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Avoidance Behavior from External Forces for Biped Vehicle

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Abstract—**This paper describes an avoidance behavior from unknown external forces for a biped walking vehicle. To distinguish between external forces from passenger and those from environments, we use the data of a force sensor mounted on foot, and external forces are estimated from ZMP errors. To guarantee a walking stability, the waist position is adjusted to match the measured ZMP to the reference ZMP, and the position of landing foot is adjusted so that the waist trajectory does not diverge. By implementing the developed method on the human-carrying biped robot, the robot realized a stable walk under unknown external forces from environments. When pushing the robot stepping, the robot moved backward and moved away from the generation source of external forces about 400 mm. When pushing the robot walking forward, the robot stopped going forward and prevented from coming closer to the generation source of external forces. We confirmed the effectiveness of the proposed control through these experiments.**

I. INTRODUCTION

NUNBER of elderly and disabled wheelchair users is going to strongly increase in a near future. Based on this statement, recently, there have been more and more attempts to implement a "barrier-free" design concept for the human environment. However, the achievement of the barrier-free concept is very expensive and complex to achieve through infrastructure improvements. Therefore, we have developed a biped robot that can let a human overcome the typical barriers within the human environment [1-4]. In particular, in November 2003, WL-16 (Waseda Leg - No. 16) has achieved the world first dynamic walking while carrying an adult human. The latest version of this biped robot is currently WL-16RV which has 6-DOF parallel mechanism legs [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.

The final goal of this research is to build a biped walking wheelchair having locomotion and mobility equivalent to a human being. The authors believe that a biped walking wheelchair can be "a solution for barrier-free engineering methodology" that will be much more effective and low-cost than improving infrastructure.

Other researches on walking robots have been carried out for practical use, including locomotion modules that can carry a human such as the "Walking Chair" [5], "i-foot" developed by Toyota Motor Corporation [6], and "HUBO FX-1" developed by KAIST [7]. Through limited information about "i-foot", the unladen weight is revealed at 200 kg, although the payload is 60 kg. As for "HUBO FX-1", the robot's weight is 150 kg, although the payload is 100 kg. They are too heavy for a human-living environment.

To realize our final goal, it is necessary to improve environmental adaptability to walk stably on uneven terrain such as gravel road, sloping road, and so on. It is also necessary to improve the loading performance such as maximum loading capacity, energy consumption and robustness against environmental disturbances. For the practical application of a biped walking wheelchair, the biped walking vehicle must compensate for the external forces from environments.

There are many previous works on disturbance compensation control under unknown external forces [8-13]. However, there are few researches on stabilization against external forces which act on a human-carrying biped walking

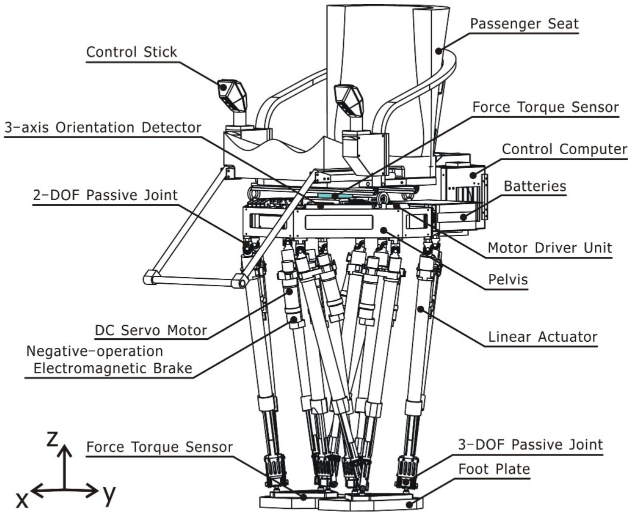

Fig. 1. Mechanism and sensors equipped with WL-16RV (Waseda Leg - No.16 Refined V).

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robot. Such disturbances can be divided into two categories. One is disturbances from a passenger and the other is disturbances from environments. When compensating for disturbances caused by a passenger, a robot should not deviate from the passenger's chosen direction. When dealing with disturbances from environments, a robot can reduce external forces by moving away from obstacles by allowing the robot to deviate from the passenger's chosen direction. To compensate for a passenger's motion, we have already proposed a disturbance compensation control [4]. To measure forces and moments caused by a passenger, we used a force sensor placed between a passenger's seat and a robot's waist. However, this compensation control cannot deal with external forces which act on lower limbs, because the force sensor placed under the passenger's seat cannot detect such external forces.

