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Realization of Biped Walking on Uneven Terrain by New Foot Mechanism Capable of Detecting Ground Surface

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Abstract— **We have developed a new biped foot mechanism capable of detecting ground surface to realize stable walking on uneven terrain. The size of the foot mechanism is 160 mm x 277 mm and its weight is 1.5 kg. The foot system consists of four spikes each of which has an optical sensor to detect ground height. The foot makes a support polygon on uneven terrain by using three or four spikes. We have conducted several experiments on the outdoor ground surface that has a slope of 7.0 degrees and a maximum height of 15 mm bumps, and the effectiveness of the foot mechanism is confirmed.**

I. Introduction

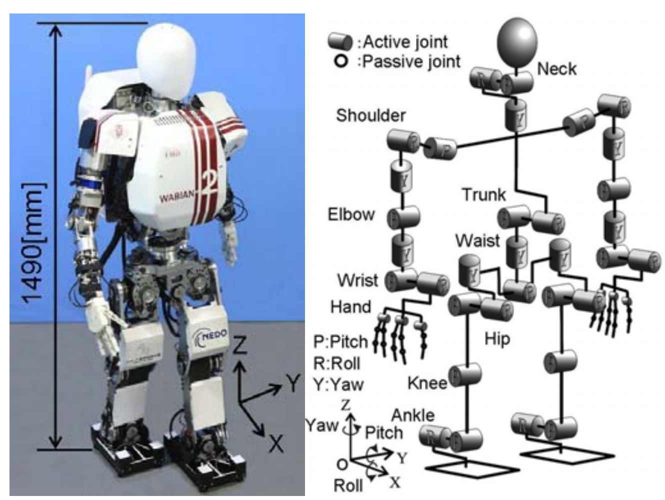
FOR a biped robot to work in real environment, stable walking on uneven terrain of outside ground surface is required. Therefore, we set a goal of developing a technology to realize stable walking in real environment. In case of moving on unexpected unstable ground surface, one solution is to detect obstacles or ground surface with external sensor such as laser range finder or CCD camera [1-4]. However, the measurement accuracy is about 1% of the measured distance, and when considering the distance from the ground surface to the position where sensor is mounted, a biped robot equipped with external sensors should have an ability to deal with unknown uneven terrain with 20 mm height.

There are many previous works on stability controls on uneven terrain [5-12], and most of them assume that a biped robot can maintain large support polygons on uneven terrain. But the many small irregularities and the undulations in an outdoor environment make it difficult for biped robots with rigid, flat soles to maintain large support polygons, meaning that such robots lose balance even when stability control is used. Hashimoto et al. developed a new biped foot system, WS-1R (Waseda Shoes - No. 1 Refined) [13, 14], which can maintain large support polygons on uneven terrain. It has four spikes at each corner of the foot, and they are locked after all the spikes follow unevenness of the ground. Although it can follow the unevenness by only a hardware mechanism, it is heavier with 1.9 kg weight than usual rigid, flat soles. Therefore, a biped robot should deal with unknown uneven terrain from both sides of hardware and software.

In this approach, Yamaguchi et al. have already developed a biped foot system, WAF-2 (Waseda Anthropomorphic Foot - No. 2) [15] for a biped robot WL-12RVI (Waseda Leg - No. 12 Refined IV), which can absorb foot-landing impact and detect ground height. But it assumes that a robot maintains large support polygons with four spikes at each corner of the foot. It is almost impossible to maintain four-point contact on uneven terrain.

The main point of this research is to maintain four-point contact on flat surface and to select three contact points out of four spikes on uneven terrain. The effectiveness of the proposed method was confirmed through walking experiments with a biped humanoid robot, WABIAN-2R (Waseda Bipedal Humanoid - No. 2 Refined) [12, 16, 17] as shown in Fig. 1.

This paper is organized as follows. Section II describes the



(a) Overview (b) DOF configuration

Fig. 1. WABIAN-2R.

