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Vertical Ladder Climbing Motion with Posture Control for Multi-Locomotion Robot

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***Abstract*— This paper introduces a vertical ladder climbing of the humanoid robot only by the posture control without any external sensors. The humanoid robot does not have any special structure for fixing the body to the ladder. The robot maintains the body on the ladder by its grippers like human does. As a problem of this locomotion, a free gripper position of the climbing robot is not controllable because a yawing of the robot body around the axis connecting a supporting gripper and foot on the ladder is not fixed. To solve this problem, the momentum around AOY caused by the gravity is used to control the yaw motion of the body so that the various gait such as pace gait and trot gait could be realized in a ladder climbing maneuver. The algorithm of ladder climbing with recovery motion is experimentally verified by using "Multi-Locomotion Robot(MLR)" which is developed to achieve various types of locomotion such as biped, quadruped walking and brachiation.**

I. INTRODUCTION

In recent years, the humanoid type robot has come to be widely used for the robotic research. The humanoid robot is considered as a kind of "Multi-Locomotion Robot (MLR)" since it is required to take various types of locomotion according to the faced environment. The MLR has a lot of DOF so that the high mobility is expected in any situation. In order for the MLR to survive in the human environment, it has to be able to transit its locomotion types autonomously(Fig. 1). F. Kanehiro et al. developed HRP-II as one of the MLRs to select the locomotion to cope with different environment[4]. Our conventional work also dealt with MLR, which can realize bipedal, quadruped walking and brachiation behavior with a single physical structure[1][2][3]. However, these types of locomotion are realized and developed separately at present. In addition to these locomotion, the climbing up locomotion is required to realize the transition from biped walking to brachiation. We focused on the vertical ladder climbing which the MLR grasp and step on the ladder to maintain the vertical climbing posture. The vertical climbing locomotion will be needed when the humanoid robot has to operate at a higher ground. As a merit of using the vertical ladder, the robot will be able to climb the ladder very fast because there is not any fixing attachment like sucker which takes a time to fix and release the hand, foot and body. For the climbing up locomotion, following the problem should be mentioned. The MLR is easily away from the ladder yawing around the axis because of the momentum caused by gravitation.

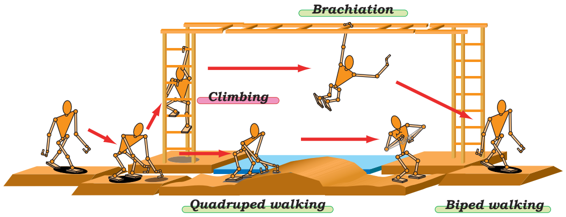

Fig. 1. Concept of MLR

In this paper, the right hand screw axis drawn between the gripping point and the foot point is refered to as "Axis of Yawing (AOY)". Three types of ladder climbing gaits can be realized without failure by adjusting the AOY: transverse gait, pace gait with constant velocity and trot gait with acceleration. Some related work as to vertical climbing motion deals with a wall climbing, a steep slope climbing and a ladder climbing. The situation which has to be avoided is that the robot is separated from the ladder while climbing, because it will make it impossible for the robot to return to the reference posture to keep climbing up. Most of the vertical climbing robot structures are designed to maintain a stable posture while moving. These robots with some fixed implements are specialized for the climbing up locomotion. As the small robot that can maintain its posture on a wall, S. Kim et al. developed the robot named Sticybot which climb on a flat and smooth surface using the intermolecular force caused by the puberulent hand and foot similar to gecko[5]. G.C. Clark et al. developed a hexapod robot named RiSE which can scratch the rough wall and move up with small nails[6]. These structures are useful for the small robot to move various environments, though they cannot be attached to big and heavy robots because the contact surface is small. H. Iida et al. developed a robot named LCR-1 for vertical ladder climbing. This robot has a pinch-hand with photoelectronic switch which can recognize and grasp the rung for certain[9]. The robot climbs up stably while all fours are gripping the ladders, though this climbing is slow and the direction is only one way. Some climbing robots use control system besides the special structures. B. Luk et al. developed a maintenance robot Robug II which uses suckers attached to the legs and the torso[7]. This robot equipped pressure sensors which is able to search foothold with tactile sensing and adjust the position of the legs by itself to spread out the force exerted on each leg. However, the work space is limited because the system is only restricted in 2-D space.

