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Inclined Plane Walking Compensation for a Humanoid Robot

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Abstract: This paper suggested the simple compensation algorithm for a humanoid robot when walking on an inclined plane. Motion transition of the robot for varying slope can be achieved from adjusting the center of mass of the robot forward/backward by compensating the robot's ankle. This proposed method used the feedback from the accelerometer in the robot's body to detect the inclination angle of the ground plane. The proposed method was tested with a small-sized humanoid and showed that it can successfully maintain stability of the walk on a varying inclined plane up to 10 degrees.

Keywords: Walking controller, Humanoid, IMU

1. INTRODUCTION

In this paper, we propose how to control a humanoid robot to walk up/down the slope when the slope is changed. For example, Christophe Sabourin et al [1] used the Fuzzy-CMAC to adapt the walking gait as a function of the information on the slope. In their simulation, the robot can walk up and down a slope when the desired slope is changing. Lin Yang et al [2] presented three basic bipedal walking gait adjustment modes which can be adapted to the rough terrain including a slope on the 2D simulation. Jun Morimoto et al [3] proposed a model-based reinforcement learning algorithm to adapt the walking cycle timing to the dynamics of the robot and environment when the robot walking up/down on the inclined plane.

Different walking controllers have been designed for a humanoid robot such as ZMP-based control, linear inverted pendulum model control (LIPM). For walking on an inclined plane or an uneven terrain, most studies used the simulation model of the robot and its environment with a known inclined angle [4] to verify the results or used a predictive controller that included external sensors such as ultrasonic [5] or camera to sense the terrain ahead.

In this paper we proposed the method that uses the information from the robot internal sensor to adjust the robot's walking control law to cope with changes of the ground plane inclined angle. The concept of this method is quite simple and straight forward. With our existing control algorithm, the joint position control was applied to all motors on the robot. The balancing control is performed by compensating the joint ankle position with the feedback signal from the gyro sensors. Without the adjustment that we are proposing here, when the robot stands on an inclined plane, it will try to stay in the upright pose, therefore the body angle as references to the world coordinate directly represents the angle of the inclined plane. Therefore, by adjusting the target position of the ankle so that it can properly compensate for the inclination angle, the robot will be more stable when walking on the incline.

2. WALKING CONTROL SYSTEM

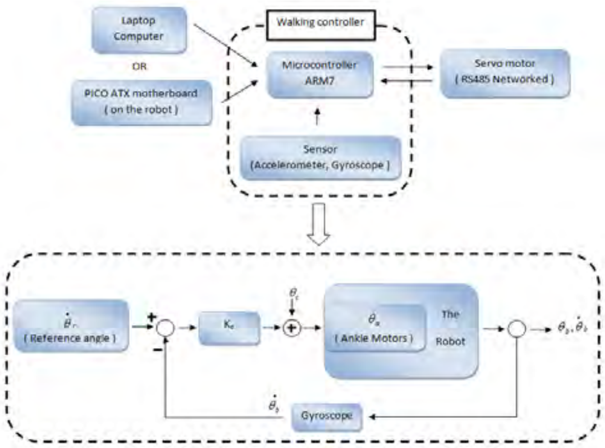

Fig. 1 The humanoid robot walking control system

Fig.1 shows the balancing control system that is used in our humanoid robot. The locomotion control algorithm is performed by the ARM7 microcontroller. After the PC sends a locomotion command to the microcontroller, the joint trajectory for walking is generated according to the walking parameters such as step height, step size, step time and the leg inverse kinematics. During the walk cycle, the balancing control is added to the ankle joint control input. The compensation value was calculated from the robot's angular velocity ($\dot{\theta}_b$) that is sensed by the gyroscope attached inside the robot's body. In the normal operation, the ankle control law can be represented by (1)

$$\theta_a = \theta_a + K_d \dot{\theta}_b \tag{1}$$

Where θ_a is the ankle angle.

K_d is the control gain.

3. ANKLE COMPENSATION FOR INCLINED PLANE WALKING

3.1 Finding ankle compensation angle

In order to walk on an incline, the balancing control alone which only uses the gyro feedback cannot cope with the changes of the body angle as references to the world. Therefore the target angle for the robot's ankle should be adjusted so that the body can lean in the right direction when walking up/down an incline. In this paper, we proposed the ankle compensation function that will be used for the inclined plane walking. We used the ankle compensation function to find the value (θ_c) to compensate the robot's ankles. Ours compensation function was calculated from the body angle that can be measured from the 2-axis accelerometer attached inside the robot's body. In the standing pose, the body angle (θ_b) can be calculated from Eq. (2).

