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Humanoid Robot: Design and Fuzzy Logic Control Technique for Its Intelligent Behaviors

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1. Introduction

A humanoid robot is a robot with its overall appearance based on that of the human body [1]. In general humanoid robots have a torso with a head, two arms and two legs, although some forms of humanoid robots may model only part of the body, for example, the upper torso. Some humanoid robots may also have a face with eyes and mouth equip with facial interfaces [2, 3, 4, 5]. A humanoid robot is autonomous because it can adapt to changes in its environment or itself and continue to reach its goal [6]. This is the main difference between humanoids and other kinds of robots, like industrial robots, which are used to performing tasks in highly structured environments.

Humanoid robots are created to imitate some of the same physical and mental tasks that humans undergo daily [7]. Scientists and specialists from many different fields including engineering, cognitive science, and linguistics combine their efforts to create a robot as human-like as possible [8, 9]. Their creators' goal for the robot is that for it to both understand human intelligence, reason and act like humans [7]. If humanoids are able to do so, they could eventually work alongside with humans.

There are many issues involves in developing a humanoid robot [1, 10, 11]. But the most difficult is balancing the robot while it does its motion. Babies take several months before they learn to walk; one reason is the gravity affecting our body weight. Like humans, robots also have gravitational force affecting on it. This is the reason why conducting research in this field is still very challenging and exciting [14.15].

The next section of this chapter is organized as follows: section 2 discusses the physical design of the robot. This involves the design and development of mechanical structure of the robot. Section 3 presents the sensors that are use for gathering environment information. The inputs from these sensors are used for robot perception and intelligence. Section 4 discusses the power needed to fully operate the humanoid robot. Section 5 discusses the microcontroller used that does the control execution and operation of the robot. Section 6 discusses the fuzzy logic algorithm developed for the total intelligence and control of the

robot. Section 7 present the experiment results conducted in this research. Discussions and analysis of these results are also presented in this section. Finally, section 8 presents the conclusion and recommendations for future work.

2. The humanoid robot mechanical design

The physical structure of the robot developed in this research is shown in figure 1. It has 17 degrees of freedom. Hence, it utilizes 17 servomotors as its actuators to perform its dynamic motions. There are 10 motors employed for the legs, 6 motors for the arms, and 1 motor for the head. The servo motor used in this research requires 3-5 Volts peak-to-peak square wave pulse. Pulse duration is from 0.9ms to 2.1ms with 1.5 ms as center. The pulse refreshes at 50 Hz (20ms). It is operated with a 4.8-6.0 Volts.

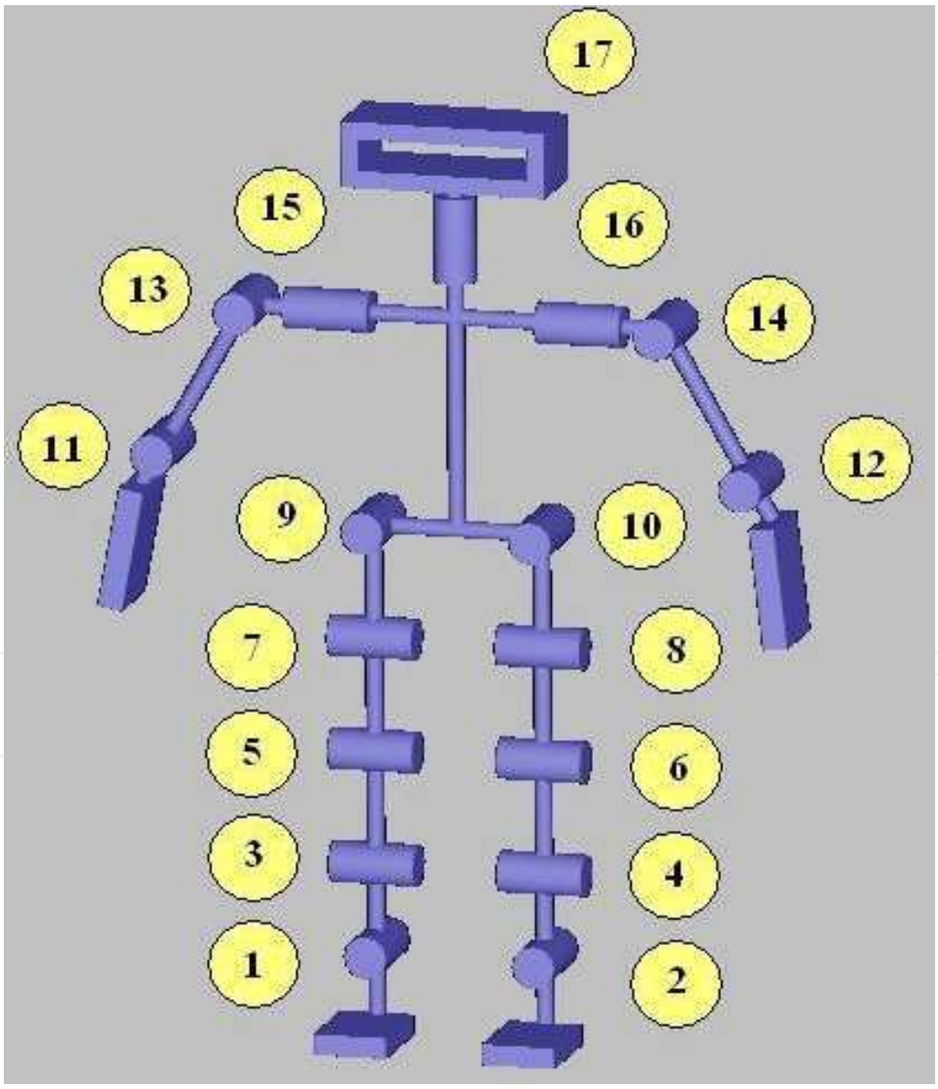


Fig. 1. Skeletal design of the humanoid robot with 17 degrees of freedom.

