

# Development of Fuzzy Logic Controllers for Controlling Bipedal Robot Locomotion on Uneven Terrains with IMU Feedbacks

Chung-Hsien Kuo<sup>1\*</sup>, Fahmi Zal<sup>1</sup> and Shih-Lin Wu<sup>2</sup>

<sup>1</sup>Department of Electrical Engineering, National Taiwan University of Science and Technology; chkuo@mail.ntust.edu.tw, fahmizal@ugm.ac.id

<sup>2</sup>Department of Computer Science and Information Engineering, Chang Gung University; slwu@mail.cgu.edu.tw

## Abstract

Locomotion controller is an important and essential aspect for bipedal robots. Typically, a Linear Inverted Pendulum Model (LIPM) is a mathematical approach to generate the Center of Mass (CoM) trajectory of a bipedal robot. By combining the swing foot trajectory, the omni-directional walking command is capable of generating joint angle control commands in terms of Inverse Kinematics (IK). To improve bipedal locomotion stability on uneven terrain situations, an Inertia Measurement Unit (IMU) was desired to place on the robot's chest was used to measure the body's tilt posture on uneven terrains. The robot body's tilt posture provided an indication of locomotion stability. The body's tilt posture information was further evaluated with a Fuzzy Logic Controller (FLC) to generate appropriate offset angles to be applied on the corresponding joints so that the body's tilt posture can be adjusted accordingly to meet a stable situation. Finally, a kid-size bipedal robot, named Huro Evolution JR, was used as the experiment platform. The proposed FLC can be applicable to the terrain conditions of maximum 25° slope in Double Support Phased (DSP) stand cases. With the walking cases, the FLC is capable of walking on maximum 12° slope, 1 cm stair height and the combined terrain situation well. In the future, the Center of Pressure (CoP) information will be accompanied with the IMU information to further improved the locomotion stability in a high dynamic environment.

**Keywords:** Bipedal Robots, Fuzzy Logic Controller, Inertia Measurement Unit, Uneven Terrain Locomotion Stability

## 1. Introduction

The biped robot has drawn a lot of attention from robotics researchers as their research target. Bipedal structure is one of the most flexible forms of a walking robot. A bipedal robot has a similar mechanism of action as a human being; hence bipedal robots are desired to walk in environments containing uneven terrains, such as slopes<sup>1</sup> and stairs<sup>2</sup>, and obstacles<sup>3</sup>. Sato et al.<sup>4</sup> proposed a walking trajectory scheme on a stair environment in terms of virtual slopes. Crisóstomo et al.<sup>5</sup> used the Support Vector Regression (SVR) to overcome the limitation on the processing time on Zero Moment Point (ZMP). Several researches proposed flexible shoes for bipedal robots to reduce energy consumption, such as<sup>6</sup>. Suwanratchatamane et al.

<sup>7</sup> proposed a haptic sensing foot module for humanoid robots. They investigated two different implementation approaches: the first one is to propose an active tactile sensing system, and it could recognize the contacting ground slope; the other is desired to keep the robot's body balance with one leg during physical interaction between human and robot.

In intelligent control areas, many researchers demonstrated that Fuzzy Logic Controller (FLC) theory can be used to overcome bipedal locomotion problems. In<sup>8</sup>, a type-2 fuzzy switching control system for the Double Support Phases (DSPs) and Single Support Phases (SSPs) have been developed for a bipedal robot. The fuzzy controller can also be realized to deal with bipedal walking on the slope with the desired ZMP trajectory

\* Author for correspondence

in<sup>10</sup>. A Dynamic Balance Control (DBC)<sup>9</sup> which consists of a Kalman Filter (KF) and a Fuzzy Motion Controller (FMC) was developed to keep the body balance while following desired ZMP references. In addition, KF was utilized to estimate the system states as well as to reduce noise inference. Moreover, the studies from<sup>11</sup> and<sup>12</sup> also proposed the techniques of sensor fusion and the application on uneven terrains.

In summary, the bipedal locomotion stability program on uneven terrain environment can be resolved in terms of sensor data collection and presentation as well as the sensor-feedback based control approaches. Therefore, this paper implemented an IMU sensor module to measure the stability indication of locomotion from the robot body tilt posture. According to the IMU sensor information, a fuzzy logic controller was developed to maintain stable locomotion on uneven terrains. Finally, a kid-size humanoid robot, named Huro Evolution JR, was used to evaluate the proposed control systems. The rest of this paper is arranged as follows. Section 2 describes the IMU sensor module and signal processing; section 3 elaborates the control systems; section 4 addresses the experiments and results; finally the conclusion and future works were summarized in section 5.

