sEnVision

A 6 DoF bipedal robot capable of human-like gait

by

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Chapter 1

Introduction

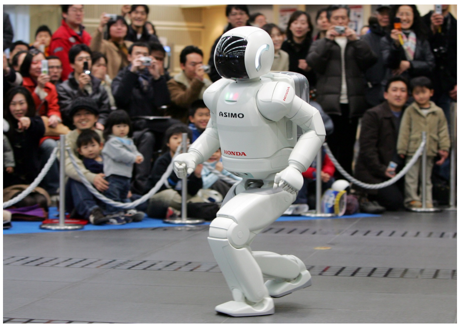
1.1 Background

The sEnVision project aims to develop a **bipedal bot** designed for efficient movement and adaptability, leveraging the advancements in mechanical design, electronics, and programming. Bipedal robots, inspired by human locomotion, are integral to robotics research due to their potential applications in surveillance, assistance in disaster scenarios, and human-robot interaction.

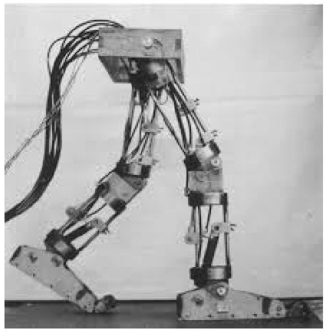
1.2 Motivation

The sEnVision Bipedal Bot is inspired by the need for robots that mimic human mobility in environments designed for people. Bipedal robots excel in navigating uneven terrains and have potential applications in fields like healthcare, disaster response, and surveillance.

This project aims to address key challenges in bipedal robotics like balance, coordination, and efficiency while promoting accessibility through cost-effective materials like 3D-printed PLA and open-source platforms like Arduino. By prioritizing sustainability and modularity, sEnVision aspires to advance low-cost robotics and inspire future innovations.



((A)) ASIMO bot by Honda



((B)) One of the first Biped bots

FIGURE 1.1: Biped Robots over the years

1.3 Previous work

Bipedal robots have been a focus of robotics research for decades due to their ability to navigate environments designed for humans, making them ideal for applications in healthcare, disaster response, and surveillance. Early developments focused on mimicking human gait, with robots like ASIMO by Honda setting a benchmark for stability and motion control. These robots used complex control algorithms and high-precision actuators to achieve balance during walking. Recent advancements have emphasized cost-efficiency and adaptability, integrating materials like 3D-printed PLA for lightweight yet durable structural components, and employing microcontrollers like Arduino to simplify control mechanisms. The use of servo motors, such as MG995, has become common for ensuring precise motion in joints while keeping the design modular and scalable.

Moreover, algorithms for trajectory planning and gait optimization have become increasingly sophisticated, enabling smooth, natural-looking movement. Innovations like dynamic trajectory adjustments and calibration techniques have improved stability on uneven surfaces. Modern bipedal robots also prioritize sustainability and rapid prototyping, reducing manufacturing costs and encouraging iterative design. Projects like sEnVision leverage these advancements, focusing on the integration of accessible technologies to create robots that not only mimic human motion but also push the boundaries of efficient and sustainable robotics.

Chapter 2

Mechanics of the Model

2.1 Link structure model

FIGURE 2.2: Gait Analysis

1. **Link 1 (L_1) and Link 2 (L_2):** These links represent the *feet* of the bipedal robot. ($L_1 = L_2$).

2. **Link 3 (L_3) and Link 4 (L_4):** These are the *lower legs* of the robot. They connect the feet to the knee joints, with both links having equal lengths ($L_3 = L_4$).

3. **Link 5 (L_5) and Link 6 (L_6):** These links represent the *upper legs* of the robot. They connect the knees to the hips, and their lengths are also equal ($L_5 = L_6$).

4. **Link 7 (L_7):** This is the *torso* of the robot, connecting the hips to the upper body.

5. **COM :** All blue dots in the diagram denote the *center of mass (COM)* of the respective links.

6. **Absolute Angles (q_i):** Absolute angles are measured with respect to a fixed global reference (either horizontal or vertical).

7. **Relative Angles (θ_i):** Relative angles are the angles between two adjacent links. to be directly actuated by servo motors

2.2 Gait structure

The gait structure of a bipedal robot defines the relationship between the links, their orientations, and their connections through joint angles. Each parameter and angle in the gait structure has a specific role in describing the configuration of the robot during motion.