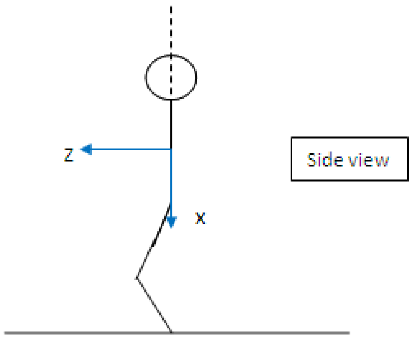

Fig. 2 Body angle calculation from 2-axis accelerometer

$$\theta_b = \tan^{-1}\left[\frac{A_z}{A_x}\right] \tag{2}$$

Where A_x is the body acceleration in X axis.

A_z is the body acceleration in Z axis.

However, during the walk, the body angle has to be estimated from the accelerometer signal using a moving average window filter. After the body angle is estimated, the target angular position of the robot's ankle should be compensated so that the center of gravity of the robot's body can be move forward when the robot is walking up/down the inclined plane as shown in Fig. 3.

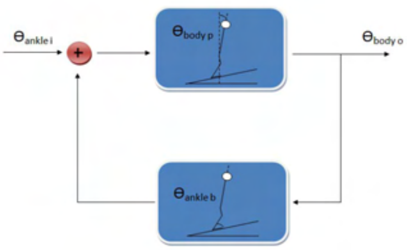

Fig. 3 Ankle angle adjustment on an inclined plane

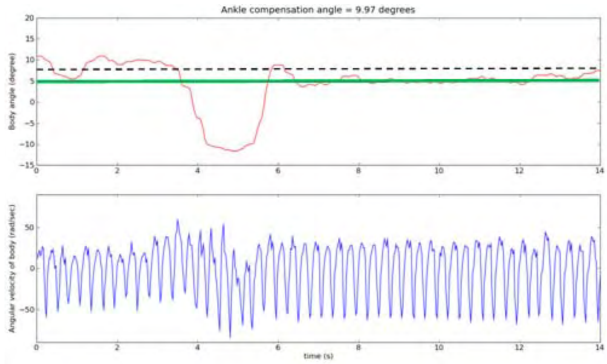

Fig. 4 The body angle and angular velocity when the robot was walking from 0 to 10 degrees incline with the ankle compensation angle of 9.97 degrees.

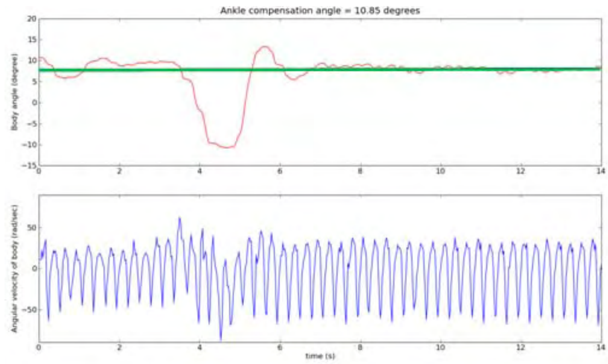

Fig. 5 The body angle and angular velocity when the robot was walking from 0 to 10 degrees incline with the ankle compensation angle of 10.85 degrees.

In order to find the appropriated compensation function, we ran an experiment to identify the proper angular bias of the robot's ankle at different inclined angles. The angular bias is selected from experiments as shown in Fig. 4 and 5. The ankle compensation of 10.85 is chosen for 10 degrees incline because the average body angle of the robot was maintained in the same level as at 0 degree, while at 9.97, the average value of body angle is lower when the incline was encountered. The angular bias that the most stable walking motion can be realized for different incline angles were summarized in Table 1. Fig.6 shows the linear function that can be derived from the relation between the inclination angle and the ankle compensation value.