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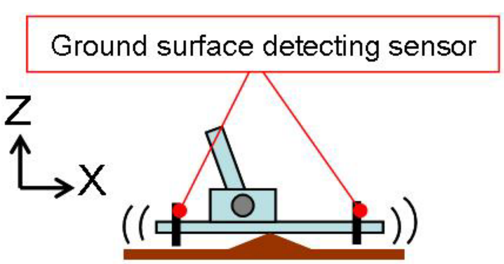
details of the foot system design, and section III describes the ground surface adaptation control by using the foot system developed. In section IV, experimental results are shown. Section V provides conclusions and future work.

II. New Biped Foot Mechanism Capable of Detecting Ground Surface

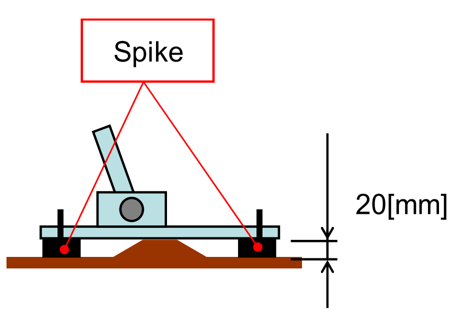
It is difficult to maintain a large support polygon on an undulation surface with rigid, flat soles due to plane contact (Fig. 2(a)). In this research, we deal with the surface undulation by adopting four-point contact with the ground (Fig. 2(b)). However, while walking on undulation surface, it is difficult to maintain four-point contact, and support polygons are not determined uniquely in some cases. The number of contact point should be three when determining support polygons uniquely. In case of walking on a flat surface, however, four-point contact is better than three-point contact. The support polygon of four-point contact is twice as large as that of three-point contact. So, the new biped foot system has four spikes at each corner of the foot, and it maintains four-point contact on flat surface and three-point contact on uneven terrain.

Vision sensors have 1% measurement error. When considering the distance from the ground surface to the position where sensor is mounted, a biped robot should have an ability to deal with unknown uneven terrain with 20 mm height. Therefore, we set the thickness of each spike's tip as 20 mm. The biped foot system developed is shown in Fig. 3.

When landing with four points of the foot, the size of the support polygon is the same as that formed by the rigid, flat foot of WABIAN-2R (160 mm x 240 mm). The external dimension is 160 mm by 277 mm and the weight is 1.5 kg.



(a) In case of plane contact



(b) In case of multi-point contact with 20 mm thick spikes

Fig. 2. Adaptation to uneven terrain.

As shown in Fig. 4, the thickness of the operating spike is 20 mm, so it can avoid convex surface up to 20 mm and adapt to the surface undulation. We used optical sensor to detect height because it is lighter and smaller than linear encoders. The optical distance sensor unit is covered because optical sensor is weak at external light.

The spikes of four edges lands on the ground earlier than the foot's base part. Then, the distance between the ground surface and the base part can be detected by measuring the displacement of the spike with optical sensor. We determined the sensor's stroke by 7.0 mm experimentally.

III. Terrain Adaptive Control Using the Developed Foot Mechanism

In this method, a support polygon can be formed by three-point contact on uneven terrain according to the sensor