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As a ladder climbing robot, S. Fujii *et al* developed the limb mechanism high mobility robot named ASTERISK. This robot has six legs and uses the force distribution control of each leg from the result of position error. This robot possess high stability because it maintains the body on the ladder using more than 4 legs when the other legs and the torso climbing, though it takes long and climbing distance is limited because the "degree of dreedom(DOF)" is few[10]. As the control of climbing gait pattern, A. Nagakubo et al. realized the wall climbing by using big robot named NINJA-I,II which has suckers in the legs[8]. He shows the static and dynamic climbing gait considered "the Λ shape foot posture" to maintain the robot on a wall, though the proof of the posture principle does not show clearly. We use the same principle posture as NINJA-II in our static gait from the basis of momentum around AOY.

In this paper, we propose to show the feasible vertical ladder climbing locomotion which the MLR without any special structures or external sensors climbs stably and fastly. The robot can climb the ladder stably with maintaining the posture to balance the momentum around AOY caused by the gravity and reaction force in static gait. In the gait close to dynamic one, we propose that the reference COG trajectory for the vertical climbing is calculated from the balance of momentum caused by the gravity and acceleration around AOY. In the scheme of this ladder climbing, we use a recovery motion to avoid the gripping error as a compensation. We demonstrate these gaits experimentally and estimate the stability from the output torque of hip and shoulder where largely sustains the body.

II. MULTI-LOCOMOTION ROBOT

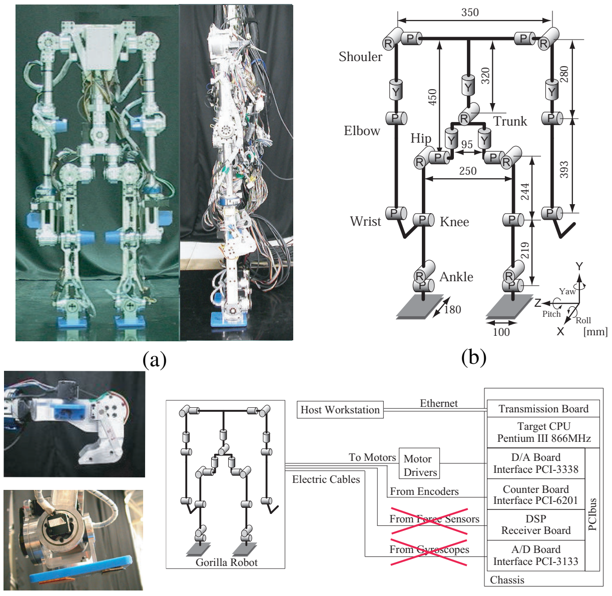
We have developed the MLR(Gorilla III) which is modelled based on the structure of actual gorilla as shown in Fig. 2(a). The spec of Gorilla III is as following; the height is 1.0[m], weight is about 22[kg], DOF of the whole body is 24(Right-hand has 5DOF, Right leg has 4DOF and Torso has 2DOF). Each link length is shown in Fig. 2(b). The hand is ape hand and it can grip a rung. The rubber plate is attached to the foot sole to prevent from slipping(Fig. 2(c)). The control system is shown in Fig. 2(e). This MLR is operated by real-time OS(VX Works). Each joint has a built-in servo motor and reduction gear. This motor executes PID control to follow the reference angle. In the experiment, some of the loaded motors' torques are estimated from the data of the encoder and output voltage. The cables connecting each motor to computer come out from the back of Gorilla III(Fig. 2(a)) so that the workspace of the robot is limited only front space of the robot.

