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Rappelling by a Humanoid Robot Based on Transition Motion Generation and Reliable Rope Manipulation

Masahiro Bando, Masaki Murooka, Iori Yanokura, Shunichi Nozawa, Kei Okada, and Masayuki Inaba

Abstract— **For robots to act in outdoor environments, the ability for locomotion is an important factor because it influences the range of activities. Humanoid robots are acquiring the ability for locomotion in horizontal directions so far, and the ability for vertical locomotion is now required in order to extend their range of activities further. Therefore, we propose rappelling as a method for vertical locomotion. Rappelling is a method to descend from a high place using a rope and a belay device. With this method, humanoid robots are expected to get the ability for vertical locomotion without additional actuators. In this paper, we propose a full-body motion for rappelling based on the sequential transition of the centroid position and the contact states. We also propose the reliable manipulation of a rope grasped by both hands. With the proposed methods, we conducted an experiment of rappelling with HRP2, and it could successfully descend from a height of 2m50cm in 277 seconds.**

Fig. 1. HRP2 while rappelling

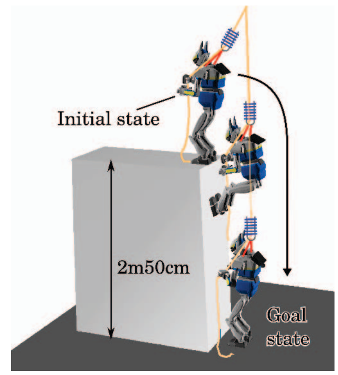

Fig. 2. Overview of rappelling by a humanoid robot

I. INTRODUCTION

One of the features of a humanoid robot is the high ability for locomotion, and many researchers focus on improvement of the ability for locomotion. In addition to walking, which is the most common and researched method, some studies implemented other ways of locomotion, such as riding a tricycle [1] and using a kick scooter[2]. While these studies improved the ability for horizontal locomotion, it is also necessary for humanoid robots to acquire the ability for vertical locomotion. As one of the solutions for vertical locomotion, some studies proposed climbing a ladder [3][4]. However, the vertical locomotion without using such facility has not been researched enough yet.

In this paper, we deal with a rappelling motion by a humanoid robot as one of the methods to move vertically. Rappelling is the method to descend from a high place with a rope and a belay device, and its advantage is that it doesn't require any additional actuator or complex tool.

Though a humanoid robot is expected to acquire the ability for vertical locomotion by rappelling, there are two problems to be resolved when it executes rappelling. First, the robot has to transit stably between two states, the state the robot supports its weight by its legs and the state the robot is suspended by a rope. Second, manipulating a rope, as required for rappelling, is not as easy as manipulating a rigid object because a soft object like a rope easily deforms by external force.

Therefore, we propose the sequential transition of the center of mass position of a robot and the contact states between the robot and an environment in order to change the tension of a rope stably. Then, we generate a full-body transition motion for rappelling based on the sequence. In addition, we also propose the reliable manipulation of a rope by grasping it with both of the robot's hands. With these methods, we enabled a humanoid robot to rapel. We believe that this is the first life-size humanoid robot which can descend along a wall.

A. Related Works and Contribution of This Paper

1) Wall Climbing Robot with Additional Actuators: In many cases, robots required to move vertically equip additional actuators specialized for adhering to a wall. Hirose et al. developed NINJA1 [5], a robot which climbs a wall with suction pumps attached to the robot's legs. H. Prahlad et al. developed a robot that uses electroadhension as a method to climb a wall [6]. Both robots have high ability to move on a vertical wall. These actuators are useful for robots specialized for climbing a wall.

However, it is difficult for a humanoid robot to use such actuators because general humanoid robots don't have enough space or power to equip large additional actuators. Even if the robot is able to equip the actuators, the robot will lose its high ability to conduct various tasks.

2) A Humanoid Robot Climbing a Ladder: As one of the methods for vertical locomotion of a humanoid robot, some studies proposed climbing a ladder as a way for a humanoid robot to move vertically [3][4].

