

Design and Implementation of Fuzzy Auto-Balance Control for Humanoid Robot

Yu-Te Su, Cheng-Hsiang Kuo, Chi-Yang Chen, Chia-Ling Hsu, Ming-Feng Lu, and Tzue-Hseng S. Li
aiRobots Laboratory, Department of Electrical Engineering
National Cheng Kung University, Tainan, 70101, Taiwan, R.O.C.
N2895109@mail.ncku.edu.tw; thsli@mail.ncku.edu.tw

Abstract

This paper is mainly to concern the research of auto-balance control for the humanoid robot. A stable gait planning is the most essential and important part in the study of humanoid robot. Therefore, we design and implement a fuzzy auto-balance controller. Firstly, this paper introduces the humanoid robot (NCKU-1) that we construct and addresses the overview of our robot system, which includes the design of mechanical structure and hardware configuration, center process unit, image process unit, sensors, and the integrated power circuit board. Furthermore, we apply two sensors, the accelerometer and the force sensor, to the robot in order to design the auto-balance controller to improve the performance of walking. Finally, our real experimental results demonstrate that our robot, NCKU-1, can balance itself on an incline, walk on a sloping surface with more smooth and stable motions.

1 Introduction

A humanoid robot has a shape like a human and a biped structure which is the most versatile machinery. With this biped structure, the humanoid robot has the ability of walking in real environments where suffice rough surfaces and lots of obstacles. In comparison with the wheeled robot, a biped robot has superior action abilities. It is obvious that avoiding obstacle, walking on a sloping surface, or climbing ladders are relatively uncomplicated work for a biped robot. As a result of the unlimited future in this field, many researchers had devoted into these issues. This field of research includes: actuator robot design and application [1], locomotion [2], pattern generation [3], motion analysis [4], sensory reflex [5], ZMP [6], and balance control [7], etc.

One of the most important issues for a biped robot is that if it can walk stably. The rest subjects will be meaningful with a stable walk. In order to stabilize the gait motion, the concept of ZMP is the most popular theorem for the criterion of stable motion. It represents

the point where the reaction force between the sole of the foot and the ground occurs. In other words, the sum of all the moments of the force on the point equals to zero. Therefore, some researchers have proposed methods of walking synthesis based on ZMP [6]. The extension of ZMP, ZMP safe zone and ZMP trajectory, indicate that if the gait is stable or not. Besides, trunk motions dominate the robot's posture and motion stability. Other researchers have proposed ZMP trajectory combined with trunk motion to stabilize the locomotion. Using these ZMP concepts into the motion planning, we can construct stable motion patterns.

The research of robot has limitless future. The interactions between robots and human are highly respected. We expect that robots can facilitate human's life, work for human in dangerous environments, provide entertainments, and bring more and more other benefits to human in the future. Follow this tendency, we construct our humanoid robot, NCKU-1. Through designing the mechanical structure, developing robot system, building the mathematical model, generating motion patterns, combining sensors with control strategies, we implement the intelligent autonomous robot. With the integration of all the modules and analysis of the robot's motions and posture, a versatile humanoid robot is realized.

This paper is organized as follows. In Section 2, we briefly introduce the overview of the humanoid robot system, including the design and development of mechanical structure. Besides, the hardware such as actuators, center process unit, image process unit, power integrated circuit, and sensors, the accelerometer and force sensors, are represented. In Section 3, the concept of ZMP is introduced firstly. Then, we design two controllers, a proportional controller and a fuzzy logic controller, to balance the robot's posture. The auto-balance mechanism is applied to realize walking on a sloping surface. Some experiments demonstrate the validity of the proposed control method in Section 4. With these two controllers, our robot can balance

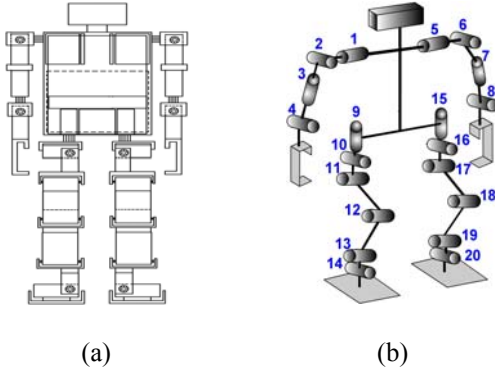


Figure 1: (a) The structure of humanoid robot, (b) The configuration of motors.

