The Seventeenth International Symposium on Artificial Life and Robotics 2012 (AROB 17th '12),
B-Con Plaza, Beppu, Oita, Japan, January 19-21, 2012

Development of flexible joints for a humanoid robot that walks on an oscillating plane

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Abstract: In this study, we develop flexible joints for a humanoid robot that walks on an oscillating plane and discuss their effectiveness in compensating disturbances. Conventional robots have a rigid frame and are composed of rigid joints driven by geared motors. Therefore, disturbances, which may be caused by external forces from other robots, obstacles, vibration and oscillation of the surface upon which the robot is walking, and so on, are transmitted directly to the robot body, causing the robot to fall. To address this problem, we focus on a flexible mechanism. We develop flexible joints and incorporate them in the waist of a humanoid robot; the experimental task of the robot is to walk on a horizontally oscillating plane until it reaches the desired position. The robot with the proposed flexible joints, reached the goal position despite the fact that the controller was the same as that used for a conventional robot walking on a static plane. From these results, we conclude that our proposed mechanism is effective for humanoid robots that walk on an oscillating plane.

Keywords: Humanoid Robot, Flexible joint, Elasticity

1 INTRODUCTION

In this study, we develop flexible joints for a humanoid robot that walks on an oscillating plane, and discuss their effectiveness in compensating disturbances. In conventional studies, robots have a rigid frame and are composed of rigid joints driven by geared motors. Therefore, disturbances, which may be caused by external forces from other robots, obstacles, vibration and oscillation of the surface upon which the robot is walking, and so on, are transmitted directly to the robot body, causing the robot to fall [1]. To prevent falling, conventional robots require various sensors and a high-spec controller for real-time processing [2]. Nevertheless, it is very difficult for the robot to react quickly and avoid a fall, which prevents robots from operating in unknown dynamic environments. To address this problem, we focus on flexible mechanisms. A flexible mechanism can adapt itself to a rapidly changing environment passively because of its dynamics and physical properties [3-5]. In addition, it requires no sensors and no controllers, because the necessary information is contained within the mechanism itself and the calculation for its control is implicitly performed by its dynamic and physical properties. In our previous study, we developed and confirmed the viability of a flexible joint whose elasticity can be adjusted to adapt to a dynamic environment. The flexible joint presented here compensates for disturbances passively, reducing the load of the controller [6]. However, the previous study was focused on the effectiveness of the flexible joint itself and the performance of the entire robot was not sufficiently discussed. In particular, the subject of autonomous control that would enable a robot to move to a desired position was not addressed.

In this study, we address the topic of autonomous walking by a robot to reach a desired position. We improve our previous flexible mechanism [6], and we develop a humanoid robot that can walk on an oscillating plane to reach a desired position by using a simple autonomous controller that is actually designed for walking on a static plane.

2 TASK AND ENVIRONMENT

For experiments on an oscillating plane, we employ a vibration generator, as shown in Fig.1. The environment measures 1000 mm × 1000 mm. The oscillation amplitude is 50 mm, and, to confirm the frequency response, we vary the frequency from 1.5 Hz to 5.0 Hz.

The task of the robot is to walk toward a target position on the oscillating plane.

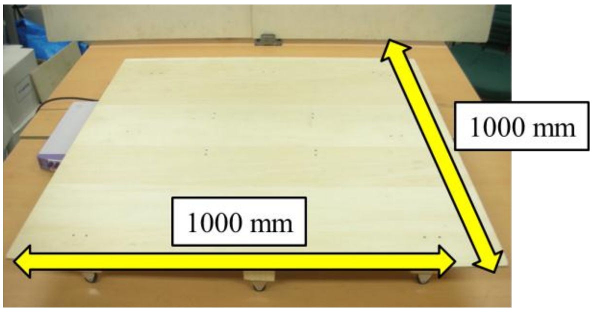
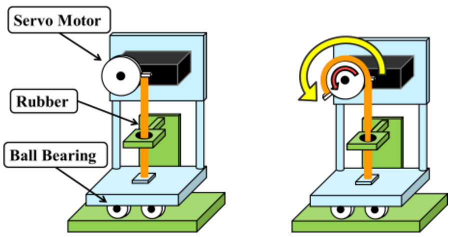


