The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Terrain-Adaptive Control with Small Landing Impact Force for Biped Vehicle

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***Abstract*—Many researchers have studied on walking stability controls for biped robots. Most of them are highly accurate acceleration controls based on the mechanics model of the robot. However, the control algorithms are difficult to be applied to human-carrying biped robots due to modeling errors. In the previous report, we proposed the landing pattern modification method, but it had a problem that a foot landing impact increased when a walking speed became fast. So, we propose a new terrain-adaptive control that can reduce a landing- impact force. To increase a concave terrain adaptation, we set a target landing position beneath a reference level. To reduce the landing-impact force, we change the position gain control value to a small value at a swing phase. Moreover, we set landing-foot speed at zero after detecting a foot-landing by the force sensor mounted on a foot. To follow uneven terrain, a virtual spring is installed to the vertical direction after detecting a foot-landing on a ground, and a virtual compliance control is applied to the roll and pitch axes. In a stable walk while carrying a 65 kg human on uneven terrain, the new control method decreased the landing-impact force than the previous terrain-adaptive control.**

I. Introduction

THE barrier-free concept has been disseminated in order to allow the elderly and disabled wheelchair users to be self-reliant and lead an active social life. However, realizing the barrier-free concept is very expensive and complex through infrastructure improvements alone. Therefore, we have developed some biped locomotors, WL-15 (Waseda Leg - No. 15) and WL-16 which have 6-DOF parallel mechanism legs [1-3] (Fig. 1). This robot consists of two legs and a waist and is capable of walking independently with an unladen weight of 75 kg. Using this robot, we studied the way to apply the biped robot to a mobile base. In November 2003, using WL-16, we realized the world's first of a dynamic biped walking while carrying a human.

The final goal of this research is to build a biped wheelchair having locomotion and mobility equivalent to a human being. We believe that a biped wheelchair is a viable solution in barrier-free engineering that is much more effective and low-cost than infrastructure improvements.

To realize our final goal, it is necessary to improve the loading performance such as maximum loading capacity, energy consumption and robustness against environmental disturbances. It is also necessary to improve environmental adaptability to walk stably in various environments such as gravel road, sandy road, sloping road, and so on.

There are many previous works on real-time stability control methods on uneven terrain [4-9]. Most of them are required to measure the ZMP (Zero Moment Point [10]), the attitude and the acceleration of the upper body of a biped robot, and so on. When a biped humanoid robot steps on uneven portions of the ground, the position, the orientation and the acceleration of its upper body are rapidly changed. Therefore, by sensing these rapid changes, a highly accurate acceleration control is operated based on the mechanics model of the robot [4-7]. These control methods will be effective to cope with uneven terrain if the robot is modelled accurately. However, it is difficult to apply such control methods to human-carrying biped robots due to modelling errors. Also, techniques modifying the landing pattern of a foot before the foot touches uneven terrain are proposed [8, 9].

Fig. 1. Waseda Leg - No.16 Refined V (WL-16RV).

This study was conducted as part of the Advanced Research Institute for Science and Engineering, Waseda University, and as part of the humanoid project at the Humanoid Robotics Institute, Waseda University. It was also supported in part by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B) 19760179, 2007, and by TMSUK Co., Ltd., HEPHAIST Seiko Co., Ltd., and SolidWorks Japan K.K., whom we thank for their financial and technical support.

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978-1-4244-3804-4/09/$25.00 ©2009 IEEE

However, these techniques are required to install sensors or special mechanisms that can detect the ground surface.

There are also many works using external sensors such as an optical imaging system, a laser range finder, a CCD camera and so on to detect obstacles or road surface profiles [11-13]. However, the measurement error is at least 1% of the measurement distance, and a biped robot equipped with external sensors should have the ability to adapt to unknown unevenness with 20 mm height, considering the distance between the mounting location of an external sensor and a ground. Therefore, we set the target unevenness at 20 mm.

In the previous report [2], we proposed a landing pattern modification method not using any other sensor information except force sensor's information. But it has a problem that a foot landing-impact increases when a walking cycle is short. It is difficult to achieve a good balance between a terrain adaptation and a landing-impact force reduction on uneven terrain.

