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Stair-Climbing Control of Humanoid Robot using Force and Accelerometer Sensors

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Abstract: In this paper, an autonomous control scheme is proposed for humanoid robot to accomplish the stair-climbing mission. At first, we design a fuzzy based auto-balance gait controller and adopt the Zero Moment Point (ZMP) criterion to construct the basic motion patterns. Next we propose a ten-step stair-climbing control scheme. For acquiring the information from the environment, two kinds of sensors, the accelerometer and the force sensor are utilized. Experimental results demonstrate that the developed humanoid robot can successfully accomplish the stair-climbing mission though stair steps are with different height.

Keywords: Fuzzy auto-balance control, Humanoid robot, Stair-climbing control, ZMP.

1. INTRODUCTION

A humanoid robot has a shape likes 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 with suffuse rough surfaces and lots of obstacles. Hence, some behaviors must be possessed, such as avoiding obstacle, walking on a sloping surface, or climbing-stairs are basic works for a biped robot. Accordingly, the researches of the humanoid robot have attracted much interest in the last decade due to their potential in dealing with ascend-a-height, which is difficult for the mobile robots. Many researchers have devoted into these issues. This field of research includes: actuator robot design and application [1]-[3], locomotion [4], pattern generation [5], motion analysis [6], sensory reflex [7]-[11], ZMP [12] [13], and balance control [14], etc.

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, indicates 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.

Through designing the mechanical structure, developing robot system, building the mathematical model, generating motion patterns, and 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 our humanoid robot system. In Section 3, we construct a fuzzy logic controller (FLC), which can balance the robot's posture. The stair-climbing mission is developed in Section 4. The experimental result is addressed in Section 5.

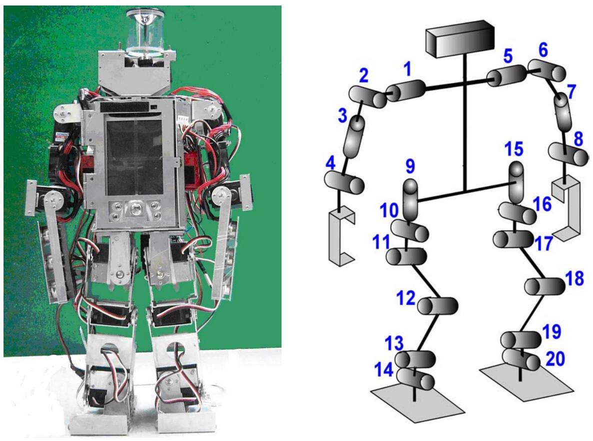
2. MECHANISM AND HARDWARE

Suitable hardware and robust mechanism are very important for a robot, especially for a biped humanoid robot. It is not necessary to consider the 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.

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



(a) (b)

Fig. 1. (a) The actual robot, (b) The configuration of motors.

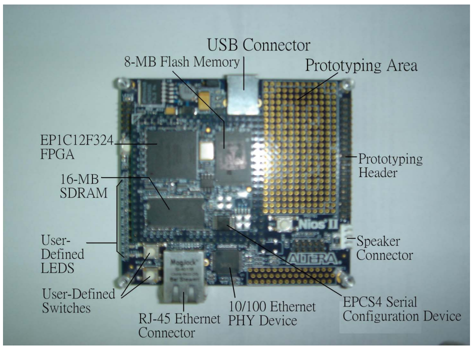


Fig. 2 The Nios II evaluation board.

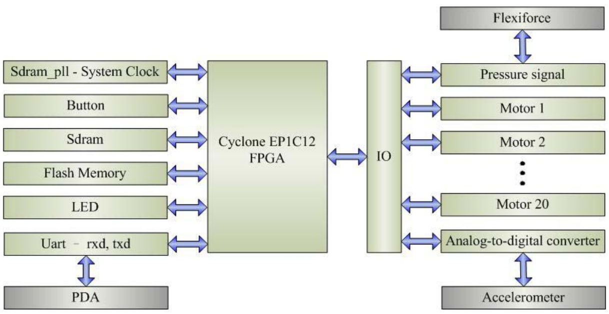


Fig. 3 Block diagram of the robot system.

