# A Semi-Minimalistic Approach to Humanoid Design

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***Abstract-*** Locomotion of a Humanoid robot with lesser number of actuators is a choice of interest, as it leads to energy efficient design. This paper put emphasis on design of a humanoid robot with minimal actuation, minimal control and minimum development cost. It describes, design considerations and methods used for balancing and walking gait generation of a Humanoid Robot with 8 Degrees of Freedom. The proposed robot finds the place in between most sophisticated, complex humanoid robots and simple, miniaturized humanoids.

***Index Terms*-** Centre of Mass (COM), Dead Weight, Degrees of Freedom (DOF), Humanoid Robot, Inverted Pendulum, Joint Structure

## I. INTRODUCTION

A Humanoid Robot has an appearance resembling a Human being. Simulation of Human body gives a better understanding about Humanoids. The research interest on Humanoid robotics has incredibly grown in last decade. This is because, Humanoid Robots have proved to be ideal robot design to interact with people naturally.

Huge amount of money is spent for developing Humanoid Robots. Many researchers had put forward minimalistic approaches for designing Humanoids, with reduced development costs. One such minimalistic approach for designing Humanoid robot is to utilize springs and the oscillatory motions of pendulum [1]. These robots have simple control mechanisms, minimal actuation and minimal energy usage. In one such design, the robot has “chicken like legs” and two cooperated pendulum arms. The swinging of the pendulum arms allows the robot to make steps [1]. This design accomplishes the locomotion of the robot, but keeps it away from productive tasks.

The main objective of this research is to develop a Humanoid robot that could find a place in between these minimal Humanoids and complex humanoids, those are similar to human beings. The development cost, control and complexity of the proposed robot will be a more than minimal humanoids but much lesser than Complex ones. The robot has 8 DOFs 4 DOFs on upper body and 4 DOFs on lower body. Design model of the proposed robot is shown in Figure 1.

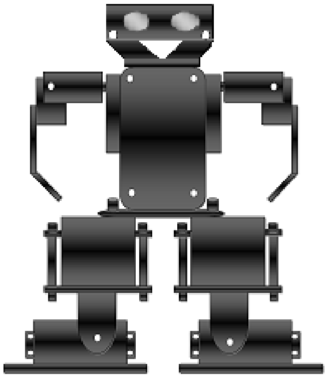


Figure 1: Model of Proposed Robot

## II. MECHANICAL DESIGN

### A. *Configuration of Links and Joints*

Figure 2 shows configuration of links and joints of the proposed robot. In the upper body, shoulders are of 1 DOF each and exhibit Pitch orientation. Elbows exhibits roll orientation and are of 1 DOF each on both arms. While considering lower body, hips exhibits yaw orientation and ankles exhibits roll orientation each of 1 DOF on both legs.

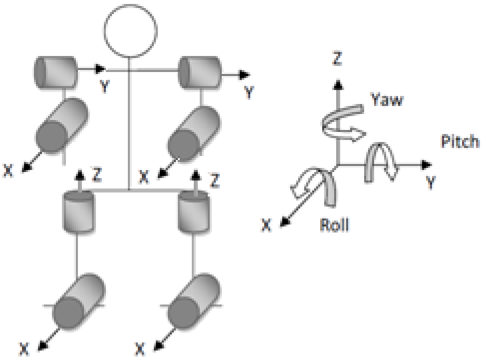


Figure 1. Configuration of Links and Joints

### B. *An Overview on Inverted Pendulum Model for stability*

A biped walker undergoes two support phases. In single support phase, only one feet of the robot is in ground and in Double support phase, both the feet are on ground [2]. During single support phase, the dynamical model of a biped robot can be represented by a simple inverted pendulum. Inverted pendulum model consists of a point mass and a mass less telescopic leg. Figure 3 shows a 3D Inverted pendulum model. The position of the point mass P is specified by variables $\theta_x$, which is the angle between the pendulum and the xz plane , $\theta_y$, is the angle between the pendulum and yz plane and L, which indicates the length of mass less leg [3,4]. If biped is walking on a flat plane and vertical height of Centre of Mass (COM) is kept constant, then the dynamics of the pendulum can be expressed as

