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New Foot System Adaptable to Convex and Concave Surface

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Abstract – **Many control methods have been studied on the assumption that the feet of biped robots contact the ground with four points. However, it is difficult for almost all of such biped robots to maintain four-point contact on uneven terrains because they have rigid and flat soles. In order to solve the problem, foot mechanisms should be studied. In 2003, we developed WS-1R (Waseda Shoes - No.1 Refined) which is able to maintain four-point contact. However, it is difficult to deal with the concave or convex ground because of the problems of the contact detection and sideways slip. So, WS-5 (Waseda Shoes - No.5) has been developed. To avoid the slip of the foot, a cam-slider locking system consisting of a solenoid and a cam is constructed and installed at the foot. Also, linear encoders are employed to measure the position of the foot sliders. Through walking experiments on uneven terrains, the effectiveness of WS-5 is confirmed.**

Index Terms* – *Biped Walking, Uneven Terrain, Locking Mechanism, Foot Mechanism

I. INTRODUCTION

RESEARCHES on biped locomotion have focused on a motion pattern generation and real-time stability control [1-4]. Most controls assume that the soles of a biped robot's feet contact the ground at four points in a single support phase. When a biped walking robot with rigid and flat soles walks on uneven terrain as shown in Fig. 1, the support polygon becomes small due to the failure of four-point contact. ZMP (Zero Moment Point) [5] is difficult to be kept within this polygon even though the robot is controlled by a moment compensatory method [6]. For stable locomotion, not only control methods but also foot systems must be improved.

Among foot systems differing from conventional systems, H6 and H7 have toe joints to walk with higher speed and larger steps [7, 8]. WAF-2, the foot system of WL-12RVI, absorbs impact and contact forces [9]. ASIMO [10, 11] and HRP-2 [12, 13] use impact absorption. However, these systems all have difficulty maintaining four-point contact on uneven terrain. The active ankle mechanism with 2 degrees of freedom (DOF) has been developed for a multi legged robot [14]. But it is difficult to apply the active ankle mechanism to a biped walking robot due to the sole elasticity. Biped robots should maintain four-point contact in the single support phase for stable walking.

A soft and compliant element added to the robot's foot can follow the unevenness of the road. However, it is difficult to adapt to uneven terrain with only a soft material because the shape of the soft material cannot be retained in the stance phase. Ideally, the foot system itself should follow the unevenness and keep the shape in the stance phase.

In this paper, we propose a new foot system adaptable to uneven terrain. In our previous report, we presented WS-1R (Waseda Shoes - No.1 Refined) which can contact the ground with four points (Fig. 3) [15]. However, WS-1R cannot cope

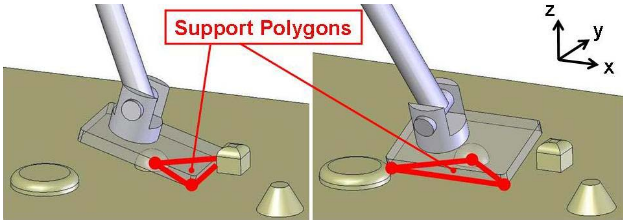

Fig. 1. Foot with rigid and flat sole

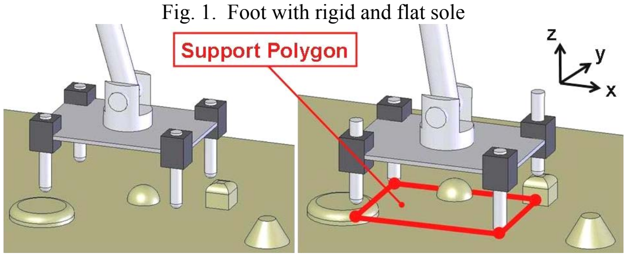

Fig. 2. New foot model

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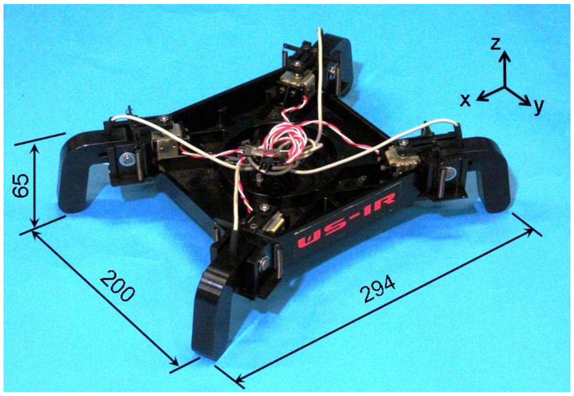