In this paper, we propose a new terrain-adaptive control reducing a landing-impact force. To increase a concave terrain adaptation, we set a target landing position beneath a reference level. To reduce a landing-impact force, we change the position gain control value to a small value at a swing phase. After detecting a foot-landing on a ground, a virtual spring is installed to the vertical direction to follow uneven terrain, and a virtual compliance control is applied to the roll and pitch axes.

This paper is organized as follows. Section II describes the details of a terrain-adaptive control with small landing-impact force, and section III shows experimental results. Section IV provides conclusions and future work.

II. Terrain-Adaptive Control with Small Landing-Impact Force

Our biped locomotors are controlled by a model-based control algorithm for dynamic walking [1]. However, since a walking pattern is previously generated offline, it makes the robot unstable when the foot lands on terrain. Also, dynamic walking is difficult to be achieved due to the unevenness of terrain and the modeling errors caused by a human riding on the robot. In this research, we aim to develop a terrain-adaptive control capable of reducing impact forces between the foot and the uneven terrain. This control method consists of the following three key points:

- Foot level modification
- Terrain-adaptive motion along the vertical axis and about the roll and pitch axes
- Returning motion to a reference walking pattern at every step

A. Foot Level Modification

Considering a vertical direction, uneven terrain can be classified into a convex surface and a concave surface. When a robot walks on uneven terrain, a convex surface can be detected earlier than a concave surface. So, it is easier to follow a convex surface than a concave surface with existing stability controls [4-7]. The time when a foot landing position can be detected as a concave surface is the just before the end of a swing phase. To adapt to a concave surface in a very few moments left, the foot speed should be increased downward. The previous landing pattern modification method [2] had a problem that it was difficult to achieve a balance between a terrain adaptation and a landing-impact force reduction especially on a concave surface. As a walking speed goes up, a landing-impact force becomes large as shown in Fig. 2. With the previous method, it was difficult to realize shorter walking cycle than 2.0 s/step due to large impact forces.

So, we devised a new foot level modification method to deal with not only a convex terrain but also a concave terrain. We set a target landing position beneath a reference level as shown in Fig. 3 to adapt to a concave surface in the last half of a foot-swing phase. A foot level displacement $H_{fed}(t)$ is added to a preset walking pattern and calculated by using a quintic polynomial as follows:

$$H_{fed}(t)=\begin{cases} L_{fed}\cdot\dfrac{6t^5-15t^3T_{lhsp}^2+10t^2T_{lhsp}^3-T_{lhsp}^5}{T_{lhsp}^5} & \text{(the last half of a swing phase)} \\ 0 & \text{(others)} \end{cases} \quad (1)$$

where L_{fed} is the target landing position, and T_{lhsp} is the total time of the last half of a foot-swing phase. In this research, we set L_{fed} as 20 mm.

This enables the foot to reach a concave surface up to the setting value of L_{fed}, and all terrains including a reference level can be considered as a convex surface. So, a

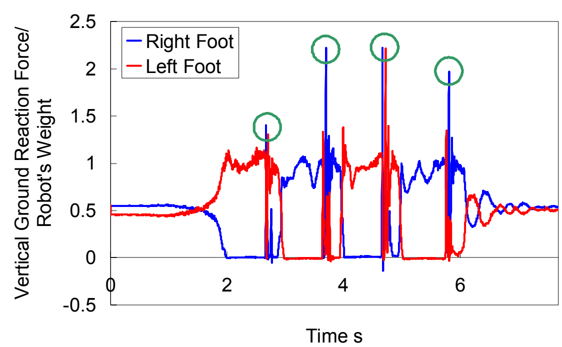

Fig. 2. Landing-impact force while walking on flat surface with the previous landing pattern modification method. The walking cycle is 1.0 s/step with a step length of 100 mm/step.

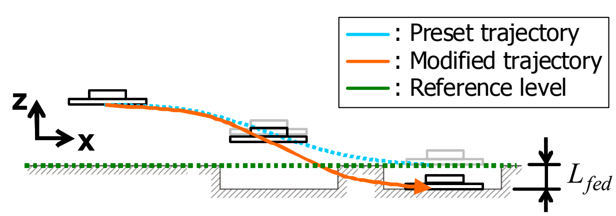

Fig. 3. Foot adaptation to concave surface with new terrain-adaptive control.

terrain-adaptive motion just has to deal with only a convex surface.