Although these studies enable humanoid robots to move vertically without losing their working ability, the robot can't use this method in the undeveloped environment without a ladder. Therefore, long vertical locomotion by a humanoid

M. Bando, M. Murooka, I. Yanokura, S. Nozawa, K. Okada, and M. Inaba are with Department of Mechano-Infomatics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan bando at jsk.t.u-tokyo.ac.jp

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robot in natural environments cannot be resolved using a ladder.

3) A Small Humanoid Robot Climbing a Rope: EVOLTA is a small humanoid robot specialized for climbing a rope[7]. EVOLTA made by Takahashi is a 17cm tall robot powered by drycell batteries. It achieved a 1000m fjord vertical climb in 11 hours and 30 minutes.

However, EVOLTA's mechanism is specialized for climbing, so the same method cannot be used for a normal life-size humanoid robot.

4) Contribution of This Paper: In this paper, we propose rappelling as a method to locomote vertically. While rappelling has a disadvantage that it is basically impossible to move upward vertically, it has an advantage that it doesn't require an additional actuator, a complex tool nor a facility like a ladder. Therefore, rappelling is suitable for descent from a high place in the outdoors, like a cliff.

To achieve rappelling, we propose the following methods.

- The sequential transition of the center of mass position and the contact states in order to dangle from a rope and land on the ground, and the transition motion generation based on the sequence.
- The reliable manipulation of a rope for rappelling by grasping the rope with both hands.

These methods are expected to enable humanoid robots to conduct rappelling.

II. APPROACH OF RAPPELLING

A. Typical Rappelling by Human

Rappelling is a method to descend vertically with a rope and a simple belay device (Fig.3). It is usually used to descend along a cliff or a building and suitable for the situation that it is difficult to prepare a crane or a winch. A belay device is a tool to control a climber's descending velocity with little force. A carabiner and a figure-eight descender are popularly used(Fig.4).

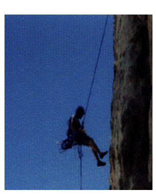

Fig. 3. A person who is rappelling[8]

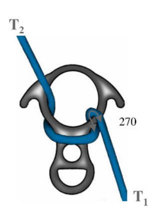

Fig. 4. Figure-eight descender[9]

Rappelling is carried out by winding a rope onto a belay device and pulling the part of the rope lower than the belay device. Depending on the tension exerted to the lower part of the rope, the maximum static friction force between the rope and the belay device changes greatly, and this static friction force supports the climber's weight. Therefore, he can stop descending by pulling the rope so that the static friction force gets more than his weight.

The required force to pull the rope can be calculated by the belt friction equation [9]. The belt friction equation is the formula about the friction force between a belt and a cylinder which the rope is wound on as shown in Fig.5. The belt friction equation is as follows.

$$T_1 = T_2 e^{\mu\theta} \quad (1)$$

T_1 is the applied tension on a rope, T_2 is the minimum required force exerted at the other side of the rope to resist, μ is the static coefficient of friction between the rope and the cylinder, and θ is the total angle that the rope is wound on the cylinder.

Fig.6 shows a principle of rappelling by approximating a belay device with a cylinder. In this figure, F and f_1 corresponds to a climber's weight and the force with which the climber pulls the rope, respectively. When the climber

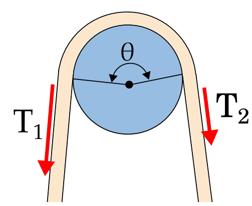

Fig. 5. The situation which belt friction equation describes.

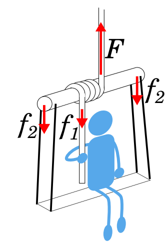

Fig. 6. Principle of rappelling

in Fig.6 keeps its height, the relation between f_1 and F is represented in the following equation by the belt friction equation.

$$F = f_1 + 2f_2 \quad (2)$$

$$F < f_1 e^{\mu\theta} \quad (3)$$

The upper limit of F increases exponentially with θ, so a climber can rappel with little force.

B. Rappelling Suitable for a Humanoid Robot

By using a belay device, a humanoid robot can conduct rappelling as a human does. It can descend by raising a rope it is grasping and stay at a certain height by holding the rope tightly. However, there are several problems with the rappelling of a humanoid robot.