## 2. Sensor Modules and Signal Processing

In this paper, a 9-DOF IMU (with type LSM303DLH) was used to measure the body tilt posture. The LSM303DLH IMU consisted of a digital 3-axis accelerometer, a digital 3-axis gyro meter and a digital 3-axis magnetometer. The accelerometer and magnetometer are used for making a tilt-compensated compass. The IMU fusion for attitude orientation is shown in Figure 1. First of all, a complementary filter was realized to combine the 3-axis accelerators (with a low pass filter) and 3-axis gyros (with a high-pass filter) to produce pitch and roll calculation. Then, the outputs of the complementary filter and the 3-axis magnetic sensor data were combined to obtain the tilt compensated heading. The equations for obtaining the roll ( $\theta$ ) and pitch ( $\phi$ ) from tilt sensing (accelerometer and gyroscope) are shown in (1) - (2). The yaw (heading) can be found from (3). It is noted that the variables of  $x, y, z, X, Y$  and  $Z$  can be found from Figure 1.

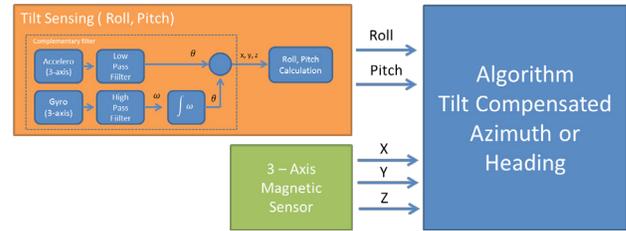


Figure 1. IMU fusion for attitude orientation.

$$\text{roll}(\theta) = \tan^{-1} \frac{y}{\sqrt{x^2+z^2}} \tag{1}$$

$$\text{pitch}(\phi) = \tan^{-1} \frac{x}{\sqrt{y^2+z^2}} \tag{2}$$

$$\text{Yaw(Heading)} = \tan^{-1} \frac{Yh}{Xh} \tag{3}$$

$$Xh = X \cos \phi + Y \sin \theta \sin \phi - Z \cos \theta \sin \phi, \\ Yh = Y \cos \theta + Z \sin \theta$$

## 3. Control Systems

### 3.1 Overall System Architecture

This paper proposes the sensor-feedback based bipedal locomotion for uneven terrains. According to the robot's body tilt posture information, the locomotion control system can be designed as shown in Figure 2. At the beginning, the  $\{x_{cmd}, y_{cmd}, \theta_{cmd}\}$  were commands that may be generated from an autonomous navigator or user's command, where  $x_{cmd}$  and  $y_{cmd}$  are relative translational landing position of a swing foot with respect to a support foot;  $\theta_{cmd}$  is the relative landing foot heading angle. Hence, the  $\{x_{cmd}, y_{cmd}, \theta_{cmd}\}$  command is an omni-directional walking command for bipedal robots that can be used to process footprint placement trajectory planning. The 18 degrees of freedom robot structure, robot picture (with 38 cm height and 2.9 kg weight) and the footprint placement coordinates are shown in Figure 3.

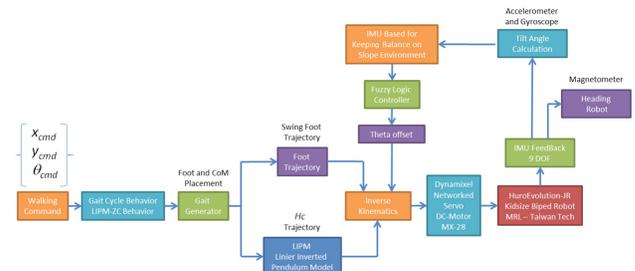


Figure 2. Overall system architecture.

