Design, Modeling and Analysis of Bipedal Walking Robot by Using Fuzzy Logic Controller

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1. ABSTRACT—This paper describes the design, solid modeling and kinematic analysis of bipedal walking robot, which is developed through a strategy of balance control and movement of bipedal robot during its walk, it will also use fuzzy logic algorithm. The assumed motion for the bipedal robot is horizontal walking on a flat surface. The actuated joints are hip, knee and ankle joints which are driven by DC servomotors. The control signals produced by the fuzzy controllers are applied to the servomotors and then the response of the servomotors will led to the walking of the robot.

Keywords—centre of mass (COM), degrees of freedom (DOF), RC servo motor, fuzzylogic

2. INTRODUCTION—A bipedal robot can be generally described as the types of autonomous system which can imitate human waling motion with maintaining postural stability during the motion. To obtain human-like robotic walking has been a long standing, if not always explicitly stated, goal of robotic locomotion. Achieving this goal promises to result in robots able to navigate the myriad of terrains that humans can handle with ease for example, important applications to space exploration, walking up on a stair etc. Moreover, if one can understand how to make robots walk like humans, this understanding can be used to build robotic assistive and prosthetic devices to aid people with walking impairments and lower extremity amputations walk more efficiently and naturally. Thus, the ability to obtain human-like robotic walking has important and far-reaching ramifications.

The main idea behind this project work is that regardless of the complexity present in human walking hundreds of degrees of freedom coupled with highly Non linear dynamics and forcing the essential information needed to understand walking is encoded in simple output functions.

Design of Bipedal robot involves equal amount of mechanical and electronics considerations. There are many factors which are to be considered are cost, actuator, size, weight and controlling of actuators. All these factors have been considered and designed. The robot has six degrees of freedom, with three degrees of freedom per leg. Each leg has Hip, Knee and Ankle.With advances in science and technology, the interest to study the human walking has developed the demand for building the Bipedal robots.

3. MECHANICAL DESIGN OF BIPEDAL ROBOT

The mechanical design forms the basis for developing of this type of walking robots. The mechanical design contains following two stages.

3.1 Determination of mechanical constraints.

3.2 Conceptual design

3.1 Determination of mechanical constraints:-

There are various design considerations when designing a Bipedal robot. Among them, the major factors that have to be considered are Robot's size selection, Degrees of freedom (D.O.F) selection, Link Design, Stability and Foot Pad design.

3.1.1 Robot's Size Selection

Robot's size plays a major role. Based on this the cost of the project, materials required for fabrication and the no of actuators required can be determined. In this project miniature size of the robot is preferred so a height of 300mm is decided which includes mounting of the control circuits, but the actual size of the robot is 230mm without mounting of controlling circuits.

3.1.2 Degrees of Freedom (D.O.F)

Human leg has Six Degrees of freedom (Hip – 3 D.O.F, Knee – 1 D.O.F, Ankle – 2 D.O.F), but implementing all the Six D.O.F is difficult due to increase in cost of the project and complexity of controlling of the actuators. Therefore 3 D.O.F per leg has been used. With these six degrees of freedom (both legs) the robot is capable of walking.

3.1.3 Link Design

In this project U-shaped bracket like arrangement is used for joints formation. The bracket consists of two parts namely Servomotor bracket A and B. Servomotor will be fixed in the bracket A and the bracket B is used to transmit the output of the servomotor. Bracket B and servomotor are coupled using servomotor horn. By using the brackets there is a greater flexibility and individual joint can be actuated without disturbing the other joints. The Servomotor brackets are designed in accordance with the motor size as shown in Fig 3.1.

Figure 3.1 U-shaped servo brackets

3.1.4 Stability

With Biped mechanism, only two points will be in contact with the ground surface. In order to achieve effective balance, actuator will be made to rotate in sequence and the robot structure will try to balance. If the balancing is not proper, in order to maintain the Centre of Mass, dead weight would be placed in inverted pendulum configuration with 1 D.O.F. This dead weight will be shifted from one side to the other according to the balance requirement. But in this project no such configuration is used.