III. MODEL OF LADDER CLIMBING

A. Basic motion model

The pitch and roll joints which is used for this ladder climbing locomotion are shown in Fig. 3(a). The idlling arm and leg motion are designed in sagittal plane for avoiding the collision with any rungs.

$$(y_a - y_{pos})^2 + (z_a - z_{pos})^2 = s^2, x_a = 0 \qquad (1)$$



(a) (b) (c) (d)

Fig. 2. Gorilla III

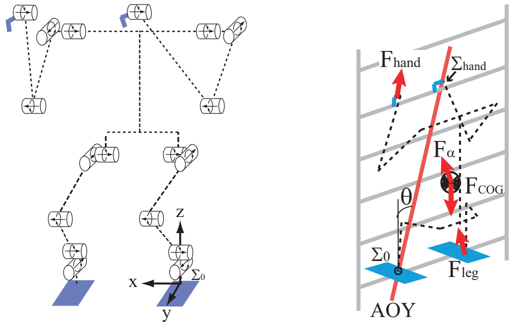
x_a, y_a, z_a are the reference trajectory of the hand and the foot, s is the trajectory parameter which is the half distance of climbing and y_{pos}, z_{pos} is the center of trajectory circle. The robot keeps the climbing motion with a constant distance between the torso and the ladder. The foot on the ladder has the gradient which the reaction force directs to COG and avoids sliding into the back of a ladder.

B. Ladder Climbing Gait

The MLR which climbs vertical ladder uses all fours as quadruped does. As the gait supporting the robot more than two points in quadruped walking, there are three supporting legs walking like transverse gait and two supporting legs walking like pace and trot gait. We propose to realize these gaits in vertical ladder climbing in order to extend the mobitily in various environment. The order of the step in each gait is shown in Fig. (4).

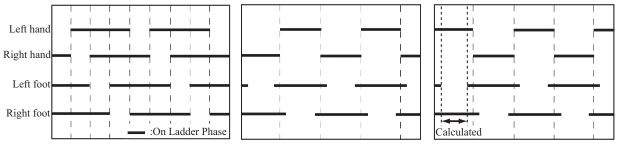
1) Transverse Gait: When the robot climbs the ladder each one step respectively about all fours, it's static gait because the body is always sustained by three points. At this time, the duty factor is 0.75.

2) Pace Gait with Constant Velocity: The duty factor of dynamic gait is under 0.5. However, this gait of ladder climbing is not same as the quadruped walking because the robot needs a period to release a hand from a rung. The duty factor of the pace gait in ladder climbing is over 0.5 and we cannot describe it is dynamic gait. Even though this gait is not dynamic, it is difficult to track the reference trajectory because the robot supports the body at two points and this period is unstable. The climbing velocity need to be slowed not to cause any disturbance. On this gait, the operator needs to decide the climbing initial velocity and a one step climbing time heuristically and has to look for the relevant conditions that the robot does not collide with a ladder.



(a) Parameters (b) Force and AOY relation

Fig. 3. Model of humanoid robot



Transverse gait Pace gait Trot gait

Fig. 4. Gait pattern

3) Trot Gait with Acceleration: The duty factor of this gait is also over 0.5. When behavior of the gravity momentum by inclination of AOY influences ladder climbing motion, it is difficult for the robot to track the reference trajectory only by the posture control because a large yawing momentum is induced. We suppose that the acceleration force which is added at COG also influences for the determination of vertical ladder climbing motion to reduce gravity momentum. We describe it in detail at next section.

C. Body Yawing Momentum

The dynamics is completely different between a vertical ladder and a step ladder. When the robot climbs a step slope or tilt ladder, the robot locomotes like biped and quadruped walking. In this case, the Zero-Moment Point(ZMP) to confirm the stability must be considered.However, ZMP is not related to the stability of vertical ladder climbing because the COG is always out from the supporting polygon of soles. We remark the momentum around the AOY to design the stable climbing motion and foot posture.