To realize a terrain-adaptive motion, we must devise the way how to detect a foot-landing to modify a foot position along the vertical direction and how to realize an adaptive motion about the roll and pitch axes. Each technique is described later.

B. Terrain-Adaptive Motion

A terrain-adaptive motion can be classified into two parts: one is the modification along the vertical axis and the other is about the roll and pitch axes.

1) Along the Vertical Axis: The terrain-adaptive motion along the vertical axis consists of the following three key points:

- Changing a position gain value for motor drivers
- Impact force reduction considering the leg mechanism of the biped vehicle, WL-16RV
- Foot speed control after detecting a foot-landing

Most stability controls on uneven terrain [4-7] are feedback approaches by using the data measured by force sensor, acceleration sensor and so on, and it is difficult to reduce the landing-impact force at the moment when a foot contacts the ground. In such cases, we should introduce not only a feedback approach but also a feedforward approach.

In this research, we realized a high compliance of the landing foot by actively decreasing a position gain value for motor drivers in a swing phase. Changing a position gain value is a feedforward approach, and a foot landing-impact force is reduced by a large position following error.

However, it is difficult to realize a precise positioning control with a low position gain, and a walking robot becomes unstable in a stance phase. So we change back to a high position gain value after detecting a foot landing on a ground.

On the other hand, the leg mechanism of WL-16RV consists of a parallel linkage mechanism called the Stewart Platform (see Fig. 4). Because it has a higher stiffness compared with a serial linkage mechanism, it is not sufficient to obtain a high compliance of the landing-foot only by changing a position gain value as mentioned above. Therefore, we realized a larger position following error by raising the foot's edge of the traveling direction and concentrating a landing-impact force to an actuator nearest to a contact area as shown in Fig. 5. As a result, we could obtain a higher compliance against ground reaction forces.

After detecting a foot-landing on a ground, the foot speed is changed to zero under the law of conservation of momentum. To detect a foot-landing on a ground, we focus attention on the force data measured by a 6-axis force/torque sensor mounted on a foot. A foot-landing is detected by measuring the rapid changes of the differential value of the force data along the vertical axis. The advantage to use the differential value is an ignorable sensor drift and a fast landing detection.

2) About the Roll and Pitch Axes: A landing-impact force can be reduced only by the above-mentioned method. However, the adaptive motion about the roll and pitch axes is not completed because the foot speed is changed to zero and

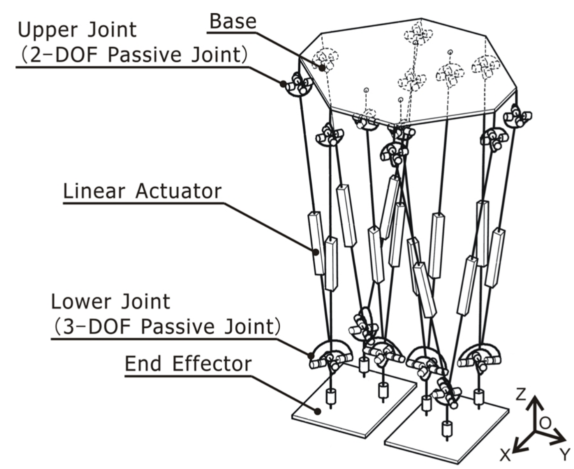

Fig. 4. DOF configuration of WL-16RV.

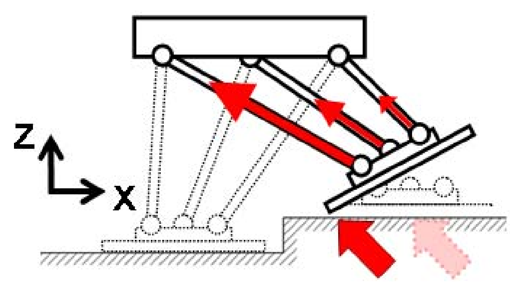

Fig. 5. Impact force reduction considering the leg's mechanism of WL-16RV.