Fig. 3. Waseda Shoes - No.1 Refined

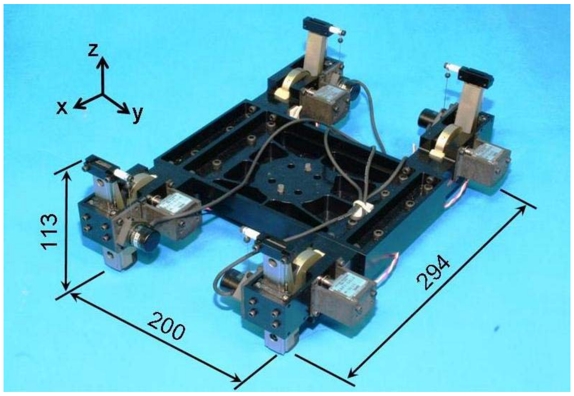


Fig. 4. Waseda Shoes - No.5, a new foot system adaptable to convex and concave surface

with concave surface due to the problem of the contact detection. And WS-1R has the difficulty in dealing with convex surface because of the problem of the locking mechanism. So, this paper reveals the problems of WS-1R and describes an improved foot system, WS-5 (Waseda Shoes - No.5) as shown in Fig. 4. The feasibility of the system is confirmed by several experiments.

This paper is organized as follows. Section II describes problems of WS-1R and a new leg-locking mechanism that can deal with concave and convex surfaces. In section III, experimental results are shown. Section IV provides conclusions and future work.

II. FOOT SYSTEM DESIGN

A. WS-1R Problems

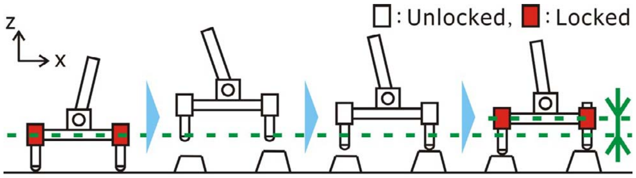


Fig. 6. Previous locking system on surface convexed at all contact points

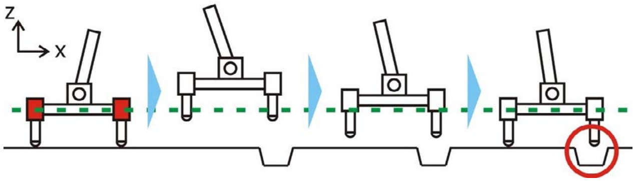
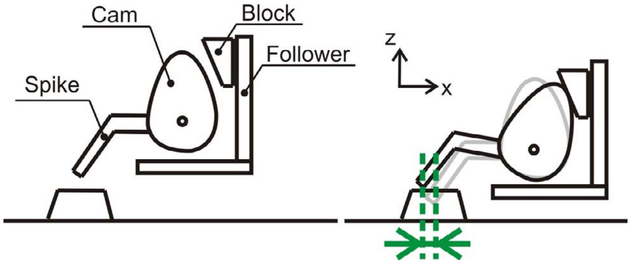


Fig. 7. Previous locking system on concave terrain



(a) Unlock (b) Lock

Fig. 8. Cam locking

We target stable dynamic walking on uneven terrain with 20 mm bumps, setting the movable z axis range for WS-1R at 20 mm. Our proposed foot, WS-1R locks when each support point is tracing uneven terrain and all four points contact the walking surface. If one point does so, supporting legs do not lock. When all support points do so, all are locked (Fig. 5). Micro switches are used to detect contact.

Based on this operating principle, it is impossible to deal with such a convex surface as all supporting legs contact it at the same time. This is because supporting legs are locked when they contact a convex part and the foot is unable to keep the standard height of the foot (Fig. 6). It is also impossible to adapt to concave terrain because supporting legs cannot reach a concave part and foot system cannot be locked (Fig. 7). WS-1R is adaptable to only such a convex surface as some of support points contact it.