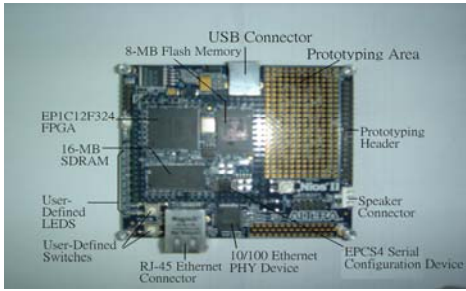


Figure 2: The FIRA.GIF figure.

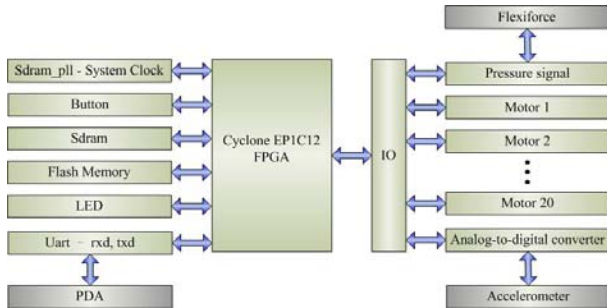


Figure 3: The robot center system.

smoothly and walk on a sloping surface successfully.

2 Mechanism and Hardware of the Humanoid Robot

Suitable hardware and robust mechanism are very important for a robot, especially for a biped humanoid robot. It is no necessary to consider factors of falling down and balancing for a wheeled robot but for a biped humanoid robot while walking. One of the most important factors is the connected component of each motor. These components must be solid enough and deformed uneasily for the stability of motions. Therefore, the strong mechanism will govern a biped humanoid robot to walk successfully. In the following, we will discuss the mechanism and hardware of our humanoid robot.

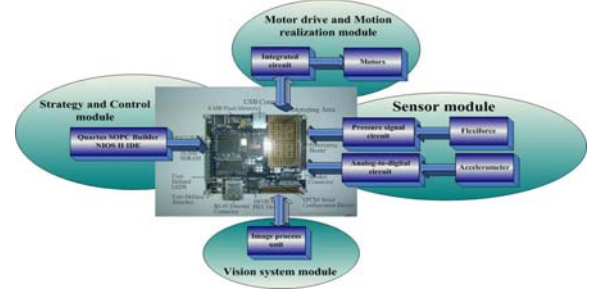


Figure 4: Overview of the robot system.

2.1 Design of Mechanism

Since the connected components of motors are very important. We choose 1mm A5052 aluminum-magnesium compound metal for these components. In addition, the ratios of each part of the robot are fitted to a human. Also, we have considered the weight of all devices and the configuration of motors. The designed structure of our humanoid robot is shown in Fig. 1(a). Fig. 1(b) illustrates the configuration of motors. There are six motors on each leg and four motors on each arm. Totally twenty motors are arranged on our robot.

2.2 The Hardware of the Robot

The hardware of our humanoid robot are described as follows. We use Altera Nios II EP1C12F324C8 evaluation board as the center process unit (Fig. 2). It is a multi-function FPGA. The core of the robot system as shown in Fig. 3 is built by the Altera SOPC Builder. The image processing unit utilizes two devices - PDA and CMOS SD camera. In the choice of motors, we adopt two kinds of RC servo motors with different torque including KRS-784ICS and KRS-2350ICS on our robot. In addition, we place a dual-axis accelerometer, ADXL311, on the top of the robot and eight pressure sensors, FlexiForce, on the sole of the robot's foot to improve the performance of robot's motion. The power system of our robot consists of four Li-Po batteries, five regulator ICs and an integrated circuit board.