In the case of rappelling by human, a belay device is attached to a climbing harness equipped at his waist, so his weight is supported by the hip. However, wearing a climbing harness is not suitable for a humanoid robot because the robot's hip doesn't necessarily have enough mechanical strength to support its weight. In addition, there is a high possibility that the harness limits the motion of the robot's legs. For these reasons, we connect a belay device to the robot's shoulders, which are strong enough to suppoert the weight.

The problem caused by connecting a belay device to the shoulders is that the robot's head may collide with the wall if the start point of the rope is ahead of the robot as shown in Fig.7. This is because the moment of the tension of the rope and the moment of the gravity exerted upon the robot cannot balance around the point at which the robot touches the wall with its feet. To avoid this problem, we set the start

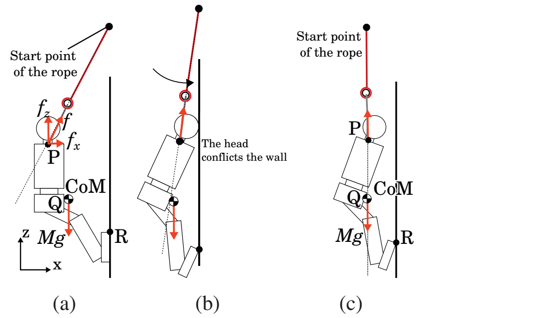

Fig. 7. (a): The posture of a robot connected a rope to its shoulder when the start point of the rope exists ahead of the robot. With this posture, the robot's center of mass usually exists ahead of the robot's shoulders. The robot's feet is just touching a wall, so f_z is almost equal to Mg. Therefore, $|(P_x - R_x)f_z| + |(P_z - R_z)f_x|$ gets larger than $|(Q_x - R_x)Mg|$. As a result the robot's head conflicts the wall as shown in (b).
(c): The posture of a robot when the start point of the rope exists just above the robot.

point of the rope almost directly above the robot in this paper. Although the robot can rappel without its head colliding with the wall by changing the start point, the situation that the start point of the rope can be set directly above a climber is uncommon. In order to carry out rappelling in general situations, a robot should connect a belay device to its waist in future work.

Another problem is that the humanoid robot we used in this paper doesn't have enough grasping power to use common belay devices like a carabiner and a figure-eight descender, so we use a rappel rack instead of common belay devices. A rappel rack is a belay device that usually used

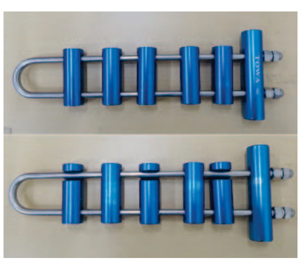

Fig. 8. The rappel rack used in this research.

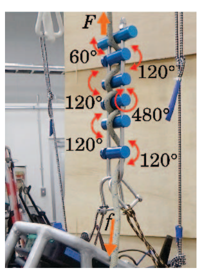

Fig. 9. How the rope is wound on the rappel rack.

for rescue. It enables rappelling with less force than usual belay devices because it has more space to wind a rope on. When a robot uses a rappel rack, the number of times that a rope is wound on the rappel rack has to be decided properly depending on the robot's weight and its grasping power. The number of times of winding a rope can be calculated from the static coefficient of friction between the rappel rack and the rope, but the coefficient of friction is usually unknown. Therefore, we checked whether the robot can stay in the air by pulling the rope for several configurations of the rope, and decided the proper way to wind the rope on the rappel rack. As a result, we wind the rope as shown in Fig.9 in the rappelling experiment.

C. Overview of the Proposed System for Rappelling

The overview of our proposed system of rappelling is shown in Fig.10. This system consists of three modules, the

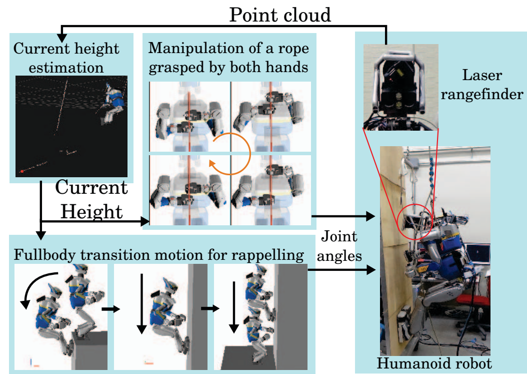

Fig. 10. The proposed system for rappelling

reliable manipulation of a rope grasped by both hands, the full body motion for rappelling, and the height estimation by laser rangefinder. We will explain the sequential transition of the center of mass and the contact states, which the full body transition motion generation is based on, in Sec. III, the reliable rope manipulation in Sec. IV and the current height estimation in Sec. V. In Sec. VI, we will show the effectiveness of the proposed system by conducting a rappelling experiment with a real humanoid robot.