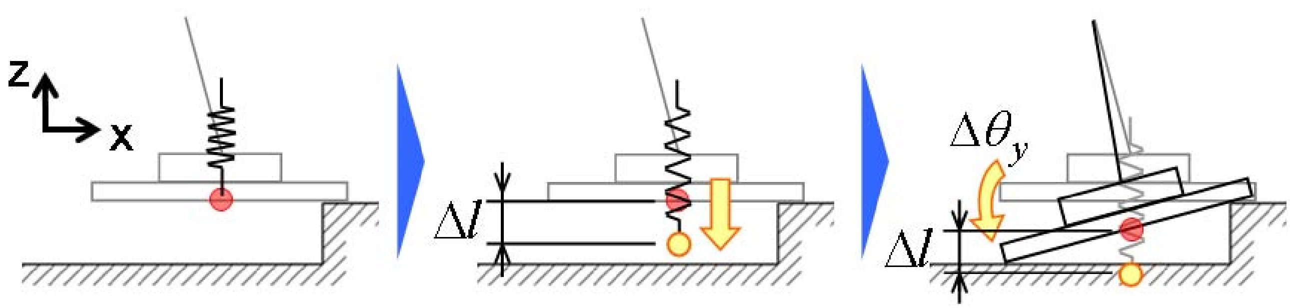

Fig. 6. Adaptive motion about the roll and pitch axes. A virtual spring extended from the natural length is installed to the vertical axis after detecting a foot-landing on a ground. A virtual compliance control is applied to the roll and pitch axes to follow uneven terrain.

the foot level is fixed after detecting a foot-landing on a ground. Therefore, to realize a terrain-adaptive motion, we firstly installed a virtual spring to the vertical axis of a robot's feet after detecting a foot-landing on a ground (see Fig. 6). The last term of (2) denotes a virtual spring extended from the natural length.

$$\Delta z_{cc}(t) = \left[K_{z1} + \frac{C_{z1}}{\Delta t} \right]^{-1} \cdot \left\{ F_z + C_{z1} \frac{\Delta z_{cc}(t-\Delta t)}{\Delta t} + K_{z2} \cdot \Delta l \right\} \tag{2}$$

where $\Delta z_{cc}(t)$ is the present compliance displacement of the foot coordinate origin along the vertical axis. $\Delta z_{cc}(t-\Delta t)$ is the compliance displacement of the foot coordinate origin along the vertical axis before one control cycle. Δt is the control cycle of 1 ms. F_z is the ground reaction force of the vertical direction. $K_{z1} = 1\,\mathrm{N/mm}$ and $C_{z1} = 3\,\mathrm{Ns/mm}$ are the virtual stiffness and damping coefficients respectively. $K_{z2} = 14\,\mathrm{N/mm}$ is the virtual stiffness coefficient, and $\Delta l = 10\,\mathrm{mm}$ is the extended length of a virtual spring.

As a result, the virtual compliance control expressed in (2) presses a swing foot toward the ground at a constant load. By utilizing the moment generated by the pressing load, we applied a virtual compliance control to the roll and pitch axes of a robot's feet, and a terrain-adaptive motion is realized as shown in Fig. 6. The stiffness and damping coefficients are set as small as possible for the feet not to vibrate and not to generate a large reaction force. The compliance displacement is calculated as follows:

$$\Delta \boldsymbol{\theta}_{cc}(t) = \left[\mathbf{K}_\theta + \frac{\mathbf{C}_\theta}{\Delta t} \right]^{-1} \cdot \left\{ \mathbf{F}_\theta + \mathbf{C}_\theta \frac{\Delta \boldsymbol{\theta}_{cc}(t-\Delta t)}{\Delta t} \right\} \tag{3}$$

where $\Delta \boldsymbol{\theta}_{cc}(t) = \left[\Delta\theta_{xcc}(t), \Delta\theta_{ycc}(t) \right]^T$ is the present compliance displacements of the foot coordinate origin about the roll and pitch axes respectively. $\mathbf{K}_\theta = \left[K_{\theta x}, K_{\theta y} \right]^T$ and $\mathbf{C}_\theta = \left[C_{\theta x}, C_{\theta y} \right]^T$ are the virtual stiffness and damping coefficients about the roll and pitch axes respectively. $K_{\theta x} = K_{\theta y} = 1\,\mathrm{Nm/rad}$ and $C_{\theta x} = C_{\theta y} = 30\,\mathrm{Nms/rad}$. $\mathbf{F}_\theta = \left[F_{\theta x}, F_{\theta y} \right]^T$ is the ground reaction force of the roll and the pitch direction.