From these hardware, we build different module and construct an entire robot system through Nios II as shown in Fig. 4. When any image information input to the image device, the vision system will transfer the information on the field through RS232 to Nios II. The vision system module is built by the embedded visual C++ (EVC) on PDA. According to these image information or any mandate we commanded Nios II directly, Nios II analyze these data and decide the best strategy and related motions. The strategies and control module are developed by C/C++ language in Nios II Integrated Development Environment interface. Then, Nios II will send each motor the PWM signals to execute

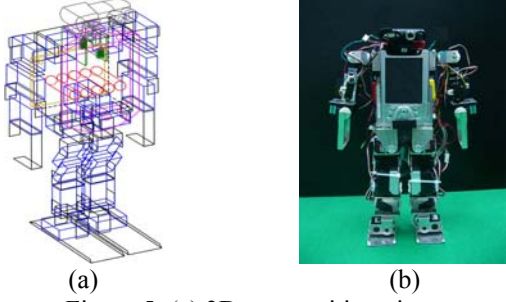


Figure 5: (a) 3D-perspective view;
(b) The actual picture the robot.

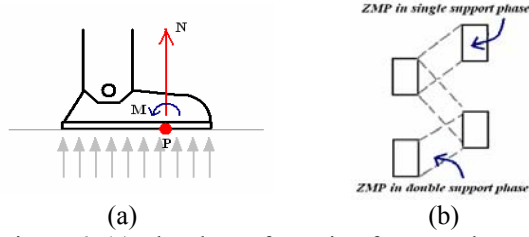


Figure 6: (a) The chart of reaction force on the ground;
(b) The ZMP point during the two phases.

Table I The base specification of our robot

Height	48 cm
Width	18 cm
Depth	11.5 cm
Weight	2.1 kilogram
Domain of freedom	20 DOFs
Material of structure	A5052 aluminum-magnesium compound metal
Actuator	RC servo motor
Controller	Altera Nios II 1C12F324C8 evaluation board
Battery	Li-Po battery, 11.1V, 1.3A
Vision System	PDA + CMOS SD camera
Sensor	Accelerometer, Pressure sensor
Development Language and Software	EVC, C/C++, VHDL, Quartus II, Nios II IDE

the motion. The motor drive and motion realization module are constructed by VHDL code in Quartus II. During each process of motion, the stability must be ensured by the sensors mounted on the robot.

The 3D-perspective view of the structure is shown in Fig. 5(a). The picture of real robot we constructed completely is shown in Fig. 5(b). Table I shows the base specification of our robot.

3 Fuzzy Auto-Balance Control

ZMP theorem is the most popular significant criterion for the stability of the robot's motion and ZMP trajectory has been applied in many studies about controlling the robot's motion. ZMP is simply the CoP as shown in Fig. 6(a). In single-support phase, ZMP point should be located inside the sole of the foot. On the other hand, it should be located outside the sole of the foot in double-support phase as shown in Fig. 6(b). The procedures of calculating ZMP equations are time-consuming and involve a large amount of calculation. It is hard to be used in real-time and in realistic games. The theorem is only suitable for simulation. Therefore, when the robot is walking, we do not calculate the ideal ZMP point. Otherwise, we take advantage of the ZMP safe zone under the sole of the foot as shown in Fig. 7. That is, as long as the robot's posture is stable, ZMP point is located inside the desired zone. We realize this theorem by the accelerometer and pressure sensors. If the ZMP point is outside the safe zone during these two support phases, the torque of hip or ankle joints must provide a compensative value to move ZMP point into the safe zone.

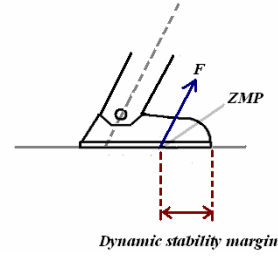


Figure 7: The ZMP safe zone and the dynamic stability margin.

3.1 The Realization of Auto-Balance Mechanism

One of the ultimate goals of the robot's task is to help human working in dangerous environments. For this reason, robots must have the ability to walk on any non-flat surface and it can sustain under any sudden situation. When a robot walks on a rough surface or a slope, it maybe inclines often. If robots want to detect the tilt conditions, it must be assisted with sensors. Therefore, our robot is equipped with an accelerometer to build up an auto-balance mechanism.