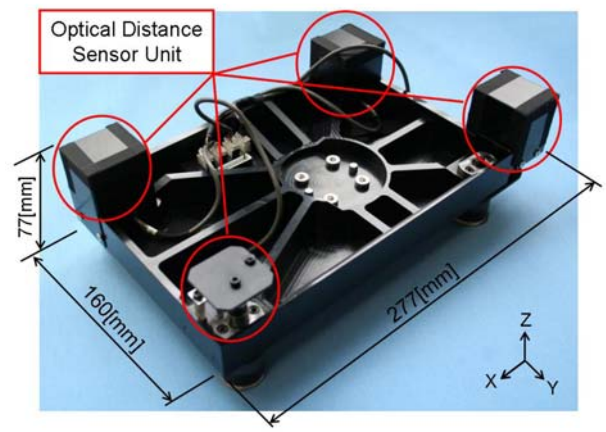
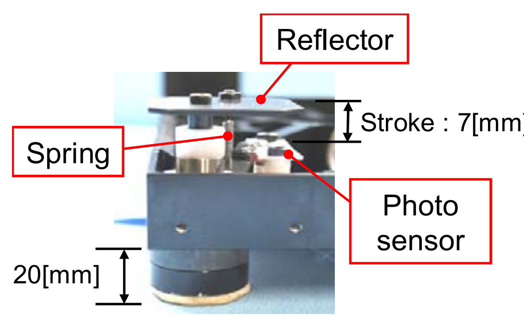
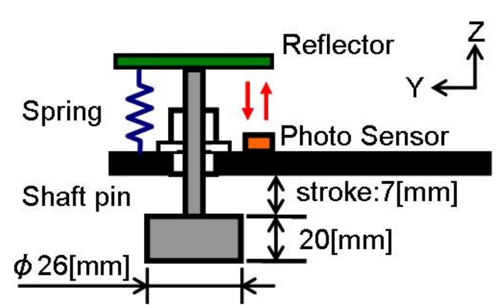


Fig. 3. New biped foot mechanism with four spikes each of which has an optical distance sensor unit to detect ground height.



(a) Photograph of actual foot mechanical structure



(b) Summary image of foot mechanism

Fig. 4. Mechanical structure of foot spike.

that firstly detects the ground surface. A robot modifies the foot-landing pattern along the vertical axis and about pitch and roll axes according to the sensor value, and this enables a biped robot to walk on unknown uneven terrain. This control consists of the following four key points:

A) Selection of a support polygon on uneven terrain
B) Landing pattern modification along the vertical axis
C) Landing pattern modification about pitch and roll axes
D) Returning to the reference walking pattern at each step

Fig. 5 shows the timing chart of the terrain adaptive control during one walking cycle. One walking cycle is divided into seven parts, and the foot position and orientation are controlled during each phase as follows:

(i) Control phase: a foot-landing pattern is modified according to the sensor values of the developed foot.

(ii) Holding phase: a modified position and orientation at the last step are held.

(iii) Returning phase: a foot position and orientation return to the preset walking pattern.

In the last half of a robot's leg swing phase, a support polygon is determined and a foot-landing pattern is modified to follow uneven terrain. The modified position and orientation are held during the stance phase. The foot position along the vertical axis returns to the preset pattern in the first half of a stance phase, and the foot orientation about pitch and roll axes returns in the first half of a swing phase.

A. Selection of a Support Polygon on Uneven Terrain

The developed foot system maintains four-point contact on flat terrain. But it is impossible to maintain four-point contact on uneven terrain, and three contact points are selected from four points according to the first ground-contacting sensor as shown in Fig. 6. A reference ZMP (Zero Moment Point) [18] in stance phase is set at the rear than the center of a foot sole to keep the reference ZMP inside the "Stability area 1" or "Stability area 2". According to it, even though the reference ZMP is not changed while walking on uneven terrain, it can form a stable support polygon. When the sensor #0 and #2 detect a contact on the ground firstly, the "Stability area 1" is selected. When the sensor #1 and #3 detect a contact on the ground, the "Stability area 1" is selected.

B. Landing Pattern Modification along the Vertical Axis

A foot-landing motion along the vertical axis is modified according to the value of sensors detectable ground height. In case of the sensor stroke is Δl , while the sensors are shortened by Δl , terrain height is detected by comparing actual and theoretical sensor length. A theoretical sensor length $\Delta x_{th}(t)$ for a robot walking on even terrain is described as follows:

(i) $\Delta l + \bar{z}_{leg}(t) < z_{waist}(t)$

$$\Delta x_{th}(t) = 0 \quad (1)$$

(ii) $\Delta l + \bar{z}_{leg}(t) \geq z_{waist}(t)$

$$\Delta x_{th}(t) = \Delta l + \bar{z}_{leg}(t) - z_{waist}(t) \quad (2)$$

where $\bar{z}_{leg}(t)$ is the height of the foot in the reference

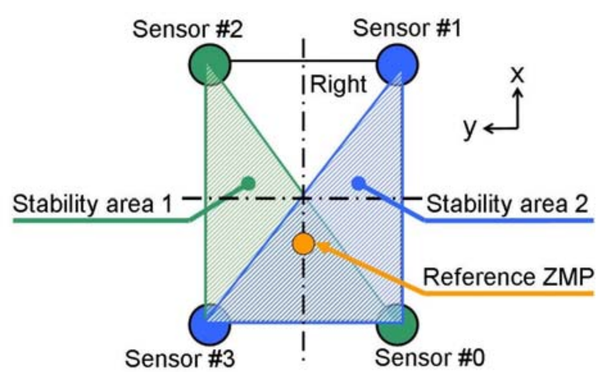


Fig. 6. Determination of support polygon.

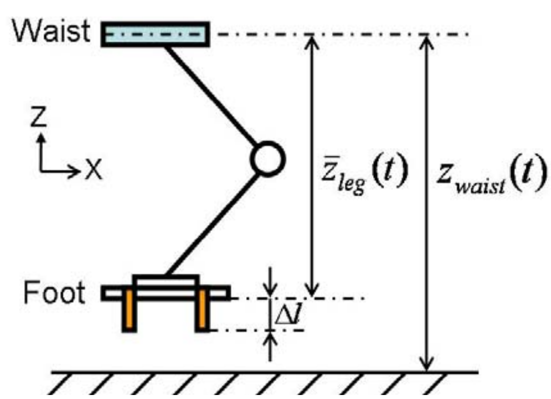


Fig. 7. Coordinates for walking control.

Axis	Double Support Phase	Swing phase		Double Support Phase	Stance phase		Double Support Phase
		first half	last half		first half	last falf	
z	Preset Pattern	Preset Pattern	Landing Control	Holding Modified Position	Returning Motion	Preset Pattern	Preset Pattern
Roll	Holding Modified Orientation	Returning Motion	Landing Control	Holding Modified Orientation	Holding Modified Orientation	Holding Modified Orientation	Holding Modified Orientation
Pitch	Holding Modified Orientation	Returning Motion	Landing Control	Holding Modified Orientation	Holding Modified Orientation	Holding Modified Orientation	Holding Modified Orientation

Fig. 5. Timing chart of terrain adaptive control.

walking pattern, $z_{waist}(t)$ the height of the robot's waist, and variables are defined as shown in Fig. 7.

Feeding landing height error $e(t)$ back at each control cycle modifies foot movement along the vertical axis. A foot height displacement along the vertical axis, $H(t)$, is calculated as follows:

$$e(t) = \Delta x_{th}(t) - \Delta x_{ac}(t) \tag{3}$$

$$H(t) = H(t-\Delta t) - K_{error} \cdot e(t-\Delta t) \tag{4}$$

where $e(t)$ is landing height error, $\Delta x_{th}(t)$ theoretical sensor length, $\Delta x_{ac}(t)$ actual sensor length, Δt the control cycle of 1ms, H(t) foot height displacement along the vertical axis, and K_{error} gain.

C. Landing Pattern Modification about Pitch and Roll Axes

A foot motion about pitch and roll axes is modified according to two sensors' values. The modification angle $\theta(t)$ is calculated as follows:

$$\theta(t) = \sin^{-1}\left\{\frac{\Delta x_{ac}(t)}{\sqrt{\Delta x_{ac}(t)^2 + L^2}}\right\} \tag{5}$$

where $\theta(t)$ is modification angle, L the distance between two sensors, and variables are defined as shown in Fig. 8.