In this paper, we propose a new stabilization control against unknown disturbances from outside of system for a human-carrying biped walking robot. A robot can reduce external forces by stepping away from obstacles or making an avoidance behavior in the pushed direction by a human. To distinguish between external forces from passenger and those from environments, we use the data of a force sensor mounted on foot to generate an avoidance behavior.

There are also researches on avoiding collision with obstacles and planning a robot's path by using vision sensors [14-16]. However, sometimes collision with obstacles cannot be avoided by only vision sensors. The proposal is a disturbance avoidance control from environments when hitting obstacles or pushed by a human.

This paper is organized as follows. Section II describes the details of avoidance behavior from external forces from the outside of system, and section III shows the walking simulation results. In section IV, experimental results are shown. Section V provides conclusions and future work.

II. AVOIDANCE BEHAVIOR FROM EXTERNAL FORCES

Our biped locomotors are controlled by a model-based control algorithm for dynamic walking. However, since a walking pattern is previously generated offline, it makes the robot unstable when external force acts on it. In this research, we aim to develop a new avoidance behavior from external forces from environments. So, we developed a new avoidance behavior control to prevent a robot from falling by generating a compensation trajectory around a reference ZMP (Zero Moment Point [17]) when external forces act on the robot. This avoidance behavior consists of the following five key points:

- Estimation of external forces
- Waist trajectory computation
- Foot-landing point variation computation
- ZMP variation computation
- Foot trajectory computation

A. Estimation of External Forces

To distinguish between external forces from passenger and those from environments, we use the data of a force sensor mounted on foot and estimate external forces. By using the following equation, ZMP errors can be converted into external forces which act on the center of mass on a robot's waist. Then, one particle model is used as shown in Fig. 2.

$$\mathbf{F}_{ex} = \frac{m_w g}{h_c}(\mathbf{x} - \mathbf{x}_{vzmp}) \tag{1}$$

where $\mathbf{F}_{ex} = \left[F_x, F_y, F_z\right]^T$ is the estimated external force which acts on a robot. m_w is the total mass including the passenger's weight. g is the gravitational acceleration. h_c is the height of the center of mass. $\mathbf{x}_{vzmp} = \left[x_{vzmp}, y_{vzmp}, z_{vzmp}\right]^T$ is the position vector of varied reference ZMP.

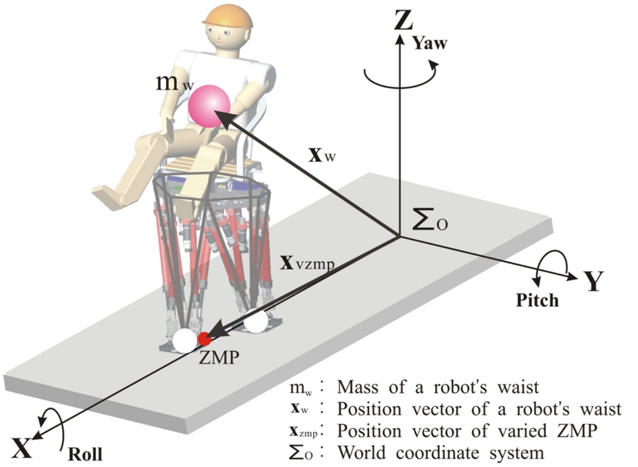

Fig. 2. Approximate model (one-particle), and definition of coordinate system and vectors.

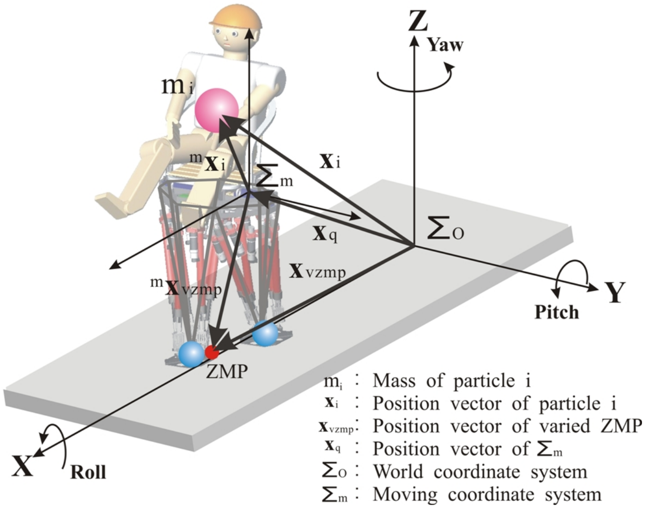

Fig. 3. Approximate model that has one particle for the waist including a passenger and two particles for the feet.