The momentum which is a rotational factor around the axis is calculated as follows on the basis of Σ_0.

$$\mathbf{M} = R_\theta \cdot \Sigma \left(\mathbf{r}_a \times \mathbf{F}_a \right) \tag{2}$$

$\mathbf{M}$: The sum of all momentum around AOY
R_θ : Rotational matrix around Y-axis
θ : The AOY inclination
$\mathbf{r}_a$: The coordinate at Σ_a
$\mathbf{F}_a$: The force vector at Σ_a

The yawing momentum around AOY calculated from Eq.(2) is as follows:

$$\begin{aligned} M_{yaw} &= a_1 \sin\theta + a_2 \cos\theta \qquad (3) \\ \theta &= \arctan\left(\frac{x_{hand}}{z_{hand}}\right) \qquad (4) \end{aligned}$$

$$\begin{aligned} a_1 &= -z_{hand}F_{y_{hand}} + y_{COG}(F_{z_\alpha} - Mg) \qquad (5) \\ a_2 &= x_{hand}F_{y_{hand}} + x_{leg}F_{y_{leg}} - y_{COG}F_{x_\alpha} \qquad (6) \end{aligned}$$

M is the total weight of the MLR and r_α is the position coordinate and F_{r_α} is r-direction element of force. When the robot keeps the motion of $M_{yaw} = 0$, it represents no momentum around the AOY, we suppose that the MLR can realize each gait stably. We decide the foot posture of each gait for the MLR with considering the momentum.

1) Three Supporting Climbing(Foots on Ladder): In this static climbing($F_{hand} = 0$, $F_\alpha = 0$), M_{yaw} is given by

$$M_{yaw} = -y_{COG}Mg\sin\theta + x_{leg}F_{y_{leg}}\cos\theta \tag{7}$$

When the reaction force $F_{y_{leg}}$ is applied well, the body is maintained at three points and the robot can climb the ladder stably. $M_{yaw} = 0$, that is $F_{y_{leg}} = \frac{y_{COG}Mg}{x_{leg}}\tan\theta$.
The vector of $F_{y_{leg}}$ is to COG and the value is minus, and y_{COG} is also minus from the coordinates. From this equation,the value of the inclination of AOY θ must be plus to maintain the body. It means the robot posture must be maintained $x_{hand} > 0$. The shape of this foot posture is like trapezoid.

2) Three Supporting Climbing(Hands on Ladder): In this static climbing($F_{leg} = 0$, $F_\alpha = 0$), M_{yaw} is given by

$$\begin{aligned} M_{yaw} = (-z_{hand}F_{y_{hand}} - y_{COG}Mg)\sin\theta \\ + x_{hand}F_{y_{hand}}\cos\theta \end{aligned} \tag{8}$$

$M_{yaw} = 0$ and $\theta > 0$ is maintained in this gait, that is $F_{y_{hand}} = \frac{-y_{COG}Mg\sin\theta}{x_{hand}\cos\theta + z_{hand}\sin\theta} > 0$. This momentum is generated from the force of supporting hands. However, this motion easily becomes unstable because the stiffness of robot with a lot of DOF is weak.

3) Two Supporting Climbing(Pace Gait with Constant Velocity): In this static two supporting climbing without any acceleration($F_{hand} = 0$, $F_{leg} = 0$, $F_\alpha = 0$), M_{yaw} is

$$M_{yaw} = -y_{COG}Mg\sin\theta \tag{9}$$

This equation means the momentum of this gait does not take when the robot maintains the posture of the inclination of AOY $\theta = 0$. The intervals of hands and foots are kept same during the robot climbing in this gait. The shape of this foot posture is like rectangle.