3.1.5 Foot Pad Design

The stability of the robot is determined by the foot pad. Generally there is a concept that oversized and heavy foot pad will have more stability due to more contact area. But there is a disadvantage in using the oversized and heavy foot pad, because the torque requirement of the motor is more and lifting the leg against the gravity becomes difficult. By considering this disadvantage an optimal sized foot pad which is neither too oversized nor too heavy was used.

3.2 CONCEPTUAL DESIGN

Initially the Bipedal robot was conceived with ten degrees of freedom with four degrees of freedom per leg and two passive degrees of freedom. Generally greater number of degrees of freedom increases the complexity of controlling the actuators and also increases the cost of the project, while the project's aim is to achieve the task at low cost. Due to these constraints, bipedal model is redesigned with eight degrees of freedom with three degrees of freedom per leg and two passive degrees of freedom. In this design all the joints are actuated in pitch orientation. On analysis of the model, drawback that all the joints are actuated in pitch orientation was brought into light. If all the joints are actuated in pitch orientation, shifting of center of gravity from one foot to another becomes impossible. Passive degrees of freedom that are used were abandoned because passive degrees of freedom don't help the robot to move and make it very difficult or impossible to lift the swing leg of the ground. In general passive degrees of freedom always compensate and precise engineering has to be done to achieve it. Finally, a new design was arrived with the knowledge gathered from developing previous Bipedal models. The new design has got Six degrees of freedom with three degrees of freedom per leg. Hip and Knee are actuated in Pitch orientation and Ankle joint is actuated in Roll orientation. This design has more stability with equal weight distribution on both the legs. Passive Degrees of Freedom considered in the previous models have been removed and both legs are connected by a link.

4. ANALYSIS OF BIPEDAL ROBOT

The analysis of bipedal robot is done by determination of Centre of mass and kinematic parameters used in the balancing of the bipedal robot.

4.1. Centre of mass

In physics, the center of mass, of a distribution of mass in space is the unique point where the weighted relative position of the distributed mass sums to zero. In this paper we are calculating the COM of bipedal robot in form of the variable form because don't know the exact dimensions. This model will be good example to calculate the COM using x, y, z variables as each link having 3 DOF movements. The following Table 4.2 will explain how to calculate the COM for each link of the bipedal walking robot.

And the centroid will be (X_t,Y_t,Z) which is defined from the product of centroid in respective axis and area of total elements in the model .

Hence the centroid of the total model is (X_t,Y_t,Z_t)

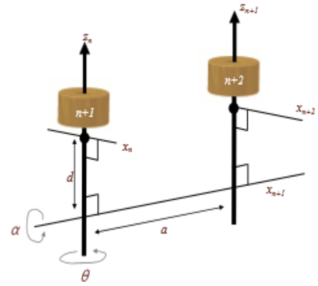
$$X_t = \frac{[\,a1x1 + a2x2 + a3x3 + a4x4 + a5x5 + a6x6 + a7x7\,]}{a1 + a2 + a3 + a4 + a5 + a6 + a7}$$

$$Y_t = \frac{a1y1 + a2y2 + a3y3 + a4y4 + a5y5 + a6y6 + a7y7}{a1 + a2 + a3 + a4 + a5 + a6 + a7}$$

$$Z_t = \frac{a1z1 + a2z2 + a3z3 + a4z4 + a5z5 + a6z6 + a7z7}{a1 + a2 + a3 + a4 + a5 + a6 + a7}$$

4.2. KINEMATIC PARAMETERS ANALYSIS

The D-H method allows the step from a link to the following link by 4 basic transformations that depends only on the robot's constructive characteristics. These are basic transformations that relate the reference system of the element n+1 with the reference system of the element n



(Fig4.1)

Figure 4.1 Basic transformations that relate the reference system of the element n+1 with the reference system of the element n.