By adding these modification displacements to the preset foot position, the foot can follow uneven terrain. After the walking pattern is modified, the modified foot motions along the vertical axis and about the roll and pitch axes are expressed as follows:

$$\begin{aligned}
\bar{z}_{final}(t) &= \begin{cases} \bar{z}_{pat}(t) - H_{fed}(t) & \text{(before detecting foot-landing)} \\ \bar{z}_{pat}(t') - H_{fed}(t') + \Delta z_{cc}(t) & \text{(after detecting foot-landing)} \end{cases} \\
\boldsymbol{\theta}_{final}(t) &= \begin{cases} \boldsymbol{\theta}_{pat}(t) & \text{(before detecting foot-landing)} \\ \boldsymbol{\theta}_{pat}(t') + \Delta\boldsymbol{\theta}_{cc}(t) & \text{(after detecting foot-landing)} \end{cases}
\end{aligned} \tag{4}$$

where $\bar{z}_{final}(t)$ is a modified foot motion along the vertical axis. $\bar{z}_{pat}(t)$ is a height of the foot in a reference walking pattern. t' is the time when detecting a foot-landing on a ground. $\boldsymbol{\theta}_{final}(t) = \left[\theta_{xfinal}(t), \theta_{yfinal}(t) \right]^T$ is the modified foot orientation about the roll and pitch axes. $\boldsymbol{\theta}_{pat}(t)$ is the preset foot orientation about the roll an pitch axes.

The reference lengths of the links are calculated by inverse kinematics, using (4). They are commanded to each joint by the position control.

C. Returning Motion to a Reference Walking Pattern at Every Step

The terrain-adaptive motion mentioned above is operated in the last half of a swing phase. The modification displacement of the vertical direction is kept during the double support phase, and the foot motion along the z axis returns to the reference walking pattern during the first half of a stance phase. A fifth-order function was adopted to generate the returning motion, $z_{return}(t)$.

$$z_{return}(t) = at^5 + bt^4 + ct^3 + dt^2 + et + f \tag{5}$$

To calculate fifth-order function coefficients, boundary conditions are given as follows:

$$\begin{aligned}
&z_{return}(0) = Z_{modif},\ z'_{return}(0) = 0,\ z''_{return}(0) = 0, \\
&z_{return}(T_{fhsp}) = 0,\ z'_{return}(T_{fhsp}) = 0,\ z''_{return}(T_{fhsp}) = 0
\end{aligned} \tag{6}$$

where Z_{modif} is the modified value along the vertical axis in the last half of a swing phase. T_{fhsp} is the total time of the first half of a stance phase.

Coefficients are obtained, and the returning motion is expressed as follows:

$$z_{return}(t) = -Z_{modif} \cdot \frac{6t^5 - 15t^4 T_{fhsp} + 10t^3 T_{fhsp}^2 - T_{fhsp}^5}{T_{fhsp}^5} \tag{7}$$

The roll and pitch compliance displacement obtained in the end of a swing phase is held during the stance phase, and the roll and pitch foot motion returns to the reference walking pattern in the first half of a swing phase.

The outline of the new terrain-adaptive control is shown in Fig. 7.

III. Experimental Tests and Consideration

We conducted an evaluation experiment to verify the effectiveness of the new terrain-adaptive control. An acrylic board with thickness of 20 mm was placed on a flat floor, and a surface with dummy unevenness was created. The human-carrying biped walking robot, WL-16RV [3] stepped on the 20 mm board along the vertical axis at the third step (Fig. 8). In this experiment, a human weighing 65 kg rode on the robot, and the walking cycle was 1.0 s/step with a step length of 200 mm/step.