4) Two supporting Climbing(with Acceleration): In this type of gait($F_{hand} = 0$, $F_{leg} = 0$), the force of acceleration F_α and M_{yaw} are given by

$$F_{z_\alpha} = M\alpha\cos\phi,\ F_{x_\alpha} = M\alpha\sin\phi \tag{10}$$

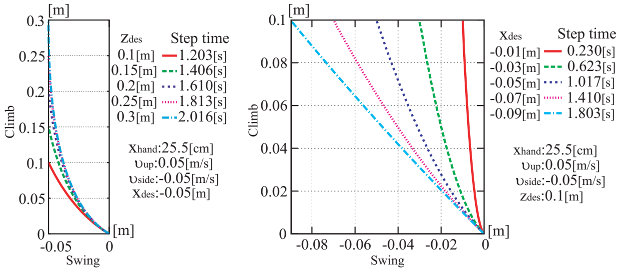
$$M_{yaw} = y_{COG}(-Mg\sin\theta + M\alpha\sin(\theta - \phi)) \tag{11}$$

The acceleration value at COG without gravity and direction are shown α and ϕ.
As the condition of constraint of this gait, the acceleration is constant. The operator chooses the initial parameters including the initial velocity. Then, the value of acceleration, direction for the COG trajectory and one step time for vertical climbing are calculated uniquely from the following

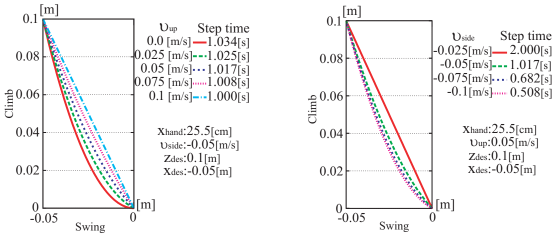
TABLE I

PARAMETER OF CLIMBING AND SWINGING DIRECTIONS

	Parameters		
DIRECTION	Initial Velocity	Destiny COG Position	Gripping position
Climbing(z)	v_z	z_{des}	z_{hand}
Swinging(x)	v_x	x_{des}	x_{hand}



z_{des} changes y_{des} changes



v_{up} changes v_{side} changes

Fig. 5. Trajectory of COG Changing Each Parameter

equations. The equation of x_{COG} and z_{COG} trajectory are as follows:

$$x_{COG} = \int_0^t \left(\int (\alpha \cos\phi - g)\, dt + v_{up} \right) dt \quad (12)$$

$$z_{COG} = \int_0^t \left(\int (\alpha \sin\phi)\, dt + v_{side} \right) dt \quad (13)$$

The parameters to calculate the reference COG trajectory from Eq. 4,11-13 are shown in TABLE I. The calculated results are in Fig. 5. The operator chooses the suitable parameters heuristically for the reference COG trajectory, acceleration and one step time which the robot can realize stably in this climbing motion.

D. Error Recognition and Escape Motion

In the ladder climbing motion, following failure cases of gripping the rung may occur:

- The robot hand fails to grip the rung.
- The hand grips the rung insufficiently.

The robot can recognize whether the hand grips a rung appropriately without any external sensors by considering the output voltage from the hand. In the case of that the robot successfully grips the rung, some voltage output from the hand is returned. However, if the less voltage output is returned, it implies that the gripping rung failed. On the other hand, if the tip of the finger reached the rung but failed to catch it successfully, larger voltage output will be retuned because the hand is overloaded. Thus, the evaluation of retuned output voltage from the hand will enable to judge whether the gripping the rung is successful or not. Therefore, we adopt this scheme to the error detection of the gripping rung and proceed to the following recovery process(Fig. 6). In 1-1, it is in the state where the hand has interfered with the rung and the robot has not fixed on the ladder. Even if the hand raises the distance shorter than the length of hand 1st link, the tip is still on the rung because the robot returns to the original position. If the hand raises more than the length of hand 1st link, the hand is not interfered with the rung to re-grip in the situation 1-1 and 1-2. Then the hand moves the length of a hand 2nd link with opening to the ladder back. At last, it returns to the original position with closing. The hand detects whether it is well grip the rung from the output voltage and repeat a series of this operation until it succeeds.