The arrangement or position of the motors is crucial for the movement of the robot. The motors are connected to each other using aluminum brackets. Design for the aluminum brackets for the arm and legs follow the movements set for the motor. Each bracket is capable of tilting to the left and right for the rotational span allowed by the servo motor. Each aluminum bracket has multiple holes for connecting plates and brackets to one another. The brackets also act as the shield that protects the servo motor and robust enough to avoid damage when it falls. Despite of its rigidity, the bracket material should be lighter and can carry the servo motors as well as the total load of the robot including its circuitry.

The body of the robot is made of a durable acrylic plastic case and is used to protect the control board and circuitry from damage. Several factors were considered in the design of the body casing. The dimensions of the casing were designed to accommodate the IC power battery and the microcontroller. It is also important for the body case to be proportional to the dimensions of the legs and the arms of the robot.

3. The sensors used for the humanoid robot intelligence

The sensors are needed by the robot to gather information about the conditions of the environment to allow the robot to make necessary decisions about its position or certain actions that the situation requires. In this research, four types of sensors are utilized: infrared and ultrasonic sensors for obstacle detection, tilt sensor for robot balancing, and color sensor for ball recognition. Details of the position of these sensors are shown in figure 2.

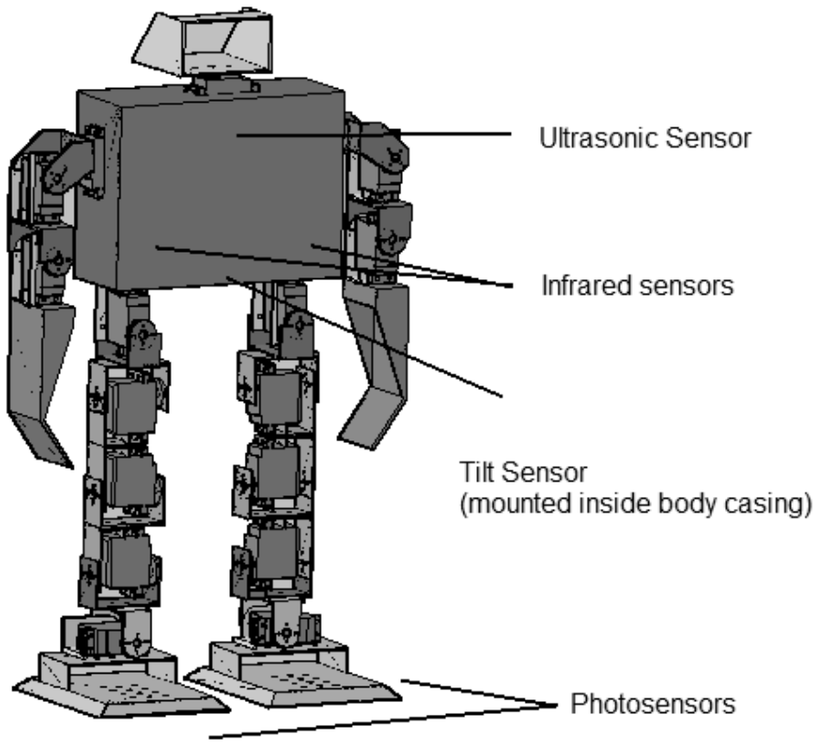


Fig. 2. The Humanoid Robot with sensors locations.

Figure3 shows the reflective infrared sensor used to detect objects in proximity. The basic circuit involves an IR LED and an IR photodiode. The IR LED will emit light and the photodiode will measure the amount of light reflected back. When an object is in proximity, more light will be reflected to the IR photodiode. The Ultrasonic Sensor SRF04 is used also in this research to avoid obstacles. This is an Ultrasonic Range Finder Designed and manufactured by Devantech and is capable of non-contact distance measurements from 3 cm to 3 m. The SRF04 is also easy to connect to the microcontroller as it only needs two I/O pins. It requires a 10uS minimum TTL level pulse input trigger. The echo pulse is a positive TTL level signal (100 uS – 18 mS), with its width proportional to the range. If no object is detected, the width of the echo is approximately 36 mS.

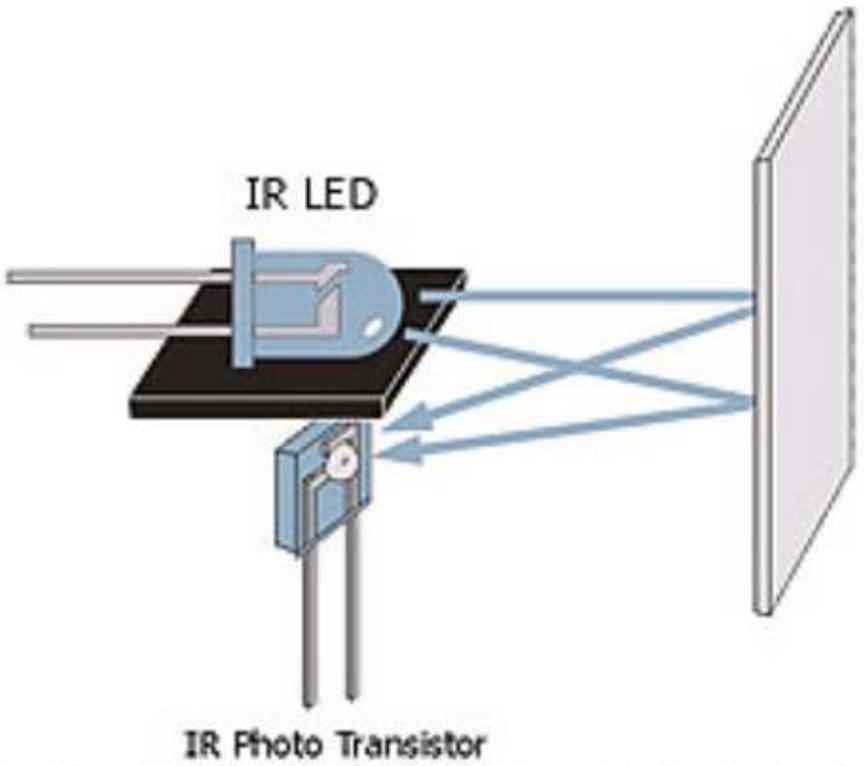


Fig. 3. Basic Reflective IR Proximity Sensor.