B. Waist Trajectory Computation

When unknown external force acts on a biped robot, first the robot accelerates the waist so that a measured ZMP is equal to a reference ZMP. To compute the waist trajectory, we define the biped walking robot system as an approximation model that has one particle for the waist including a passenger and two particles for the feet as shown in Fig. 3. The moment balance around ZMP can be expressed as follows:

$$\begin{aligned}&\sum_{i}^{All\ Particles} m_i\left(\mathbf{x}_i-\mathbf{x}_{vzmp}\right)\times\left(\ddot{\mathbf{x}}_i+\mathbf{G}\right)\\ &\quad-\left(\mathbf{x}_s-\mathbf{x}_{vzmp}\right)\times\mathbf{F}_{ex}+\mathbf{T}_0=\mathbf{0}\end{aligned} \tag{2}$$

where m_i is the mass of particle i. $\mathbf{x}_i=\left[x_i, y_i, z_i\right]^T$ is the position vector of particle i. $\mathbf{x}_{vzmp}=\left[x_{vzmp}, y_{vzmp}, z_{vzmp}\right]^T$ is the position vector of varied reference ZMP. $\mathbf{G}=\left[0,0,g_z\right]^T$ is the gravitational acceleration. $\mathbf{x}_s=\left[x_s, y_s, z_s\right]^T$ is the position vector of a force sensor placed on waist. $\mathbf{F}_{ex}=\left[F_x, F_y, F_z\right]^T$ is the estimated external force from ZMP errors. $\mathbf{T}_0=\left[0,0,T_z\right]^T$ is the total torque acts on varied reference ZMP.

To consider the relative motion of each part, a moving coordinate $\sum_m$ is established on the waist of the robot parallel to the fixed coordinate $\sum_O$. $\mathbf{x}_q=\left[x_q, y_q, z_q\right]^T$ is the position vector of the origin of $\sum_m$ from the origin of $\sum_O$. Using the moving coordinate frame, equation (2) can be modified as follows:

$$\begin{aligned}&\sum_{i}^{All\ Particles} m_i\left({}^m\mathbf{x}_i-{}^m\mathbf{x}_{vzmp}\right)\times\left({}^m\ddot{\mathbf{x}}_i+\ddot{\mathbf{x}}_q+{}^m\mathbf{G}\right)\\ &\quad-\left({}^m\mathbf{x}_s-{}^m\mathbf{x}_{vzmp}\right)\times{}^m\mathbf{F}_{ex}+{}^m\mathbf{T}_0=\mathbf{0}\end{aligned} \tag{3}$$

Assuming that a moving coordinate does not rotate and the waist does not move vertically, this equation is expanded into the following equation by putting the term representing the waist acceleration on the left-hand side and the rest are on the right-hand side.

$$\begin{aligned}{}^m\ddot{x}_w&=-\ddot{x}_q+\frac{1}{B}\left\{m_w\left({}^m x_w-{}^m x_{vzmp}\right){}^m g_z-\Phi_{foot\_y}+\Phi_{ex\_y}\right\}\\ B&=m_w\left({}^m z_w-{}^m z_{vzmp}\right)\\ \Phi_{foot\_y}&=\sum_{i}^{All\ Foot} m_i\{({}^m z_i-{}^m z_{vzmp})({}^m\ddot{x}_i+\ddot{x}_q)\\ &\qquad-({}^m x_i-{}^m x_{vzmp}){}^m g_z\}\\ \Phi_{ex\_y}&=\left({}^m z_s-{}^m z_{vzmp}\right){}^m F_x-\left({}^m x_s-{}^m x_{vzmp}\right){}^m F_z\end{aligned} \tag{4}$$

where Φ_{foot_y} is the moment generated by the feet particles when following the varied reference ZMP, and Φ_{ex_y} is the moment generated by disturbances when following the varied reference ZMP. As for the y axis, we solve in the same way on the x axis. Therefore, we omit the method of solution for the y axis.