The sensor value is obtained at every 1 ms, and the average of displacement amount is calculated at every 10 ms to reduce the vibration of sensor and the noise effect. The modification amounts are added to the standard walking pattern.

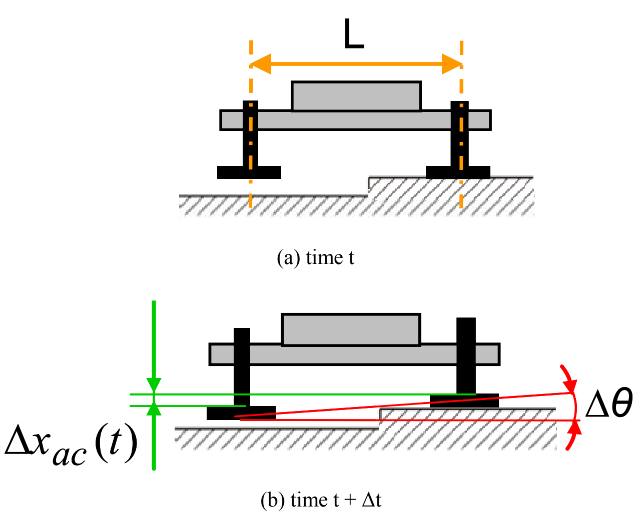


Fig. 8. Modification about pitch and roll axes.

D. Returning to the Reference Walking Pattern at Each 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 vertical 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, $z_{return}(t)$.

$$z_{return}(t) = at^5 + bt^4 + ct^3 + dt^2 + et + f \tag{6}$$

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

$$\begin{aligned} &z_{return}(0) = Z_{modif},\ z'_{return}(0) = 0,\ z''_{return}(0) = 0, \\ &z_{return}(T_{fhsp}) = 0,\ z'_{return}(T_{fhsp}) = 0,\ z''_{return}(T_{fhsp}) = 0 \end{aligned} \tag{7}$$

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:

$$z_{return}(t) = -Z_{modif} \cdot \frac{6t^5 - 15t^4 T_{fhsp} + 10t^3 T_{fhsp}^2 - T_{fhsp}^5}{T_{fhsp}^5} \tag{8}$$

The modification displacement about pitch and roll axes 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.

IV. Evaluation Experiment

We conducted evaluation experiments to verify the effectiveness of the new terrain-adaptive control by using a biped humanoid robot, WABIAN-2R.

A. Verification Experiment for the Target Ground Surface with 20 mm Bump

We conducted a walking experiment as each spike of the developed foot system stepped on the 20 mm board. Then, the walking cycle was 1.0 s/step, and the step length was 200 mm/step. As an experiment result, when a certain spike grounds on the bump, a support polygon was selected as it was already set and a stable adaptive motion was realized as shown in Fig. 9.

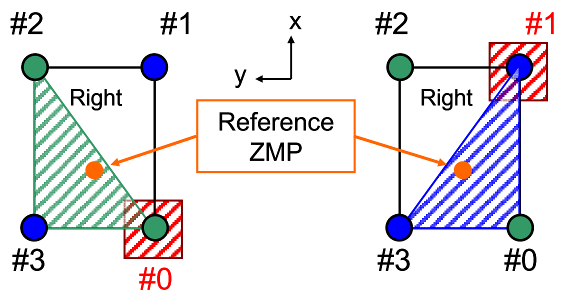
We then randomly placed acrylic boards whose maximum thickness was 20 mm in a laboratory as shown in Fig. 10. WABIAN-2R walked stably forward on such uneven terrain using the control we developed. When each spike stepped on obstacles, three contact points were selected from four points according to the first ground-contacting sensor. Fig. 11 shows ZMP trajectory.

B. Walking Experiment on Inclined Surface

The terrain-adaptive control developed can be applied to an inclined surface as well, so we performed a walking experiment on an inclined surface of 7.0 degrees as shown in Fig. 12. Then, the walking cycle was 1.0 s/step, and the step length was 200 mm/step. From the 3rd step, the robot started to land on the slope. At the 7th or 8th step, the robot finished climbing up the slope, and a stable walk on inclined surface was realized. Fig. 13 shows modified foot angles, and about 7.0 degrees modification about pitch axis is confirmed.