In each motion step, the robot's trunk must be fitted in with the desired posture. The realistic tilt angle of the robot's posture is measured by the accelerometer. If the robot is affected by any irregular external force or the robot's trunk isn't the expected posture, the accelerometer will detect the slanted angle and send a control signal to Nios II. Nios II will then adjust the hip or ankle motors immediately to avoid the robot falling down. We design two controllers, a proportional

controller and a fuzzy logic controller (FLC), to realize the mechanism of auto-balance.

Fig. 8 exhibits the proportional controller we designed. The input data of the controller are from the output of the two-axis accelerometer. The gain of the controller - k is adjustable and determined by the inclined condition and sensor feedback signals.

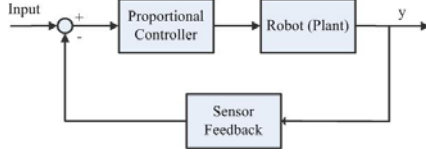


Figure 8: The system of the proportional controller.

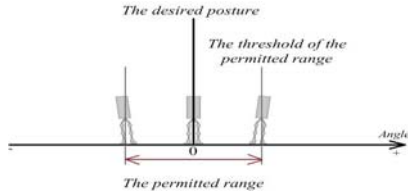


Figure 9. The chart of tilt range.

When our robot is standing, the robot's trunk exists a very little vibration due to the little shock caused by motors. This factor must be considered in our controller to improve the performance of this system. Also, the variation of posture between the previous motion and the current motion must be stable. Hence, we set a desired criterion of angles and a permitted range. The gain k must be adjusted under different tilt conditions separately. We discuss several conditions as shown in Fig. 9.

- (i) When the angle of the robot's posture is equal to the desired angle, k is zero.
- (ii) When the angles of the robot's posture are in the permitted range, k is zero.
- (iii) When the angles of the robot's posture are lay on the threshold of the permitted range, k is a small constant.
- (iv) While the angles of the robot's posture are out of the range, k will increase following the absolute value of the difference between the current angle and the desired angle.

If the angles are out of the criterion we requested or the angles vary too much, the system will send a "balance PWM signal" to hip motors. That is, when any slope angle input to the system, this input of tilt angles or variation will be multiplied by a scale k. Then the output of the system will be transferred to hip motors to control the posture of robot. Equation (1) expresses the proportional controller.

$$\Delta\phi_h = \begin{cases} 0, & \text{when } \alpha = 0 \text{ or } |\alpha| < \alpha_{\text{threshold}} \\ \pm k_1 (\alpha_c - \alpha_p), & \text{when } |\alpha| = \alpha_{\text{threshold}} \\ \pm k_2 (\alpha_c - \alpha_p), & \text{when } |\alpha| > \alpha_{\text{threshold}} \end{cases} \quad (1)$$

where $\Delta\phi_h = \theta_h$, and k_1 is a small constant, k_2 is decided by the difference of the current angle and desired

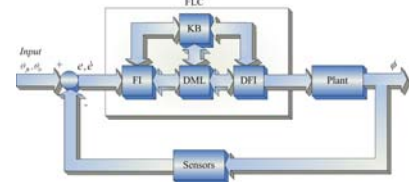


Figure 10: The system structure of FLC.

angle. The auto-balance mechanism will continue adjusting $\Delta\phi_h$ until it reaches the desired value. With this improved method, the posture of our robot can be more stable.

3.2 The Design of Fuzzy Auto-Balance Controller

Fig. 10 shows the structure of the FLC. Our FLC should be with sufficient ability to handle any sudden situation on any inclined surface. Hence, we construct two FLCs: X-FLC and Y-FLC. The balances of X-axis and Y-axis are governed by their own controller individually. The robot system will detect the variations of two axes from the accelerometer to determine which FLC will be enabled.

The inputs of the FLC are θ and $\bar{\theta}$. ϕ is the output control signal. θ and $\bar{\theta}$ are shown in Fig. 11 and defined as follows:

θ = the angle of current posture - the angle of desired posture

$\bar{\theta}$ = the angle of current posture - the angle of pervious posture

where the values of θ and $\bar{\theta}$ may be positive or negative. Positive values mean that the robot is toward forward or left side. Otherwise, negative values indicate that the robot is toward backward or right side. The magnitudes of these two values represent the varied trend of robot's posture.

