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Bipedal Locomotion In Humanoid Robot

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Abstract: Humanoid robots capable of walking on two legs are an important research area in robotics because they enable robots to operate effectively in human environments. This project presents the design and development of a humanoid robot capable of basic bipedal locomotion integrated with artificial intelligence based interaction. The system uses Raspberry Pi 4 as the primary processing unit along with servo motors, IMU sensors, camera modules and ultrasonic sensors to enable stable walking and environmental perception. The robot is developed in two phases: Phase 1 focuses on AI based human–robot interaction using voice recognition and computer vision, while Phase 2 introduces bipedal locomotion using servo-driven joints and real-time balance feedback. The integration of locomotion control, sensor feedback and AI interaction enables the robot to walk, detect obstacles and interact with users. This work demonstrates how embedded systems, robotics and intelligent control can be combined to develop a functional humanoid platform for future applications in service robotics, healthcare and human-robot collaboration.

***Index Terms* -** Humanoid Robot, Bipedal Locomotion, Raspberry Pi, Servo Motor Control, IMU Sensor

I. INTRODUCTION

Humanoid robots are designed to mimic human structure and movement so that they can operate naturally in environments designed for humans. One of the most complex tasks in humanoid robotics is achieving stable bipedal locomotion. Walking on two legs requires precise coordination of joints, balance control and continuous feedback from sensors.

The ability of robots to walk like humans opens opportunities in areas such as healthcare assistance, service robotics, search and rescue operations and industrial automation. However, maintaining stability during walking remains a significant challenge because small disturbances can cause the robot to lose balance.

This project focuses on designing a humanoid robot capable of basic walking while also integrating artificial intelligence interaction features. The system is divided into two phases. The first phase enables the robot to communicate with users through voice commands and visual perception. The second phase introduces bipedal locomotion using servo motors and balance feedback from inertial sensors.

By combining AI interaction with locomotion capabilities, the proposed system demonstrates a humanoid platform that can both interact with humans and move within its environment.

THE OBJECTIVE OF THIS PROJECT IS TO DEVELOP A HUMANOID ROBOT CAPABLE OF:

- Walking on two legs
- Maintaining balance using sensor feedback
- Recognizing voice commands
- Performing AI-based interaction
- Detecting obstacles using ultrasonic sensors
- Responding intelligently using camera-based vision

This project is divided into two major development phases:

- Phase 1 – AI Interaction Module
- Phase 2 – Bipedal Locomotion and Balance Control

II. LITERATURE REVIEW

Several research studies have focused on improving humanoid robot locomotion and stability.

Learning-based gait generation techniques use deep reinforcement learning to generate stable walking patterns for bipedal robots. These techniques allow robots to adapt to disturbances and varying environments but require large training datasets and high computational power.

Model Predictive Control (MPC) has been widely used in humanoid robotics to predict future system states and optimize control inputs for walking stability. This method improves balance control and footstep planning but requires complex mathematical models and high processing capability.

Bio-inspired gait planning techniques such as the Spring Loaded Inverted Pendulum (SLIP) model replicate the natural walking behavior of humans. These methods improve energy efficiency and produce smooth walking motions.

Vision-aided balance control combines information from cameras and inertial sensors to improve robot stability and environmental awareness. Sensor fusion techniques allow robots to maintain balance even in dynamic environments.

Adaptive balance control methods using Linear Quadratic Regulator (LQR) provide stable walking performance by adjusting motor control signals based on sensor feedback.

These studies demonstrate that stable bipedal locomotion requires the integration of advanced control algorithms, sensor feedback, and mechanical design.

III. METHODOLOGY

The humanoid robot is developed using a modular system architecture that integrates mechanical structure, sensors, and intelligent control algorithms.

The Raspberry Pi 4 serves as the main processing unit responsible for running artificial intelligence algorithms, processing sensor data, and controlling the locomotion system. Servo motors are used to drive the hip, knee, and ankle joints required for walking.

Sensors such as the BNO055 IMU provide orientation and balance data, while ultrasonic sensors detect obstacles in the robot's environment. A camera module is used for computer vision and gesture recognition.

The development of the system is divided into two phases.

Phase 1 – AI Interaction

In Phase 1, the robot is capable of voice-based interaction.

1. User voice input is captured via USB microphone.
2. Raspberry Pi processes speech using speech recognition.
3. Chatbot generates appropriate response.
4. Output is delivered via speaker or display.
5. Camera processes visual data using OpenCV/Mediapipe.

This phase establishes human–robot communication.

Phase 2 – Bipedal Locomotion

Phase 2 integrates walking and balance control.

1. Walking command generated by Raspberry Pi.
2. PCA9685 servo driver converts signals to PWM.
3. Servo motors move hip, knee, and ankle joints.
4. BNO055 IMU provides tilt and orientation data.
5. Ultrasonic sensor detects obstacles.
6. Feedback is processed to adjust posture dynamically.