WS-1R has one more demerit. The cam locking is adopted for a foot spike (Fig. 8). The operating principle is that the cam rotates, the follower block is inserted into the space, and supporting legs are locked based on a wedge. Because the supporting legs rotate according to the movement of the tip, the tip must be slipped sideways. If a supporting leg contacts a convex part on the edge, the support point may fall down. So, new locking needs to have only vertical movement when

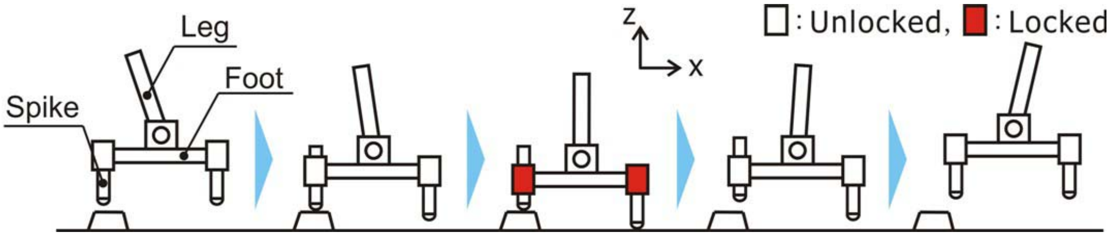


Fig. 5. Operating principle of Waseda Shoes - No.1 Refined

it adapts to the ground.

B. New Leg-locking Mechanism

To solve WS-1R problems, the functional requirements for new locking mechanism are set as follows:

- Adaptability to convex surface at all supporting legs
- Adaptability to not only convex surface but also concave surface with 20 mm height
- New locking which have no horizontal movement when it adapts to the ground

To satisfy the first requirement, we change the timing to lock the supporting legs. Supporting legs are locked at the change from a swing phase to a stance phase, regardless of ground contact conditions (Fig. 9). It depends on a walking pattern data. WS-1R is also adaptable to the convex surface at all supporting legs by changing the locked timing.

To deal with a concave surface, the middle of slider's movable range is adjusted to the starting position (Fig. 10). Then, the movable z axis range for new locking needs 40 mm to adapt to a convex and concave surface with 20 mm height. So, a new locking mechanism is designed that has a stroke with 40 mm or more and can deal with a slipping sideways problem.

Locking is the most important element in foot development because it must withstand the impact of contact and maintain locking during walking. If locking is complex, the foot may become heavy, requiring simple locking.

1) Locking with Compression Pawl: Applying a compression pawl to locking requires that only pawl compression be considered. The disadvantage is that it locks digitally (Fig. 11). Biped robots cannot continue walking on uneven terrain with bumps of a few millimetres without real-time stability control. So, a locking mechanism that can be locked on an arbitrary position is required.

2) Slide Locking: Frictional locking quickly locks in an arbitrary position, as by sliding a block (Fig. 12). The sliding block is pushed in a stance phase, and supporting legs are locked. A solenoid may serve as an actuator because it is easier to control than a motor and has a faster response. We made a mock-up and conducted experiments, but cylinder slipped even with a little force. Changing the block angle reduces slippage. Taking solenoid stroke into account, it is difficult for locking to achieve a movable range of 40 mm along the z axis.

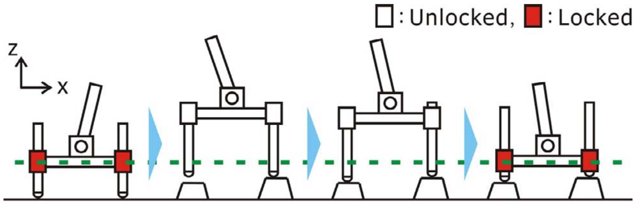


Fig. 9. New locking system on surface convexed at all contact points

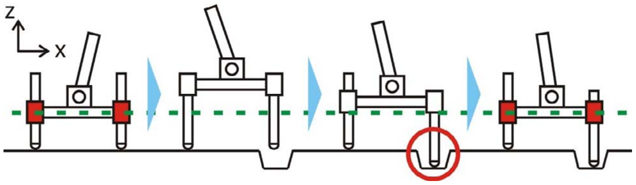
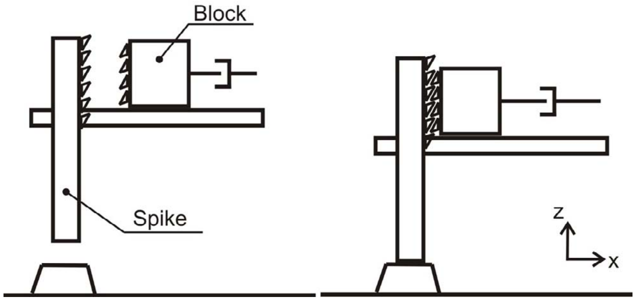