2.3 Kinematics

2.3.1 Forward Kinematics Equations

The positions for each link and center of mass (COM) are defined as follows:

$$x_2 = L_1 - \alpha \cdot L_1,$$

$$y_2 = \beta \cdot l$$

$$x_4 = L_1 \cdot (1 - a) + \alpha_{13} \cdot L_3 \cdot \sin(-q_4),$$

$$y_4 = l + \alpha_{13} \cdot L_3 \cdot \cos(-q_4)$$

$$x_6 = L_1 \cdot (1 - a) + L_3 \cdot \sin(-q_4) + \alpha_{56} \cdot L_6 \cdot \sin(-q_6),$$

$$y_6 = l + L_3 \cdot \cos(-q_4) + \alpha_{56} \cdot L_6 \cdot \cos(-q_6)$$

$$x_7 = L_1 \cdot (1-a) + L_3 \cdot \sin(-q_4) + L_6 \cdot \sin(-q_6) + L_7 \cdot \sin(-q_7),$$

$$y_7 = l + L_3 \cdot \cos(-q_4) + L_6 \cdot \cos(-q_6) + L_7 \cdot \cos(-q_7)$$

$$x_5 = L_1 \cdot (1-a) + L_3 \cdot \sin(-q_4) + L_6 \cdot \sin(-q_6) + L_5 \cdot (1-\alpha_{56}) \cdot \sin(q_5),$$

$$y_5 = l + L_3 \cdot \cos(-q_4) + L_6 \cdot \cos(-q_6) - L_5 \cdot (1-\alpha_{56}) \cdot \cos(-q_5)$$

$$x_3 = L_1 \cdot (1-a) + L_3 \cdot \sin(-q_4) + L_6 \cdot \sin(-q_6) + L_5 \cdot \sin(q_5) - L_3 \cdot (1-\alpha_{13}) \cdot \sin(-q_3),$$

$$y_3 = l + L_3 \cdot \cos(-q_4) + L_6 \cdot \cos(-q_6) - L_5 \cdot \cos(q_5) - L_3 \cdot (1-\alpha_{13}) \cdot \cos(-q_3)$$

$$\begin{aligned} x_1 &= L_1 \cdot (1-a) + L_3 \cdot \sin(-q_4) + L_6 \cdot \sin(-q_6) + L_5 \cdot \sin(q_5) - L_3 \cdot \sin(-q_3) + l \cdot (1-\beta) \cdot \sin(q_1) \\ &\quad + L_1 \cdot (a-\alpha) \cdot \cos(q_1) \end{aligned}$$

$$\begin{aligned} y_1 &= l + L_3 \cdot \cos(-q_4) + L_6 \cdot \cos(-q_6) - L_5 \cdot \cos(q_5) - L_3 \cdot \cos(-q_3) - L_1 \cdot (a-\alpha) \cdot \sin(-q_1) \\ &\quad - l \cdot (1-\beta) \cdot \cos(q_1) \end{aligned}$$

2.3.2 Inverse Kinematic Relations

The joint angles are related as follows, ensuring the biped's configuration aligns with the required motion:

$$q_2 = 0 \quad \text{(Foot parallel to the ground)}$$

$$q_4 = \theta_2 - 90 \quad \text{(Lower leg angle relative to vertical)}$$

$$q_6 = \theta_4 + q_4 - 180 \quad \text{(Upper leg angle relative to lower leg)}$$

$$q_7 = \theta_6 + q_6 - 180 \quad \text{(Torso angle relative to upper leg)}$$

$$q_5 = 180 + q_7 - \theta_5 \quad \text{(Hip angle)}$$

$$q_3 = 180 + q_5 - \theta_3 \quad \text{(Knee angle)}$$

$$q_1 = 90 + q_3 - \theta_1 \quad \text{(Final joint angle)}$$

2.4 Dynamics

The dynamics of a bipedal robot involves modeling its motion, which is governed by a set of differential equations. These equations relate the torques, forces, and motion variables (e.g., joint angles, link velocities) of the robot. This report focuses on deriving the equations of motion using the Lagrangian formulation.

The Lagrangian is given by:

$$L = T - V$$

Substituting T and V into the Euler-Lagrange equation for each joint q_i, we obtain:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = \tau_i$$

The coupled equations of motion for the bipedal robot can be expressed as:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \tau$$

where:

- $\mathbf{q} = [q_1, q_2, \ldots, q_n]^T$: Vector of joint angles.
- $\mathbf{M}(\mathbf{q})$: Mass/inertia matrix.
- $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$: Coriolis and centrifugal forces matrix.
- $\mathbf{G}(\mathbf{q})$: Gravitational force vector.
- τ: Vector of joint torques.