The tilt sensor ADXL202 is used in this research to determine the inclination of the robot which is then used by the controller developed to stabilize and balance the robot. It measures the tilting in two axes of a reference plane. Full motion uses at least three axes and additional sensors. One way to measure tilt angle with reference to the earth's ground is to use the accelerometer. The ADXL202 is a low-cost, low power 2-axis accelerometer which can measure both dynamic acceleration and static acceleration. This accelerometer is small, requires small amount of voltage, and outputs an analog voltage that could readily be used by the main controller. A Photo Sensor is used to identify the yellow ball which the robot has to kick. The circuit of this sensor is basically a voltage divider a simple linear circuit that generates an output voltage that is a fraction of its input voltage. Voltage division refers to the partitioning of a voltage among the components of the divider.

The Photo Sensor circuit component is a photoresistor or an LDR (Light Dependent Resistor) in series with a fixed resistor. The LDR must be a part of a voltage divider circuit in order to give an output voltage which varies with illumination. The super bright light emitting diode will provide the light to the LDR. When an object is placed in front of the LDR and LED at about 10-20mm away, some of the light will reflect back to the LDR, depending on the material. A material with a bright color will reflect more light to the LDR. A black material will absorb all the light and nothing will be reflected. In this project, the robot needs to detect a yellow ball for it to kick. The disadvantage with the circuit presented is that it will also detect a material brighter than yellow. However, the scope of this project is only to detect the yellow ball, and not to differentiate it from other colors.

4. Power management and power source

Power management is an essential part of the humanoid robot. This part functions to ensure that the proper voltage is supplied to the servos as well as the sensors and the microcontroller. There are circumstances where in the power supplied to the motors exceeds the power required. In cases like this, probable damage could occur. That is why it is essential to have the voltage regulated.

For voltage regulation, the LM338k transistor was used as the primary part of the regulator circuit. The primary choice would have been the LM7805, which is the most widely used transistor. It supplies 5 volts and is capable of generating 1 to 1.5 A of current. However, with the number of motors used in this project, the current rating of the LM7805 would be insufficient. Hence, the LM338k was opted due to its higher current rating at about 1 to 5 Amperes, ensuring that ample amount of current is supplied to the motors.

There are six outputs in the circuit for the servo motors. Four voltage regulators were used to accommodate 24 motors. Only 17 motors were used but additional outputs were added to accommodate the sensors and other additions. The output voltage can be solved using the formula

$$Vo = V_{ref} + (1 + R2/R1) + I_{adj}R2 \quad (1)$$

An output of 5.9 volts is desired so R2 is set at 450 ohms, and R1, which is constant, is 120 ohms. Vref = 1.25 and Iadj = 50uA.

Substituting,

$$Vo = 1.25(1+450/120) + 50uA(340) \quad (2)$$

the value of Vo is obtained.

$$Vo = 5.95\ V \quad (3)$$

This research utilizes packed 7.2 volt Lithium Ion Batteries as the power source of the robot. It would then be regulated to approximately 5.9 volts. Lithium Ion batteries are light weight which is a big factor for this project considering the size and the movements needed to be performed by the robot. NiMH batteries (Nickel Metal Hydrite) were also an option but to be able to supply the required voltage needed by the robot, the battery has to be customized, which made the batteries bulky and heavy. Litihium Ion Batteries were also readily available.

5. The microcontroller: Robot brain

The Atmega128 microcontroller used in this research serves as the main controller of the entire system. It is in-charge for processing all the input data and output data needed by the robot. Input data refers to the information taken from all the sensors and control switches. Output data are the signals needed by the servo motors in order to provide proper results in different situations for robot actions. Being the only microcontroller in the system, information from all modules is all carried in and out from this single controller. These modules are: the power management unit, the sensor information unit, the servo motor control unit, the artificial intelligence unit, and the central control unit.

The power management unit is the one responsible for distributing and monitoring the power to the entire system supplied by the batteries. If one of these batteries reaches critical level, the power management unit updates the microcontroller about the situation so that the microcontroller will be able to decide if the robot should continue its task or should stop.

The sensor information unit is responsible for all the system inputs of the robot. All of these inputs are fed into the microcontroller and then processed to provide the robot appropriate action for every situation.

The servo motor control unit is responsible for providing signals for each servo motor of the robot. Timing is considered an important factor in this module unlike all other modules where timing is not as important. One problem encountered in this research was that it would be difficult to control all motors from the output port pins of the microcontroller. Because of this problem, several approaches were considered. Using a separate microcontroller was first considered for controlling all the 17 servo motors. But using another microcontroller just for controlling the servo motors will defeat the purpose of using just one microcontroller for the whole system and will only pose new problems for the whole system like the communication and synchronization of the two microcontrollers. The solution was to make use of the Atmega128's timer/counter and connect the 17 servo motors to two 4017 decade counters.

The central control unit is responsible for the main controls of the robot. This module is a switch panel consists of a power supply switch, a reset switch, and 8 action switches. All batteries are connected to the power supply switch which turns the robot on and off. The reset switch is a normally open tact switch that is connected to the active low reset pin of the microcontroller and ground. The action switches determine what action the robot will be performing. These switches are connected to the 8 external interrupt pins of the microcontroller which are configured as level triggered, meaning the interrupt will trigger once the switch is held low. Also, these external interrupts INT0-INT7 have priority levels. INT0 being the most prioritized and INT7 as least prioritized interrupt.

6. The robot intelligence: Fuzzy logic system

The Fuzzy Logic System module is used for the artificial intelligence control algorithm of the robot. This module is responsible for the stability and balancing of the robot while it is performing actions such as walking and kicking. Implementation of fuzzy logic is inside the microcontroller software which is modifiable and adjustable. Since the implementation is in software, this procedure is processed inside the microcontroller in which the input values are taken from the tilt sensor and the output values provide the servo motors correct positions.