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. 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. 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 the image information or any mandate we commanded Nios II directly. Nios II analyzes these data and decides the best strategy and related motions. The strategy 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 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. Table 1 lists the base specification of our robot.

3. FUZZY BASED AUTO-BALANCE CONTROLLER

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 inclines. If robots want to detect the tilt condition, 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 that will then adjust the hip or ankle motors immediately to avoid the robot falling down.

3.2 The design of fuzzy auto-balance controller

In this section, two FLCs: X-FLC and Y-FLC, are mentioned for the stair-climbing mission. 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 $\overline{\theta}$. ϕ is the output control signal. θ and $\overline{\theta}$ are shown in Fig. 4 and defined as follows:

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

Table 1 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

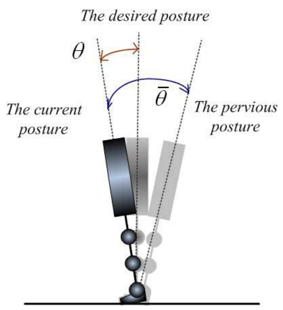


Fig. 4 The chart of θ and $\bar{\theta}$.

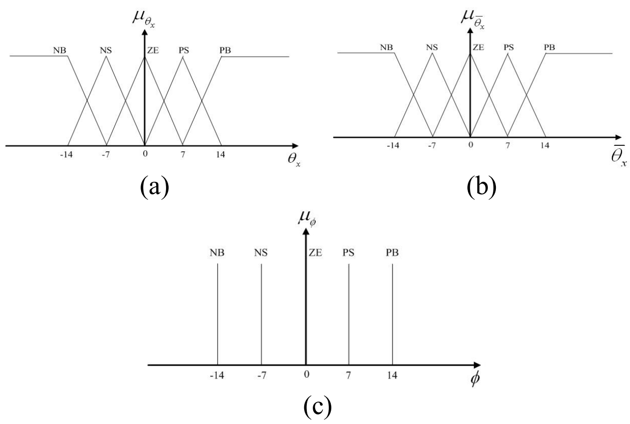


Fig. 5 The membership functions of (a) θ, (b) $\bar{\theta}$,and (c) ϕ .

$\bar{\theta}$ = 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 moving forward or left side. Otherwise, the robot is moving 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

Table 2 The fuzzy rule table

$\bar{\theta}_{x,y}$ \ $\theta_{x,y}$ / ϕ	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

(negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). The partitions and the membership function are described in Fig.5. The 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 2, where 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*

⋮

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

The aim of this method is to keep the angle of robot's posture equal to the desired angle. When the trunk is moving too forward, the hip motors must support a large value of $\Delta\phi_h$ to balance the posture. If a proportional control is applied, this condition can be solved by increasing the P gain. But if the demands of compensation are too large, the instantaneous increased values are hard to achieve. Besides, the loads of motors may 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 is 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:

$$\phi = \begin{cases} 0, & when\ \alpha = 0 \\ \Delta\theta_{hip}, & when\ \alpha > 0\ and\ \Delta\phi_h \le \Delta\phi_{critical} \\ \Delta\theta_{hip} + \Delta\theta_{ankle}, & when\ \alpha > 0\ and\ \Delta\phi_h > \Delta\phi_{critical} \end{cases} \quad (1)$$

where $\phi = \Delta\phi_h = \theta_h$ and the $\Delta\phi_{critical}$ is decided by the membership function.

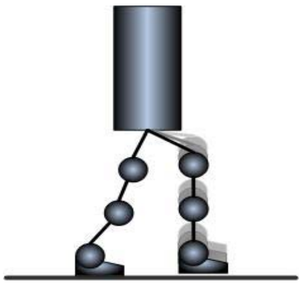


Fig. 6. The ankle position descend vertically.