Using the Runge-Kutta method, the waist motion at next control loop is computed. However, as for the initial value problem, the solved trajectories do not converge. So, it is possible to inhibit the divergence of the waist trajectory by changing a foot-landing point and varying a reference ZMP trajectory inside a support polygon.

C. Foot-Landing Point Variation Computation

The divergence of the waist trajectory can be inhibited by changing a foot-landing point. To compute the landing point variation, we use a one particle model for the waist as shown in Fig. 2. Then, the mass of the legs are assumed to be 0. The moment balance around a varied reference ZMP can be expressed as follows:

$$\begin{aligned}&m_w\left({}^m z_w-{}^m z_{vzmp}\right)\left({}^m\ddot{x}_w+\ddot{x}_q\right)\\ &\quad-m_w\left({}^m x_w-{}^m x_{vzmp}\right){}^m g_z=0\end{aligned} \tag{5}$$

The deviation from the preset trajectory of the waist is ${}^m\Delta x_w$ and the changing value of the ZMP is ${}^m\Delta x_{zmp}$. Then, we obtain the differential equation on the deviation.

$$\begin{aligned}&m_w\left({}^m z_w-{}^m z_{vzmp}\right){}^m\Delta\ddot{x}_w\\ &\quad-m_w\left({}^m\Delta x_w-{}^m\Delta x_{vzmp}\right){}^m g_z=0\end{aligned} \tag{6}$$

The solution of (6) is described as follow:

$$\begin{aligned}{}^m\Delta x_w&=\frac{A\left(X_0-R_{p0}\right)+\dot{X}_0}{2A}e^{At}+\frac{A\left(X_0-R_{p0}\right)-\dot{X}_0}{2A}e^{-At}+R_{p0}\\ {}^m\Delta\dot{x}_w&=\frac{A\left(X_0-R_{p0}\right)+\dot{X}_0}{2}e^{At}-\frac{A\left(X_0-R_{p0}\right)-\dot{X}_0}{2}e^{-At}\\ A^2&=\frac{{}^m g_z}{{}^m z_w-{}^m z_{vzmp}},\ X_0={}^m\Delta x_w\Big|_{t=t_0},\\ \dot{X}_0&={}^m\Delta\dot{x}_w\Big|_{t=t_0},\ R_{p0}={}^m\Delta x_{vzmp}\Big|_{t=t_0}\end{aligned} \tag{7}$$

Equation (7) expresses deviations ${}^m\Delta x_w$ and ${}^m\Delta\dot{x}_w$ past t seconds after a certain time when deviations X_0 and $\dot{X}_0$ are given as initial values. By solving the boundary value problem to make the deviation of velocity on the second step equal to 0, we can compute the changing value of the ZMP for the first step.

Now, when the deviation of the waist is X_{t_0} and $\dot{X}_{t_0}$ $(t = t_0)$, the deviation on the first step and second step, namely X_T and X_{2T} are described as follows:

$$X_T = \frac{A\left(X_{t_0} - R_{p0}\right) + \dot{X}_{t_0}}{2A} e^{A(T-t_0)} + \frac{A\left(X_{t_0} - R_{p0}\right) - \dot{X}_{t_0}}{2A} e^{-A(T-t_0)} + R_{p0}$$

$$\dot{X}_T = \frac{A\left(X_{t_0} - R_{p0}\right) + \dot{X}_{t_0}}{2} e^{A(T-t_0)} - \frac{A\left(X_{t_0} - R_{p0}\right) - \dot{X}_{t_0}}{2} e^{-A(T-t_0)} \tag{8}$$

$$X_{2T} = \frac{A\left(X_T - R_{p1}\right) + \dot{X}_T}{2A} e^{AT} + \frac{A\left(X_T - R_{p1}\right) - \dot{X}_T}{2A} e^{-AT} + R_{p1}$$

$$\dot{X}_{2T} = \frac{A\left(X_T - R_{p1}\right) + \dot{X}_T}{2} e^{AT} - \frac{A\left(X_T - R_{p1}\right) - \dot{X}_T}{2} e^{-AT} \tag{9}$$

T is the time spent for one stepping motion, which is the same as half the time of one walking period. R_{p0} and R_{p1} means the changing value of the ZMP between $t = t_0$ and $t = T$, and between $t = T$ and $t = 2T$. However, R_{p0}, the changing value of 0 step before the first stepping motion starts is 0, because the foot of the supporting leg is still on the ground.