Fuzzy logic is a problem-solving control system methodology that mimics how humans derive a conclusion based on vague, ambiguous, imprecise, noisy or missing input information [12, 13]. The general idea about fuzzy logic is that it takes the inputs from the sensors which is a crisp value and transforms it into membership values ranging from 0 to 1. It then undergoes fuzzy reasoning process using the obtained membership values with the set of rules created. From the previous process, the system obtains a fuzzy set that will be transformed back to crisp values which controls the servo motors [12, 13]. Fuzzy logic systems are capable of processing inexact data and produce acceptable outputs. In addition, there is no need for very complex mathematical computations to control the robot. Also, the physical design of the robot does not need to be very exact and complicated as the fuzzy logic system can compensate for these flaws. Since the fuzzy logic is implemented using software, adjustments in the system is easier, cheaper and additional space is not needed which will only mean additional weight to the robot.

Two fuzzy logic system (FLS) controllers are developed in this research for the robot's balancing and stability. One FLS controls the left and right tilt and the other FLS controls the forward and backward tilt. Tilt angle in the first fuzzy logic system, which is for the left and right tilt, is taken and processed. Then the second fuzzy logic system will do the same with the forward and backward tilt angle. The idea is to operate the two fuzzy logic systems independently. This approach is more advantageous in terms of software implementation and complexity of the entire fuzzy logic system.

The Mamdani's method was used for implementing the fuzzy logic systems because of its simple yet great composition of 'min-max' operations [16]. Sample membership functions are shown in figures 4 to 9. Tables 1 and 2 shows the fuzzy associative memory matrix of the 2 fuzzy logic systems with the corresponding rules. Tables 3 and 4 show the final output on deciding what motors to activate. The idea is all the affected motors are going to increase or decrease their current angle until the system becomes stable. The amount of the angle shift will depend on the position of the motor in the robot. Observably, change in the angle of the motors located near the ground will have greater effect to the whole body than motors located less near the ground.