III. THE SEQUENTIAL TRANSITION OF CENTER OF MASS POSITION AND CONTACT STATES

The robot is in one of three states during the whole rappelling motion, the state the robot is standing on the edge of a cliff, the state the robot is suspended by a rope, and the state the robot is standing on the ground. The transition from one state to the next state is executed by controlling the tension of the rope with the robot's feet. To shift from the first state to the second state, the robot has to decrease the load on its feet and increase the tension in the rope, and we call this transition "Dangling motion" (Fig.11). For the transition from the second state to the third state, the robot has to increase the load on its feet and decrease the tension in the rope, which we call "Landing motion" (Fig.12). The robot conducts rappelling by switching its state to the next one with these transition motions.

To generate each transition motion, we propose the sequential transition of the robot's center of mass (CoM) position and the contact states between the robot and surrounding environment.

A. Detail of the Dangling Motion

In the dangling motion, a robot shifts from the state in which it is standing on the edge of a cliff to the state in which it is suspended by a rope. If this transition is conducted carelessly, the robot may fall down and lose its stability, so it has to take the load of its feet and the tension of the rope into consideration to keep its stability. Therefore, we define the sequential transition of the CoM position and the contact

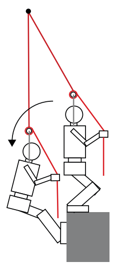

Fig. 11. Dangling motion

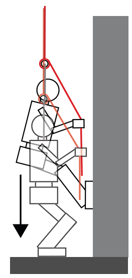

Fig. 12. Landing motion

states as shown in Table I, and generate the dangling motion based on the sequence. The contact states in the table means what the robot's limbs are touching.

TABLE I

THE SEQUENTIAL TRANSITION OF THE COM POSITION AND THE CONTACT STATE.

	CoM position	Feet contact state
State1	Above the feet	Edge of a cliff
State2	Rear outside of the feet	Edge of a cliff
State3	Under the rope	Edge of a cliff lightly
State4	Almost under the rope	Side of a cliff

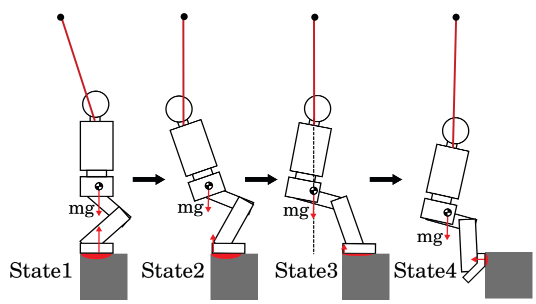

Fig. 13. The dangling motion sequence. The red zones mean the contact area.

State1 is the initial state. In State2, the CoM of the robot is out of the robot's support polygon, so the weight of the robot is supported by both of the rope and the feet. State3 is the preparation to move the robot's feet to the side of the cliff. By moving the CoM directly underneath the rope, the reaction force on the robot's feet becomes almost zero. In State4, the robot is completely suspended by the rope, so it can start descending along the cliff.

During State1, State2, and State3, the robot remains in contact with the edge of the cliff to avoid rotating around the rope. The proposed full body motion is generated by connecting these states sequentially.

1) The transition from State1 to State2: First, the robot squats down and pulls the rope by its shoulders via the rappel rack. As the tension of the rope increases, the robot rotates backward slowly around its heels by the moment of the tension, and its CoM moves backward. After the moment that the CoM exists right above the heels (Fig.14.B), the robot starts falling down backward dynamically because the moment around its heels cannot be counteracted. The robot stops falling down at the point that the moment around its heels balances again (Fig.14.C). Then, the robot rotates its ankles to touch the edge of the cliff with its soles and completes the transition to State2. (Fig.14.D)

It is desirable that this motion consists of quasi-static movements, but it is impossible to remove the dynamic backward falling down from the transition to State2. Therefore, we adopt this dynamic movement into the transition motion.