Fig. 10. New locking system on concave terrain

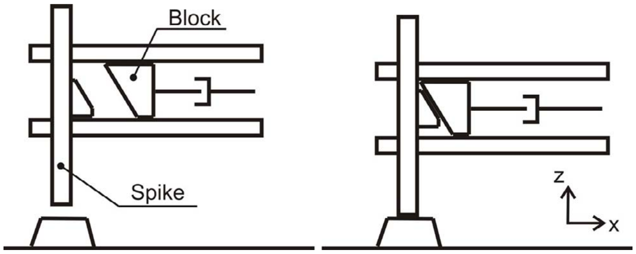
3) Cam-slider Locking: The cam-slider locking was designed instead of slide locking. The operating principle is that the slider moves upward to follow the ground, the cam is rotated, and supporting legs are locked based on a wedge (Fig. 13). A mock-up confirmed its effectiveness. Since supporting legs are locked more securely than the slide locking and its simplicity reduces weight, we used this cam-slider locking for a robot foot spike.

Whether the cam locks or not depends on the cam shape and the static friction coefficient between the cam and the spike. Based on measurement, we found that the static friction coefficient was about 0.7. Assuming Coulomb friction, the cam locks if the inclined angle of the spike is 11.5 degrees or less, so we set the inclination of the spike at 10 degrees to provide a margin of safety. The cam is designed for the movable range of 50 mm along the z axis. Ideally, the spike should move upward at a constant rate compared to cam



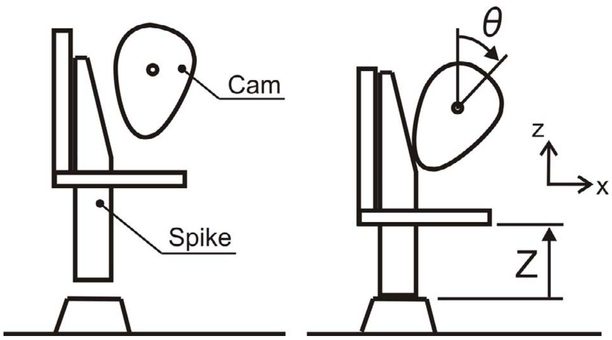
(a) Unlock (b) Lock

Fig. 11. Locking with compression pawl



(a) Unlock (b) Lock

Fig. 12. Slide locking.



(a) Unlock (b) Lock

Fig. 13. Cam-slider locking

rotation angle θ. These specifications are met by approximating an elliptical cam. The relationship between rotation angle θ and the movable range Z is shown in Fig. 14.

C. *Waseda Shoes - No.5*

The WS-5 base is designed to be lightweight and highly rigid, using finite element method (FEM) COSMOS [16]. The cam-slider locking mechanisms are arranged in each corner of the foot. The photograph of WS-5 is shown in Fig. 4. Specifications are given in Table I. Although WS-1R uses micro switches to detect contact, WS-5 employs linear encoders to measure the position of the foot sliders as shown in Fig. 15. And a rotary solenoid is used as an actuator to rotate the cam. In stance phase, solenoids are energized and supporting legs are locked. Moreover, in swing phase, solenoids are energized in the opposite direction and locks are released.