In addition to the omni-directional walking command, the bipedal locomotion is desired with a Linier Inverted Pendulum Model (LIPM)<sup>11</sup> to generate Center of Mass (CoM) trajectory. With the generated CoM trajectory, the trajectory of the hips' center ( $H_c$ ) can be also obtained accordingly. The components of  $H_c$ , ( $h_{xc}$ ,  $h_{yc}$ ,  $h_{zc}$ ) can be found in (4) - (6),

$$h_{xc}(t) = [x(0) - p_x] \cosh\left(\frac{t}{T_c}\right) + T_c x'(0) \sinh\left(\frac{t}{T_c}\right) + p_x \quad (4)$$

$$h_{yc}(t) = [y(0) - p_y] \cosh\left(\frac{t}{T_c}\right) + T_c y'(0) \sinh\left(\frac{t}{T_c}\right) + p_y \quad (5)$$

$$h_{zc}(t) = base_z + amp_z \times \{0.5 - 0.5 \cos(4\pi f) + 0.02 \sin(4\pi f)\} \quad (6)$$

Where  $p_x$ ,  $p_y$ , and  $p_z$  are the hip position in  $x$ -,  $y$ - and  $z$ -coordinates respectively which will be updated each time regarding to the hip position changes;  $base_z$  is the hip height;  $amp_z$  is the amplitude for the hip swing;  $T_c$  is the time constant;  $t$  is the time. The time constant  $T_c$  is defined in (7) where the  $g$  is the gravity; the  $LipmZ_c$  is the robot LIPM center of mass.

$$T_c = \sqrt{\frac{LipmZ_c}{g}} \quad (7)$$

To achieve the trajectory of planed locomotion, the end position of each foot is also required. The trajectory of the swing foot is formed as a cycloid curve as indicated in (8) - (10). It is noted that  $x_s$ ,  $y_s$  and  $z_s$  are the position of the swing foot;  $Length$ ,  $Height$  and  $Shift$  are the desired strike length, the strike height and the shift distance;  $\rho$  is the time percentage of the period time when the foot reaches the highest position;  $T_s$  is the period time. To get the real robot rotation based on the desired rotation, (11) is utilized to do so, where  $T_{\theta C}$  is the rotation time

constant. As a consequence, the gait trajectory can be obtained as the swing foot trajectory and the  $H_c$  trajectory. The inverse kinematics (IK) can be applied to the gait trajectory to find the joint angles of the bipedal leg model. The joint commands were sent to the RC motors (type: Dynamixel RX-28). The IMU sensor worked in real time to get the aforementioned stability indication. The IMU feedback loop is shown in the right-hand-side loop of Figure 2. The feedback control loop is elaborated in the next subsections.

$$x_s(t) = \frac{Shift}{2\pi} \left[ 2\pi \frac{t}{T_s} - \sin\left(2\pi \frac{t}{T_s}\right) \right], \quad 0 \leq t \leq T_s \quad (8)$$

$$y_s(t) = \frac{Length}{2\pi} \left[ 2\pi \frac{t}{T_s} - \sin\left(2\pi \frac{t}{T_s}\right) \right], \quad 0 \leq t \leq T_s \quad (9)$$

$$z_s(t) = \begin{cases} \frac{Height}{2\pi} \left[ 2\pi \frac{t}{\rho T_s} - \sin\left(2\pi \frac{t}{\rho T_s}\right) \right], & 0 \leq t \leq \rho T_s \\ Height - \frac{Height}{2\pi} \left[ 2\pi \frac{t - \rho T_s}{(1-\rho)T_s} - \sin\left(2\pi \frac{t - \rho T_s}{(1-\rho)T_s}\right) \right], & \rho T_s < t < T_s \end{cases}$$

$$hip_{rotation} = \frac{\left| \frac{1}{2} \theta_{vector} \right|}{T_s(1-2T_{\theta C})} \quad (10)$$

$$hip_{rotation} = \frac{\left| \frac{1}{2} \theta_{vector} \right|}{T_s(1-2T_{\theta C})} \quad (11)$$

### 3.2 Fuzzy Logic Controller Design

In this paper, the body posture can be adjusted in terms of applying appropriate offsets to the corresponding joint angles that were obtained from IK to maintain locomotion stability on uneven terrains. The related body posture parameters are illustrated in Figure 4 for the future uses of FLC. In Figure 4, 10 bipedal joint angles, bipedal limb lengths and inclination offsets are defined. In the frontal plane, four joints consisting of left hip roll ( $\theta_{2L}$ ), left ankle roll ( $\theta_{4L}$ ), right hip roll ( $\theta_{2R}$ ) and right ankle roll ( $\theta_{4R}$ ) are used. In the sagittal plane, six