When a walking cycle was short as 1.0 s/step, the robot could not walk on even a flat surface with the previous landing pattern modification method due to the large landing-impact force. However, with the new terrain-adaptive control, WL-16RV realized a stable walk on uneven terrain. The landing-impact force was also small as shown in Fig. 9. Also, the noise generated by the landing-impact was reduced from 85 dB to 75 dB by using the new control, and we succeeded in reducing the noise by 10 dB.

Secondly, we placed several acrylic boards whose maximum thickness was 20 mm so that a large support polygon can be formed between a robot's feet and the ground in a single support phase as shown in Fig. 10. If a robot steps on uneven terrain at the center of the foot, the support polygon becomes small and it is difficult to maintain the robot's stability only by the proposed control. Then, the walking cycle was 1.0 s/step, and the step length was 200 mm/step. The measured ZMP followed the reference ZMP,

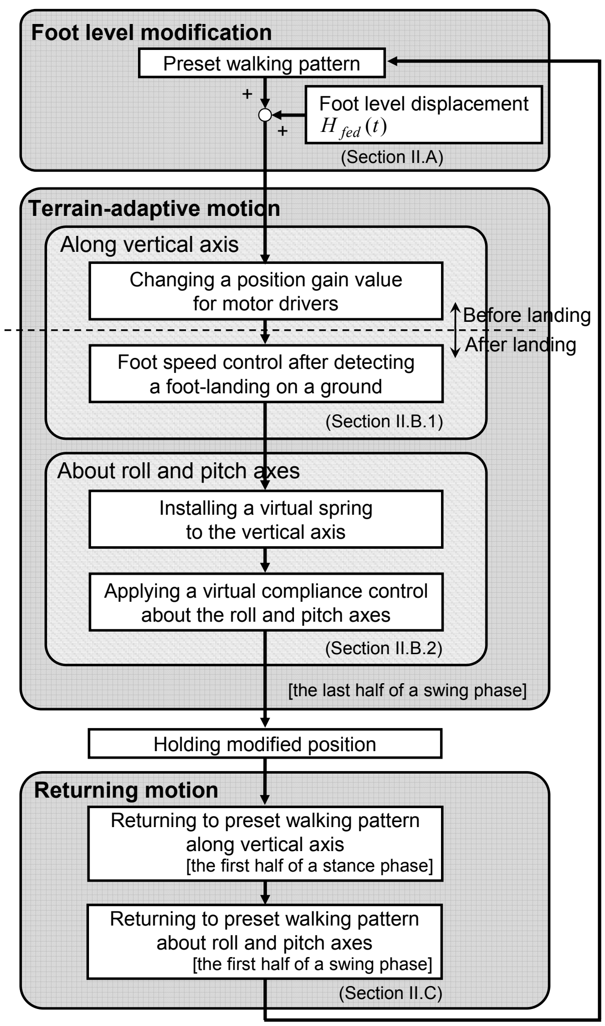

Fig. 7. Outline of the new terrain-adaptive control with small landing impact force.

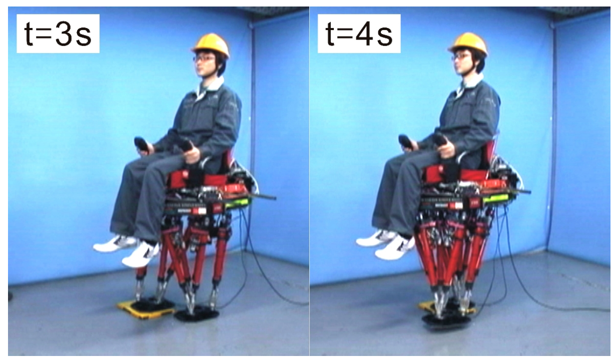

Fig. 8. Walking experiment, stepping on a 20 mm board along the vertical axis. The walking cycle is 1.0 s/step with a step length of 200 mm/step.

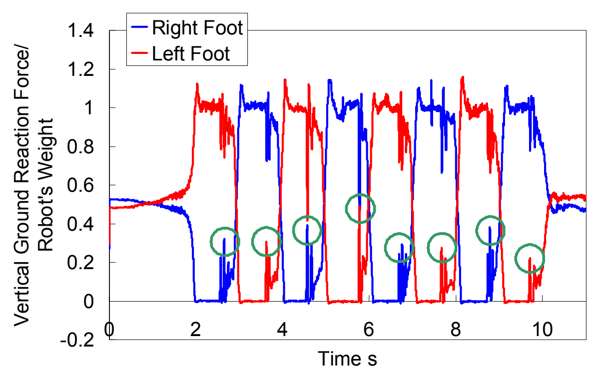

Fig. 9. Foot landing-impact forces with new terrain-adaptive control while stepping a 20 mm board along the vertical axis.