$$\ddot{x} = \frac{g}{L}x + \frac{1}{mL}\tau_y \tag{1}$$

$$\ddot{y} = \frac{g}{L}y + \frac{1}{mL}\tau_x \qquad (2)$$

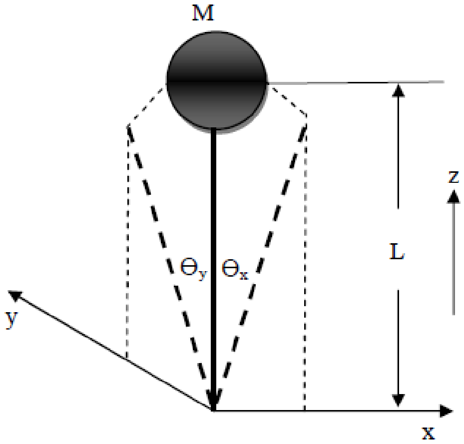


Figure 3. 3D Inverted Pendulum Model

where

g is gravitational acceleration

$\tau_x$ and $\tau_y$ are Torque applied across x and y axis respectively.

Figure 4 shows, Linear biped Model. It consists of two super imposed Linear Inverted Pendulum models (LIPM) in x-plane. It represents a biped in Double Support Phase [5]. Then equation (1) could be rewritten as

$$\ddot{x} = \frac{g}{L}x + \frac{\tau}{mL} \qquad (3)$$

Then the dynamics of two super imposed LIPM could be formed from Equation (3) as follows

$$\ddot{x} = \frac{g}{L}\omega_L(X - x_L) + \frac{g}{L}\omega_R(X - x_R) + \frac{\tau_L + \tau_R}{mL} \qquad (4)$$

where

$x_L$ and $x_R$ are locations of two feet

$X = \frac{1}{2}(x_L + x_R)$ is distance halfway from two feet

$\omega_L$ and $\omega_R$ are stance weight of Left and Right legs respectively

$\tau_L$ and $\tau_R$ are torque applied to both feet.

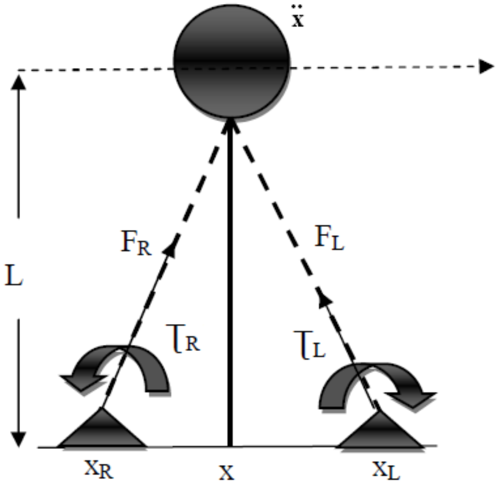


Figure 4. Linear Biped Model; Two super imposed LIPM

### C. *Kinematic Model of a 4 DOF Lower limb*

Calculating the position and orientation of the end effectors of the robot is called Forward kinematic analysis. Here the end effectors are the foot of the robot that enables locomotion. Kinematic modeling is the computation of Joint space from Cartesian space. This computation is necessary, as it determines orientation of the foot, position of COM of the links, generalized position vector ($q$), generalized velocity vector ($\dot{q}$) and generalized acceleration vector ($\ddot{q}$) . Figure 5 shows Joint angles and link parameters of a 4 DOF lower limb.

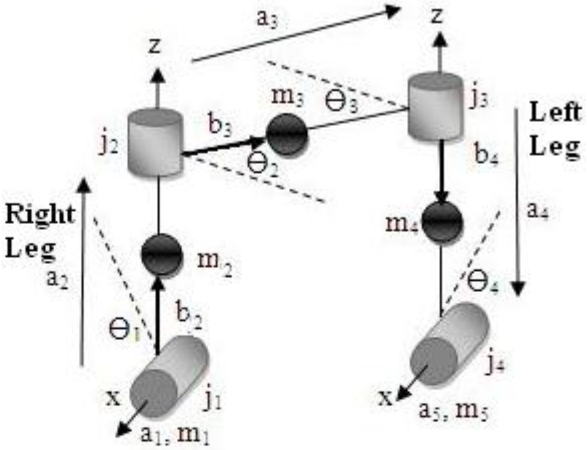


Figure 5. Joint angles and link parameters

The robot basically has 5 links and 4 joints at its lower body. To reduce the mathematical complexity, the foot links, $a_1$ and $a_5$ are virtual links with zero mass and zero length [6]. Thus the structure reduces to a 3 links, 4 joints biped model From figure 5,

