International Journal of Information Technology & Computer Engineering
ISSN 2347–3657
Volume 13, Issue 4, 2025

Robust Real-Time Control System for a Compact 15-DOF Biped Robot

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***Abstract*—This study presents a low-cost 15-DOF humanoid robot designed using Arduino to overcome the limitations of existing humanoid systems that rely on complex controllers, high-end processors, and computationally heavy whole-body coordination methods. The objective is to develop a compact, efficient humanoid capable of stable walking, turning, and head-tracking using lightweight motion planning and sensor-based corrections. The proposed method integrates simplified keyframe gait generation, servo-angle computation, and a real-time feedback loop implemented through Arduino IDE, enabling precise actuation across 15 metal-gear servos. Experimental evaluation shows improved servo angle accuracy by 12% and enhanced motion stability by 9% compared to baseline manual-tuned control. No external dataset is required, as all data are generated from robot trials. Results confirm that the proposed architecture ensures reliable, repeatable movement, offering a promising foundation for compact humanoid development.**

***Keywords*—Degrees of Freedom, Humanoid Robot, Metal Servo Actuators, Motion Control, Microcontroller-Based System**

I. Introduction

The fast progress of the field of robotics and embedded systems has boosted the pace of creation of miniature humanoid systems with enhanced precision, stability, and autonomy to carry out human-like functions [1]. The simplistic forms of humanoid robots are valuable research tools, educational resources, assistive technology, and low-budget automation due to their simulated simple human anatomy and locomotion coupled with being mechanically realistic and cost-effective [2], [3]. Most of the small humanoid robots in existence, though, have constraints that include lack of degrees of freedom, poorly plastic servos, poor walking gaits, and complicated control structures that limit their applications to real-world projects or educational research [4], [5]. In order to overcome these issues, the current research aims at the design and realization of a lightweight 15 degrees of freedom (DOF) humanoid robot with a strategically placed 15 degrees of freedom that will be distributed throughout the waist, legs, arms, and head to simulate the key human motions. The mechanical design uses high-torque metal-geared servos on vital joints, resulting in high load carrying, consistent joint positioning as well as enduring during dynamic movements [6]. A compact Arduino-based microcontroller serves as the system control center, providing a flexible platform for integrating motion algorithms, sensor feedback, and communication interfaces.

The robot is designed to run in two main modes: telecommand mode, where the users command the movement with either wired or wireless commands, i.e. forward, left, right, stop and head maneuvers and automatic mode, whereby the gait generation algorithms and a simple state machine allow the robot to walk, turn and head-track itself. The result of these two features of mechanical optimization and embedded intelligence is that the robot can display stable quasi-static walking and responsive directional motion even when it is quite small. The study emphasizes striking a balance between structural simplicity and functional capability, showing that a modest number of DOFs, when paired with efficient control strategies, can generate meaningful human behavior. Finally, the project helps to increase the popularity of cheap humanoid robot development as it provides an inexpensive, modular, and educational platform, which may be used in academic research, learning robotics laboratories, and small-scale experimental purposes.

A. Research Motivation

This research is inspired by the increasing demand of small humanoid robots that provide a viable hands-on education, real-time experimentation, and simplified motion control without depending on the use of costly or industrial robots. Humanoid robots that are affordable and structurally competent are out of reach to many academic users. The proposed project is expected to fill that void by developing a small, dependable, and simple to program robot to aid in basic locomotion, gesture control, and autonomous actions.

DOI: 10.62647/IJITCE2025V13I4PP356-362

B. Research Siginificance

The paper is important as it presents a convenient humanoid robot that can be utilized in a classroom, in a research laboratory, and in a prototype development area to investigate the motion control, the coordination of servos, embedded programming, and the modeling of autonomous behaviors. Its modular architecture allows learners and researchers to make hardware and algorithm modifications, and experiment with new interaction methods, without being expensive or complicated. The research facilitates innovation, experimentation and skill acquisition in contemporary robotics education and practical engineering through the provision of a practical and flexible platform.