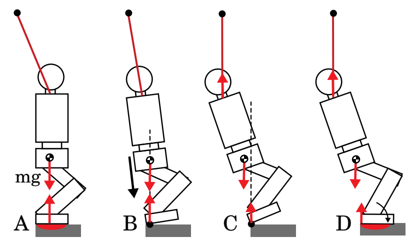

Fig. 14. Detail of the transition from State1 to State2

2) The transition from State2 to State3: In this motion, the robot has to move its CoM directly underneath the rope attachment while remaining in contact with the cliff. The robot can rotate around the point that the rope is connected to the robot by moving its feet upward, so the required posture is acquired by calculating the position of the robot's feet such that its CoM is directly underneath the rope. After this transition, the robot is almost suspended by the rope and touches the cliff just lightly.

3) The transition from State3 to State4: The robot moves to the side of the cliff in this motion. First, it moves its feet backward (Fig.15.B) and rotates its ankles so that its soles touch only the edge of the cliff (Fig.15.C). Then, it descends a certain distance along the side of the cliff by rappelling. (Fig.15.D) After the robot has descended, it moves its feet to touch the side of the cliff with its soles (Fig.15.E).

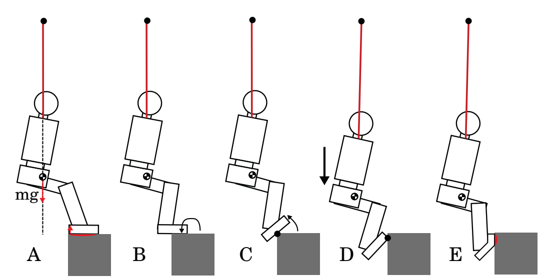

Fig. 15. Detail of the transtion from State3 to State4

B. Detail of the Landing Motion

In the landing motion, the robot transits from the state in which it is suspended by the rope to the state in which it is standing on the ground. The robot has to lower its foot to stand on the ground, but it cannot avoid rotating around the rope if it gets its feet away from the cliff. Therefore, the robot shifts to a posture in which it touches the cliff with a single hand and a single foot. With this posture, it can lower its foot, avoiding rotation around the rope. We define this landing motion as the sequential transition of the position of the robot's CoM and the contact states as shown in Table II We will explain each transition motion from one state to the next in the following paragraphs. These motions are conducted sequentially in the landing motion.

TABLE II
THE SEQUENTIAL TRANSITION OF THE CoM POSITION AND THE CONTACT STATE IN THE LANDING MOTION.

	Centroid position	Feet contact state	Hands contact state
State1	Under the rope	R: Side of a cliff L: Side of a cliff	R: Grasping a rope L: Grasping a rope
State2	Under the rope	R: Side of a cliff L: Side of a cliff	R: Side of a cliff L: Grasping a rope
State3	Under the rope and above the right foot	R: Horizontal in the air L: Side of a cliff	R: Side of a cliff L: Grasping a rope
State4	Above the right foot	R: On the ground L: Side of a cliff	R: Side of a cliff L: Grasping a rope
State5	Above the feet	R: On the ground L: On the ground	R: Side of a cliff L: Grasping a rope

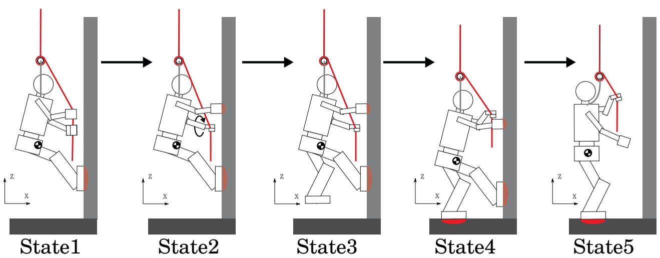

Fig. 16. The landing motion sequence. The red zones mean the contact area.