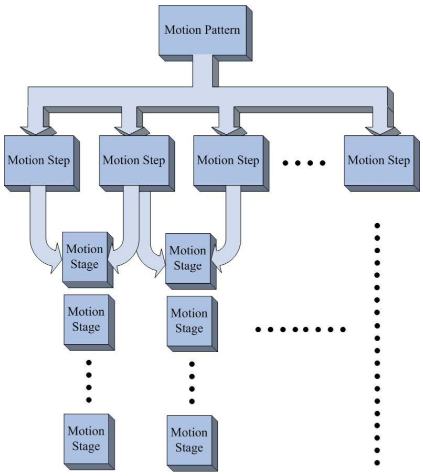


Fig. 7. The relationship of motions.

4. STAIR-CLIMBING CONTROL

When a robot is walking on an uneven surface, its foot may contact the ground early or later. With this unexpected accident, the robot may fall down easily due to the suddenly external force caused by the undulate ground. Besides, the robot's posture would be unstable and hard to compensate only with the accelerometer. Hence, we wish not only balance the posture but also keep the motions proceeding. In addition to the accelerometer, we add force sensors to accomplish the motion and balance the posture.

When the height of ground is higher than the anticipation, the sole of the robot's foot contacts the ground early. Force sensors detect this impact and send pressure signals to Nios II immediately. Nios II stops sending motion steps and puts down the leg. That is, the robot pulls up the ankle position to avoid colliding. On the contrary, if the motion step ends and Nios II do not receive any pressure signals, the robot lowers the ankle position to prevent tilting. There are two methods to avoid the robot unstable and finish the motion with these pressure signals.

(I). When the motion step proceeds to the robot stretch the leg. We modify next motion step. It is replaced by adjusting the ankle position descending vertically until Nios II receives pressure signals. Fig. 6 shows this method. Eq. (2) depicts this mathematical method.

$$\Delta Z_a = \begin{cases} c_1 \times h_a, & when \quad F > F_{critical} \\ 0, & when \quad 0 < F < F_{critical} \\ c_2 \times h_a, & when \quad F = 0 \end{cases} \qquad (2)$$

where $F_{critical}$ is decided by the pressure integrated circuit. c_1 is a positive constant and c_2 is an negative constant. $F > F_{critical}$ means the sole of the robot's foot is contacted with the ground early, the robot needs to pull up the foot immediately. The height of ankle Z_a is increasing. $F = 0$ means the sole of the foot does not contact with the ground yet, the robot will decrease the height of ankle until it touches the ground. $0 < F < F_{critical}$ indicates that the foot just steps on the ground. In order to make the foot moving up or down vertically, the motors of hip, knee, and ankle need to be controlled carefully to reach vertical move. During the motion of vertical move, the angle variations of each joint are different. This method will involve large amount of calculation due to the complex dynamic equation and the mechanical structure. But the robot can adapt surface with different height with this method.

(II) The second method is focused on the interpolations of motion steps called motion stages here. Fig. 7 depicts the relationship of these motions. As long as we receive any pressure signals in any motion stage, these series of motion stages finish and the procedure of motion go to next motion step. In comparison with the former method, this one is faster and effective in real time. We apply this method to realize the application of climbing stairs.

In the application of climbing stairs, we integrate all the sensors and propose a motion-step based behavior control method. According to the behavior of climbing stairs and the stairs with three layers, we construct ten motion steps as follows:

[Step 1] Stand with the initial pose.

[Step 2] Shift the trunk to one side.

[Step 3] Lift one leg to the desired height and position.

[Step 4] Stretch the lifted leg forwards.

[Step 5-1] Put down the leg on the height of three layer stair

[Step 5-2] Put down the leg on the height of two layer stair

[Step 5-3] Put down the leg on the height of one layer stair

[Step 6-1] Lead the body forward on the height of three layer stair

[Step 6-2] Lead the body forward on the height of two layer stair

[Step 6-3] Lead the body forward on the height of one layer stair

[Step 7] Shift the trunk to another side.