By computing R_{p1} so that the deviation of the waist's velocity on the second step, namely $\dot{X}_{2T}$ is equal to 0, we obtain the changing value of the ZMP for the first step, which is the target foot-landing points of the swing leg.

D. ZMP Variation Computation

Reference ZMP is changed by multiplying a proportional gain by the deviation between a reference and an actual waist trajectory. By generating a compensation trajectory around a varied reference ZMP, the divergence of a waist motion can be delayed and inhibited. However, the reference ZMP, x_{pzmp}, is planned near the center of a support polygon, and a large ZMP modification makes a robot unstable due to the foot plate's deflection and so on. In this research, we limit the ZMP modification value to 40 mm along the x axis and 30 mm along the y axis. The limitation number was determined through basic experiments. When generating an avoidance behavior from external forces, a waist position is moved from an initial position. So, the deviation of the waist position, ${}^m x_{offset}$, is considered as follows:

$$\begin{aligned} {}^m\Delta x_{zmp} &= K_p\left({}^m\Delta x_w - {}^m x_{offset}\right) + K_v\, {}^m\Delta\dot{x}_w \\ {}^m x_{vzmp} &= {}^m x_{pzmp} + {}^m\Delta x_{zmp} \end{aligned} \tag{10}$$

E. Foot Trajectory Computation

According to the computation of the foot-landing point, foot trajectory is finally generated. The foot trajectory along the vertical axis adopts the reference walking pattern, and a quintic polynomial is adopted to generate the feet trajectory along the x and y axes.

III. WALKING SIMULATIONS

On the basis of the control method, we developed a simulation program to confirm the basic function of the avoidance behavior from external forces from environments, and we examined its effect by changing various parameters such as force strength, its acting time width and so on.

Fig. 4 shows one example of walking simulations. In this simulation, an external force is rectangular, and the forth strength is 80 N and its acting time width is 0.3 seconds. External forces act on a robot's waist forward, rightward and

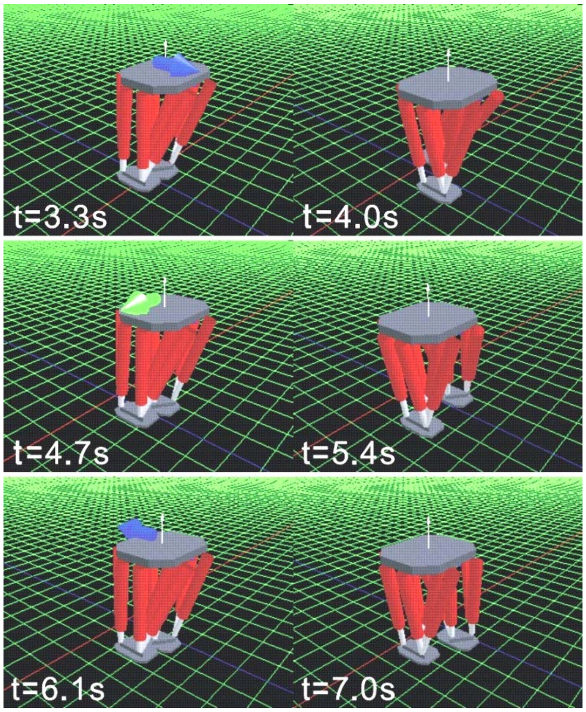

Fig. 4. Walking simulation under unknown external forces from environments while the robot steps. The walking cycle is 1.0 s/step.

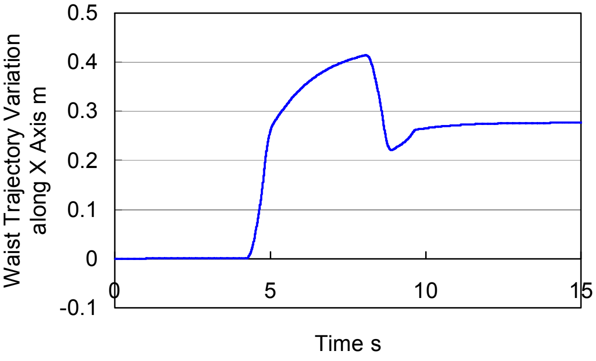

Fig. 5. Waist trajectory variation along the x axis.