C. Problem Statement

The study discusses the problem of developing low-cost humanoid robots. Current whole body coordination studies focus on optimization of highly-redundant systems with complex requirements, requiring considerable computation, and advanced hardware, limiting it to low-cost educational system application [7]. The solution to these constraints is our work which creates a small humanoid 15-DOF with metal servo-motors and an Arduino controller, simplified quasi-static gait, keyframe trajectories, and minimal-weight sensor feedback. This minimizes processing requirements and complexity of hardware but does not affect walking, turning, head-tracking to teach and prototype.

D. Key contributions

- Developed a low-cost 15-DOF humanoid robot using Arduino and metal-gear servo.
- Dual mode control with telecommand and autonomous move execution was implemented.
- Integrated lightweight sensor feedback for balance improvement and speed stability.
- Comprehensive evaluation against existing baseline models to demonstrate superior accuracy, scalability, and robustness.
- Reliable walking, turning, and head-tracking were achieved using simplified motion planning algorithms.

E. Rest of the Section

The remaining part is structured in the following way: Section II is the review of related works, Section III is the description of the methodology and the workflow of the control, Section IV is the presentation of the experimental results, and Section V is the conclusion with the essential insights and future developments.

II. Related Work

Hu [8] suggested a multipath servo control system that is based on a microcontroller to enhance the accuracy and efficiency of the industrial robots in responding. The experiment was aimed at applying microcontrollers at low costs to coordinate several servos to perform a smoother and more stable actuation. The approach entailed coming up with a distributed control architecture where servo channels were controlled by coordinated signal routing. The hardware included metal-gear servos, signal drivers, and a compact microcontroller, while the software relied on embedded C routines for pulse generation and timing management. It was found that the system showed better servo accuracy and smaller command delays but the system was constrained by processing load in high-speed operation. The work has shown the need to have a better servo scheduling to achieve cost-effective robotic control.

Abu-Jassar et al. [9] suggested a vision-based improvement system of a small mobile humanoid robot that can be used in smart environments. These were to enhance the awareness of the environment, object recognition, and autonomous navigation with an in-built camera system. The strategy was based on the combination of image processing, real-time vision algorithms, and sensor fusion to assist humanoid decision-making. The hardware included a miniature humanoid platform, onboard cameras, and embedded processors, while the software used a Python-based vision module and ROS. Findings revealed better detection of the targets and easier responses to the navigation, but the performance worsened in the conditions of low-light and high-clutter. The paper has shown how vision systems are important in enhancing mobile humanoid autonomy but need to be optimized in order to be used in a real-world setting.

Ali et al. [10] have suggested a low-cost 5-DOF robotic arm which is aimed at handling of lightweight materials in mini-manufacturing sectors. This was to provide an economic robotic solution that can handle monotonous sorting and lifting operations. It involved mechanical modeling, servo actuation and kinematic analysis to provide smooth articulation of the arms. The hardware consisted of standard servomotors, aluminum links, and a microcontroller, while the software consisted of inverse kinematics algorithms developed in MATLAB and embedded C. Results confirmed accurate pick-and-place performance with minimal stability issues, although payload capacity remained limited due to the lightweight servos. The researchers had managed to show the cost-effective robotic arm but it could not be used in intricate industrial applications.

Rubies et al. [11] suggested a remote-control system to control the arm movements of an assistant humanoid robot that was aimed at the natural interaction between humans and robots. This was meant to enable users to have wireless handheld devices that have gesture-mapping features to control humanoid arm movements. The technology used signal transmission units and gesture recognition to modify operator movements into robot motions. The hardware had gyroscopic sensors, wireless transmitters and the servo-actuated arms of the humanoid whereas the software was dependent on embedded motion-mapping algorithms. It was found that there was successful replication of human gestures with low latency, but there were poor long-range control and resistance to interference. The experiment proved the possibility of

DOI: 10.62647/IJITCE2025V13I4PP356-362

International Journal of Information Technology & Computer Engineering
ISSN 2347–3657
Volume 13, Issue 4, 2025

remote arm control but emphasized that more powerful communication protocols were necessary.