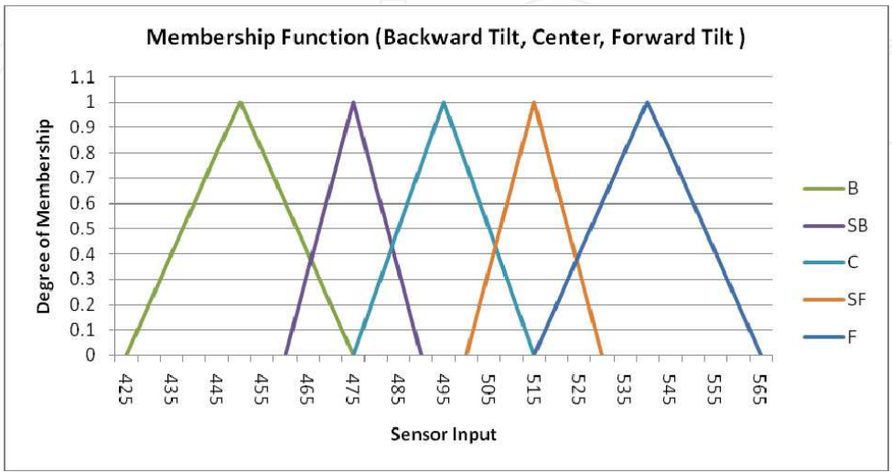


Fig. 4. Backward-Forward Membership Function

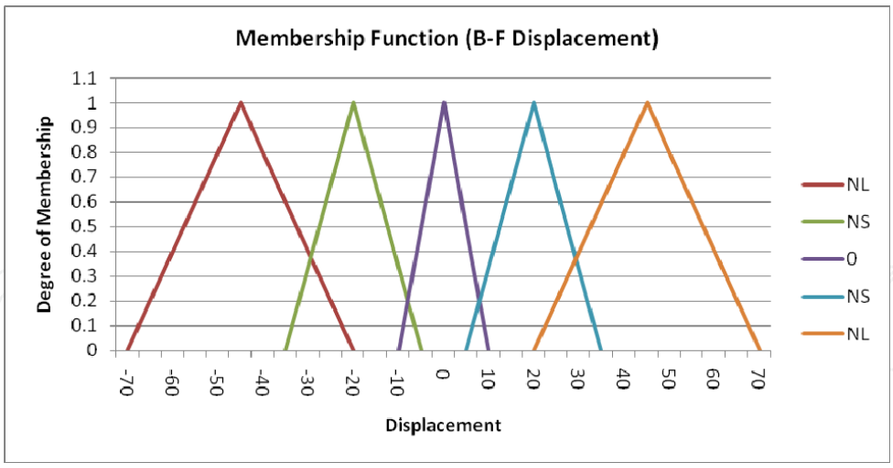


Fig. 5. B-F Displacement

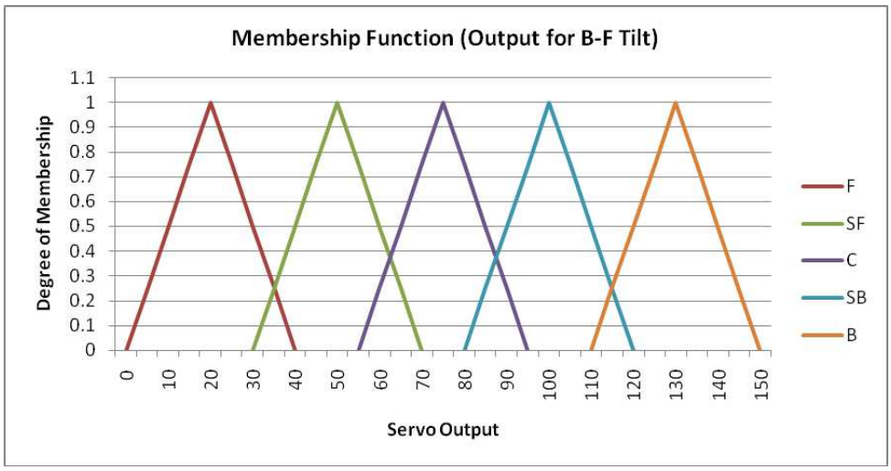


Fig. 6. Membership Function for B-F Tilt Servo Output

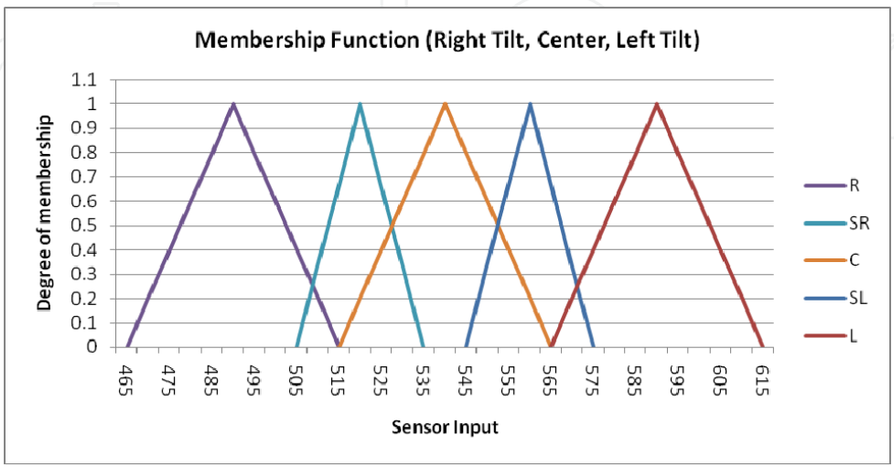


Fig. 7. Right-Left Membership Function

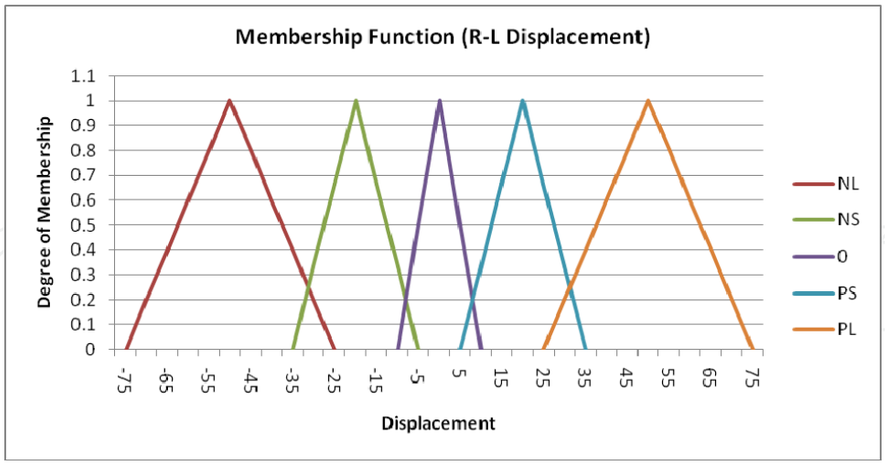


Fig. 8. R-L Displacement

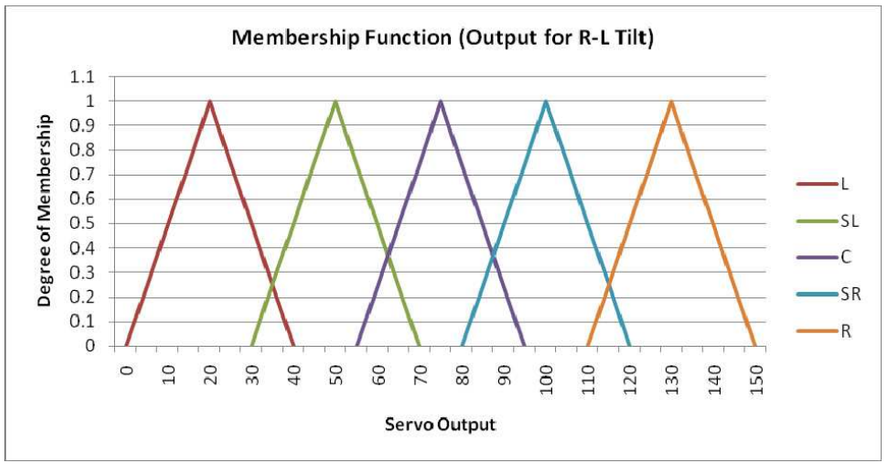


Fig. 9. Membership Function for R-L Tilt Servo Output

FLC 1		Displacement				
		NL	NS	0	PS	PL
B-F Tilt	B			F	F	F
	SB			SF	SF	F
	C	C	C	C	C	C
	SF	B	SB	SB		
	F	B	B	B		

Table 1. Fuzzy Logic Controller (FLC) 1 FAM

B – backward

F – forward

R - right

L - left

C - center

SB - slightly backward

SF - slightly forward

SR - slightly right

SL - slightly left

NL - negative large

NS - negative small

0 (zero) - negligible

PS - positive small

PL - positive large

RULES for (FLC) 1

1. if tilt is B and delta x is 0 (zero) then output is F.
2. if tilt is B and delta x is PS then output is F.
3. if tilt is B and delta x is PL then output is F.
4. if tilt is SB and delta x is 0 (zero) then output is SF.
5. if tilt is SB and delta x is PS then output is SF.
6. if tilt is SB and delta x is PL then output is F.
7. if tilt is C and delta x is NL then output is C.
8. if tilt is C and delta x is NS then output is C.
9. if tilt is C and delta x is 0 (zero) then output is C.
10. if tilt is C and delta x is PS then output is C.
11. if tilt is C and delta x is PL then output is C.
12. if tilt is SF and delta x is NL then output is B.
13. if tilt is SF and delta x is NS then output is SB.
14. if tilt is SF and delta x is 0 (zero) then output is SB.
15. if tilt is F and delta x is NL then output is B.
16. if tilt is F and delta x is NS then output is B.
17. if tilt is F and delta x is 0 (zero) then output is B.

FLC 2		Displacement				
		NL	NS	0	PS	PL
R-L Tilt	R			L	L	L
	SR			SL	SL	L
	C	C	C	C	C	C
	SL	R	SR	SR		
	L	R	R	R		

Table 2. Fuzzy Logic Controller (FLC) 2 FAM

RULES for (FLC) 2

1. if tilt is R and delta x is 0 (zero) then output is L.
2. if tilt is R and delta x is PS then output is L.
3. if tilt is R and delta x is PL then output is L.
4. if tilt is SR and delta x is 0 (zero) then output is SL.
5. if tilt is SR and delta x is PS then output is SL.
6. if tilt is SR and delta x is PL then output is L.
7. if tilt is C and delta x is NL then output is C.
8. if tilt is C and delta x is NS then output is C.
9. if tilt is C and delta x is 0 (zero) then output is C.
10. if tilt is C and delta x is PS then output is C.
11. if tilt is C and delta x is PL then output is C.
12. if tilt is SL and delta x is NL then output is R.
13. if tilt is SL and delta x is NS then output is SR.
14. if tilt is SL and delta x is 0 (zero) then output is SR.
15. if tilt is L and delta x is NL then output is R.
16. if tilt is L and delta x is NS then output is R.
17. if tilt is L and delta x is 0 (zero) then output is R.