Chapter 3

Physical Model

This chapter discusses the design - various features and constraints - put of the physical model of the autonomous bipedal bot.

3.1 Design Iteration

The sEnVision bipedal bot underwent multiple design iterations to improve functionality, stability, and aesthetics. Initially, short leg links ensured stability but limited step size and gait. To overcome this, leg proportions were optimized by adjusting shin and thigh lengths through mechanical analysis and prototyping, enhancing range of motion and achieving natural, human-like movement while maintaining balance. 3D-printed PLA enabled rapid prototyping and refinement, while adjustments to servo motor placement ensured smooth trajectories. The final design features proportionate legs balancing functionality, stability, and appearance.

3.1.1 Lift off Torque Requirement

1st Iteration The initial torque analysis used the first model iteration, estimating a maximum step size of 60% of the foot length (= 180mm). From the FBD, step size = 2x = 60 / 100 * 180, hence x = 54mm.

Mass estimate for lift-off = 1.5kg (Servos 100g x 5, Battery 600g, Links 300g, Electronics 100g).

Torque $\geq$ mgx = 1.5 * 9.81 * 54 / 1000 = 0.795 Nm.

The minimum torque required is 0.8 Nm, so we used MG995 servos with a maximum torque of 1.2 Nm.

Strengths: Stable model with sufficient torque at all joints.
Drawbacks: Short link lengths in the initial model limited range of motion, step size, and gait appearance.

2nd Iteration

These drawbacks helped us in optimising the link lengths. Since the step size increased by a small factor, the torque requirements were still in the range of the available servo motors.
Strengths of this model:
A further increase in the range of motion and the step size. This increased range of motion also helped in giving the bot a more human-like gait motion.

3.2 CAD Model

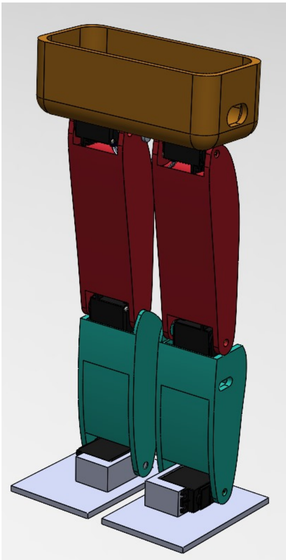


Figure 3.1: CAD for the Bot

3.2.1 Links

The bipedal robot's links are made from 3D-printed PLA (Polylactic Acid), offering a lightweight yet rigid structure ideal for dynamic motion. PLA is cost-effective, readily available, and customizable, enabling easy adjustments in geometry and size. The 3D printing process ensures precise dimensions and simplifies the integration of mounting features, facilitating assembly, disassembly, and adaptability during prototyping and testing.

Dimension	Waist	Thigh	Leg	Foot Height	Foot Base
Length	170 mm × 75 mm × 60 mm	163.5 mm	126 mm	70 mm	115 mm × 80 mm

3.2.2 Motors

Servo motors ensure precise motion and torque control for the bipedal robot. All parts are 3D-printed with PLA using FDM technology. The waist integrates servo mounts, linking thighs, legs, and feet for stable, coordinated movement. Lightweight PLA mounts secure motors, while the modular design allows easy assembly, maintenance, and modifications.

3.2.3 Electronics

The bipedal robot's electronics include a PCA9685 servo driver, Arduino Uno, MG995 servo motors, and a 12V 4500mAh battery, all mounted on the waist. This centralized setup ensures precise motion control, efficient functionality, and portable operation, with the battery powering the system and the servo motors enabling joint articulation.

Chapter 4

Gait Trajectory

The gait trajectory defines the sequence of movements a bipedal robot or human uses for locomotion, ensuring smooth, coordinated walking with stability and efficiency. Inspired by the human gait cycle, it involves alternating phases of weight-bearing and forward propulsion. The gait cycle is typically divided into two main phases: the **stance phase**, where one foot supports the body, and the **swing phase**, where the other foot moves forward. These phases are repeated to maintain continuous and stable walking.

4.1 Phases of the Gait Trajectory

1. **Stance Phase**

   The stance phase occurs when the foot is in contact with the ground, supporting the body's weight, making up about 60% of the gait cycle. It includes:

   - **Heel Strike:** The foot touches the ground, stabilizing the body.
   - **Midstance:** The supporting leg bears the weight as the center of mass shifts forward.
   - **Push-Off:** The foot propels the body forward, preparing for the swing phase.