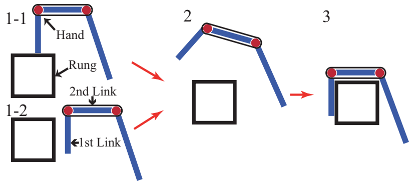


Fig. 6. Recovery Motion Model for Gripping Rung

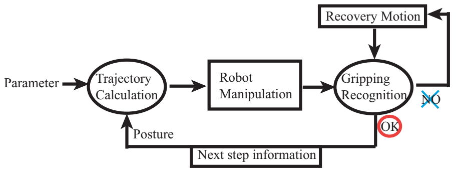


Fig. 7. The Control Flow in Continuous Ladder Climbing

In this case, we need to consider the robot posture in the same condition that the three supporting climbing(foot on ladder), that is the $x_{hand} \geq 0$, because the hand is free but the foot is on the rung in recovery motion. Considering this case, we decided the robot posture which the foot interval is wider than hand interval.

The control flow of ladder climbing is as follows(Fig. 7).

1) The operator gives the suitable parameters for basic motion.
2) The computers calculate the AOY inclination, the reference COG trajectory and one step period from the parameters.
3) The robot tracks the reference COG trajectory.
4) It judges the gripping situation from the hand output voltage.
5) It operates a recovery motion or not, then computer calculates the gripping position as a parameter from the robot posture.
6) Back to 2).

We confirmed that this control flow is useful to operate the continuous vertical ladder climbing experimentally.

IV. EXPERIMENT

We conducted experiments with Gorilla III to validate the proposed control method. The experimental condition is as follows:

- The ladder is set up vertically, and the interval of rungs of the ladder is constant 0.2[m] with each other.
- Cross section of rung is square of 2 × 2[cm^2] and is covered with a rubber plate for slip prevention.

In this experiment, we realize the three types of ladder climbing gait and observe the output of joint torque of the hips and the shoulders to estimate the stability of climbing motion.

A. *Transverse Gait*

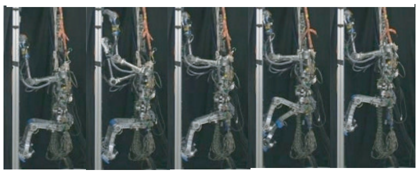
In the experiment of ladder climbing of transverse gait, x_{hand} is 0.045[m] and the MLR keeps the foot posture like trapezoid not to cause the body yawing. The climbing speed is 1.67[cm/s] and one step cycle is 12.0[s]. Figure 8 shows the experimental snapshot of the ladder climbing with transverse gait. From the figure, it is shown that the MLR stably climb the ladder with no yawing moment. Since the robot supports the body at three points in this gait, the shoulder and the hip joint torques were well dispersed and the trapezoid foot posture for the motionw is considered suitable to the stable climbing of the ladder(Fig. 9).

B. *Pace Gait with Constant Velocity*

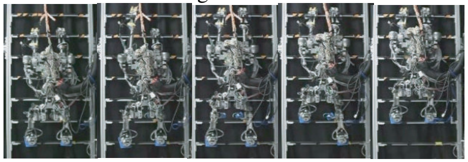
In the case of pace gait, the MLR keeps the foot posture like rectangle($x_{hand} = 0.0$) which the interval of the hands and the foots equal. The climbing speed is set to 5[cm/s] which was determined heuristically taking account not to cause any disturbance. The pace gait cycle is almost one third of static gait. Figure 10 shows the experimental snapshot of the ladder climbing with pace gait. From the figure, it is shown that any disturbance was not caused, and the MLR stably climb the ladder continuously. The result of the periodic output torque in Fig. 11 also shows that any disturbance is not caused whiles the robot climbing in this gait and the rectangle posture is considered suitable for this pace gait.