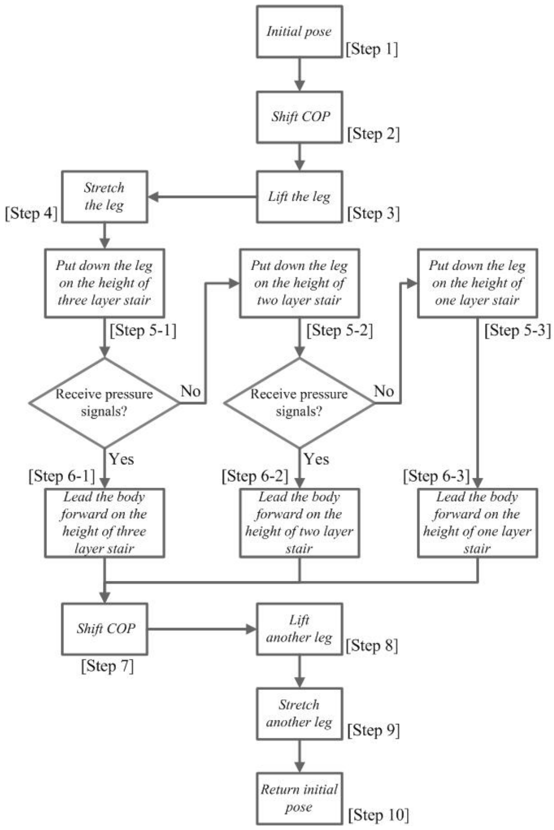


Fig. 8. The flow chart of the stair motion.

[Step 8] Lift another leg to the desired height and position.

[Step 9] Stretch another lifted leg forwards.

[Step 10] Return to the initial pose.

We do not choose the motion steps we need. Otherwise, the choice of the motion steps is decided by the strategy and Nios II with force sensors. In the motion pattern of climbing stairs, the robot executes the motion steps until reach the motion Step 4. Between the Step 4 and Step 5-1, Nios II will send motion stages and observe the pressure signals at the same time. As long as Nios II receives any pressure signals before or just at the end of Step 5-1, next step will be the Step 6-1. Otherwise, next step will be the Step 5-2. So do the Step 5-2 and Step 5-3. Then, the robot will finish the remaining steps and accomplish the behavior of climbing stairs. The flow chart of climbing stairs is shown in Fig. 8.

5. Experimental Results

In this section, we present the functions of climbing stairs. According to the pressure sensors mounted under the sole of the feet, the robot can choose the motion steps depending on the sensor signals and climb different height of stairs successfully. In Fig. 9, we demonstrate the robot climbs the stairs with different step heights.

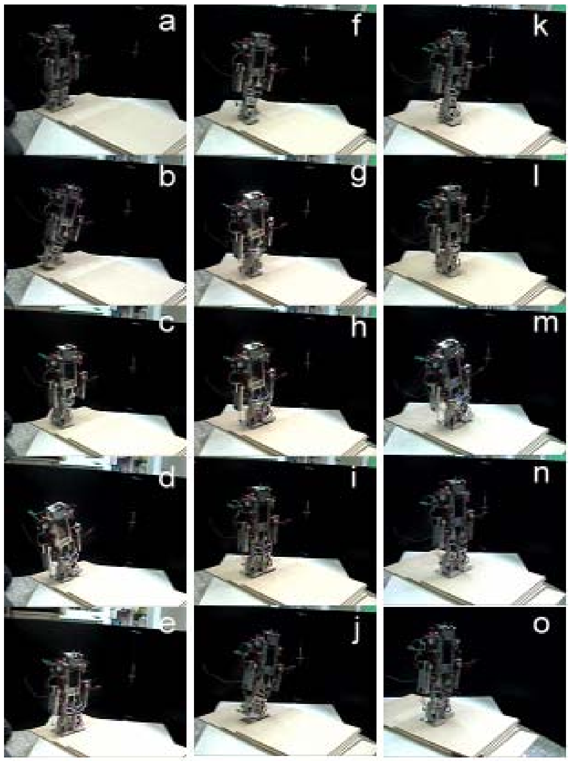


Fig. 9 Experiment results of stair climbing with ifferent step heights.

6. Conclusion

In this paper, we have designed and implemented an autonomous intelligent humanoid robot. First, we introduce our robot system, which includes the vision system, strategy decision maker, behavior mode based gait controller, action execution and sensor feedback modules. Through the structure of dual processes, the load and time of the strategy decision maker can be decreased in practice. 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 climbing stairs. Finally, experimental results illustrate the feasibility of the proposed method.

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