2. **Swing Phase**

   The swing phase, accounting for 40% of the gait cycle, occurs when the foot moves forward:

   - **Initial Swing:** The leg lifts off the ground, ensuring clearance.

- **Midswing:** The leg moves forward, aligning for landing.
- **Terminal Swing:** The foot is positioned for landing, transitioning into stance.

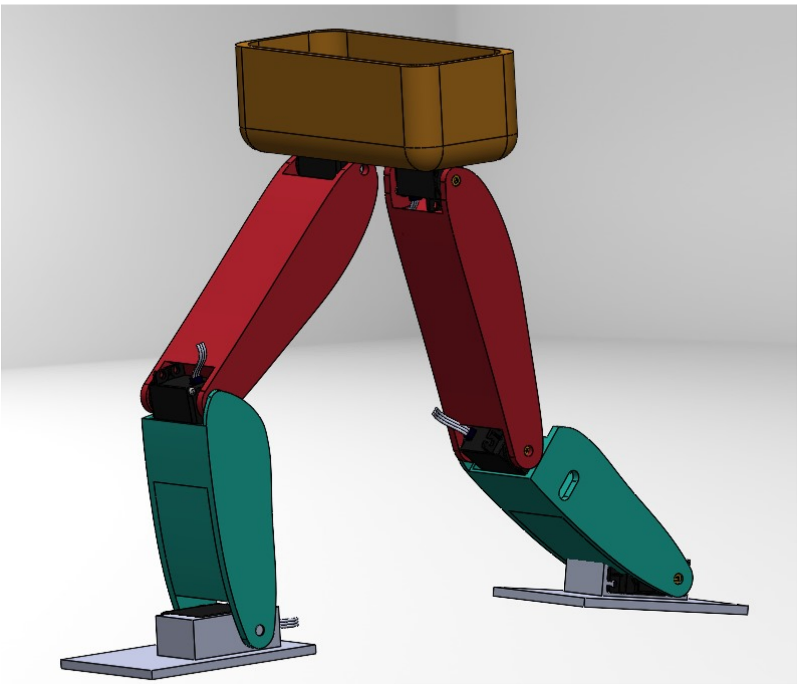


FIGURE 4.1: Stance Swing

In the bipedal robot design, each joint and link is essential for smooth, synchronized motion. The robot has six links, interconnected by joints, with angles defining its movement during the gait cycle. We model motion at three time stamps: 0, $T/2$, and T, where T is the cycle period. At each time stamp, joint angles (θ_1 to θ_6) are recorded, dictating the robot's posture at specific moments in its movement.

The recorded angles at the time stamps are:

Time	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
0	65°	65°	130°	180°	-155°	155°
$T/2$	65°	65°	180°	130°	-205°	205°
T	65°	65°	130°	180°	-155°	155°

To achieve smooth movement, linear interpolation is applied between time stamps for each joint angle. This allows the robot to transition smoothly between postures by filling intermediate positions. Linear interpolation assumes a constant rate of change in angle between consecutive time stamps, ensuring a natural, realistic gait for the robot.

For instance, if the angle of a joint at $t = 0$ is θ_a, and at $t = T/2$ is θ_b, the interpolated angle $\theta(t)$ at a time t between 0 and $T/2$ is calculated as:

$$\theta(t) = \theta_a + \frac{t}{T/2}(\theta_b - \theta_a), \quad 0 \leq t \leq T/2.$$

Similarly, the interpolation for $T/2 \leq t \leq T$ is given as:

$$\theta(t) = \theta_b + \frac{t - T/2}{T/2}(\theta_c - \theta_b),$$

where θ_c is the angle at $t = T$.

Chapter 5

Results

5.1 Simulation results

We were able to simulate trajectory planning in MATLAB. Using the same notations as above, we defined the model using Symbolic for simulation. We implemented the constraints discussed above, namely, ensuring that the waist is upright always and ensuring a leg does not go below ground. We assumed that at at least one leg is always firmly on the ground. With these constraints, we were able to effectively reduce the degree of freedom of the system from 6 to 4, allowing a lower dimensional system to be used to design our trajectory. To get a natural looking trajectory, we made a GUI which contained sliders for different angles, By adding different constraints in code, we were able to control fewer sliders in the GUI to extract intermediate angles to get our trajectory.