Fig. 1. Oscillating Plane

3 FLEXIBLE JOINT

Fig. 2 shows an illustration of the flexible joint [6]. An upper link and a lower link are brought into contact through the ball bearing and a rubber band. It is possible to for them to interact through the rubber band. If the upper link slides, the rubber cord is pulled and the upper link is pulled back. The length of rubber cord can be adjusted with the servo motor, which causes the rigidity of the flexible joint to change.

Due to the viscoelasticity of rubber, the flexible joint has the characteristics of a low-pass filter. This implies that high-frequency oscillations are removed on account of its dynamic properties.



a) Adjustment of flexibility

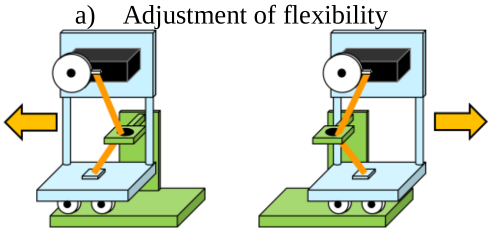

b) Slide mechanism

Fig. 2. Diagrammatic illustration of the flexible joint

4 DEVELOPED ROBOT

4.1. Humanoid robot

Fig. 3 shows our previous robot [6], and Figs. 4 to 6 show the robot that we discuss in this paper, and Table 1 lists its specifications. In our previous robot, two flexible joints are embedded in each leg, increasing the complexity and the weight. In particular, increase of the legs' weight causes a decrease in the robot's mobility. In this paper, we improve these issues by embedding two flexible joints in the robot's waist. By this mechanism, we reduce the number of the flexible joints and can employ legs with both a simple design and high mobility.

As shown in Fig. 5, the two flexible joints in the robot's waist are at right angles to each other, and can handle two-dimensional horizontal oscillation.

A CCD camera for detecting a target position is installed in the robot's head, and a micro-computer for controlling the servo motors is mounted on the body.

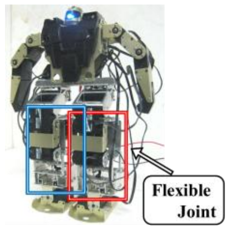


Fig. 3. Previous humanoid robot

Table 1. Details of a humanoid robot

Height	380 mm	Weight	1.78 kg
Width	180 mm	Actuator	KRS-4034HV, KRS-788HV
Depth	130 mm	Degree of freedom	16

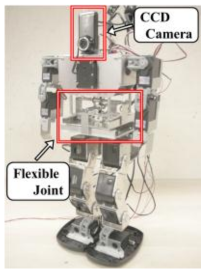


Fig. 4. Humanoid robot

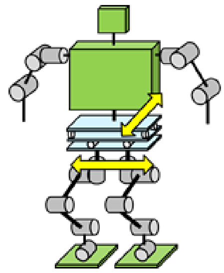


Fig. 5. Sliding direction of the flexible joints

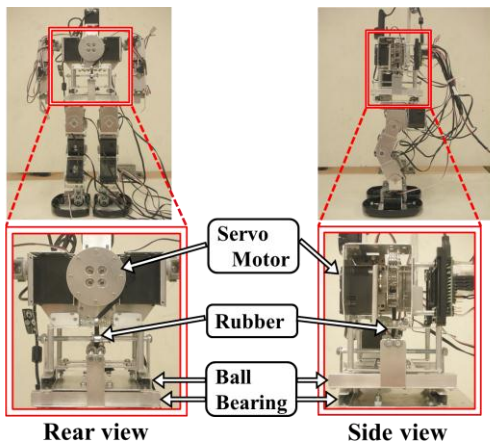


Fig. 6. Developed flexible joint

4.2. Adjustment of the spring constant

Fig. 6 shows the developed flexible joint. The pulling force of the rubber in the horizontal direction F can be approximated by equation (1). As shown in Fig. 7, the elasticity (k of equation (1)) of the flexible joint can be adjusted by rolling up the rubber band through use of the servo motor.