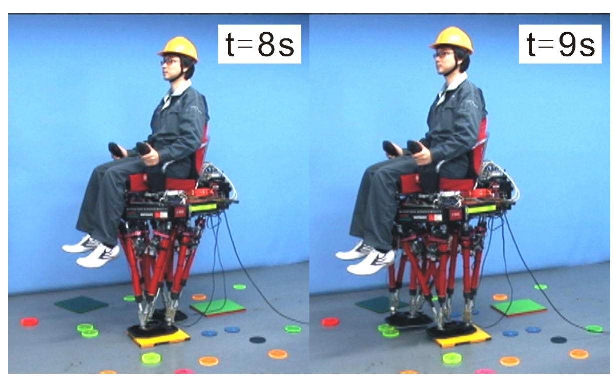

Fig. 10. Walking experiment on uneven terrain. The maximum height of the boards is 20 mm. The walking cycle is 1.0 s/step with a step length of 200 mm/step.

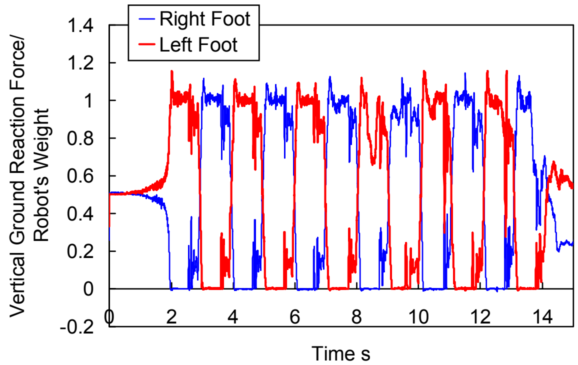

Fig. 11. Foot landing-impact forces while walking on uneven terrain.

Fig. 12. Walking experiment outdoors with 7 degrees inclination. The walking cycle is 2.0 s/step with a step length of 200 mm/step.

and stable walking was achieved with small landing impact force as shown in Fig. 11.

Finally, we did a human-carrying walking experiment outdoors. The walking experiment was conducted to walk down the slope with about 7 degrees inclination. If the walking cycle is 1.0 s/step, the robot's feet cannot follow the high inclination due to the motor's response speed. Therefore, the walking cycle in this experiment was 2.0 s/step with a step length of 200 mm/step, and a stable walk was achieved without falling as shown in Fig. 12.

We confirmed the effectiveness of the proposed method through these experiments.

IV. Conclusions and Future Work

We have developed a new terrain-adaptive control that can reduce a landing-impact force that arose between a foot and the ground. To increase a concave terrain adaptation, we set a target landing position beneath a reference level. To reduce the landing-impact force, we change the position gain value for motor drivers to a small value at a swing phase. Moreover, we set landing-foot speed at zero when the foot landing is detected by the force sensor mounted on a foot. After detecting a foot-landing on a ground, a virtual spring extended from the natural length is installed to the vertical axis, and a virtual compliance control is applied to the roll and pitch axes to follow uneven terrain.

By applying the new terrain-adaptive control to the human-carrying biped walking robot, WL-16RV, a stable dynamic walk was realized on uneven terrain with small landing-impact force. The impact force was reduced to 400 N that is 35 % of the total weight including the robot and the rider. Moreover, the noise generated by the landing-impact was reduced by 10 dB. The effectiveness of this control was confirmed through many walking experiments.

However, the developed terrain-adaptive control cannot be applied to soft and deformable surface such as a sandy beach, a dirt road, a snowy road and so on. Our next goal is to develop a walking technology adaptable to soft and deformable surface and conduct further walking experiments carrying a human in real environments. Moreover, to realize a multi-purpose bipedal locomotor sufficient for practical use, we will also continue to study more intelligent walking control methods that can adapt to various environments.

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