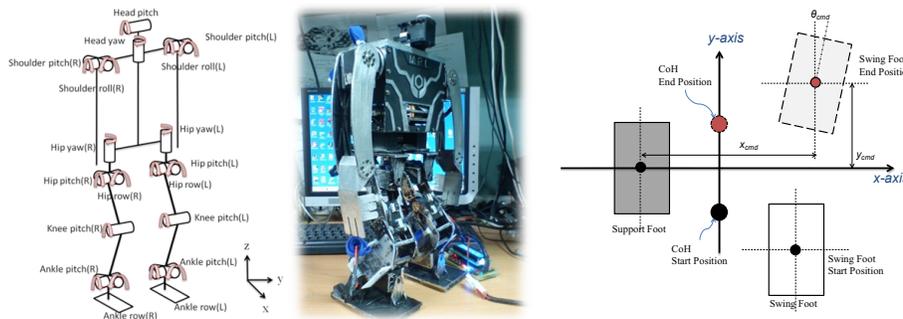


Figure 3. Bipedal robot picture and the footprint placement coordinates.

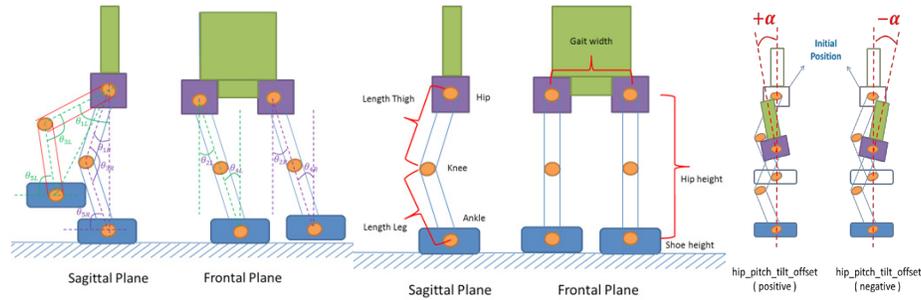


Figure 4. Parameter definition of body posture control.

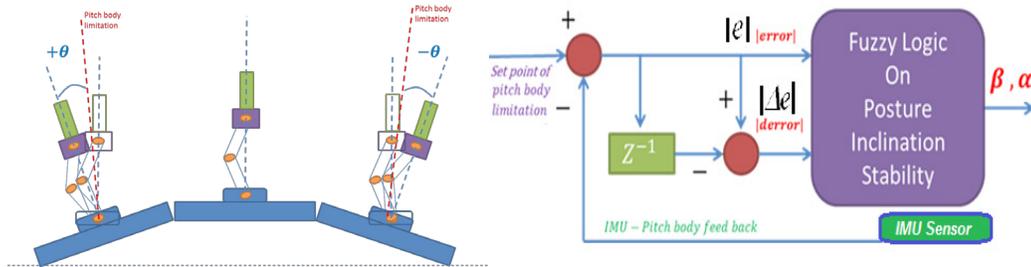


Figure 5. Body tilt posture indication and the proposed FLC.

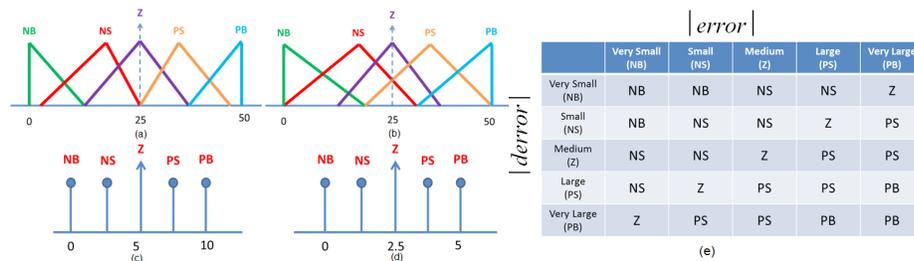


Figure 6. Details of FLC design, including input/ output membership functions and rule tables.

joints consisting of left hip pitch ( $\theta_{1L}$ ), left knee pitch ( $\theta_{3L}$ ), left ankle pitch ( $\theta_{5L}$ ), right hip pitch ( $\theta_{1R}$ ), right knee pitch ( $\theta_{3R}$ ), right ankle pitch ( $\theta_{5R}$ ) are used. There are several parameters that will be used to adjust the posture of the bipedal robot, and they are  $hip\_x\_offset$  ( $\beta$ ),  $hip\_pitch\_tilt\_offset$  ( $\alpha$ ),  $hip\_height$ ,  $length\_of\_thigh$ ,  $length\_of\_leg$ ,  $shoe\_height$  and  $gait\_width$ .