From preliminary experiments, the relation between k and the angle of rotation of the servomotor was given by Fig. 7, and it can be approximated by equation (2).

$$F = -kx \tag{1}$$

$$k = 0.36\frac{\theta}{\pi} + 0.15 \tag{2}$$

k : Constant of spring [N/mm]

θ : Angle of rotation of the servo motor [rad]

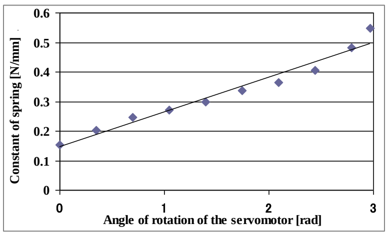


Fig. 7. Constant of spring

4.3. Frequency response of the flexible joint

The motion equation of a flexible joint is shown by equation (3). The frequency response of the flexible joint is shown in Fig. 8. The dotted line represents a high-elasticity (k = 0.50) joint and the solid line represents a low-elasticity (k = 0.15) joint. The cut off frequency of the high-elasticity joint is 7.7 Hz, and that of the low-elasticity joint is 3.7 Hz.

$$M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + kx = f \tag{3}$$

M : Mass [kg]
D : Viscosity resistance [Ns/m]
k : Constant of spring [N/mm]
f : External force [N]

Table 2. Value of parameters

M	D	k (low)	k (high)
0.88 kg	1.00 Ns/m	0.30 N/mm	1.00 N/mm

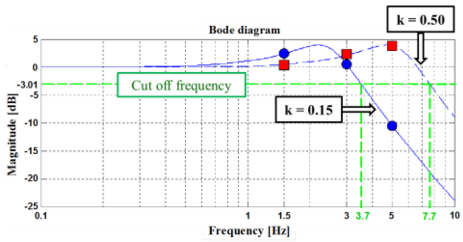


Fig. 8. The frequency response of a flexible joint

5 EXPERIMENT

To demonstrate the effectiveness of the proposed flexible joints, we conduct two experiments. In one experiment, the robot has to stand still on a horizontally oscillating plane, and in the other, the robot is required to walk on the oscillating plane toward a red colored moving target. The target is sensed by a CCD camera, and its image is transmitted to a PC, as shown in Fig. 9. The control signal that causes the robot to start moving to the target is generated by the PC and is transmitted to the micro-computer. The micro-computer generates walking behavior on the basis of the transmitted control signal and the already programmed walking patterns designed for static surfaces. The important point to note is that the oscillation of the surface is not measured and only the walking patterns for a static surface are employed. The oscillation is compensated for by the flexible joints, and hence, the load of the controller is reduced.

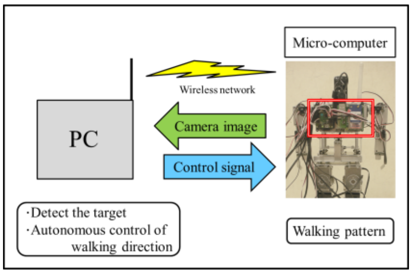
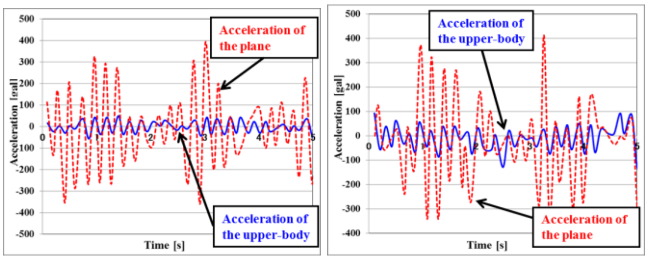


Fig. 9. Intercommunication network

5.1 Experimental Results when the robot stands still

Fig. 10 and Table 3 show the experiment results of standing still. In Fig. 10, the solid line shows the acceleration of the upper body and the broken line shows the acceleration of the plane. Table 3 shows the ratio of the amplitude of the oscillation of the upper body to the amplitude of surface oscillation. From Table 3, we see that sympathetic vibration occurs when the spring constant is low, leading the robot to fall at a frequency of 1.5 Hz. However, the surface oscillation is absorbed when the spring constant is low in cases of higher frequency oscillation, and the oscillation of the upper body of the robot is decreased.