Having established these two fuzzy logic systems, the balancing task will entirely depend on these. Failure to one of these systems would mean failure to the entire balancing task of the robot.

Output	Affected Motor
L	1,2,3,4,5,6,7,8
SL	1,2,3,4,5,6,7,8
C	None
SR	1,2,3,4,5,6,7,8
R	1,2,3,4,5,6,7,8

Table 3. Fuzzy Logic System R-L Output

Output	Affected Motor
F	3,4,7,8
SF	3,4,7,8
C	None
SB	3,4,7,8
B	3,4,7,8

Table 4. Fuzzy Logic System B-F Output

7. Experiment results

7.1 Inclined steel plate balancing experiments

In this experiment, a steel plate platform was used to measure the balancing capability of the robot. One end of the platform was gradually elevated so that the robot is standing on an inclined plane and the maximum angle the robot can stay on standing position is

recorded. Figures 10-13 shows the sample results of the real and physical experiments conducted. It can be seen in this figure that the robot uses its left foot to maintain its balance that compensate the angle taken on the inclined plane.

There were 4 tests of experiments conducted based on actual position of the robot relative to the inclined plane. The first test was the robot facing right of elevated steel plate as shown in figure 7. The second test was the robot facing left of the inclined steel plate as shown in figure 8. The third was the robot facing front of the inclined steel plate as shown in figure 9. And the fourth was the robot facing back of the inclined steel plate as shown in figure 10. It can be seen from these pictures that the robot uses its foot and body to maintain its stability. Figures 14a and 14b shows the results of these experiments with a comparison of the performance of the fuzzy logic controller against the conventional controller. Clearly from these results we can see the superiority of the fuzzy logic controller developed.

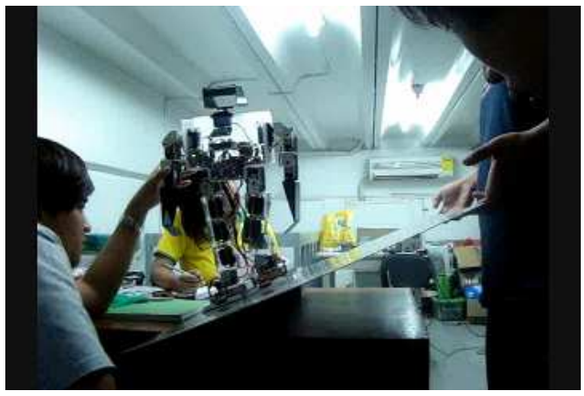


Fig. 10. Robot Inclined Steel Plate Balancing Experiment. Right position. Note that the hand of the person is not touching the robot. This is just in preparation to catch the robot when it falls.



Fig. 11. Robot Inclined Steel Plate Balancing Experiment. Left position. Note that the hand of the person is not touching the robot. This is just in preparation to catch the robot when it falls.



Fig. 12. Robot Inclined Steel Plate Balancing Experiment. Back position. Note that the hand of the person is not touching the robot. This is just in preparation to catch the robot when it falls.



Fig. 13. Robot Inclined Steel Plate Balancing Experiment. Front position. Note that the hand of the person is not touching the robot. This is just in preparation to catch the robot when it falls.

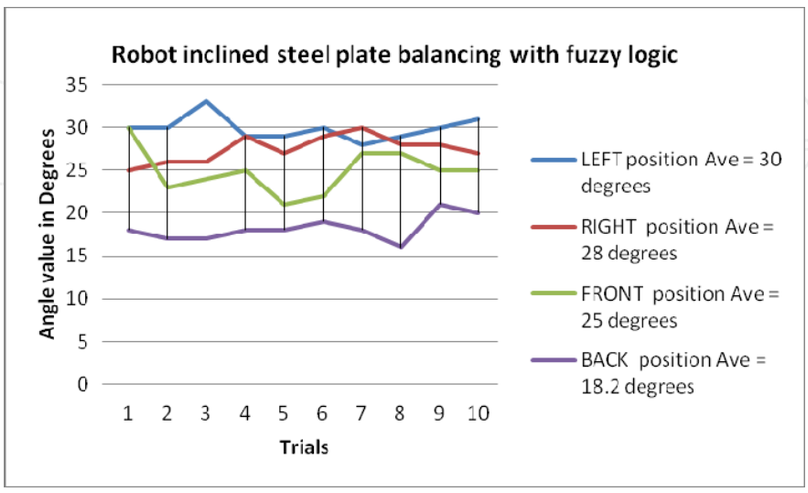


Fig. 14a. Humanoid robot steel plate balancing performance with fuzzy logic controller

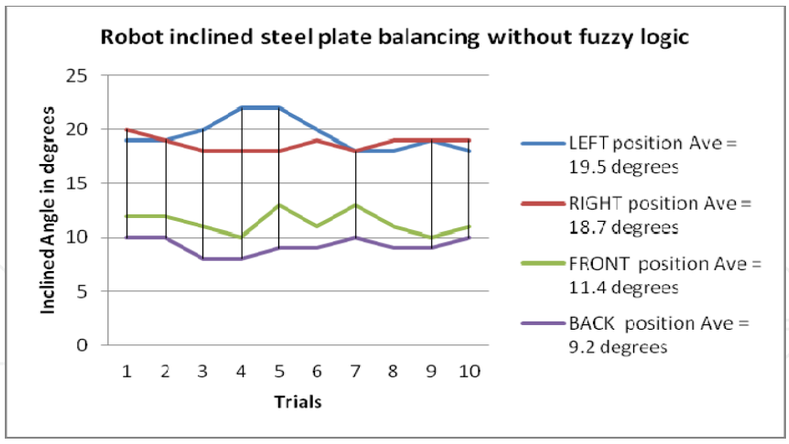


Fig. 14b. Humanoid robot steel plate balancing performance without fuzzy logic controller

7.2 Ball kicking experiments

The humanoid robot developed in this research can identify and kick a yellow tennis ball. A photo sensor is installed on the foot of the robot. Once the sensor found the ball the robot position itself to do the kicking. Complete animation of this task is shown in figure 15.