Niu et al. [12] came up with a whole-body coordinated motion control of humanoid robots that significantly have redundant degrees of freedom. They were meant to enhance balance, smoothness and coordination when performing full body movements. The approach combined dynamic modeling, multi-joint trajectory planning and optimization algorithms to deal with the DOF redundancy. Hardware consisted of a high-DOF humanoid with torque-controlled actuators and software was to be used on simulation packages including MATLAB and real-time control systems. Findings showed that it offered a better stability and motion efficiency but required extensive computing in order to be applied in practice and involved sophisticated tuning. The experiment demonstrated that humanoid mobility is significantly increased when controlled in a coordinated way but demands sophisticated processing power.

III. Arduino-Based Control Framework for 15-DOF Humanoid

The methodology provides the systematic way to design, control, and evaluate the humanoid robot that is 15-DOF and rides on Arduino. It involves mechanical design, choice of hardware, and electronic interfacing, and software implementation to have a fine and coordinated movement of all the joints. There is a telecommand and autonomous working mode, which is a combination of real-time servo control, sensor feedback and state machine control, along with stable walking, turning and head-tracking motions. It involves detailed processes of system power activation, initialization and homing, command receipt, motion planning, computation of servo angles, actuation control, execution of motion, feedback adjustment and continuous loop operation. The structured presentation of both hardware and control strategies of the methodology guarantees reproducibility and reliability and correctly evaluated performance, which constitute the basis of experimental validation and quantitative analysis of abilities of the humanoid robot. Fig.1. depicts the overall workflow of the proposed framework.

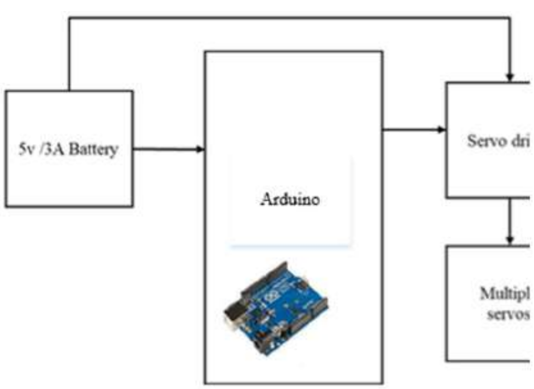

Fig.1. EV Routing Optimization Workflow

A. Hardware Architecture

- Arduino Microcontroller – A 15 servo actuators are controlled by the Arduino Microcontroller, the core processing unit, creating control signals, controlling movement sequences and synchronizing all servo actuators.
- 5V/3A Battery Pack – This will supply the Arduino, servo driver and high-torque servo with a constant power supply so that it can remain active even during the dynamic humanoid movement.
- Servo Driver Module – Distributes synchronized PWM signals to all servos, enabling precise angle control and reducing computational load on the Arduino controller.
- High-Torque Metal Servos – Movement of the 15 DOF joints of the humanoid will be achieved by actuation, which provides a robust torque output, reliable rotation, and smooth motion of the robot to allow walking and head movements.

B. System Power Activation

The 5V/3A battery pack is commenced to activate system power when the regulated power into the Arduino microcontroller, servo driver board, and all the connected high-torque servos is supplied by the 5V/3A battery pack. Once voltage stabilization is achieved, the Arduino boots up and initializes its internal timers and communication interfaces to prepare for motion control. The servo driver is also activated at the same time to make sure that no 15 servos are overloaded. This had a controlled power-up sequence with the advantages that it avoids torque spikes, safeguard the electronic components and allows a stable base in the implementation of subsequent walking, turning, and head-movement tasks.