(a) Side to side (b) Front to back

Fig. 10. Result of acceleration (5.0 Hz, k = 0.15)

5.2 Result of the experiment where robot moves to target position

Fig. 11 shows an example of the result. In the case where the constant of the spring is low (k = 0.15), the robot could walk on the oscillating plane and move to the target. On the other hand, in the case where no flexible joints are present (all joints are fixed), the robot falls.

Table 3. Ratio of amplitude (Maximum acceleration of upper body [gal] / Maximum acceleration of ground [gal])

	1.5 Hz		3.0 Hz		5.0 Hz	
	side to side	front to back	side to side	front to back	side to side	front to back
fixing	36 / 36	36 / 36	falling	falling	falling	falling
k = 0.50	38 / 36	38 / 36	falling	falling	falling	falling
k = 0.23	falling	falling	60 / 146	93 / 150	102 / 405	184 / 394
k = 0.15	falling	falling	73 / 148	117 /153	56 / 393	93 / 414

From these results, we can confirm that the developed flexible joint has the characteristic of a low-pass filter, and due to this characteristic, the robot can move to the goal position on the oscillating plane without controllers for handling the oscillation.

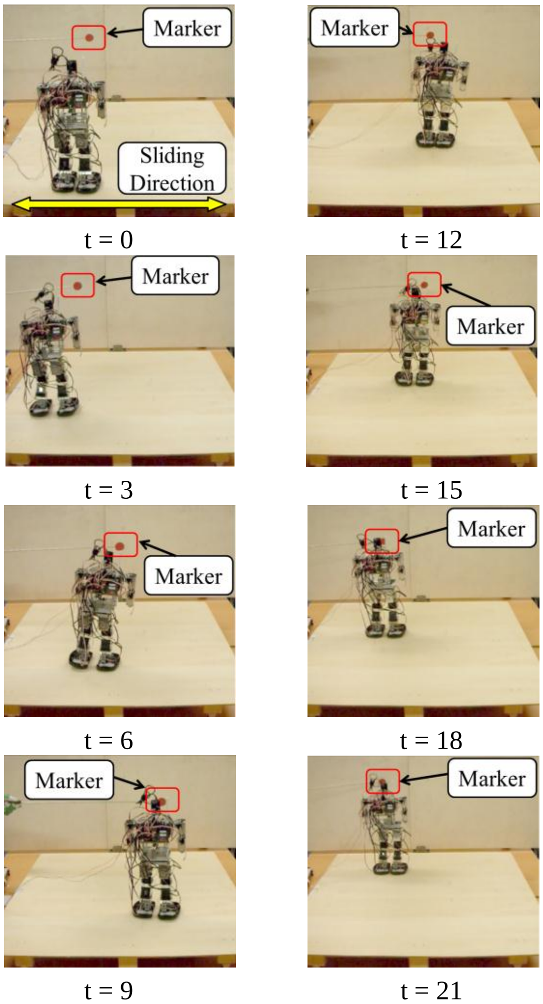


Fig. 11. Walk on the oscillating plane (5.0 Hz, k = 0.15)

6 CONCLUSION

In this study, we developed flexible joints for a humanoid robot that walks on an oscillating plane. By incorporating the flexible joint into the waist of a humanoid robot, we made it possible for the robot to move toward a goal position on a horizontally oscillating plane.

To demonstrate the effectiveness of the developed flexible joint, we conducted two experiments, in which effective walking behaviors were observed.

ACKNOWLEDGMENT

This work was supported by a 2011 Grant-in-Aid for Young Scientists (B), 22700156, from the Ministry of Education, Science, Sports and Culture of Japan.

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