1. A rotation θ_{n+i} about the Z_n axis (to bring X_n parallel with X_{n+1})

2. A translation d_{n+i} along the Z_n axis (to make the x-axes collinear)

3. A translation a_{n+i} along the X axis (to make the z-axes coincide)

4. A rotation α_{n+i} about the X_n axis (to bring Z_n parallel with Z_{n+1})

Together, these four transformations in the above order lead to an unique homogeneous transformation matrix with four variables representing the relationship between these two links. Since the matrix product is not commutative, the operation should be made in that order.

$$^{n}L_{n+1} = Rot(z,\theta_{n+1}) * Trn(0,0,d_{n+1}) *Trn(a_{n+1},0,0) * Rot(x,\alpha_{n+1})$$

NOTE:-

Rot = rotation, Trn = translation

Following is the homogenous transformation matrix $^{n}L_{n+1}$ =

$$\begin{bmatrix} \cos\theta_{n+1} & -\sin\theta_{n+1}\times\cos\alpha_{n+1} & \sin\theta_{n+1}\times\sin\alpha_{n+1} & a_{n+1}\times\cos\theta_{n+1} \\ \sin\theta_{n+1} & \cos\theta_{n+1}\times\cos\alpha_{n+1} & -\cos\theta_{n+1}\times\sin\alpha_{n+1} & a_{n+1}\times\sin\theta_{n+1} \\ 0 & \sin\alpha_{n+1} & \cos\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where θ_{n+1}, d_{n+1}, a_{n+1}, α_{n+1} are the D-H parameters for the i link. Thus, is enough to identify the θ_{n+1}, d_{n+1}, a_{n+1}, α_{n+1} parameters to obtain the $^{n}L_{n+1}$ matrices and relate each robot's link.

LINK	a_i	∞_i	d_i	$Ø_i$
1.	0	90^0	0	$ø_1$
2.	0	0	d_1	$ø_2$
3.	0	-90^0	d_2	$ø_3$
4.	L_3	90^0	0	0
5.	L_5	0	0	$ø_5$
6.	0	90^0	0	$ø_6$

Table. 4.1 D-H parameters of the bipedal robot

Now substitute the values in the table. 4.1 in $^{n}L_{n+1}$ to get the homogenous transformation matrix for each link in the robot. So six matrixes will be obtain because having six links. By the product of six matrixes total homogenous transformation matrix will obtain.

$$[^0L_6] = [^0L_1] \times [^1L_2] \times [^2L_3] \times [^3L_4] \times [^4L_5] \times [^5L_6]$$

$$[^0L_1]=\begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$[^1L_2] = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 1 & 0 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$[^2L_3] = \begin{bmatrix} \cos\theta_3 & 0 & -\sin\theta_3 & 0 \\ \sin\theta_3 & 0 & \cos\theta_3 & 0 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$[^3L_4] = \begin{bmatrix} 1 & 0 & 0 & L_3 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$[^4L_5] = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & L_4 cos\theta_5 \\ \sin\theta_5 & \cos\theta_5 & 0 & L_4 sin\theta_5 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$[^5L_6] = \begin{bmatrix} \cos\theta_6 & 0 & \sin\theta_6 & 0 \\ \sin\theta_6 & 0 & -\cos\theta_6 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The total transformation matrix is product of above all six matrix that is shown below as

$$[^0L_6]_{4x4} =$$

$$\begin{bmatrix} cos\theta_1 cos\theta_{2356} & sin\theta_1 & sin\theta_1 sin\theta_{2356} & cos\theta_1(L_4 cos\theta 235 + L3cos\theta 23) + sin\theta 1(d1+d2) \\ sin\theta 1cos\theta 2356 & cos\theta 1 & -cos\theta 12356 & sin\theta 1(L4cos\theta 235 + L3cos\theta 23) - cos\theta 1(d1+d2) \\ sin\theta 2356 & 0 & 0 & L_4 sin\theta_{235} + L_3 sin\theta_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.3. INVERSE KINEMATIC ANALYSIS

The purpose of solving the inverse kinematics is to find the angle of each joint for a known foot position. The equation provides the solution for the forward kinematics with matrix P being the result. The translation vector $\{P_x, P_y, P_z\}$ gives the position of the foot and the orientation matrix shows the direction of the foot in the space of the motion. Based on the assumption that the values in P are known, the joint angles can be calculated.

The orientation matrix is given as

$$O=\begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

General transformation matrix as

$$T=\begin{bmatrix} n_x & o_x & a_x & d_x \\ n_y & o_y & a_y & d_y \\ n_z & o_z & a_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Hence the orientation and position will be determined by the comparison of above two matrixes with the total transformation matrix $[^0L_6]_{4x4}$. So, the angular position of the hip joint, knee joint and ankle joints are given as below.