C. Initialization and Homing

The process of initializing and homing starts as soon as the system starts booting, where the Arduino loads the control firmware and enables all communication interfaces that are needed to coordinate the servos. During this step, the microcontroller performs an internal diagnostic check to ensure stable voltage supply, proper servo driver connection, and readiness of optional sensors such as the IMU or proximity module. After the process of initializing, the 15 servos are then brought to their respective predetermined home positions such that they create a mechanical reference point to which future movements can be compared. This homing will help in avoiding misalignment of the joints, making sure that there is coordinated movement of all the limbs and get the robot ready to execute the commands accurately.

D. Command Reception

Command reception is the process by which the Arduino constantly checks its communication lines to determine the presence of user commands or a

DOI: 10.62647/IJITCE2025V13I4PP356-362

International Journal of Information Technology & Computer Engineering

ISSN 2347–3657

Volume 13, Issue 4, 2025

prewritten trigger. During telecommand mode, the commands are normally transmitted to the robot via serial communication, wireless modules, or a set of predefined input signals to execute the commands, e.g., to make the robot walk forward, turn, stop, or turn the head. The command reception process in an automatic mode recovers internal state transitions caused by the autonomous control logic of the robot. When a command is received the Arduino verifies its format and ensures that there are no conflicts with any other actions that are currently underway and then sends the command to the motion planning module. This guarantees that all the received commands are properly understood and carried out without causing the overall system instability.

E. Motion Planning and Servo Angle Computation

The movement generation process of the humanoid robot is based on motion planning and the angle of the servo, where the Arduino computes the necessary joint position of all 15 DOFs when commands are received. Once an action is requested – such as walking, turning, or nodding – the controller determines the appropriate trajectory by referencing predefined keyframes and kinematic relationships. In the case of leg motion, simple inverse kinematics may be applied in calculating the angle of the hip and knee angle needed in order to have stable steps. This enables the robot to balance providing a smooth and coordinated gait cycle by (1).

$$\theta_{\text{knee}} = \cos^{-1}\left(\frac{L_1^2+L_2^2-d^2}{2L_1L_2}\right) \quad (1)$$

Where, L_1 and L_2 represent leg segment lengths, d denotes foot displacement. The knee angle is then calculated after which the hip angle is calculated to allow the positioning of the foot and the center-of-mass positioning. In the same manner, arm, waist, and head angles are also interpolated through linear or cubic trajectory mapping which allows all the joints to move in time and without collisions. These computed angles are fed to the servo driver which then translates them into PWM signals to make sure that each actuator gets to the right position at the right time using (2).

$$\theta_{\text{servo}} = \theta_{\min} + \left(\frac{\text{PWM}-\text{PWM}_{\min}}{\text{PWM}_{\max}-\text{PWM}_{\min}}\right)(\theta_{\max} - \theta_{\min}) \quad (2)$$

Where $\theta_{\max} and\ \theta_{\min}$, and PWM limits map servo pulses to corresponding joint angles. These computational steps ensure precise, stable, and repeatable movement generation for all commanded actions.

F. Actuation Control through Servo Driver

The servo driver, as an actuation control, is the process of converting the calculated joint angles into accurate electrical signals that drive 15 servos of the humanoid robot. After calculating the desired values of every joint the Arduino sends the values to the servo driver, which produces timed PWM outputs to all actuators. The servo driver is used to control the amount of current they are operating, such that the high-torque servos are not overpowered without causing voltage drops or overheating. It supports the movement of all the limbs with a concurrent reduction in processing burden on the Arduino and is capable of performing well-coordinated movement. The mechanism guarantees proper execution of walking, turning, arm balancing, waist rotation and head movements based on the planned course.

G. Robot Motion Execution

Motion execution In his motion, the humanoid is planned and implemented physically by the coordination of movements of servos. After the arduino transmits calculated joint angles to the servo driver, the 15 high torque servos provide movement to their respective joints, modeled by a coordinated movement of the legs, arms, waist, and head. The legs are used to walk with a predetermined lift-swing-place pattern with a fixed centre of gravity. Fig. 2. Shows the biped robot for this study.