$J_i$ represents joint associated with link $i$ and are revolute joints,

$a_i$ is the link vector connecting the joints $j_{i-1}$ to $j_i$,

$b_i$ is the COM vector specifying the COM of link $i$ ,

$m_i$ is the Mass of link $i$ and

$\Theta_i$ represents angle of rotation of each joints.

The orientation of the third link frame of the biped structure shown in Figure 5, can be found using

$${}^0_3R(\Theta_1, \Theta_2, \Theta_3) = {}^0_1R_x(\Theta_1)\ {}^1_2R_z(\Theta_2)\ {}^2_3R_z(\Theta_3) \qquad (5)$$

Rotation around x axis is defined as

$$ {}^{i-1}_{i}R_x(\Theta_i) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & Cos\Theta_i & -Sin\Theta_i \\ 0 & Sin\Theta_i & Cos\Theta_i \end{bmatrix} \qquad (6)$$

Rotation around y axis is defined as

$$ {}^{i-1}_{i}R_y(\Theta_i) = \begin{bmatrix} Cos\Theta_i & 0 & Sin\Theta_i \\ 0 & 1 & 0 \\ -Sin\Theta_i & 0 & Cos\Theta_i \end{bmatrix} \qquad (7)$$

And Rotation around z axis is defined as

$$ {}^{i-1}_{i}R_z(\Theta_i) = \begin{bmatrix} Cos\Theta_i & -Sin\Theta_i & 0 \\ Sin\Theta_i & Cos\Theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (8)$$

The orientation of the first link frame is

$$ {}^{0}_{1}R(\Theta_i) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_1 & -S_1 \\ 0 & S_1 & C_1 \end{bmatrix} \qquad (9)$$

where $C_1$= Cos($\Theta_1$) and $S_1$=Sin($\Theta_1$)

The orientation of second link frame is

$$ {}^{0}_{2}R(\Theta_1,\Theta_2) = \begin{bmatrix} C_2 & -S_2 & 0 \\ C_1S_2 & C_1C_2 & -S_1 \\ S_1S_2 & S_1C_2 & C_1 \end{bmatrix} \qquad (10)$$

and orientation of third link frame is

$$ {}^{0}_{3}R(\Theta_1,\Theta_2,\Theta_3) = $$

$$ \begin{bmatrix} C_2C_3 - S_2S_3 & -C_2S_3 - S_2C_3 & 0 \\ C_1S_2C_3 + C_1C_2S_3 & -C_1S_2S_3 + C_1C_2C_3 & -S_1 \\ S_1S_2C_3 + S_1C_2S_3 & -S_1S_2S_3 + S_1C_2C_3 & C_1 \end{bmatrix} \qquad (11)$$

The iterative equation for position of COM of link $i$+1 is

$$ P_{i+1} = \begin{bmatrix} x_{i+1} \\ y_{i+1} \\ z_{i+1} \end{bmatrix} = {}^{0}_{i}Rb_i + P_{j_i} \qquad (12)$$

where

$P_{j_i}$ is the position of joint $i$ defined as

$$ P_{j_i} = \begin{bmatrix} x_{j_i} \\ y_{j_i} \\ z_{j_i} \end{bmatrix} = {}^{0}_{i-1}Ra_i + P_{j_{i-1}} \qquad (13)$$