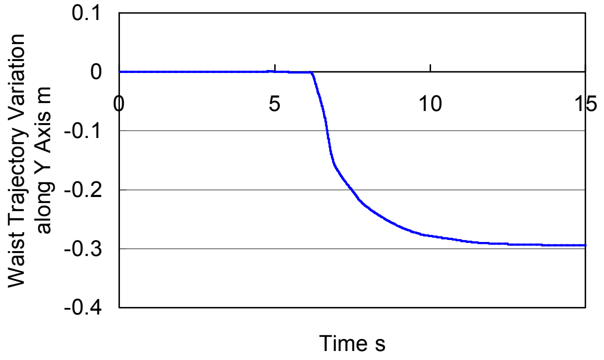

Fig. 6. Waist trajectory variation along the y axis.

backward at the first step, the third step and the fifth step respectively while the robot is stepping with the walking cycle of 1.0 s/step. Figs. 5 and 6 show the waist trajectory variation along the x axis and y axis.

Through the walking simulation, the basic effectiveness of the developed disturbance compensation control was confirmed.

IV. EXPERIMENTAL TESTS AND CONSIDERATION

We implemented the developed method on the human-carrying biped walking robot, WL-16RV (Fig. 1) and conducted some walking experiments under unknown external force from environments. First, we conducted a walking experiment as a human pushed the robot's waist to confirm whether the robot could adapt to external forces from environments or not. A human added such a large instantaneous force at the third step as an actual ZMP moved to the edge of the support polygon and continued to add a continuous force backward while WL-16RV was stepping with the walking cycle of 1.0 s/step (Fig. 7).

The robot equipped a level meter made of LEDs. We can see the strength of the external force visually. One line represents 10 N, and it can show up to 100 N. However, external forces are estimated from ZMP errors in this research. So, the value indicated by the level meter is not a real one but an estimated one computed by using the data of a force sensor mounted on foot.

When a human added an instantaneous force at the third step, the estimated force was 90 N, and WL-16RV realized a stable walk by changing foot-landing points. The robot could also adapt to a continuous force by changing a foot-landing point up to 200 mm in one step and moved away from the initial position about 400 mm in total as shown in Fig. 8. The reference ZMP is also varied about 400 mm along the x axis as shown in Fig. 9.

We also conducted a walking experiment while carrying a 60 kg human. While WL-16RV walked forward, a human pushed the robot's waist from the outside of the robot (Fig. 10). By changing a foot-landing point up to 170 mm as shown in Fig. 11, the robot prevented from coming closer to the generation source of external forces and realized a stable walking. From the data of measured ZMPs as shown in Fig. 12, we can find that WL-16RV stops going forward from 9 seconds to 11 seconds.

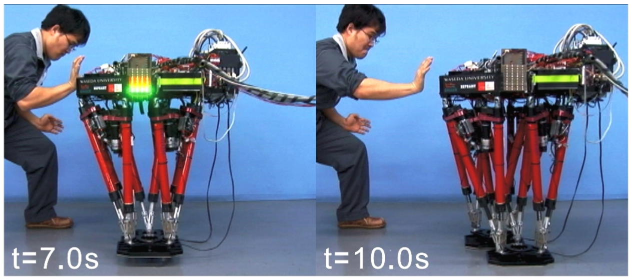

Fig. 7. Walking experiment under unknown external forces from environments while the robot steps. The walking cycle is 1.0 s/step.

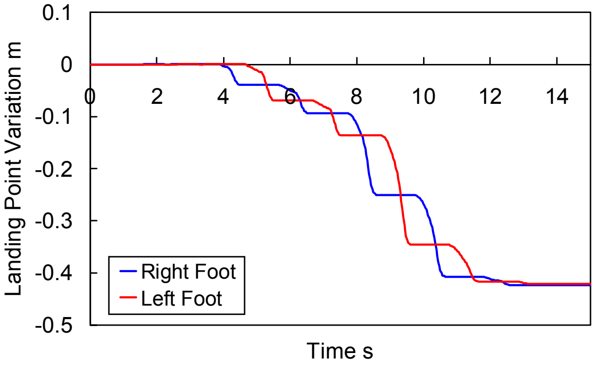

Fig. 8. Foot trajectory variation along the x axis. The robot moved away from the initial position about 400 mm in total to avoid external forces.