1) The transition from State1 to State2: To keep the robot's attitude stable, its right hand has to release the rope and touch the cliff. However, there is a possibility that its left hand slides against the rope due to the decrease in gripping power. Therefore, the robot rotates its left hand and winds the rope around its hand first, after which its right hand releases the rope and touches the cliff. By winding the rope around the left hand, the robot can increase its gripping power.

2) The transition from State2 to State3: The robot gets its right foot away from the cliff and moves the foot underneath the CoM. By keeping its right hand in contact with the cliff, it can keep its attitude stable after it has moved the foot. Next, it makes the right foot parallel to the ground and prepares for landing. From this posture, the robot can stand on the ground with the right foot without falling down.

3) The transition from State3 to State4: The robot descends along the cliff by rappelling and lands on the ground with the right foot. It can detect the ground by the force sensor attached to its feet.

4) The transition from State4 to State5: From the state in which the robot is standing with a single leg, the robot shifts to the state in which it is standing with both legs. First, it gets its left foot away from the cliff and moves the left foot to touch the ground. Then, the robot moves its CoM above the center of the feet support polygon. Finally, the robot stretches its legs and supports its weight totally with its legs.

IV. RELIABLE MANIPULATION OF A ROPE USING BOTH HANDS

Manipulation of a rope is an important factor for rappelling because it controls speed of descent of the robot. By raising a rope the robot is grasping, the static friction force between the rope and the belay device becomes weak, and the robot starts descending. Therefore, the robot repeatedly executes a rope manipulation cycle which consists of raising the rope and grasping the lower part of the rope. However, it is generally difficult to grasp a soft objects like a rope because it moves easily and makes the point to grasp unstable.

One strategy to grasp the rope is to plan how to grasp the rope based on the recognition. This strategy is very universal as long as the recognition and the planning works correctly, but there is a high possibility that this strategy fails due to several problems. One of those problems is that grasping the rope causes it to be occluded, and it obstructs the recognition. Another problem is that the robot has to plan how to grasp the rope considering the future position of the rope when it is moved by an external force. Neither the recognition of the rope with occlusion nor planning how to grasp a moving rope is easy, so we abandoned this strategy.

Another strategy is to manipulate the rope by partial caging [10]. By partial caging, the position of the rope is limitted in the hands, so it becomes easy to grasp the rope without recognition. This strategy enables reliable manipulation of a rope, but the robot cannot pass the rope from one hand to the other, because the rope moves out of the hand. This means that typical rope manipulation consisting of raising a rope and passing it from one hand to the other repeatedly is impossible. Therefore, we propose the manipulation of the rope by grasping it with both hands, as shown in Fig.17. With this manipulation, a robot can raise the rope while keeping the rope in the robot's hands.

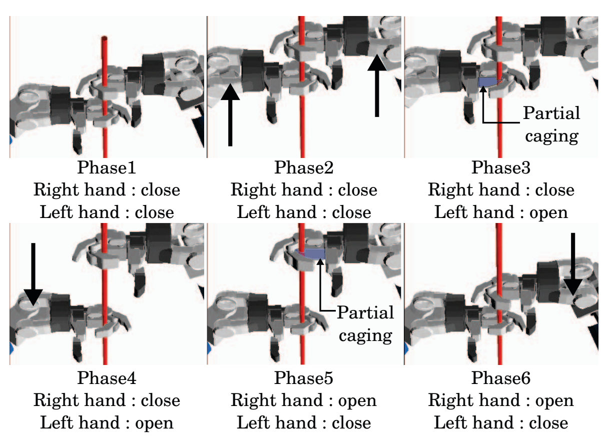

Fig. 17. Reliable manipulation of the rope using both hands.

From the state in which the robot is grasping a rope with both hands (Phase1), the robot raises the rope by moving its hands upward (Phase2). If the descent of the robot is detected by height estimation, the lower hand of the robot releases the rope (Phase3) and moves downward, keeping the rope in it (Phase4). Then, the lower hand grasps the rope again, and the upper hand releases the rope (Phase5). Finally, the upper hand moves downward and grasps the rope again (Phase6). There is a possibility that the rope moves out of the hand in Phase4 and Phase6, so the robot conducts these phases quickly (in 1 sec) to reduce the possibility. This manipulation doesn't require the hand to move away from the rope, so it has enough reliability without recognition.