C. *Trot Gait with Acceleration*

This gait has an AOY with inclination. The parameters to determine the posture and motion are shown in TABLE II and the calculated values for each step are on TABLE III. This ladder climbing motion with trot gait is realized with the flow of motion planning and control(Fig. 7). Figure 12 shows the experimental snapshot of the ladder climbing with trot gait. From the figure, it is shown that the MLR climbed each one step faster than other gaits with acceleration and more stable with the recovery motion, though the foots shifted side to side a little when the hand grip a rung. The result of the periodic output torque in Fig. 13 also shows the validity of the flow of this motion and the problem of the foot stablilzing. We checked the result of the error recognition to continue the climbing motion from the output voltage of the hand. The MLR recognized the successful hand gripping at the time where the step number and the enclosure is drawn in Fig. 14. From these results, the flow of this gait motion with reference COG trajectory, error recognition and recovery motion sufficiently functioned to maintain the body and stable climbing on the ladder for the MLR.

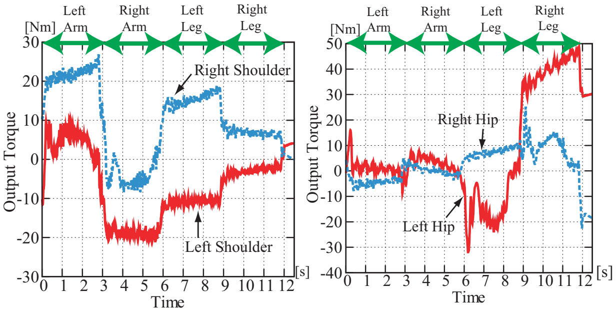


Sagittal view



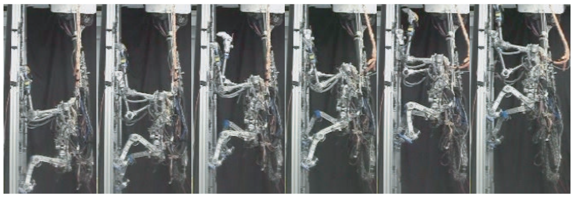
Lateral view

Fig. 8. Snapshots of Transverse gait

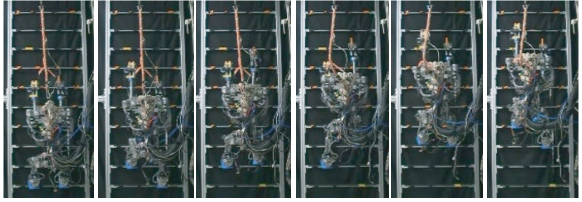


Shoulder Hip

Fig. 9. Output Torque of Transverse Gait

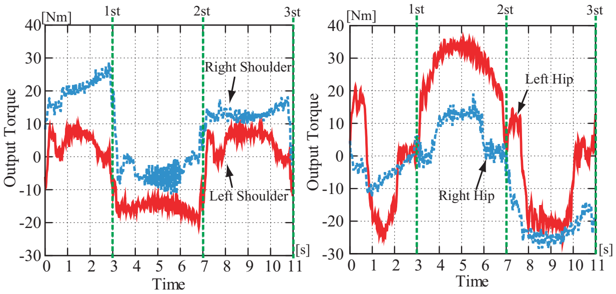


Sagittal view



Lateral view

Fig. 10. Snapshots of Pace Gait with Constant Velocity



Shoulder Hip

Fig. 11. Torque result of Pace gait with constant velocity

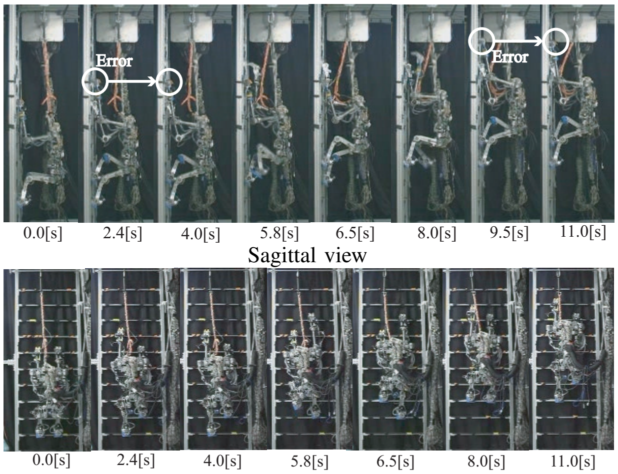