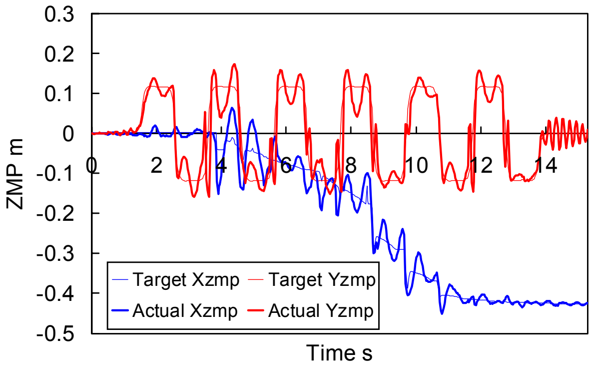

Fig. 9. ZMP trajectories. The reference ZMP is changed about 400 mm along the x axis.

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

V. CONCLUSIONS AND FUTURE WORK

We developed a new stabilization control against unknown disturbances from the outside of a robot for a biped walking vehicle. To distinguish between external forces from passenger and those from environments, we use the data of a 6-axis force/torque sensor mounted on foot to generate an avoidance behavior. And we developed a new avoidance behavior control to prevent a robot from falling by generating

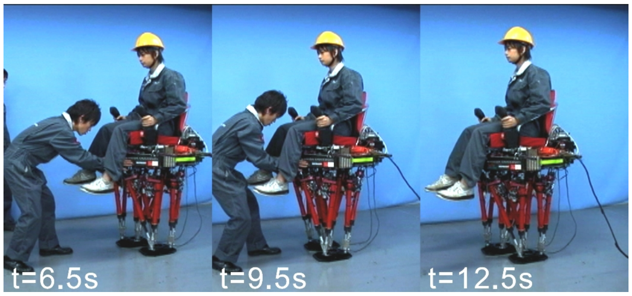

Fig. 10. Walking experiment under unknown external force from environments while carrying a 60 kg human. The walking cycle is 1.0 s/step and the step length is 100 mm/step.

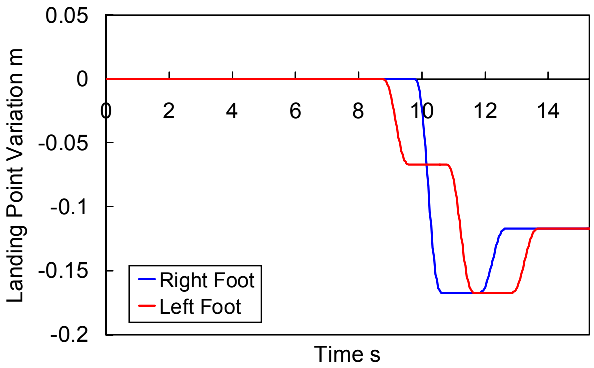

Fig. 11. Foot trajectory variation along the x axis. When a human pushed the robot's waist from outside the robot, a foot-landing point was changed about 170 mm.

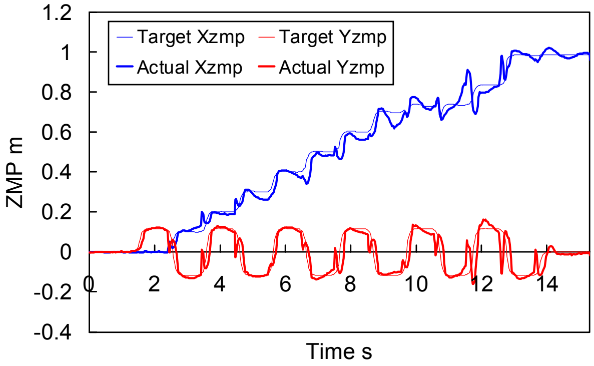

Fig. 12. ZMP trajectories. The robot stopped going forward while a human pushed the robot.

a compensation trajectory around a reference ZMP when large external forces act on the robot. ZMP errors are converted into external forces which act on a robot's waist, and a compensation motion against external forces is generated.

By implementing the developed method on the human-carrying biped walking robot, WL-16RV realized a stable dynamic walk under unknown external forces from the outside of the robot. When pushing the robot stepping, WL-16RV moved backward and moved away from the generation source of external forces about 400 mm. When pushing the robot walking forward, WL-16RV stopped going forward and prevented from coming closer to the generation source of external forces. We confirmed the effectiveness of the proposed control through these experiments. However, to evaluate the proposed method quantitatively, an external disturbance generator should be developed.

Our next goal is to combine the proposed method and external sensors and construct a disturbance compensation control which involves disturbance prediction. Moreover, we should develop a safety system for emergency stop.

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