$\Theta_1 = \tan^{-1} (\sin\theta_1 / \cos\theta_1)$;

Where $\cos\theta_1 = -(ax/az)$, $\sin\theta_1 = \sqrt{(1-\cos\theta_1^2)}$

$\Theta_2 = \tan^{-1}(r_{31}/r_{32})$,

$\Theta_3 = \tan^{-1}(\sin\theta_3/\cos\theta_3)$;
Where $\cos\theta_3 = \sqrt{([r_{31}+r_{32}]/ 2[r_{32}-r_{31}])}$

$\Theta_5=\tan-1(\sin\theta_5/\cos\theta_5)$;

Where $\cos\theta_5= \{dx^2+dy^2+dz^2+(d1+d2)^2-[L_4^2+L_3^2]\}/ 2L_4L_3$

$\Theta_6 = \tan^{-1} (\sin\theta_6/\cos\theta_6)$; where $\cos\theta_6 = [r_{11}+1]-\cos\theta_5$

Above angles are defined by considering both legs in bipedal robot. So, this is the kinematic parameters analysis to the bipedal robot. It may vary according to the movement and rotation of the robot.

LIST OF COMPONENTS

5.1 Microcontroller

The ATmega16A provides the following features: 16K bytes of in-system programmable flash program memory with read while write capabilities, 512 bytes EPROM, 1K byte SRAM, 32 general purpose I/O lines, 32 general purpose working registers, an interface for boundary scan, on chip debugging support and programming, three flexible timer/counters with compare modes, internal and external interrupts, a serial programmable USART, a byte oriented two wired serial interface, an 8-channel, 10-bit ADC with optional differential input stage with programmable gain, a programmable watchdog timer with internal oscillator, an SPI serial port, and six software selectable power saving modes.

The ADC noise reduction mode stops the CPU and all I/O modules except asynchronous timer and ADC, to minimize switching noise during ADC conversions. In standby mode, the crystal/resonator oscillator is running while the rest of the device is sleeping as shown in Fig 3.3.This allows very fast start up combined with low-power consumption. The device is manufactured using Atmel's high density nonvolatile memory technology. The on chip ISP flash allows the program memory to be reprogrammed in system through an SPI serial interface, by a conventional memory programmer, or by an on chip boot program running on the AVR core. By combining an 8-bit RISC CPU within system self-programmable flash on monolithic chip, the Atmel ATmega16A is a powerful microcontroller that provides a highly flexible and cost effective solution to many embedded control applications. The ATmega16A AVR is supported with a full suite of program and system development tools including: C compilers, macro assemblers, program debuggers/simulators, in-circuit emulators, and evaluation kits

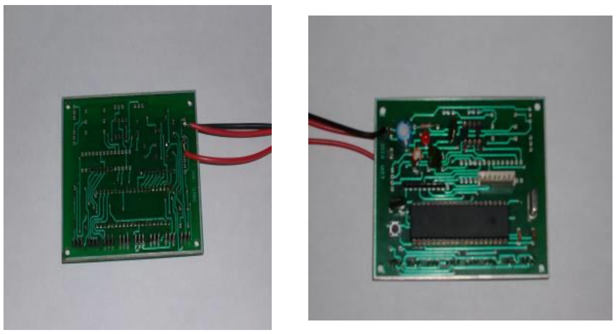


Figure 5.1.1: Top and Bottom side of Controller Board

5.2. RC Servomotor

RC Servomotors are basically geared DC motors with positional feedback control, which can accurately position the shaft. The motor shaft of RC Servomotor is positioned by Pulse Width Modulation (PWM). Generally Angles are coded as pulse width, so based on the pulse width duration the motor rotates as shown in Fig 5.1 and 5.2. The motor can rotate from 0˚ to 180˚ and it can be rotated in a second. In this project RC Servomotor is used which has a torque of 14 Kg-cm. It is the maximum rated torque available in the market. Based on the availability the robot has been designed. In general 14 Kg-cm torque is sufficient for static walking robots.