The input variables θ_x (θ_y), $\bar{\theta}_x$ ($\bar{\theta}_y$), and ϕ are decomposed into five fuzzy partitions, denoted by NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). The partitions and the membership function are described in Fig. 12 DML utilizes the membership state generated by the FI. Each discourse is divided into five subsets, so that two

inputs will construct 25 fuzzy rules. The inference rules can be illustrated as follows and the corresponding rule table is shown in Table II. And the 25 fuzzy rules are illustrated as follows:

Rule1: If $\theta_x(\theta_y)$ is NB and $\bar{\theta}_x(\bar{\theta}_y)$ is NB, then ϕ is PB

Rule2: If $\theta_x(\theta_y)$ is NB and $\bar{\theta}_x(\bar{\theta}_y)$ is NS, then ϕ is PB

⋮

Rule11: If $\theta_x(\theta_y)$ is ZE and $\bar{\theta}_x(\bar{\theta}_y)$ is NB, then ϕ is PS

Rule12: If $\theta_x(\theta_y)$ is ZE and $\bar{\theta}_x(\bar{\theta}_y)$ is NS, then ϕ is PS

⋮

Rule24: If $\theta_x(\theta_y)$ is PB and $\bar{\theta}_x(\bar{\theta}_y)$ is PS, then ϕ is NB

Rule25: If $\theta_x(\theta_y)$ is PB and $\bar{\theta}_x(\bar{\theta}_y)$ is PB, then ϕ is NB

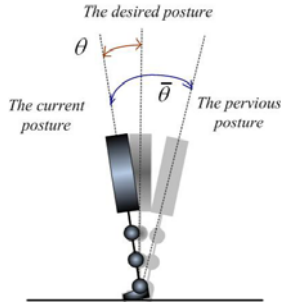


Figure 11: The chart of θ and $\bar{\theta}$.

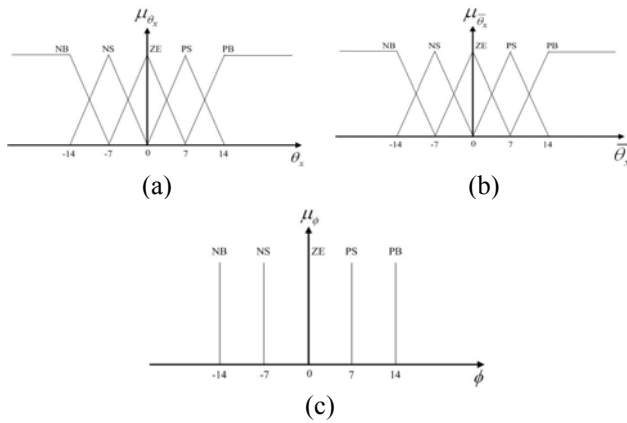


Figure 12: The membership function of (a) θ , (b) $\bar{\theta}$ and (c) ϕ .

In the pervious section, we set a range of angles to allow the little vibration caused by the motors. However,

this little vibration will have minimum influence on the robot's stability nevertheless while walking. For more precise control, we do not ignore this vibration. We eliminate this vibration with the FLC. Therefore, we set a desired angle. The permitted range is cancelled. The aim of this method is to keep the angle of robot's posture equal to the desired angle.

Table II The fuzzy rule table

$\bar{\theta}_{x,y}$	NB	NS	ZE	PS	PB
NB	PB	PB	PS	PS	ZE
NS	PB	PS	PS	ZE	NS
ZE	PS	PS	ZE	NS	NS
PS	PS	ZE	NS	NS	NB
PB	ZE	NS	NS	NB	NB