V. HEIGHT ESTIMATION BY LASER RANGEFINDER

In order to start the landing motion after the robot has gotten close to the ground, the robot has to know its height from the ground. There are many methods to measure the current height, and we select to use a laser rangefinder (LRF) attached to the head of the robot for height estimation. A LRF is a device that can measure point clouds in 2D using a laser. The humanoid robot we used in this paper has a Multisense SL which has a rotating LRF and a stereo depth camera(Fig.18). To measure the robot's height, the robot tilts its head to scan the ground, searches the lowest point in the measured point cloud, and regards the position of the lowest point as the position of the ground.(Fig.19) The current attitude of the robot is measured by the IMU in the robot. This method can measure current height with enough

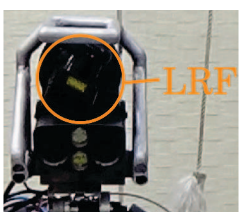

Fig. 18. Multisense on the head of HRP2

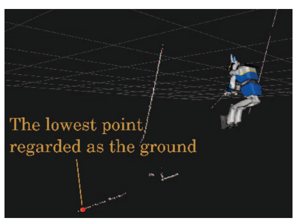

Fig. 19. Height estimation by detecting the lowest point in 2D point cloud measured by LRF

accuracy and frequency, but it requires some assumptions to work correctly. The first assumption is that there is no point lower than the ground in the environment, and the second assumption is that the LRF attached to the robot can always scan the ground. Our environment satisfied the first assumption, and the second assumption was satisfied by tilting the robot's head to look at the ground.

VI. EXPERIMENT WITH A REAL ROBOT

We conducted a rappelling experiment with the life-sized humanoid robot HRP2 [11], which weighs 60kg. The overview of this experiment is as shown in Fig.2. The robot starts rappelling from the state in which it is grasping the rope with both hands and standing on the edge of the high place. Then, the robot descends along a flat wall by rope manipulation using both hands. The height of the initial position is 2m50cm, and the robot normally descends 15cm in one cycle of the rope manipulation. After the height of the robot's hip has got less than 1m25cm, the robot changes the descent distance in one cycle from 15cm to 5cm because it has to avoid getting too close to the ground. When the height of its hip above the ground becomes 95cm, the robot executes the landing motion and stands on the ground. We performed this experiment successfully 5 times in a row.

The snapshots of the rappelling experiment we conducted are shown in Fig.23. It took 277 seconds to execute all the motion, excluding the time during which the experimenter paused the experiment to get down to the ground. The dangling motion, the rappelling motion and the landing motion took 83 seconds, 120 seconds, and 74 seconds respectively.

Fig.20 shows the z component of the force measured by the force sensors attached to the robot's feet during the dangling motion. After the robot started the first motion, f_z in world frame decreased due to the tension of the rope, and the force of each foot decreased to less than 50N at the end of the dangling motion.

Fig.21 shows the z component of the force exerted upon the robot's feet in the landing motion. The force exerted upon the right foot increased at the moment of landing (t=249s), and the robot detected the ground. The graph shows that the robot was able to stand with less load than its weight because of the tension of the rope.

Fig.22 shows the estimated height of the robot's waist. The vertical distance between the feet and the waist is 65 cm in the initial state. Some outliers shown in the graph are probably due to the failure of scanning the ground by LRF.

We used euslisp [12] and ROS [13] to implement this rappelling experiment. To search the lowest point in the acquired point cloud, we used PCL [14].