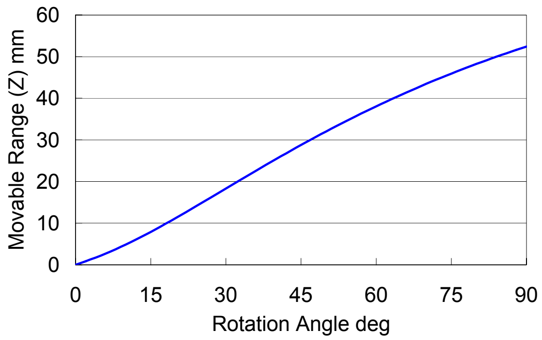


Fig. 14. Rotation angle θ versus movable range Z

Table I
WS-5 Specifications

Size	200 × 294 × 113 mm
Weight	2930 g
Movable range on z axis	50 mm
Actuator drive	4 rotary solenoids

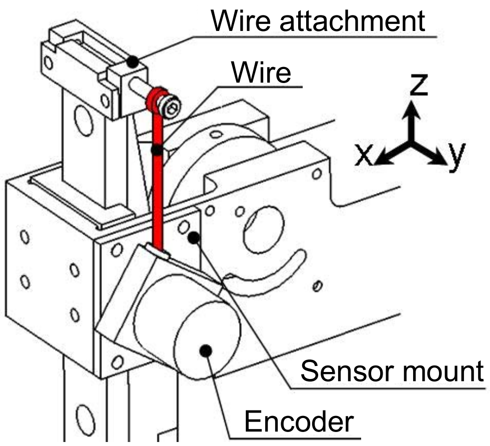


Fig. 15. Sensor arrangement on locking system

III. EXPERIMENTAL TESTS AND CONSIDERATION

WS-5 has a design universally applicable to all biped robots. We evaluated it in three experiments using the multi-purpose biped locomotor WL-16RIII (Waseda Leg - No.16 Refined III) [4, 6, 17]. Encoders are initialised when the foot sliders move downward to bottom, and the sliders are locked when the sliders move upward by 20 mm. This makes WS-5 adaptable to a concave surface with 20 mm height in theory. The number of linear encoders arranged in each foot slider was set as shown in Fig. 16.

An acrylic board 20 mm thick was placed on a flat floor and a surface with dummy unevenness was created. Walking experiments of 200 mm/step and walking for 2.04 s/step were conducted. WL-16RIII with WS-5 partly stepped on a convex

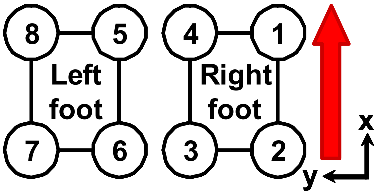


Fig. 16. Number of encoders of WS-5

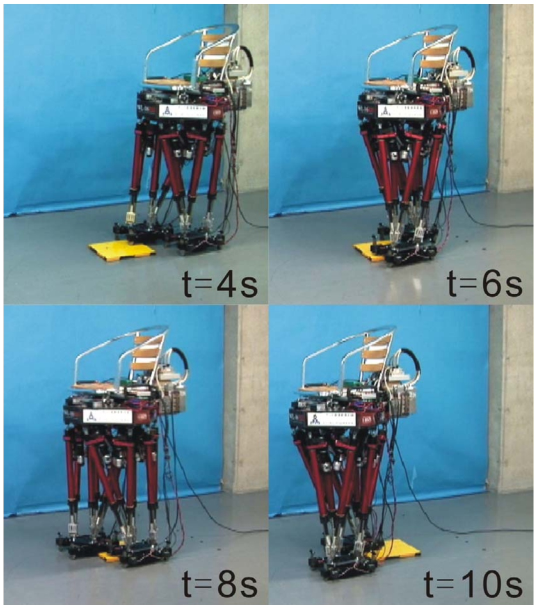


Fig. 17. Walking experiments on the 20 mm board. The walking cycle is 2.04 s/step and the step length is 200 mm/step.

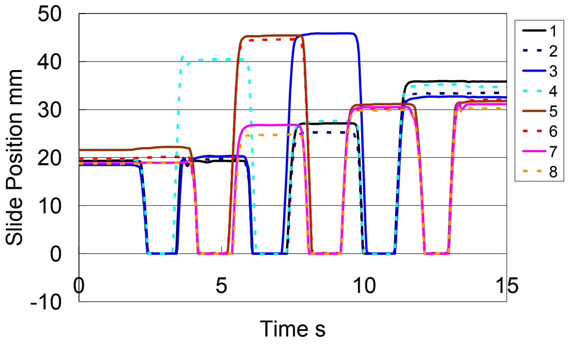


Fig. 18. Measurements of potentiometer on the 20 mm board

surface and achieved forward walking on the acrylic board (Fig. 17). Fig. 18 shows the slide positions of the spikes. As shown in Fig. 18, we can find that the slide positions move upward from 20 mm to 40 mm when encountering a convex surface from steps 2 to 4. However, the slide positions move upward by about 30 mm after WL-16RIII goes over the 20 mm thick board. Under ordinary circumstances, the encoder's value should be 20 mm. The reference walking pattern is set that the foot is parallel to the waist. If the waist is not parallel to the ground due to the difference of the slider's initial position, the structural deflection and so on, the foot cannot horizontally land a flat terrain. Therefore, the error of slide position is accumulated during walking.