The Generalized position vector is

$$ q = \begin{bmatrix} x \\ y \\ z \\ \Theta \end{bmatrix} \qquad (14)$$

where

$$ x = [x_1 \quad x_2 \quad x_3]^T $$
$$ y = [y_1 \quad y_2 \quad y_3]^T $$
$$ z = [z_1 \quad z_2 \quad z_3]^T $$

which contains $x$, $y$, $z$ co-ordinates of all COM's

$$ \Theta = [\Theta_1 \quad \Theta_2 \quad \Theta_3 \quad \Theta_4]^T $$

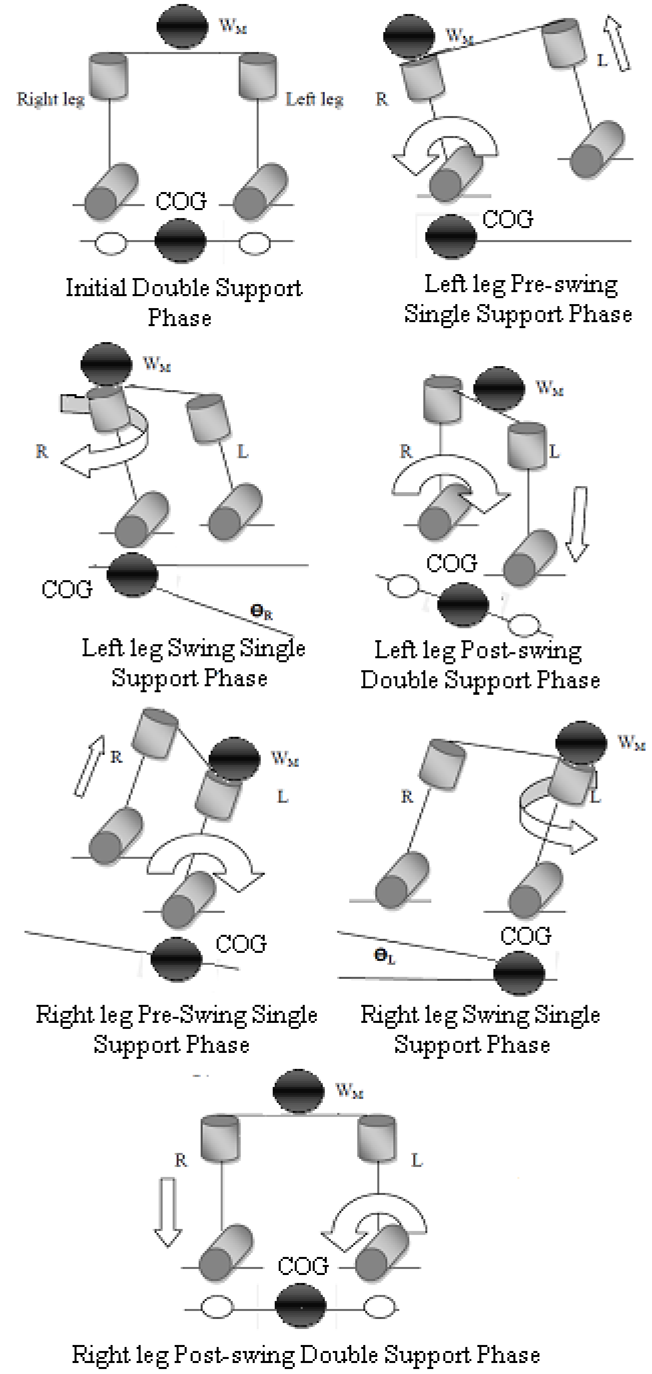
contains all joints

Generalized velocity vector

$$ \dot{q} = \frac{\partial q}{\partial t} \qquad (15)$$

and generalized acceleration vector

$$ \ddot{q} = \frac{\partial^2 q}{\partial t^2} \qquad (16)$$



Initial Double Support Phase

Left leg Pre-swing Single Support Phase

Left leg Swing Single Support Phase

Left leg Post-swing Double Support Phase

Right leg Pre-Swing Single Support Phase

Right leg Swing Single Support Phase

Right leg Post-swing Double Support Phase

Figure 6. Step by step illustration of forward walking

### *D. Biped Logic Gait Phases*

For a biped robot to walk, it stands on single leg and rotates, the other leg about the standing leg . When both legs comes to footing, the robot is said to be in stable condition. To provide stability in single support phase, concept of Inverted pendulum , as discussed earlier is used. According to this concept, the upper body “Dead Weight” is moved so as to bring the centre of gravity on the axis of footing leg. Various phases of forward walking of the proposed robot is illustrated in figure 6. From figure 6,

$W_M$ is the Weight of the upper body,

$\Theta_R$ and $\Theta_L$ are angles around the axis of Left and Right legs respectively.