In this subsection, the design of FLC is to deal with the posture inclination stability problem. The implementation of fuzzy logic controller followed the procedures of 1) crisp input, 2) fuzzification, 3) fuzzy input, 4) rule evaluation, 5) fuzzy output, 6) defuzzification, and 6) crisp output. In order to control the bipedal robots to be able to walk on uneven terrain and slope environments, the stability indication from an IMU sensor was calculated to present the trunk body inclination.

The proposed FLC is a two inputs and two output control system, as shown in Figure 5. The inputs are  $|e|$  (i.e.,  $|error|$ ) and  $|\Delta e|$  (i.e.,  $|derror|$ ), where  $|e|$  is the absolute value of error between the current body tilt angle and the pitch body limitation (for example  $\pm 9^\circ$  in this paper);  $|\Delta e|$  is for differential term application with 100 Hz sampling. That means if the body posture could be controller within this range, the robot would not walk stably. However, such a range limitation has to be adjusted manually according to the bipedal robot's condition, such as foot pad size, CoM, etc. The outputs of the FLC are  $\alpha$  and  $\beta$ , and they are  $hip\_pitch\_tilt\_offset$  and  $hip\_x\_offset$ .

The details of the FLC are further illustrated as shown in Figure 6, where (a) and (b) are the input membership functions of  $|error|$  and  $|derror|$ , respectively; (c) and (d) are the output membership functions of  $\alpha$  and  $\beta$ ,

respectively. The result (outputs) of defuzzification on this case is the *hip\_x\_offset* and *hip\_tilt\_offset*. The offset values were applied for adjusting the robot body posture tending to lean backwards or forwards on the pitch tilt angle of robot. In order to provide more effective balance locomotion, the robot's upper arms were also further utilized. The tilt angles of two upper arms were controlled simultaneously following the *hip\_tilt\_offset* angle,  $\alpha$ , with a constant gain  $k$ . Hence, the upper arm's tilt angle ( $k\alpha$ ) is also varied with the *hip\_tilt\_offset* angle, as shown in Figure 7. Finally, the bipedal locomotion controller and FLC were realized with an Arduino DUE ARM (Advance RISC Machine) 32-bit microcontroller (type: Atmel SAM3X8E ARM Cortex-M3 CPU) running at 84 MHz clocks. Moreover, the bipedal locomotion controller and FLC executed at 100 Hz for generating final servo motor commands.

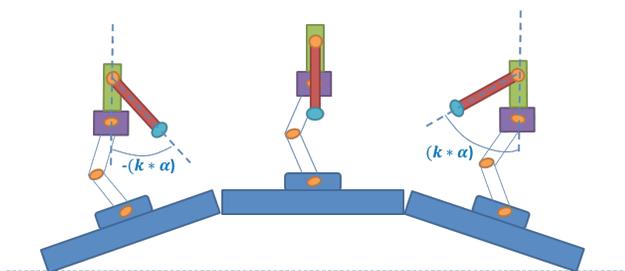


Figure 7. Upper arm angle control scenario for different terrain slopes.

## 4. Experiments and Results

This subsection shows the results on evaluating the accelerometer and gyroscope components in an IMU sensor. As shown in Figure 1, the cut-off frequency of

the high pass filter is 0.5 Hz; the cut-off frequency of the low pass filter is 5 Hz. The high pass filter was desired to remove the DC drift of the gyroscope; the low pass filter was desired to reject the high frequency interference from the accelerometer. The reason of selecting the 2.5 Hz as the cut-off frequency of the low pass filters is the low-frequency characteristics of mechanical bipedal locomotion. Figure 8 (a) shows the filtering results of the accelerometer data, and it can obtain reasonable signal quality for the further tilt angle indication. In addition, Figure 8 (b) shows the final roll-pitch-yaw angles which was addressed in (1) - (3).