We then placed wooden boards with 20 mm thick on a flat floor for a walking experiment with walking at 2.04 s/step for 200 mm/step (Fig. 19). WL-16RIII with WS-5 stepped on a convex surface where all spikes contact at the same time. By changing the timing to lock the supporting legs, WL-16RIII achieved a stable walking on such a surface. Slide positions when stepping on the 20 mm thick board is shown in Fig. 20. As shown in Fig. 20, we can find that the slide positions move upward from 20 mm to 40 mm when encountering a convex surface.

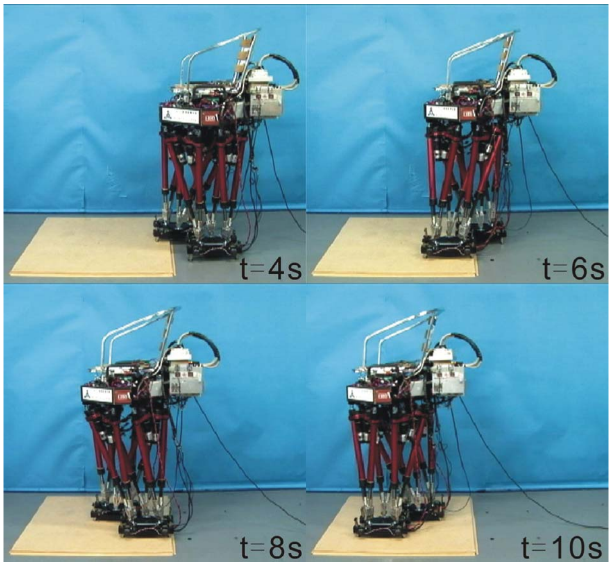


Fig. 19. Walking experiments when stepping on the 20 mm board. The walking cycle is 2.04 s/step and the step length is 200 mm/step.

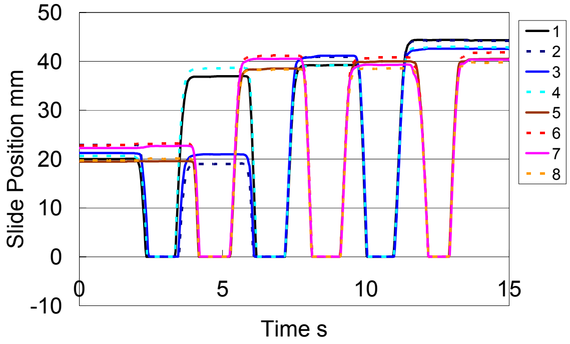


Fig. 20. Measurements of potentiometer when stepping on the 20 mm board

Finally, the walking experiment is conducted to confirm if WS-5 is adaptable to concave terrain. WL-16RIII started walking on the wooden board with 20 mm thick and stepped down the 20 mm thick board (Fig. 21). The walking cycle was 2.04 s/step, and a step length was 200 mm/step. Without stability control, ZMP error is relatively small (Fig. 22) and walking was stable. However, as shown in Fig. 23, the slide position moves upward by about 5 mm even after WL-16RIII steps down the wooden board. This is caused by the same reason above-mentioned. To solve this problem, attitude