Table 1 The ankle compensation angle

Inclination angle (Degrees)		Ankle compensation angle (Degrees)	
Walking up	Walking down	Walking up	Walking down
2	-2	2.19	-2.63
4	-4	4.39	-4.98
6	-6	6.30	-7.47
8	-8	8.21	-9.67
10	-10	10.85	-11.73

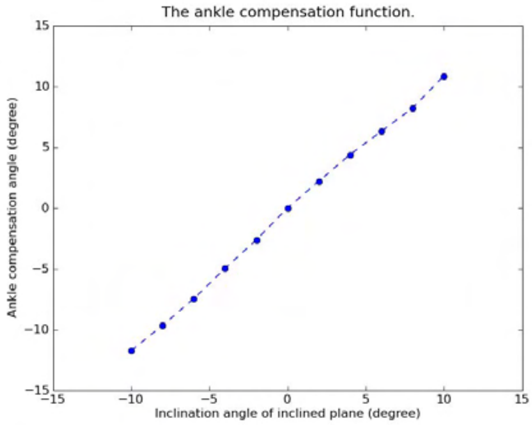

Fig. 6 The linear relation between the ankle compensation angle and the inclination angle

3.2 Walking compensation

From Table 1, we found that the compensation function for the target angular position of the robot's ankle according to the measured body's angle can be fitted into a linear function as shown in Fig.6. Therefore, after the body angle is estimated from the 2-axis accelerometer, the new ankle position (θ_c) of the robot can be calculated from the compensation function as shown in eq.3.

$$\theta_a = \theta_c + K_d \dot{\theta}_b \qquad (3)$$

Fig. 7 showed the estimation of the body angle from the accelerometer data that changed due to the changing inclined angle of the plane. The new ankle position is calculated when the body angle estimation changes more than a specified threshold. Normally, during the walk on a flat plane, the robot's body will lean forward about 7 degrees. We intentionally set the body angle of the robot to lean forward during that walk for the faster walking speed. In Fig.7 (a) when the robot walked from the flat plane to the slope of 10 degrees inclination, the body angle estimation was largely reduced (at around time 3 to 4 seconds). The new ankle position was set when the body angle estimation became lower than 4 degrees. After the new ankle position was set according to the ankle compensation function, the body angle increased to the same level of 7 degrees as before. The same behavior was shown in Fig. 7 (b) when the robot walked down from the incline of -10 degrees to 0 degrees. When the change of inclination angle was encountered, the body angle estimation became lower. The new ankle position was compensated when the body angle estimation was lower than 4 degrees, so that the body angle increased back to about 7 degrees.

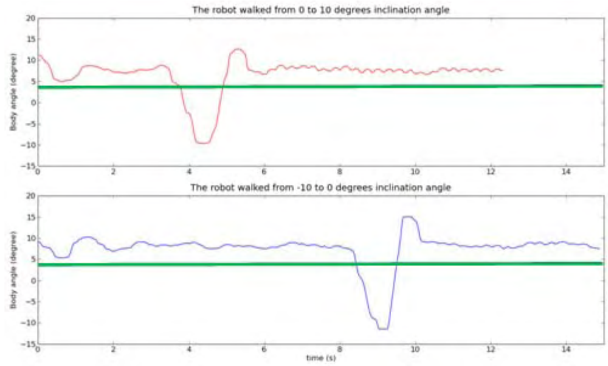

Fig. 7 The estimation of the body angle when the inclination angle of the plane is changed
(a) Walking up from 0 to 10 degrees, (b) Walking down from -10 to 0 degrees

4. EXPERIMENT

The small-sized humanoid robot KM-3 was used in this experiment. KM-3 has 18 DOF with 6 DOF in each leg. This robot is 49 cm tall and weighs 3.3 kg. The 2-axis accelerometer sensors and the 2 axis gyro sensors were installed inside the robot's body. The specification of KM-3 is shown in Table 2.

Table 2 KM-3 Specification

Actuators	Servo motor : ROBOTIS Dynamixel		
		RX-28	Rx-64
	Max Holding Torque (kgf.cm)	37.7(at 16V)	64(at 18V)
	Speed (Sec/60 degrees)	0.126	0.162
Sensor	Camera : Logitech Quickcam Pro9000		
	Accelerometer: Memsic MX2125 (+/- 3g)		
	Rate Gyro (2X) : Silicon Sensing Systems, CRS03-02 (+/- 100 deg/sec)		
Processor	Locomotion controller: Philips LPC-2138 (ARM7 TDMI-S 60MHz)		

In this experiment, the robot blindly walked on the inclined plane that changed its inclination angle from 0 degrees to 1-10 degrees and from -10 degrees to -9 until 0 degrees. Two cases were compared, without the ankle compensation and with the proposed ankle compensation method. In each experiment, the robot walked up and down 10 trials. The location of the incline change is randomly chosen at each trial, thus the robot can only sense the location of the inclination changes from the changes of its body angle estimation using the accelerometer.