According to the IMU sensor feedback, the bipedal locomotion controller accompanied with the proposed FLC could perform locomotion stability performance on uneven terrains. Figure 9 (a) shows a simple balance test experiment on different slope angles without walking. It is obviously that the robot may maintain a stable posture with respect to different slope angles (up to 25°). A walking experiment for up and down walking with the same FLC setting was demonstrated in Figure 9 (b). It is noted that the slope angle is 12°, and time stamps were indicated with the pictures.

To validate the performance of the proposed PLC for complicated terrain situations, a specific uneven terrain environment was produced by combining 1 cm height stairs and a 10° slope. The bipedal robot was capable of stable walking in this complicated terrain situation by real-time adjusting the corresponding robot's joints' angles from the intervention of the proposed FLC. Figure 10 shows the snapshot of experiment with time stamps. The experiments shown in Figures 8 - 10 were recorded as video films, and they will be played in the conference if this paper could be accepted.

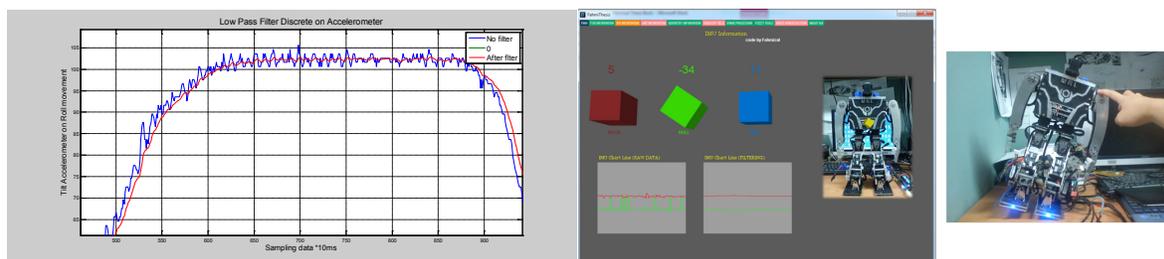
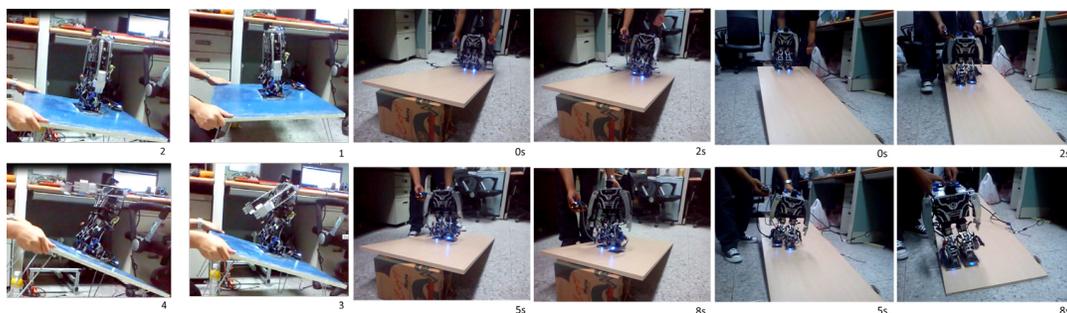
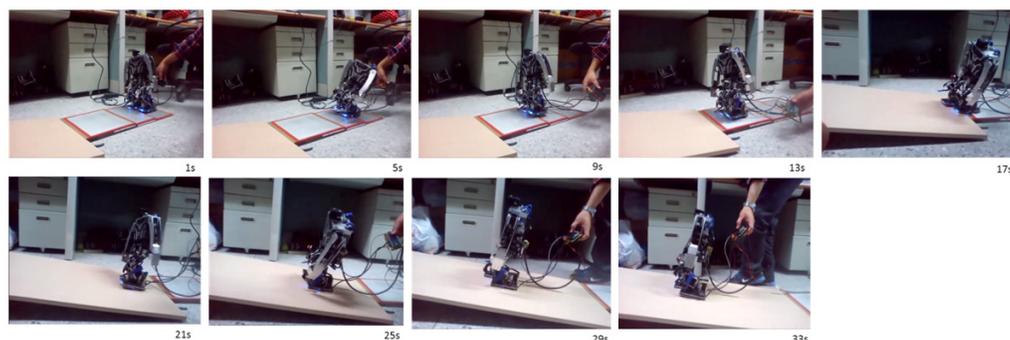


Figure 8. (a) Low pass filter for accelerometer with frequency cutoff at 2.5 Hz; (b) a graphical user interface for indicating the roll-pitch-yaw angles in terms of (1) - (3).