C. Walking Experiment in Outdoor Environment

The effectiveness of the terrain-adaptive control was confirmed indoors, and we conducted walking experiments outdoors as shown in Fig. 14. The maximum angle of



(a) Sensor #0: Roll (b) Sensor #1: Pitch

Fig. 9. Determination of stability area depending on which sensor detects the ground first.

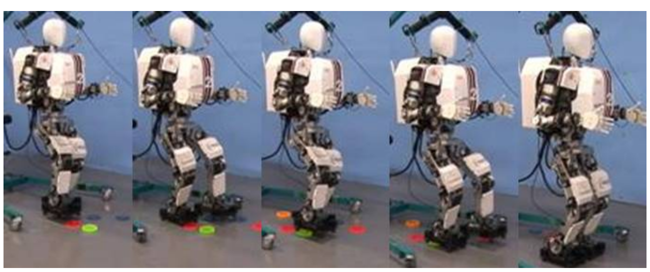


Fig. 10. Walking experiment on uneven terrain. The maximum height of the boards is 20 mm. The walking cycle is 1.0 s/step with a step length of 200 mm/step.

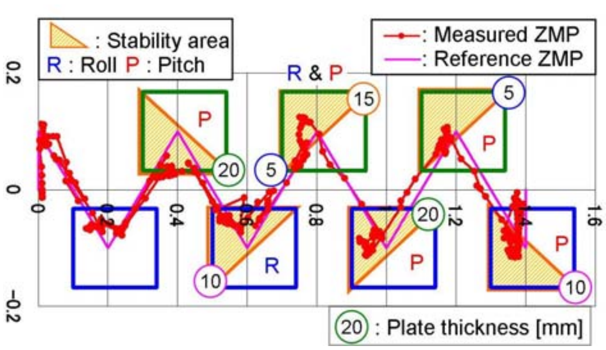


Fig. 11. ZMP trajectories when walking on uneven terrain.

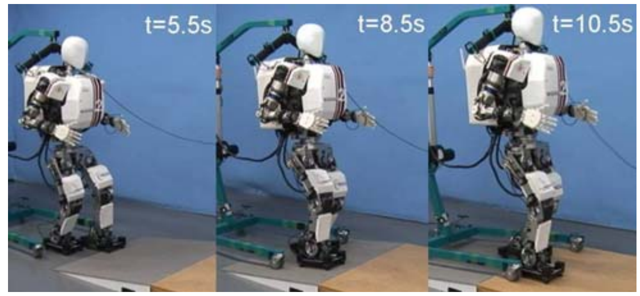


Fig. 12. Walking experiment on slope of 7.0 degrees. The walking cycle is 1.0 s/step with a step length of 200 mm/step.

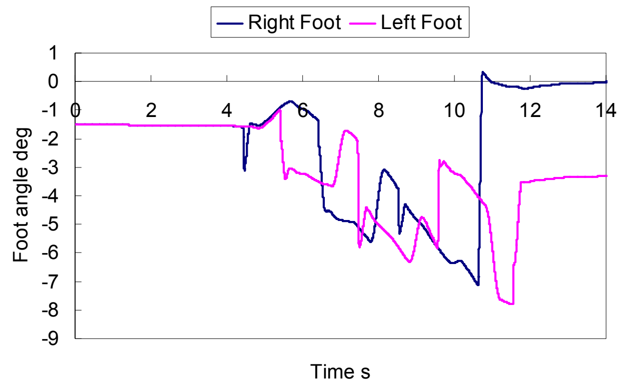


Fig. 13. Modification of foot angle on slope of 7.0 degrees.