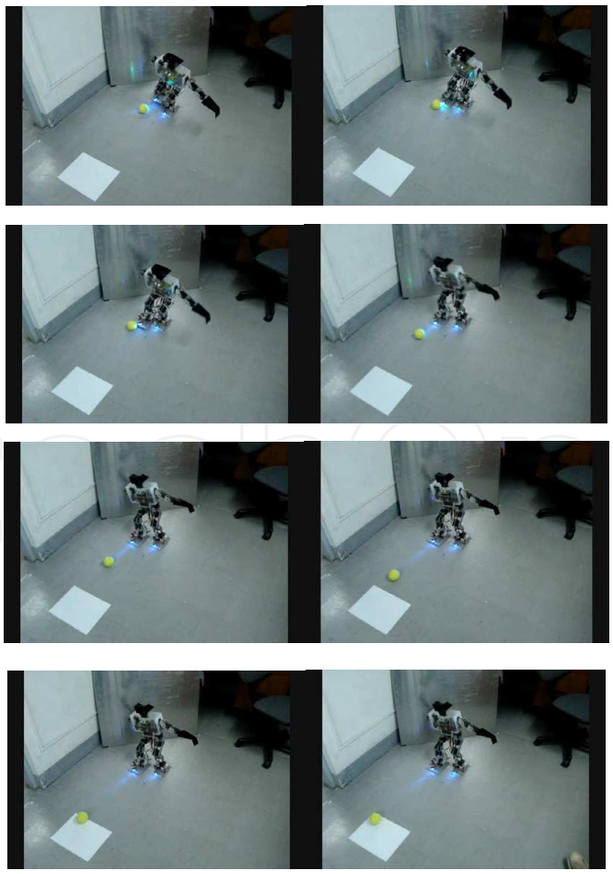


Fig. 15. Ball kicking experiment results

The robot uses its arm to balance itself in addition to its body alignment. Figure 16 shows the statistics of the robot performance in kicking the ball. The average distance the ball travel after kicking is 14.6 inches. Clearly from this figures the robot is very stable and reliable in performing this motions.

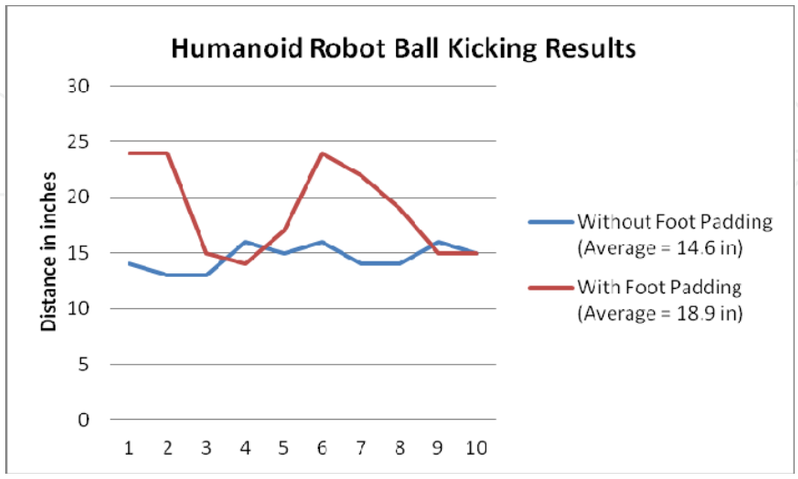
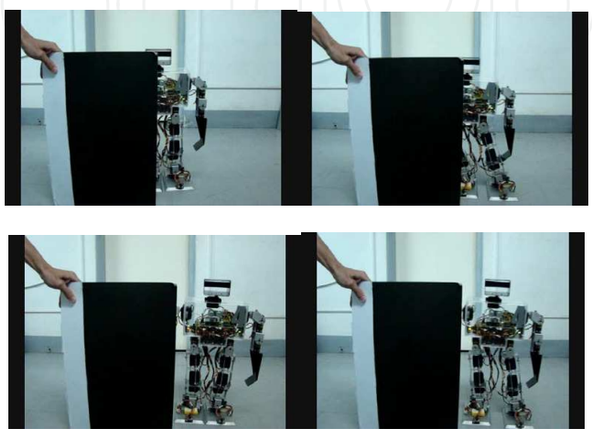


Fig. 16. Humanoid robot ball kicking controller performance.

7.3 Obstacle avoidance experiments

The robot uses ultrasonic and infra red sensors to detect the obstacles on its path. The positions of these sensors are evenly distributed on the robot's body. It is at the right, left, and center positions. When only the right sensor detects the obstacle the robot will do left side step motions until no obstacle is found. When only the left sensor detects the obstacle the robot will do right side steps motions until no obstacle is found. When all three ultrasonic sensors detect obstacle the robot will stop. If there are no more obstacles found the robot will walk forward right away. Figure 17 shows the animated motions of the robot in performing this task. The obstacle is on the right side of the robot hence the robot did left side step motion until the obstacle is not found. Figure 18 shows the distance accuracy of the robot in detecting obstacles. In all obstacle avoidance experiments conducted the robot shows very accurate, reliable, and robust behavior.



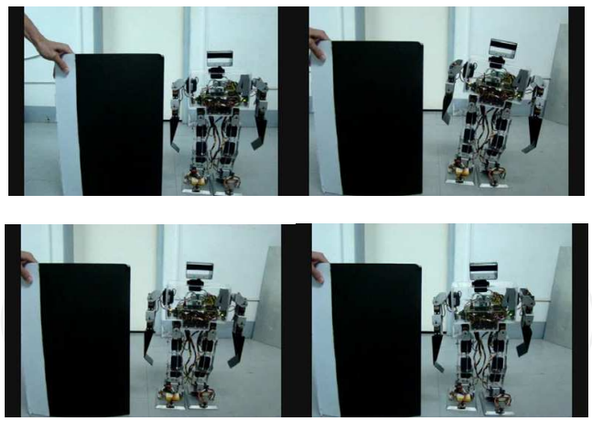


Fig. 17. Humanoid robot obstacle Avoidance - side step and forward motion.