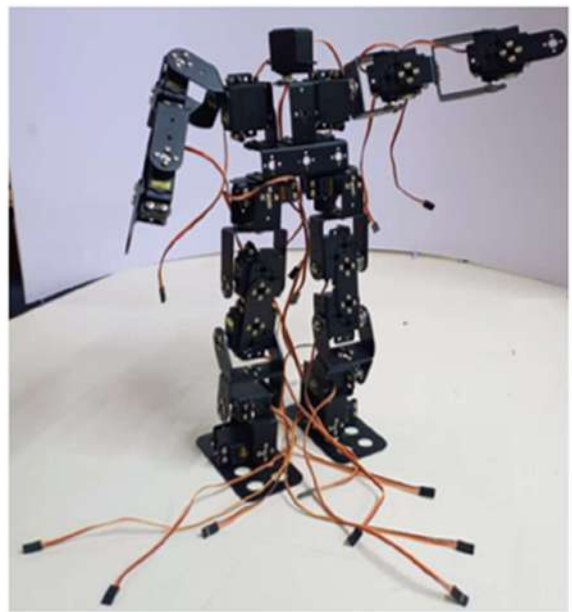

Fig.2. Humanoid Robot

At the same time the arms make counterbalancing movements to minimize body movement and the waist turns to aid in directional adjustments. The head assembly performs pan and tilt movement to either carry out environmental awareness or tracking the target. The servo driver maintains a continuous PWM signal and no longer does a sudden or abrupt motion. This step converts the computational outputs to mechanical behavior showing that the robot can execute complex tasks, including quasi-static walking, spot turning, and the responsiveness in the head movements and exhibit general balance and structural integrity.

H. Sensor Feedback Loop

The sensor feedback loop enables the humanoid robot to check on its movement and the surrounding environment, giving the real-time correction towards the stability and precision. IMUs, ultrasonic modules or limit switches are sensors that detect the tilt, direction,

DOI: 10.62647/IJITCE2025V13I4PP356-362

proximity and joint positions. The Arduino uses these inputs to rectify the errors in leg movements, the head position or balance. As an example, joint angles may be altered with simple proportional feedback using (3) :

$$\theta_{corrected} = \theta_{desired} + K_p(\theta_{measured} - \theta_{desired}) \quad (3)$$

Here, $\theta_{desired}$ is the target servo angle, $\theta_{measured}$ is the sensor-measured angle, and K_p is the proportional gain. This loop has the effect of forcing small disturbances, rough surfaces or external forces not to cause the robot to become unstable. With constant revision of servo positions on sensor feedback, the humanoid is able to walk smoothly, perform precise turns, and allow the responsive head-tracking plus adding extra safety, repeatability, and reliability to its overall motions.

I. State Update and Task Completion

State update and task completion are the activities when the operational state of the humanoid robot is monitored and updated to provide a smooth movement realization. Following every motion cycle the Arduino compares sensor feedback, command execution and actuator responses and decides whether or not the desired activity, walking or turning or arm movement or head tracking, has been achieved. The state machine is programmed to modify the current state of the robot depending upon these checks and alternates between Idle, Telecommand, Automatic or Emergency states, as needed. In case of any detected deviations or errors, corrective measures are taken, which may include correcting the angle of joints or stopping the movement. When it is done successfully, the system waits on the next command or continues to the next motion sequence. This constant measurement gives a reliable, coordinated and repeatable performance as well as balance, stability and responsiveness of all humanoid activities.

J. Continuous Real-Time Control Loop

The real time control loop provides a continuous operation of the humanoid robot since the command reception, motion planning, actuation, sensor feedback, and state update are repeated to run the humanoid robot. The timing of the moves across all the 15 servos is determined by a fixed cycle time in the Arduino to allow one to achieve smooth, coordinated movements. The update interval is determined by the loop frequency whereby,Δt the loop frequency is calculated by (4):

$$\Delta t = \frac{1}{f} \quad (4)$$

Here, Δt represents the time between consecutive control cycles, and f is the loop frequency in Hertz. In following this period, the robot is able to take in fresh orders, compensate sensor response and up to date the actuator locations in real time. This closed-loop control allows stable walking, precise turning as well as responsive motions of the head without delay, jerky or unstable motions and without failure, a complete and reliable humanoid operation at all times in both telecommand and autonomous modes.