IV. System Architecture

1. The system architecture consists of several interconnected modules.
2. Processing Unit

The Raspberry Pi 4 acts as the central controller responsible for executing AI algorithms and controlling the robot's movements.

3. Sensor System

Sensors such as IMU, ultrasonic sensors, and camera modules provide environmental and balance information.

4. Actuation System

Servo motors are used to drive the robot’s joints and generate walking motion.

5. Communication Interface

Microphone and speaker modules enable voice-based interaction with users.

6. Power Supply

A Li-ion battery pack and voltage regulator supply power to all electronic components

V. Procedure

The working procedure of the humanoid robot involves multiple stages that coordinate sensor inputs, processing units, and actuation systems to enable interaction and locomotion. The overall operation of the system is divided into two major phases: AI interaction and bipedal locomotion.

1. System Initialization

The first step in the procedure is system initialization. During this stage, all hardware components such as the Raspberry Pi 4, PCA9685 servo driver, IMU sensor, ultrasonic sensor, camera module, microphone, and speaker are activated. The Raspberry Pi loads the operating system and initializes the required software modules including speech recognition, computer vision libraries, and locomotion control algorithms. Communication between the processing unit and peripheral devices is established through interfaces such as I2C and GPIO pins.

2. Voice Input Acquisition

After initialization, the robot begins waiting for user interaction. The user provides a voice command through the USB microphone connected to the Raspberry Pi. The microphone captures the audio signal and converts it into digital data that can be processed by the system.

3. Speech Recognition and Processing

The captured voice signal is processed using speech recognition algorithms running on the Raspberry Pi. These algorithms analyze the audio input and convert it into text commands. The system interprets the command and determines the appropriate response or action. For example, commands may include greeting responses or instructions to initiate robot movement.

4. Response Generation

Once the command is recognized, the robot generates an appropriate response. The response may be delivered through a speaker as voice output or displayed on a screen if available. This stage enables human–robot interaction and confirms that the command has been successfully recognized.

5. Vision and Environmental Monitoring

The camera module continuously monitors the robot’s surroundings. Using computer vision techniques, the system can detect gestures or objects in the environment. This visual data helps the robot understand its surroundings and improves interaction capability. In addition, ultrasonic sensors measure the distance between the robot and nearby obstacles.

6. Walking Command Execution

When a walking command is issued, the Raspberry Pi sends control signals to the PCA9685 servo driver module. The servo driver converts these signals into Pulse Width Modulation (PWM) signals required to control the servo motors. Each servo motor corresponds to a joint in the robot's legs, such as the hip, knee, and ankle.

7. Joint Movement and Locomotion

The servo motors rotate according to predefined gait patterns programmed in the controller. These coordinated movements generate the stepping motion required for bipedal locomotion. The robot alternates the movement of its legs to simulate a human-like walking pattern.

8. Balance Monitoring

Maintaining balance during locomotion is essential for a bipedal robot. The BNO055 9-DOF IMU continuously measures the robot's orientation, tilt, and acceleration. This sensor provides real-time feedback about the robot's posture.

9. Balance Adjustment

If the IMU detects that the robot is tilting beyond a certain threshold, the control algorithm adjusts the positions of the servo motors. These corrective actions help the robot maintain stability and prevent it from falling. This process occurs continuously while the robot is walking.

10. Obstacle Detection and Safety Control

The ultrasonic sensor measures the distance to nearby obstacles. If an object is detected within a predefined distance, the system modifies the robot's movement or stops the walking motion. This safety mechanism prevents collisions and protects both the robot and surrounding objects.

11. Continuous Feedback Loop

All sensor data including IMU readings, ultrasonic measurements, and camera input are continuously monitored by the Raspberry Pi. The control system processes this data in real time and adjusts the robot's movements accordingly. This feedback loop ensures stable locomotion and responsive interaction with the environment.

12. System Operation Outcome

Through the integration of voice interaction, sensor feedback, and coordinated motor control, the robot is capable of performing basic humanoid behaviors. The system successfully demonstrates the ability to interact with users, monitor its surroundings, maintain balance, and perform controlled bipedal locomotion.

VI. Data Analysis

The data analysis for the humanoid robot system focuses on evaluating the performance of the locomotion control system, balance stabilization mechanism, sensor accuracy, and human–robot interaction capabilities. The robot integrates multiple sensors including an MPU6050 inertial measurement unit (IMU), ultrasonic sensor, camera module, and microphone, which continuously generate data that is processed by the Raspberry Pi controller to make real-time decisions.

The collected data is analyzed to determine the effectiveness of the robot's walking stability, obstacle detection capability, and interaction response.

A. Balance and Orientation Analysis

Maintaining dynamic balance is one of the most critical challenges in bipedal locomotion. The MPU6050 IMU sensor continuously measures the robot's orientation by providing accelerometer and gyroscope data.