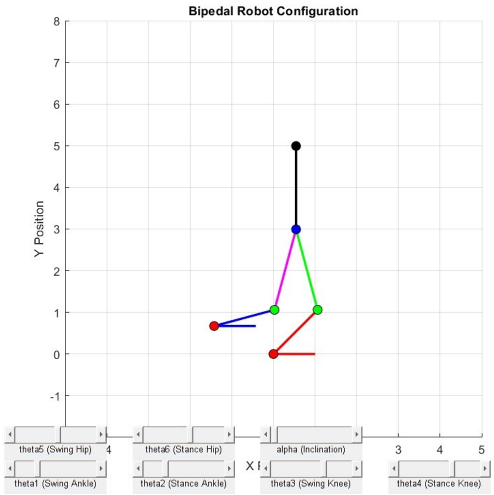


FIGURE 5.1: MATLAB GUI for trajectory design and verification

5.2 Hardware results

We were able to fabricate all parts of the robot using PLA with FDM printing. We used dynamic equation with continuous trajectories to estimate the torque requirements to get the maximum torque rating for our motors, We finalized to use MG995 servo motors for position control of the robot. We used an Arduino UNO microcontroller with a PCA9685 servo driver to control the robot. We calibrated all the servos so that the notation of angles from design can be directly used in code. We used an interrupt service routine for a timer to implement a trajectory running at a fixed rate.

```
uint16_t servos_des_angle(uint8_t servonum, float t){
  // give time t, what angle should servonum should have
  uint16_t angle = 0;
  bool left_fwd = int(t)/(2*step_time)<step_time;
  float s = (int(t)%step_time)/step_time;
  switch(servonum+1){
    case 1: // left ankle
      if(left_fwd)  angle = (uint16_t) 65 + 0*s;
      else          angle = (uint16_t) 65 - 0*s;
      break;
    case 2: // left knee
      if(left_fwd)  angle = (uint16_t) 130 + 50*s;
      else          angle = (uint16_t) 180 - 50*s;
      break;
    case 3: // left hip
      if(left_fwd)  angle = (uint16_t) 155 + 50*s;
      else          angle = (uint16_t) 205 - 50*s;
      break;
    case 4: // right hip
      if(left_fwd)  angle = (uint16_t) 150 + 50*s;
      else          angle = (uint16_t) 205 - 50*s;
      break;
    case 5: // right knee
      if(left_fwd)  angle = (uint16_t) 180 - 50*s;
      else          angle = (uint16_t) 130 + 50*s;
      break;
    case 6: // right ankle
      if(left_fwd)  angle = (uint16_t) 65 + 0*s;
      else          angle = (uint16_t) 65 - 0*s;
      break;
  }
  return angle;
}
```

FIGURE 5.2: Arduino code encoding trajectory for various servos as a function of time

5.3 Discussions

We noticed a jitter in the motion of the robot. We found out that this largely depended on the rate at which the code runs. Many a times, an iteration of the loop took longer to run and caused a lag in the motion of the robot. Although these sightings were rare, we realized the needed of embedded system for running our servos which can perform tasks in real time with reliability. Further, we noticed that the lateral sway in robot arising out of manufacturing defects actually helped the robot to balance by transferring the center of mass of the robot towards the stance leg.

Chapter 6

Conclusion

6.1 Summary

The ”sEnVision” report outlines the design and development of a cost-effective bipedal robot with human-like gait, created by IIT Bombay students. It details the robot’s mechanics, 3D-printed PLA structure, and use of MG995 servo motors for motion control. Linear interpolation ensures smooth gait transitions. Iterative design improved stability, range of motion, and aesthetics. The report highlights simulation and hardware results and suggests future enhancements like advanced sensors, autonomous navigation, and adaptive gait learning.

6.2 Further Work

- **Enhancing Stability on Uneven Terrain** - Implement advanced sensor integration, such as gyroscopes, accelerometers, or LiDAR, to enable dynamic balance adjustments and obstacle detection. Develop real-time feedback algorithms to adapt gait trajectories based on environmental inputs.

- **Autonomous Navigation** - Integrate computer vision systems for path planning and obstacle avoidance. Implement SLAM (Simultaneous Localization and Mapping) for autonomous movement in unknown environments.
- **Advanced Gait Patterns** - Develop more complex gait trajectories, such as running, climbing stairs, or jumping. Incorporate machine learning to allow the bot to learn and optimize its gait over time.

6.3 Contibrutions

Everyone contributed equally in effort and rigour. We are happy to take part in this project. It was a great learning opportunity!