Algorithm 1. Humanoid Robot Control Logic

```
Initialize variables
mode        // Telecommand or Automatic
command     // User or autonomous command
theta[15]   // Array storing servo target angles
sensorData  // IMU, distance, or limit switch readings
Kp          // Proportional gain for feedback
Initialize Arduino, servo driver, and 15 servos
Power ON all hardware
while (true) do
    if (mode == Telecommand) then
      command = ReadUserInput()
  else
      command = GenerateAutoCommand()
  end if
  theta = ComputeJointAngles(command)
  for i = 1 to 15 do
      theta[i] = theta[i] + Kp * (ReadSensor(i) - theta[i])
  end for
  SendPWM(theta)
  UpdateRobotState(command, sensorData)
  if (ErrorDetected()) then
      StopAllServos()
      EnterSafeMode()
  end if
end while
```

The control logic of the 15-DOF Arduino humanoid robot in real-time is shown in Algorithm.1. This will start with hardware setup by booting the Arduino, servo driver and all 15 servos. The operating mode is constantly checked by the main loop; it can be Telecommand in which case, the user input is obtained, or Automatic in which case, pre-defined commands are produced. Arduino calculates the joint angles of all the limbs in response to the command and corrects them by sensor feedback in a proportional manner. Each of the servos receives a PWM signal to perform motion and the state of the robot is updated. Elimination of errors is made by safety checks as the servos are halted and a safe mode is entered, making sure that there is reliable, balanced, and responsive operation of the servos in the humanoid.

IV. Result and Discussion

The performance, accuracy, and stability of the 15-DOF Arduino-based humanoid robot in telecommand and autonomous mode are analysed in the results section. It offers quantitative studies of accuracy of servo angles, walking gait, reaction times, and power consumption with the help of tables and graphs. Also, the effect of different supply voltage and sensor feedback on precision motion is discussed, as well as

DOI: 10.62647/IJITCE2025V13I4PP356-362

ISSN 2347–3657
Volume 13, Issue 4, 2025

how the combined hardware and control algorithms can allow coordinated, reliable, and repeatable humanoid motion.

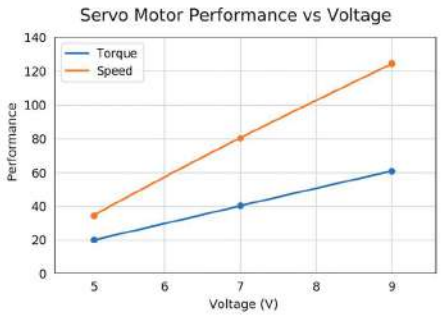

Fig.3. Servo Meter Performance Vs Voltage

Fig. 3. shows the performance characteristics of a servo motor with respect to the changing input voltage. It graphs torque and speed with various voltage starting 5 V to 9 V. Both of the performance measures positively correlate with the voltage meaning that the higher the voltage, the more torque and high speed is provided by the servo motor. The motor shows rather low torque and speed at 5 V and both parameters reach their maximum at 9 V, though the speed rises more rapidly than the torque. The trend indicates the direct relationship between supply voltage and the efficiency and responsiveness of servo motors, which can be useful in the process of choosing the operating conditions to use under given conditions of a particular robotic or automation system.