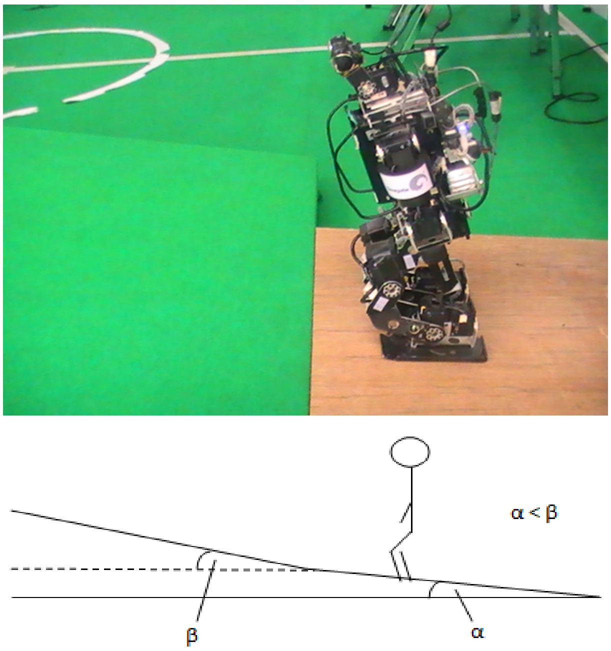

Fig. 8 The experimental humanoid robot

4.1 Walking up an incline

In this experiment, the robot would walk up on the flat plane (0 degree) into the inclined plane that has 10 degrees inclination angle using the compensation function that we found from Table 1. The robot's body angle was set to lean forward at 7 degrees during the walk. The walking parameters were set as shown in Table 3. The new ankle angle was adjusted when the estimated body angle from the accelerometers was lower than 4 degrees.

Table 3 Walking parameters

Parameter Name	Parameter Value	
	Walk up	Walk down
Step size (m)	0.025	0.02
Step height (m)	0.025	0.025
Step time (s)	0.14	0.14
Walking speed (m/s)	~0.175	~0.14

The experimental results show that with the proposed ankle compensation based on the body angle estimation from accelerometer sensor, the robot can successfully walk up the inclined plane that changed from 0 to 10 degrees. Fig.9 showed the frame sequence of the robot that can walk up on the inclined plane that changed from 0 to 10 and Fig. 10 showed the comparison of the body angle estimation of the robot with and without ankle compensation. Without ankle compensation, the robot fell backward after the inclination change was encountered.

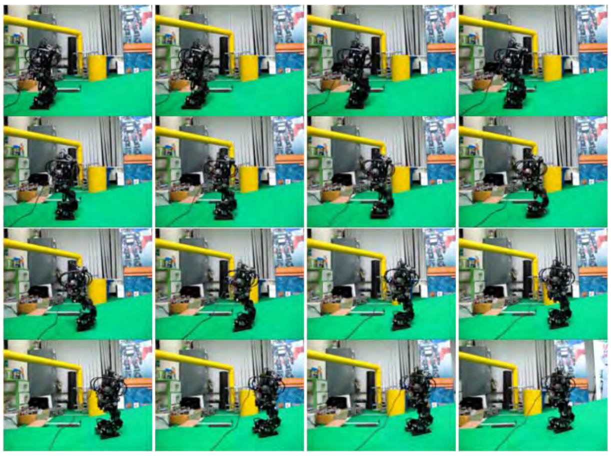

Fig. 9 Sequence of successive frames extracted from the video showing the robot when walking up on the inclined plane that changed from 0 to 10 degrees successfully.