Each phases are described as follows

- **Initial Double Support Phase**- The robot is in neutral condition. The upper body weight is shared among the two legs. Thus Centre of Gravity (COG) is maintained between the legs.
- **Left leg Pre-swing Single Support Phase**- The robot leans from left to right. The upper body weight is shifted towards right leg. The COG is now concentrated on right foot region.
- **Left leg Swing Single Support Phase-** The lifted left leg swings in air, keeping right feet under the upper body.
- **Left leg Post-swing Double Support Phase-** After swinging the left leg to highest point of its trajectory, the feet is lowered back to ground. The COG is now between the two legs.
- **Right leg Pre-Swing Single Support Phase**- The robot leans from right to left. The upper body weight is shifted towards left leg.
- **Right leg Swing Single Support Phase-** Right leg swings in air.
- **Right leg Post-swing Double Support Phase-** The right feet is lowered back to ground.

While walking these phases are repeated continuously [2,7,8,9].

### *E. Mechanical Calculations*

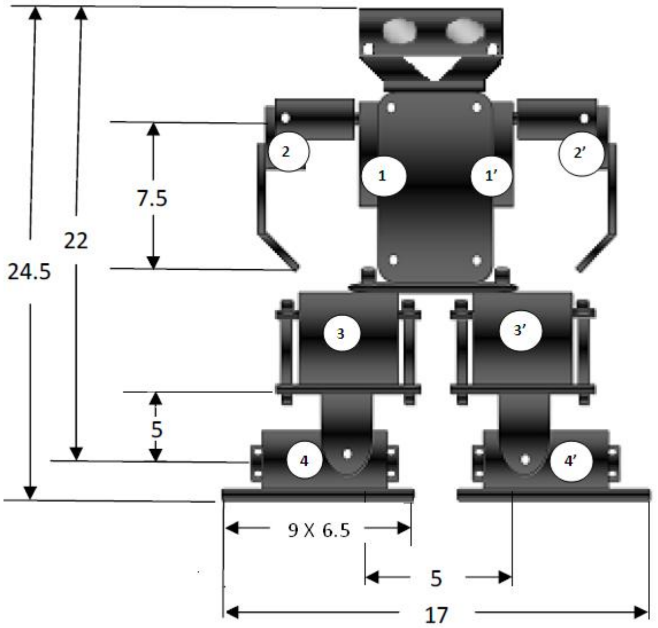


Figure 7. Dimensions and position of motors; All measurements are in centimeters

The dimensions and position of various motors are shown in Figure 7. All motors on right side of the robot is numbered from 1 to 4. Position of motors on left are symmetric to that of right.

- **Torque Calculations**

The Torque required by each motors are calculated by the equation

$$\tau = rF \tag{17}$$

Here , $F$ is the applied load,
$r$ is the distance from centre support point,
$\tau$ is the resulting torque

Motor 1:
The motor is placed at the shoulder of the robot, which allows the arm of the robot to rotate in pitch orientation.
Weight of the arm including the elbow motor: ~0.025 Kg
Length from centre of shaft of the motor:7.5 Cm
Using equation (16)
Torque of Motor 1= 0.025*7.5=~ 0.1875 Kg Cm

Motor 2:
The motor is placed on the elbow of the arm, exhibiting Roll orientation.
Weight of the arm link:~0.015 Kg
Length of the arm from shaft of the motor:7.5 Cm
Torque of Motor 2= 0.015*7.5=~0.1125 Kg Cm

Motor 3:
This motor is at the hip of the robot. It exhibits yaw orientation. During Single support phase, the entire weight of the robot excluding the weight of ankle motor and links of the standing leg is concentrated on to this motor.
Applied load:~ 0.410 Kg
Length of the shaft of the motor: 5 Cm
Torque of Motor 3= 0.410*5=~2.05 Kg Cm

Motor 4:
This motor is at the ankle of the leg and exhibits roll orientation. During Single support phase, the entire weight of the robot excluding the weight of the motor itself is concentrated on to this motor.
Applied Load:~0.510 Kg
Length of the shaft of the motor: 5 Cm
Torque of Motor 4= 0.510 *5=~2.55 Kg Cm

## III. ELECTRICAL CONSIDERATIONS

The required Electrical power for each motors discussed above could be determined by the equation

$$P = \frac{2\pi N\tau}{60} \tag{18}$$

Where N is RPM of the motor and $\tau$ is the Torque.
The current required for each motors are determined by the basic equation

$$I = \frac{P}{V} \tag{19}$$

Where P is the electrical power and V is the applied voltage.
All motors used are of 50 RPM and applied voltage is 5V. Then required electrical power and current for each motors could be calculated.