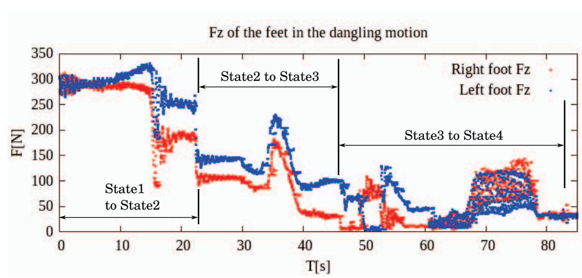

Fig. 20. f_z of the feet in the dangling motion

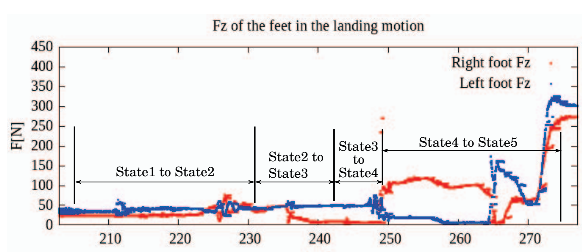

Fig. 21. f_z of the feet in the landing motion

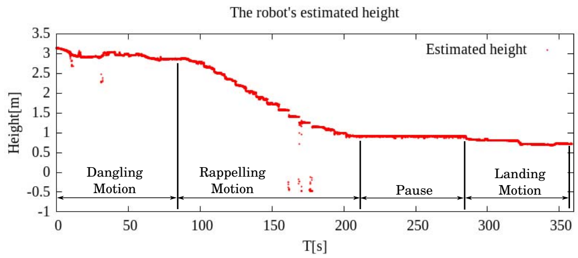

Fig. 22. The robot's estimated height

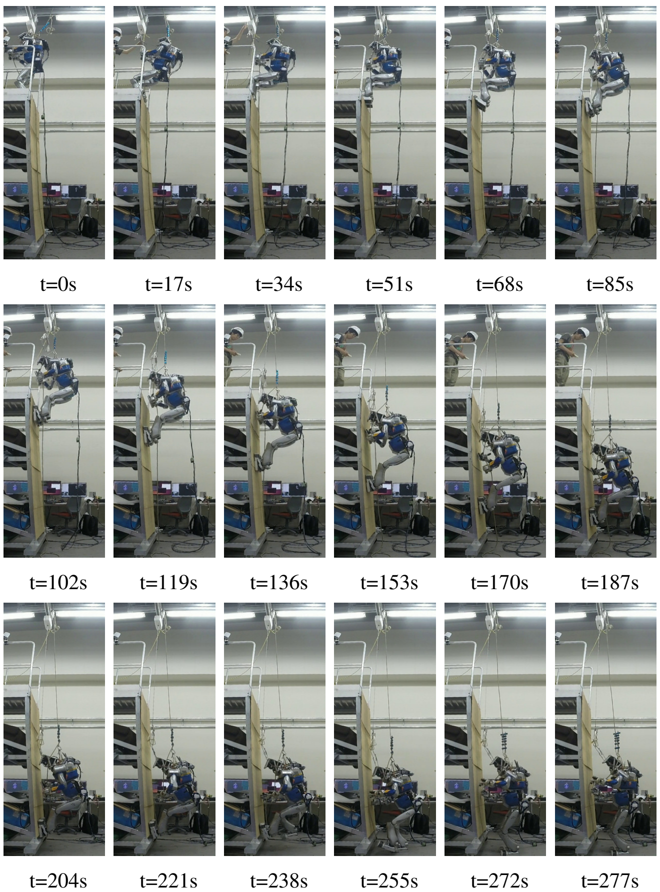

Fig. 23. The snapshots of the experiment of rappelling by HRP-2

VII. CONCLUSION

In this paper, we proposed rappelling for a humanoid robot as a method to locomote vertically. We proposed following methods to conduct rappelling:

- A full-body transition motion for rappelling based on the sequential transition of the center of mass position and the contact states of a robot's limbs.
- Reliable manipulation of a rope by grasping it with both hands.

We confirmed that the humanoid robot HRP2 could conduct rappelling from a height of 2m50cm with the proposed methods in 277 seconds. It is expected that standard humanoid robots can also conduct rappelling with our methods.

On the other side, there are several problems associated with the method of rappelling proposed in this paper. First, the start point of the rope has to be just above the robot, while this limitation is probably hard to satisfy in real environments. To set the start point of the rope ahead of the robot, the robot has to connect a belay device to its waist. Second, the robot slides along the flat wall in the experiment, so the robot cannot descend along a rough wall nor a wall with high coefficient of static friction.

In the future work, we will implement rappelling of a humanoid robot suspended by a rope connected to its waist. In addition, we will introduce a walking motion on a rough wall to descend along a side of a real cliff. This future work will enable more general rappelling by a humanoid robot in the real natural environment.

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