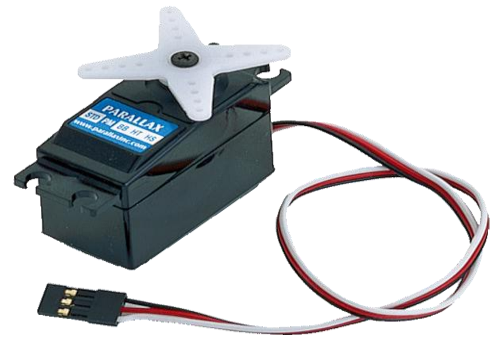


Figure 5.1 RC Servomotor image

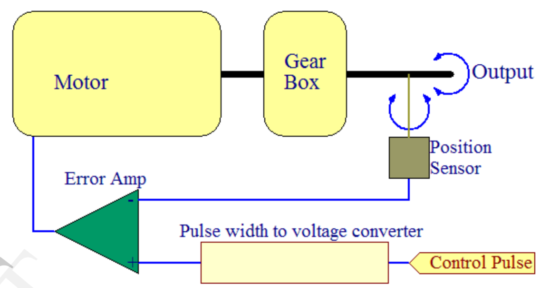


Figure 5.2 Block diagram of RC Servomotor

2. SOLID MODELLING OF BIPEDAL ROBOT—There are various design considerations when designing a bipedal robot. Among them, the major factors that have to be considered are robot's size selection, degree of freedom selection, link design, stability and foot pad design. In this project U-shaped bracket like arrangement is used for joints formation. The bracket consists of two parts namely servomotor bracket A and B as shown in Fig 6.1 and 6.2.

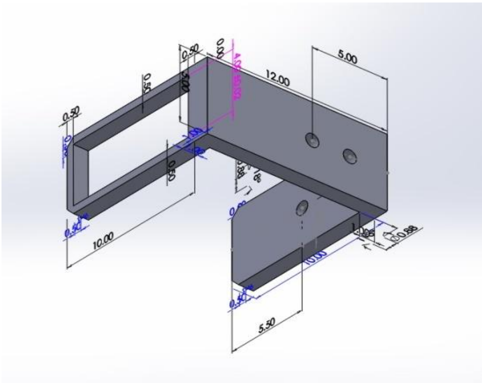


Figure 6.1 Upper bracket A

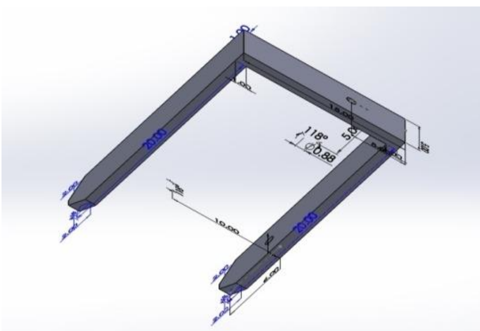


Figure 6.2 Lower bracket B

Now by placing the RC Servomotor between the two brackets A and B with revolving joints. Two brackets are connected each other in order to create a link of the bipedal walking robot. This link is considered as joint which can make 3 DOF moments fig6.3

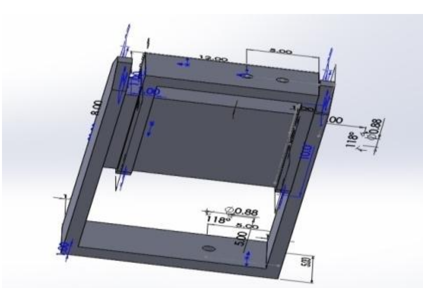


Figure 6.3 Joint of the robot

By connecting same bracket each other robot leg will be obtained as shown in the (Fig 6.4)