When the trunk is too toward forward, the hip motors must support a large value of $\Delta\phi_h$ to balance the posture. In the pervious section, this condition was solved by increasing the gain k . But if the demands of compensation are too large, the instantaneous increased values are hard to achieve. Besides, the loads of motors maybe rise in a short period of time. It could damage the motors. Here, we propose another idea to deal with this predicament. In order to improve the performance of the FLC and protect motors in the same time, when ϕ is PB or NB, the compensation will not be accomplished only by the hip motors. We set hip motors and ankle motors working together to complete this mission. The design of fuzzy based auto-balance controller is:

$$\phi = \begin{cases} 0, & \text{when } \alpha = 0 \\ \Delta\theta_{hip}, & \text{when } \alpha > 0 \text{ and } \Delta\phi_h \leq \Delta\phi_{critical} \\ \Delta\theta_{hip} + \Delta\theta_{ankle}, & \text{when } \alpha > 0 \text{ and } \Delta\phi_h > \Delta\phi_{critical} \end{cases} \quad (2)$$

where $\phi = \Delta\phi_h = \theta_h$ and the $\Delta\phi_{critical}$ is decided by the membership function. No matter the proportional controller or the fuzzy logic controller, both them provide well mechanism of auto-balance to avoid the robot falling down and increase the stability of robot's posture. As long as the robot's posture is stable, ZMP point is located inside the ZMP safe zone. Fig. 13 shows the flow chart of any motion pattern combined with these proposed controllers.

4 Experimental Results

In this section, the implementation of the auto-balance mechanism with two kinds of controller is presented. The experimental site is on a board. During the process of experiments, we continue rising the board until reach the threshold angle then put it down to demonstrate the

ability of balance. The threshold angle is the tilt angle that causes the robot slipping. It is decided by the mass of the robot and the friction force between the board and the sole of the robot's foot. In general, the proportional controller is applied when the robot is standing and the FLC is adopted when the robot is walking. Then, we apply the balance mechanism to practice the robot walking on a sloping surface. The demonstration shows that the robot can walk smoothly on a slope with the mechanism of auto-balance as shown in Fig. 14.

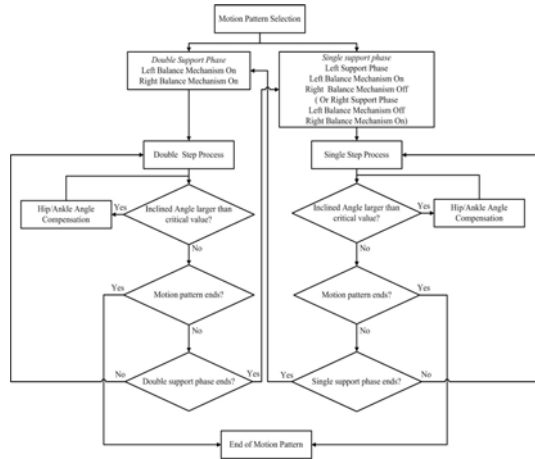


Figure 13: The flow chart of auto-balance.

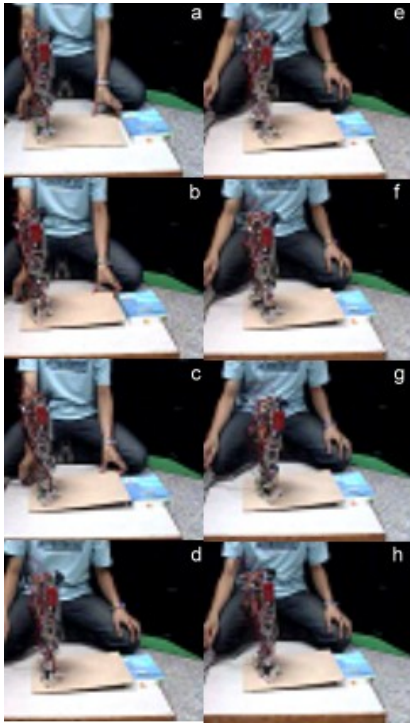


Figure 14: Experiment result of walking on a slope with the mechanism of auto-balance.

5 Conclusions

In this paper, we have designed and implemented an autonomous intelligent humanoid robot. First, we introduce our robot system includes the vision system, strategy decision maker, fuzzy auto-balance control, and sensor feedback modules. Through the structure of dual processes, the load and time of the strategy decision maker can be decreased in practice and in the real competition. Then, we introduce the concept of ZMP briefly. Motions are combined with the ZMP theorem and sensors to ensure the stability. In addition, we discuss the posture of the trunk and analyze leg locomotion. Through these analyses, we establish the auto-balance mechanism to provide our robot high movement abilities on sloping surfaces and ladders. Finally, experimental results illustrate the feasibility of the proposed method.

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