Motor 1:
Torque=~ 0.1875 Kg Cm
Using equation (18) , required power = 0.9806 Watts
Required current I=0.9806/5=0.1961 A

Motor 2:
Torque=~0.1125 Kg Cm
Required power= 0.5884 Watts
Required Current I=0.5884/5=0.1176 A

Motor 3:
Torque=~2.05 Kg Cm
Required power=10.76 Watts
Required Current I=10.76/5= 2.144 A

Motor 4:
Torque=~2.55 Kg Cm
Required power=13.34 Watts
Required Current I=13.34/5= 2.668 A

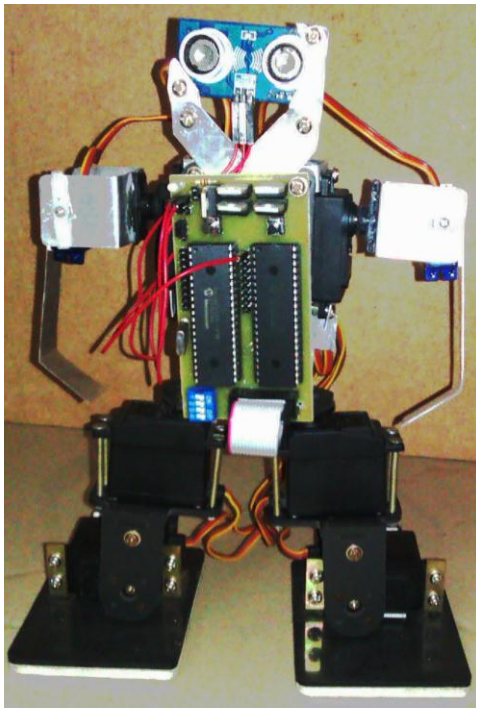


Figure 8: Fabricated Model of the Robot

## IV. CONCLUSION

The final fabricated model of the proposed robot is shown in Figure 8. Figure 9 shows the implemented results of various phases of robot gait. This paper is discussing only the designing and gait generation of a simplified humanoid robot. Various applications like obstacle detection, pick and place etc. could be incorporated on to this robot. Human Robot Interaction could also be implemented. Further research is necessary to explore the applications that can be initiated by this robot model. This paper lays foundations for future research and development of humanoid robots with minimum number of DOFs.

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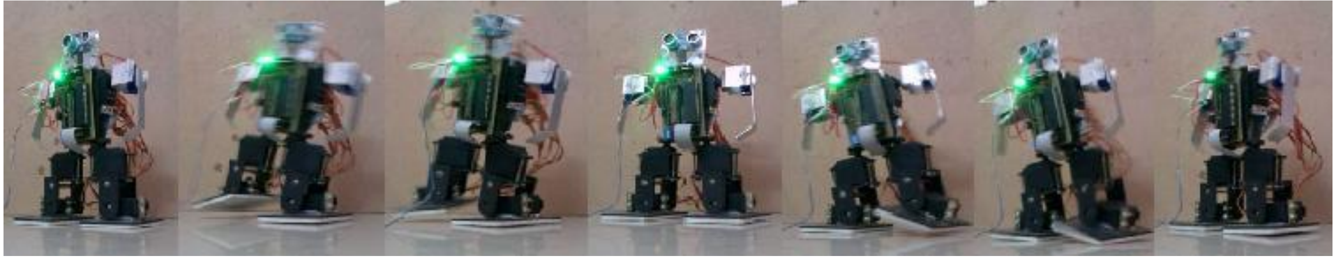

Figure 9: Implemented Results of Phases of robot Gait