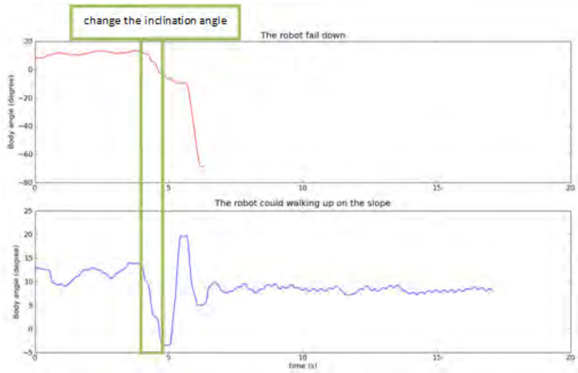

Fig. 10 The body angle estimation of the robot when walking on the changing slope from 0 to 10 degrees. (a) Without compensation, (b) With ankle compensation

4.2 Walking down an incline

After we successfully applied the ankle compensation control to make the robot walk from the flat plane up to the inclined plane. We also used this proposed method to control the robot to walk downward from the inclined plane that has -10 degrees inclination angle to the flat plane.

However, when the robot is walking down on the inclined plane, it has higher acceleration than walking up. Therefore, the robot’s walking velocity had to be reduced by adjusting the step size. We decreased the step size from 0.025 to 0.02 meters/step in the walking down experiment. Other walking parameters were kept to be the same as in the walking up experiment as shown in Table 4. The experimental result was shown in Fig. 11~12.

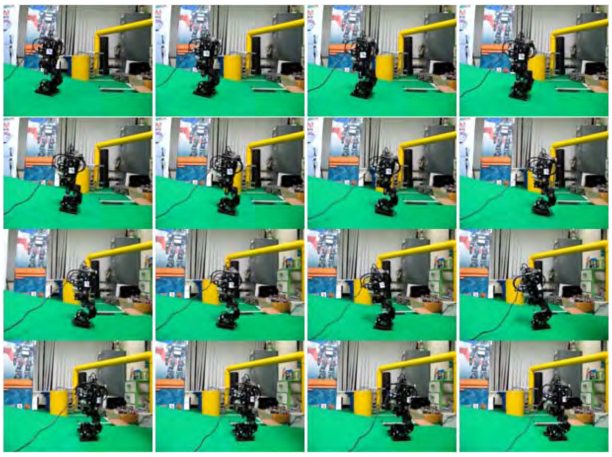

Fig. 11 Sequence of successive frames extracted from the video showing the robot when walking up on the inclined plane that changed from -10 to 0 degrees successfully.

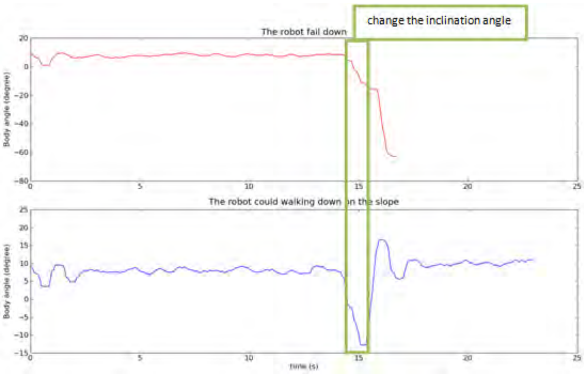

Fig. 12 The body angle estimation of the robot when walking on the changing slope from -10 to 0 degrees. (a) Without compensation, (b) With ankle compensation

Without the proposed compensation method, the robot cannot maintain stability when the inclination angle of the plane changes. This proposed compensation method is very simple and can be computed in real-time using the on-board microcontroller. This method does not require additional sensors such as force sensor or camera. However, the proposed method is quite limited in its lack of predictability of the action ahead because the compensation can only activated based on the change of its body angle after the robot is already on the inclined plane.

5. CONCLUSION

In this work, the compensation control law for the humanoid robot for inclined plane walking is proposed. By estimating the body angle of the robot from the 2-axis acceleration sensors which were processed by the moving-average window filter, the new target position of the ankle was compensated based on the compensation function derived from the experimental result in Table 1. From the experiment, the humanoid robot can walk up/down the slope with the inclination angle changes from 0 to 10 degrees and from -10 degrees to 0 degrees successfully using the proposed ankle compensation method. However, since the compensation ankle adjustment can only be calculated from the body angle measurement from the accelerometers, this method would not be sufficiently robust to cope with large changes of inclination angle of more than 10 degrees. Additional sensors that can provide predictive information of the terrain ahead might be useful when the changes of inclination angle are large.

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