder Climbing Control for Limb Mechanism Robot ASTERISK", Proc. 2008 IEEE ICRA, pp.3052-3057, 2008.
[18] K. Inoue, K. Ooe: "Development of Working Six-Legged Robots Capable of Locomotion and Manipulation in Three Modes", Proc. the 39th ISR, pp.365-370, 2008.