**Figure 9.** (a) A simple balance test without walking; (b) a walking experiment on a 12° slope.



**Figure 10.** Experiment of walking in a complicated terrain situation.

## 5. Conclusion and Future Works

This paper first presents the approach of evaluating the bipedal locomotion stability with a low cost IMU sensor. Based on the IMU-based locomotion stability indication, a FLC was designed to maintain stable bipedal locomotion on uneven terrains. In addition to the proposed FLC, a bipedal locomotion controller which can perform omni-walking footprint trajectory planning was also realized. The FLC can provide joint angle offsets to be applied to bipedal locomotion joint commands so that the bipedal robot could be applicable to uneven terrain situations. With a kid-size bipedal robot with 38 cm height and 2.9 kg weight, the FLC can be applicable to the terrain conditions of maximum 25° slope in DSP stand cases. With the walking cases, the FLC is capable of walking on maximum 12° slope, 1 cm stair height and the combined terrain situation well. In the future, the Center of Pressure (CoP) sensor modules will be developed to measure another stability indication. By combining the IMU and CoP information, the bipedal locomotion controller would be able to deal with more dynamic terrain situations as well as to react on a certain level of external forces. Furthermore, the power efficiency study will be

also considered in our next humanoid robot project.

## 6. Acknowledgements

The authors appreciate the supports from MOST, Taiwan, under grants MOST 103-2221-E-011-160 and 104-2221-E-182-032.

## 7. References

1. Zheng YF, Shen J. Gait synthesis for the SD-2 biped robot to climb sloping surface. *IEEE Transactions on Robotics and Automation*. 1990; 6:86–96.
2. Fu C, Chen K. Gait synthesis and sensory control of stair climbing for a humanoid robot. *IEEE Transactions Industrial Electronics*. 2008; 55:2111–20.
3. Ohashi E, Aiko T, Tsuji T, Nishi H, Ohnishi K. Collision avoidance method of humanoid robot with arm force. *IEEE Transactions on Industrial Electronics*. 2007; 54:1632–41.
4. Sato T, Sakaino S, Ohashi E, Ohnishi K. Walking trajectory planning on stairs using virtual slope for biped robots. *IEEE Transactions Industrial Electronics*. 2011; 58:1385–96.
5. Crisostomo M, Coimbra A. Adaptive PD controller modeled via support vector regression for a biped robot. *IEEE Transactions Control Systems Technology*. 2013; 21:1385–96.

6. Minakata H, Seki H, Tadakuma S. A study of energy-saving shoes for robot considering lateral plane motion. *IEEE Transactions Industrial Electronics*. 2008; 55:1271–6.
7. Suwanratchatamane K, Matsumoto M, Hashimoto S. Haptic sensing foot system for humanoid robot and ground recognition with one-leg balance. *IEEE Transactions Industrial Electronics*. 2011; 58:3174–86.
8. Liu Z, Zhang Y, Wang Y. A type-2 fuzzy switching control system for biped robots. *IEEE Transactions Systems, Man, and Cybernetics, Part C: Applications and Reviews*. 2007; 37:1202–13.
9. Choi KC, Lee HJ, Lee MC. Fuzzy posture control for biped walking robot based on force sensor for ZMP. *International Joint Conference on SICE-ICASE*. 2006. p. 1185–9.
10. Li T, Su YT, Liu SH, Hu JJ, Chen CC. Dynamic balance control for biped robot walking using sensor fusion, Kalman filter, and fuzzy logic. *IEEE Transactions Industrial Electronics*. 2012; 59:4394–408.
11. Faraji S, Colasanto L, Ijspeert AJ. Practical considerations in using inverse dynamics on a humanoid robot: torque tracking, sensor fusion and Cartesian control laws. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2015. p. 1619–26.
12. Sung KW, Jung SW, Park MY, Jeong YK, Lee WS, Park IM, Han SH. A study on stable walking control of biped robot on uneven terrain. *International Symposium on Robotics*. 2013; 1–3.
13. Kajita S, Kanehiro F, Kaneko K, Yokoi K, Hirukawa H. The 3D linear inverted pendulum model: a simple modeling for a biped walking pattern generation. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2001. p. 239–46.