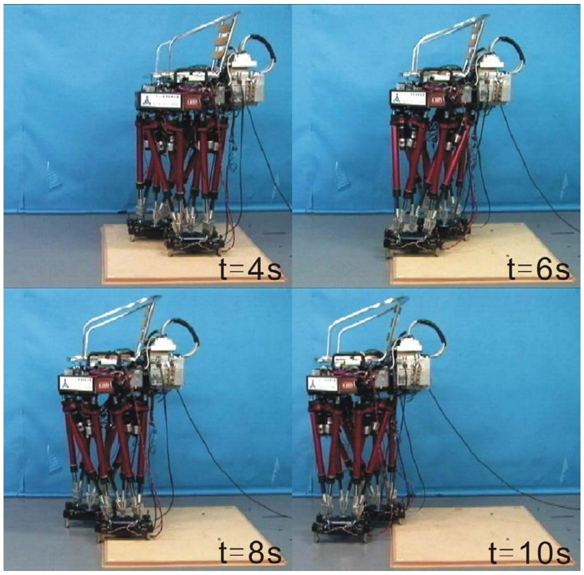


Fig. 21. Walking experiments when stepping down the 20 mm board. The walking cycle is 2.04 s/step and the step length is 200 mm/step.

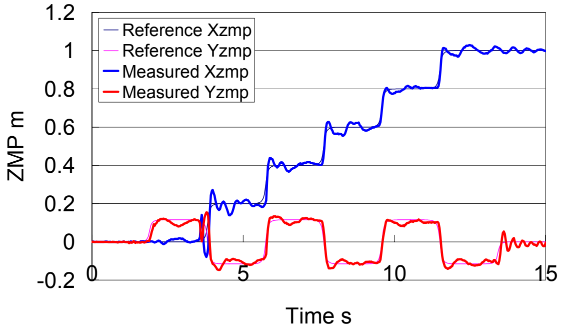


Fig. 22. ZMP trajectories when stepping down the 20 mm board

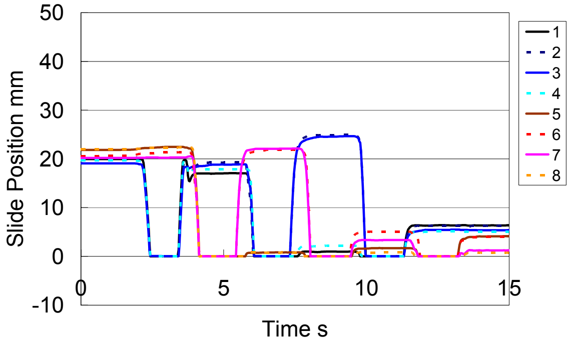


Fig. 23. Measurements of potentiometer when stepping down the 20 mm board

angle and the height of the waist should be modified according to the value of linear encoders.

The above experiments confirmed the effectiveness of this foot system. By developing a new biped foot system, WS-5, stable walking was achieved on such a convex surface as all supporting legs contact it at the same time and a concave surface. If WS-5 is operated with real-time stabilization control, the robot may be able to walk stably on bumpier terrain.

IV. CONCLUSIONS AND FUTURE WORK

We have developed a new foot system, WS-5 which maintains four-point contact on uneven terrain. Then, a new operating principle was designed so as to adapt to concave surface and convex surface at all contact points. To avoid the slip of the foot and obtain wide movable range, a cam-slider locking was constructed. The unevenness to which WS-1, WS-1R and WS-5 can adapt is shown in Fig. 24.

Experiments using WL-16RIII on WS-5 were conducted on uneven terrain. Walking forward was realized on a wooden 20 mm board, and then we confirmed that WS-5 is adaptable to such a convex surface as all supporting legs contact it at the same time and a concave surface. But the error of slide position is accumulated during walking due to the structural deflection and so on. This makes it difficult to continue walking for a long time. To solve this problem, attitude angle and the height of the waist should be modified according to the value of linear encoders.

Our next goal is to solve the problems and combine this new foot system with stability control. We plan to conduct further walking experiments on bumpier terrain and in real environments such as in the home and on the street.

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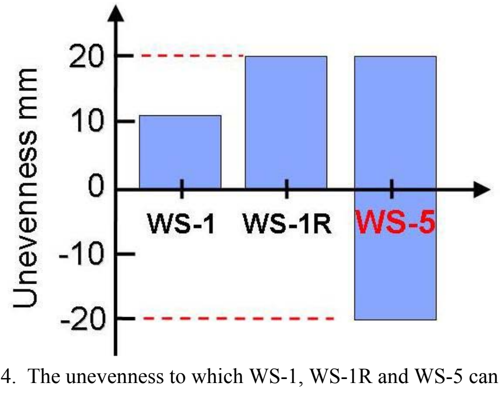

Fig. 24. The unevenness to which WS-1, WS-1R and WS-5 can adapt

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