Data Collected

- Pitch angle (forward/backward tilt)
- Roll angle (side tilt)
- Angular velocity
- Linear acceleration

Analysis Method

The orientation data obtained from the IMU sensor is processed using a sensor fusion algorithm such as a complementary filter or Kalman filter. This reduces noise and provides accurate tilt measurements.

A PID control algorithm uses this tilt data as feedback to adjust the servo motor positions at the hip and ankle joints. If the robot leans forward or sideways, corrective adjustments are applied to restore the upright posture.

Performance Indicators

- Tilt deviation from vertical position
- Balance correction time
- Number of balance adjustments during walking

Lower tilt deviation and faster correction time indicate better stability.

B. Locomotion Performance Analysis

The locomotion performance of the robot is evaluated by analyzing the coordination of servo motors and the stability of the walking gait.

Data Collected

- Servo motor angles for hip, knee, and ankle joints
- Step duration
- Walking speed
- Number of completed steps without falling

Analysis Method

The gait cycle is analyzed by observing the synchronization between the left and right legs during the single support and double support phases of walking. Servo motor commands generated by the inverse kinematics algorithm are monitored to ensure accurate joint movement.

Performance Indicators

- Step consistency
- Walking stability
- Smoothness of joint movement
- Energy consumption of servo motors

Stable locomotion is achieved when the robot performs multiple walking cycles without losing balance.

C. Obstacle Detection Analysis

Obstacle detection is performed using the HC-SR04 ultrasonic sensor. The sensor measures the distance between the robot and nearby objects by emitting ultrasonic waves and calculating the echo time.

Data Collected

- Distance readings from ultrasonic sensor
- Detection frequency
- Obstacle distance threshold

Analysis Method

Distance measurements are compared with predefined safety thresholds. If an obstacle is detected within the threshold range, the locomotion controller modifies the robot's movement or stops the walking motion.

Performance Indicators

- Detection accuracy
- Reaction time to obstacle
- Collision avoidance success rate

Accurate distance measurement and fast reaction time improve the robot's ability to navigate safely.

D. Interaction System Analysis

The AI interaction module allows the robot to communicate with users through voice commands and visual recognition. Data Collected

- Voice input signals captured by microphone
- Speech recognition results
- Gesture detection from camera module
- Response generation time

Analysis Method

Voice commands are converted into text using speech recognition libraries and processed by the chatbot logic. The system then generates responses using text-to-speech libraries. Gesture detection algorithms analyze camera images to identify hand movements or user commands.

Performance Indicators

- Voice recognition accuracy
- Gesture recognition accuracy
- Response time of the robot
- User interaction success rate

Efficient interaction is achieved when the robot correctly interprets commands and generates responses quickly.

E. Overall System Performance

The overall performance of the humanoid robot is evaluated by integrating data from all subsystems including locomotion control, sensor feedback, and AI interaction.

Key system performance parameters include:

- Walking stability
- Balance correction efficiency
- Obstacle avoidance capability
- Interaction responsiveness

The results obtained from the analysis demonstrate that the integration of sensor feedback, control algorithms, and AI processing enables the humanoid robot to perform stable walking while interacting with its environment.

VII. Results

- The developed humanoid robot successfully demonstrates both AI interaction and locomotion capabilities.
- In Phase 1, the robot successfully recognizes voice commands using the microphone and responds through audio output. The integration of speech recognition and computer vision allows the robot to interact with users effectively.
- In Phase 2, the robot integrates servo motors and balance sensors to achieve basic walking motion. The IMU sensor provides continuous feedback to maintain balance, while ultrasonic sensors help detect obstacles.
- The system demonstrates stable operation and effective coordination between hardware and software components.

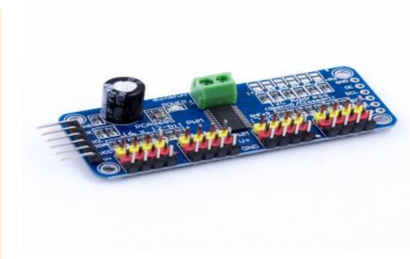
VIII. System and Components

The humanoid robot system consists of multiple components.

- Raspberry Pi 4 – Main processing unit for AI and locomotion control

- Servo Motors – Drive the robot's leg joints.

- PCA9685 Servo Driver – Controls multiple servo motors.



- BNO055 IMU – Provides orientation and balance data.

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- Camera Module – Enables computer vision.

- Microphone – Captures voice commands.

- Speaker – Produces audio responses.
- 12 v adapter – Powers the system.

IX. CONCLUSION

This project presents the development of a humanoid robot capable of AI-based interaction and basic bipedal locomotion. The system integrates sensors, servo motors and embedded processing to enable stable walking and intelligent communication.

Phase 1 successfully implemented voice interaction and visual perception. Phase 2 introduced locomotion control and balance stabilization using servo motors and IMU feedback.

The results demonstrate that the integration of AI interaction and locomotion control can produce a functional humanoid platform capable of operating in human environments. Future improvements may include advanced gait planning, improved balance algorithms and dynamic walking capabilities.

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