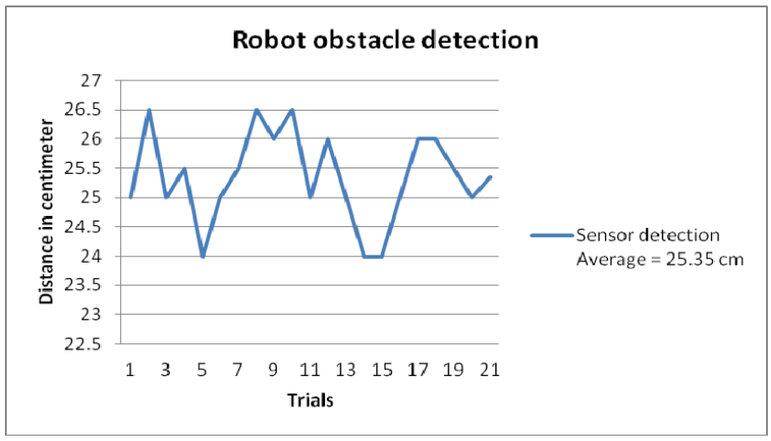
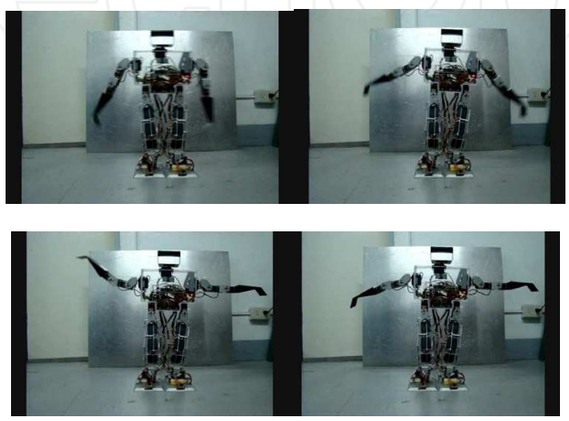


Fig. 18. Robot accuracy in detecting obstacles

7.4 Robot dancing experiments

The humanoid robot developed in this research has the capability to entertain people by dancing. In this experiment, the beat of the music is synchronized to the robot body, arm, head, and leg motions. Figure 19 shows the sample robot dancing motions with the music beats.



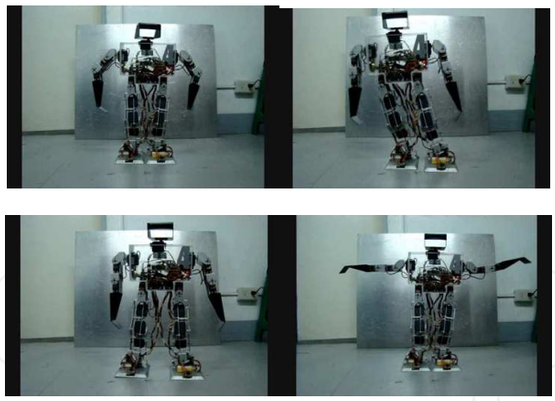


Fig. 19. Humanoid robot dancing results

8. Conclusions and recommendation

The paper showed a working prototype of a humanoid robot with artificial intelligence that has the ability to walk on two legs, kick a tennis ball, balance in an inclined steel plate, avoid obstacles, and dance with the beat of the music. Harmony between the parts of the robot namely mechanical, electrical and software is a must. The mechanical design deals with the overall physical architecture of the robot. It considers everything about the robot's whole skeletal system. The degrees of freedom for the robot are determined in this part. Proportion between the parts of the robot is very important as it would help in its stability thus making it easier to control.

The software design tackles all the decision making of the robot. This acts as the main brain of the robot. Fuzzy logic is implemented in order for the robot to maintain its balance and stability. The controller developed using fuzzy logic in this research exhibits very accurate, reliable, and robust behavior as shown in the defferent experiments conducted in section seven.

Electrical design deals with connecting the mechanical and software parts of the robot to translate into actual robot movement. Tilt sensor, infrared and ultrasonic is provided with ample voltage supply to work efficiently. An analog to digital converter is not needed anymore as Atmega128 has its built in capability. Power sources were designed to output sufficient amounts of energy that would run the motors and sensors efficiently. A double sided PCB is used to implement the circuit main board. The result of using a big and dual sided PCB was a harder time troubleshooting when problems occurred as well as aligning the two sides correctly.

All of these parts are needed to be done meticulously with the aim of making it very reliable. A design plan should always be followed as well as coordination between all of its parts. A conflict was experienced on whether to use rubber padding or not for the feet. Balancing in an inclined plane would require rubber padding. Without rubber padding, the robot slips down the plane. However, with the rubber padding on, the robot's walking is compromised even with slightly slippery rubber padding. The authors decided not to use the rubber padding as the robot's walking has a higher priority. For future works, it will be good to put an internal vision system on this robot in order for it to recognize and know the environment better.

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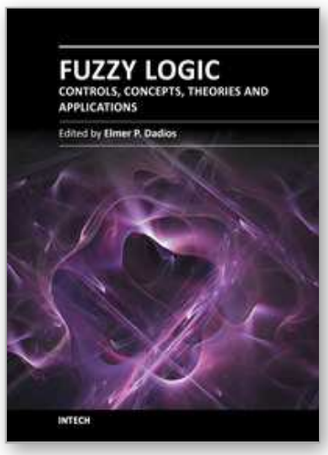
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This book introduces new concepts and theories of Fuzzy Logic Control for the application and development of robotics and intelligent machines. The book consists of nineteen chapters categorized into 1) Robotics and Electrical Machines 2) Intelligent Control Systems with various applications, and 3) New Fuzzy Logic Concepts and Theories. The intended readers of this book are engineers, researchers, and graduate students interested in fuzzy logic control systems.

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