Fig. 12. Snapshots of Trot gait with accerelation velocity

TABLE II

PARAMETER OF UP AND SIDE DIRECTIONS

		Parameters		
Step	Direction	Initial Velocity[m/s]	Destiny COG Position[m]	Gripping position[m]
1st	Cilmb	0.05	0.1	1.0
	Swing	-0.05	-0.05	0.245
2st	Cilmb	0.05	0.2	1.0
	Swing	0.05	0.05	-
3st	Cilmb	0.05	0.2	1.0
	Swing	-0.05	-0.05	-

TABLE III

THE CALCULATED PARAMETERS FOR EACH STEP IN TROT GAIT

Step number	Gripping position[m]	Step period[s]
1st	0.245	2.244
2st	0.237	2.616
3st	0.213	2.568

V. CONCLUSION AND FUTURE WORK

A. Conclusion

In this paper, we realize the various types of vertical ladder climbing locomotion by using Multi-Locomotion Robot: static gait, pace gait with continuous velocity and trot gait with acceleration. The stability of vertical ladder climbing of MLR in static gait and pace gait is maintained with the posture control considering the momentum around axis of yawing. Even if the axis has inclination, the reference COG trajectory and acceleration is calculated to determine the motion which can maintain the stability of posture on the ladder. The control flow with the error recognition from output voltage and recovery motion were well operated and the MLR realized the continuous ladder climbing in the trot gait.

B. Future Work

Additional use of some other sensors would improve the stability of climbing furthermore. Also, we are attempting to realize a transition from the biped walking posture to the ladder climbing mode using an external sensor.

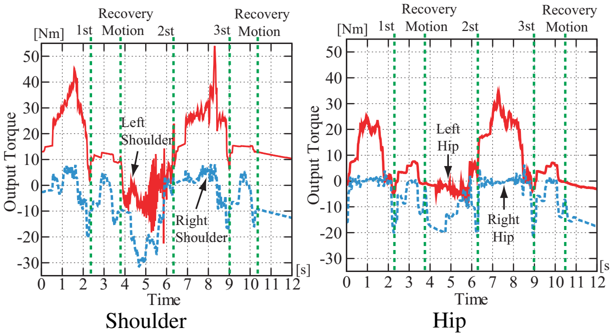


Fig. 13. Output Torque of Trot Gait with Acceleration

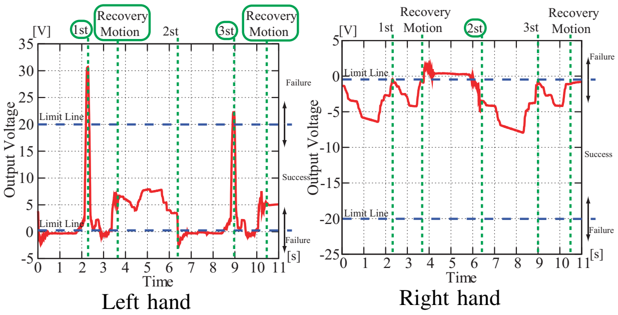


Fig. 14. Hands Output Voltage for Error Recognition in Trot Gait

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