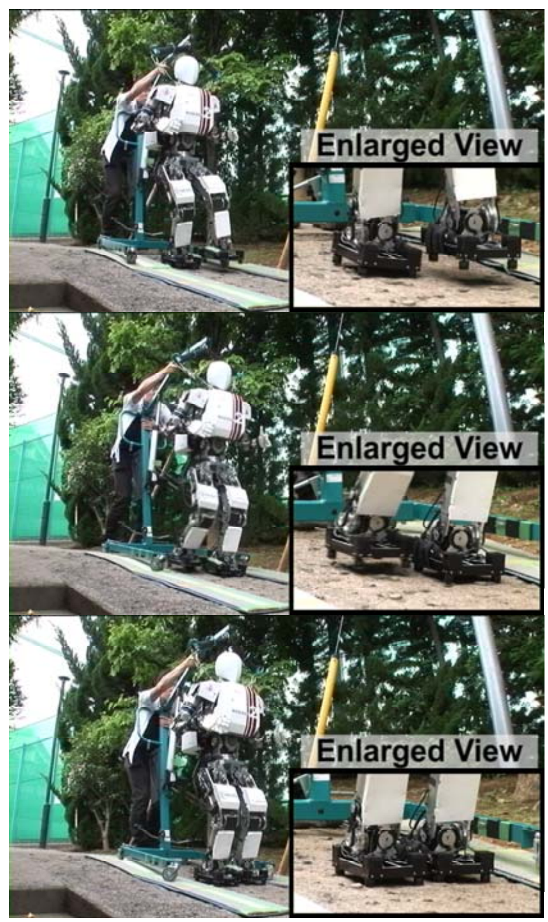


Fig. 14. Walking experiment outdoors. The maximum angle of inclination is 7.0 degrees and the maximum height of unevenness is 15 mm. The walking cycle is 1.0 s/step with a step length of 200 mm/step.

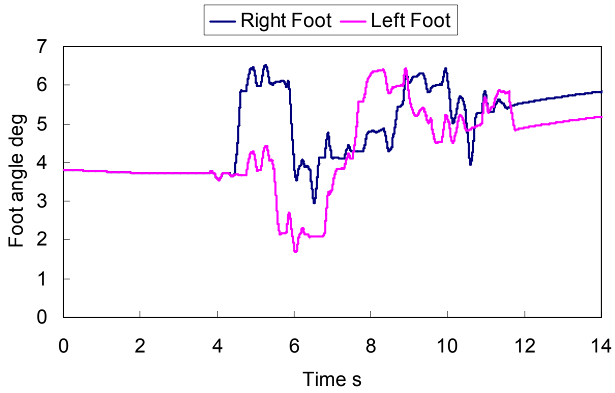


Fig. 15. Modification of foot angle when walking on outdoor.

inclination is 7.0 degrees and the maximum height of unevenness is 15 mm. The walking cycle was 1.0 s/step, and a step length was 200 mm/step. Fig. 15 shows modified foot angles. About 7.0 degrees modification about pitch axis is confirmed. As a result, we confirmed a stable walking was realized.

As an experiment result, WABIAN-2R succeeded in walking on such uneven terrains and we confirmed the effectiveness of the developed terrain-adaptive control.

V. Conclusion

We aimed a stable walking in real environment, and developed a terrain-adaptive control system that can realize stable walking on an inclined surface with bumps up to 20 mm height. To explain in detail, we developed a new biped foot mechanism with four spikes each of which has an optical distance sensor unit to detect ground height. When walking on uneven terrain, a support polygon can be formed by three-point contact on uneven terrain according to the sensor that firstly detects the ground surface. A robot modifies the foot-landing motion along the vertical axis and about pitch and roll axes according to the sensor value, and this enables a biped robot to walk on unknown uneven terrain.

Through walking experiments, we confirmed the effectiveness of the proposed method that maintained a support polygon on uneven terrain with bump and slope, and we succeeded in walking on an uneven terrain with the mixture of bump up to 20 mm and on outdoor environment.

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.

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