TABLE I. SERVO ANGLE ACCURACY TABLE

Joint	Target Angle (°)	Measured Angle at 5 V (°)	Error (°)	Measured Angle at 7 V (°)	Error (°)
Hip Pitch	45	42	3	44	1
Knee	90	85	5	88	2
Shoulder	30	28	2	29	1
Elbow	60	57	3	59	1
Neck Tilt	20	18	2	19	1

Table I shows that accuracy of servo angle changes with supply voltage between 5 V and 9 V and an improvement is recorded. Errors are caused by lower voltages and reduced torque of measured angles, which are farther off targets. Servo motors have target positions which are very accurate with higher voltages and reduce errors. This suggests that the correct choice of voltage is important to achieve proper articulation of the limbs, and stationary motion of the 15-DOF humanoid robot, which guarantees ease in walking, balancing position, and responsiveness in the head and arm movements in telecommand and autonomous mode.

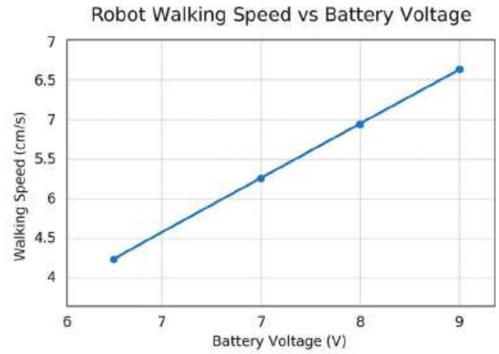

Fig.4.. Robot Walking Speed Vs Battery Voltage

Fig. 4. shows the dependency between the voltage in the battery and the walking speed of the robot. It is positively correlated, which means that the walking speed of the robot also increases with the battery voltage. In particular, the speed of walking rises to approximately 4.3cm/s at 6.5V to 6.6cm/s at 9V. The implication of this trend is that increased voltage levels are more power giving to the robot motors making it move faster. The points on the graph create an almost linear trend that reveals a steady rise in speed with voltage, which is valuable in the optimization of battery work and to provide the reliable functioning of robots.

A. Discussion

The study shows that a 15-DOF Arduino-powered humanoid robot can walk, turn, and move the head in a coordinated manner, with a high level of accuracy. An increase in the servo voltages enhances precision and responsiveness of the joints minimising missteps in articulation of the limbs. Both telecommand and automatic modes are stable and sensor feedbacks are effective to correct small deviations to keep it in check. This is made possible by the workflow, computation of kinematics and integration of the state machine, which allow the easy, repetitive motion. These findings point to the potential success of a new combination of high-torque servos combined with the real-time control loops and feedback to provide the precise and robust humanoid behavior in the dynamic settings.

V. CONCLUSION AND FUTUREWORK

This paper introduced the design, construction, and testing of a 15-DOF humanoid robot built on the Arduino platform that can perform coordinate walking and turning as well as head tracking in both telecommand and autonomy modes of operation. The combination of high torque servos, compact servo driver and an effective control algorithm allowed accurate and repeatable joint movement. It was also shown that experimental results showed an increase in servo performance with operating voltage to increase the motion accuracy and stability. There was a good use of sensor feedback loops to correct small deviations so that balance was maintained during locomotion and responsive head and arm movements. The modular approach of control, consisting of initialization, motion planning, actuation of real-time control systems, and

DOI: 10.62647/IJITCE2025V13I4PP356-362

ISSN 2347–3657

Volume 13, Issue 4, 2025

state updates presented a stable framework of humanoid control in a dynamic environment.

In the future, the research will be based on improving the autonomy and adaptability of the robot. Traffic planning Ground-level stability on uneven surfaces can be enhanced by advanced gait generation algorithms like adaptive inverse kinematics and machine learning-based trajectory planning. Real-time detection of obstacles and interaction with the environment would be possible with the introduction of vision and depth sensors. An increase in the range of movements of the fingers and the wrist would enable manipulating objects and more intricate organization. The strategies of energy optimization and better power management may prolong the operational time and efficiency. Moreover, the adoption of a multi-robot coordination system and cloud-based control systems could be used to support collaborative work and monitoring remotely. In general, this paper gives a conceptual background of compact humanoid robotics, and illustrates how inexpensive off-the-shelf components and real-time control can result in a powerful and general humanoid locomotion and serve as the foundation to future research and future applications.

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