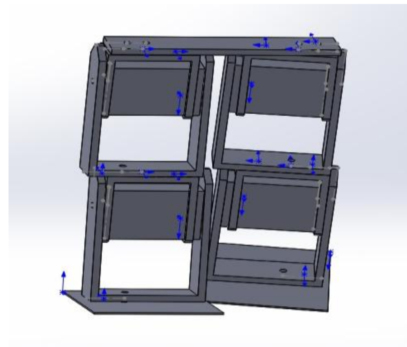


Figure 6.4 Total assembly of bipedal robot

6. SIMULATION OF BIPEDAL WALKINGROBOT

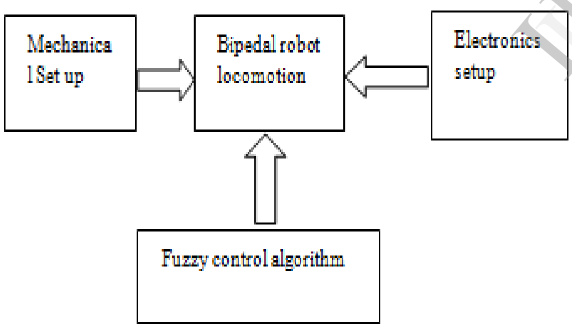
The biped locomotion consists of simultaneous movements of knee, hip and ankle joints in real time environment. Hence locomotion of the bipedal robot is simulated through MAT LAB programming. By using MAT LAB programming following movements will be obtained.

1. Angular position and velocities
2. Forces on end stance of the leg
3. Control signals
4. Linear displacement of each leg in biped robot

5. Acceleration of hip, knee and ankle joints of right leg
6. Acceleration of hip, knee and ankle joints of left leg
7. Motion of biped robot and resultant forces acting on the robot

7 .EXPERIMENTAL SETUP

The successful working of the fabricated model requires the synchronized working of the mechanical structure, positioning of servo motor and the commands from the controller circuit which acts as the brain behind the biped robot prototype. The biped robot consists of four servo motors which makes the system as a multi input and multi output system.



7.1 FUZZY CONTROLLER DESIGN

A fuzzy controller consists of a set of rules, an interface engine, a fuzzifier and a de fuzzifier. Rules may be provided by an expert (i.e. a human) or can be extracted from numerical data. The fuzzifier maps crisp numbers into fuzzy sets. Its job is to activate tools associated (through linguistic variables) with fuzzy sets. Fuzzy interface is expressed in terms of fuzzy variables that are ambiguous or imprecise.

7.1.1 BASIC FUZZY LOGIC BLOCK DIAGRAM

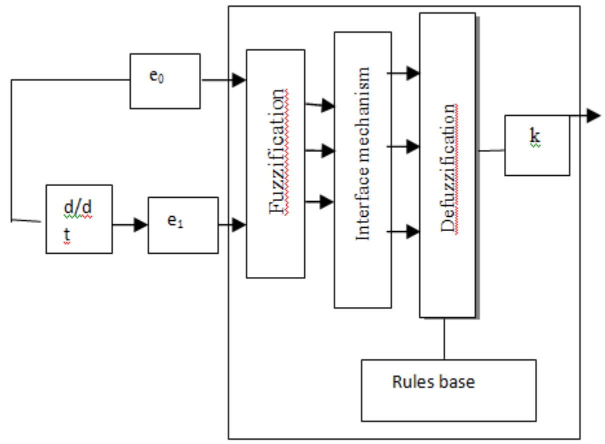


Fig 7.1.1 Basic fuzzy logic block diagram

7.1.2 INPUT OUTPUT VARIABLE—The first step in fuzzy controller defines the input and output variable so as to determine which parameters to be optimized in the control system.

The input variables are defined as error in the system and derivative of error. The output variable is the motor rpm.

8. CONCLUSION

According to this paper DC servomotors can operate simultaneously one after one as fuzzy logic algorithm by the microcontroller to generate the walking motion of the robot. The angular velocities of the hip, knee and ankle joints are controlled through programming for walking of bipedal robot. Angular orientations and transformation of the links are determined by the kinematic analysis. Bipedal robot will walk by the balancing of the center of mass (COM) calculated above.

It is clear that more complicated models of actual human lower limbs or the whole body with more degrees of freedom may be obtained and controlled utilizing the same approach. Observing the system performance by means of the included mechanics module will give a better understanding of the studied system and reduce the cost of the experimental setup of prototype of the system.

9. SCOPE OF FUTURE WORK

The present prototype can only generate simple walking motion up to four steps. The same prototype can be used for making motion like climbing up a stair or climbing up in a slope with maintaining postural stability. At this time the system becomes highly nonlinear and number of parameters to be controlled increases with complexity. Hence to analyze the system high level programming is required and in addition to it advanced controller algorithm to be used for maintaining walking stability in bipedal robot.

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