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Humanoid 17 DOF Precision Robot with Advanced Servo Control

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Abstract- The research paper presents the development of a **17DOF Humanoid Robot**, titled "**Humanoid 17DOF - Precision Robot with Advanced Servo Control**," designed to achieve human-like movements with high precision. Utilizing an **ESP32 microcontroller**, **17 MG995 servo motors**, and a **PCA9685 servo controller**, the robot is controlled wirelessly via a **Bluetooth-enabled joystick**. The project focuses on implementing **Inverse Kinematics (IK)** for coordinated joint movements, enhancing manoeuvrability and natural motion. The proposed system adopts an **Embedded C programming approach** with real-time motion control and robust power management using a **7.4V lithium polymer battery**. Extensive testing demonstrates the robot's responsiveness, stability, and efficiency in performing complex tasks. The study highlights potential applications in **research, education, and human-robot interaction**, contributing to advancements in affordable, versatile humanoid robotics.

Keywords- 17 Degrees of Freedom (DOF), Precision Robotics, Advanced Servo Control, ESP32 Microcontroller, PCA9685 Servo Controller, Human-Robot Interaction, Wireless Control, and PWM Signal Synchronization.

I. INTRODUCTION

Humanoid robots are designed to replicate human movements with precision, making them valuable for research, education, and human-robot interaction. This project, "Humanoid 17DOF - Precision Robotics with Advanced Servo Control," develops a 17 Degrees of Freedom (DOF) humanoid robot capable of executing complex and natural motions.

Powered by an ESP32 microcontroller, the robot enables real-time processing and wireless Bluetooth communication via a joystick module. 17 MG995 metal gear servos provide high-torque joint control, managed through a PCA9685 servo

controller for smooth and synchronized movements. Inverse Kinematics (IK) is implemented to calculate precise joint angles, allowing the robot to perform dynamic tasks with balance and agility.

The lightweight aluminium frame ensures durability, while a Lithium Polymer battery supports extended operation. LM2596 step-down transformers regulate power, ensuring stable performance. The system's modularity allows easy upgrades, making it a scalable platform for advanced robotics research.

II. LITERATURE REVIEW

A. Design and Implementation of a 17 DOF Humanoid Robot

Radhamma *et al.* [1] present a humanoid robot designed for entertainment and security functionalities. The robot integrates servo motors, an Arduino microcontroller, NodeMCU, and an ESP32-CAM module for real-time surveillance [2]. The primary contributions include replicating human movements such as walking and waving, along with remote-controlled surveillance features. The addition of a Passive Infrared (PIR) sensor enhances security applications.

B. Biped Intelligent Machine (BIM-UIA)

Akhtaruzzaman and Shafie [3] developed the Biped Intelligent Machine (BIM-UIA) as a research platform for humanoid robot navigation. The paper discusses lower torso strategies, optimal actuator control, and adaptability mechanisms [4]. Notably, it emphasizes the challenges in designing toe, ankle, knee, hip, and waist joints, which are critical for achieving human-like mobility.

C. Advancements in Humanoid Robots

Tong *et al.* [5] provide a comprehensive review of humanoid robots, discussing key technologies such as control, decision-making, and perception. The study highlights challenges in bio-inspired motion, energy utilization, and material applications, proposing the integration of artificial intelligence and brain-inspired intelligence for enhanced humanoid functionality [6].

D. Kinematics and Dynamics of a 16 DOF Humanoid Robot

Hernandez-Santos *et al.* [7] introduce a novel 16 DOF humanoid biped robot incorporating an active toe joint. The study presents kinematic equations and Lagrangian dynamics to improve stability and natural gait, highlighting the importance of toe joint actuation in achieving human-like locomotion [8].

E. Embedded Walking Algorithm for 17 DOF Humanoid Robots

Sherif *et al.* [9] develop a walking algorithm for a 17 DOF humanoid robot using Arduino Mega 2560. The work focuses on joint coordination and the integration of an open-loop control system to improve walking stability [10]. The study identifies gravitational, frictional, and inertial forces as key external disturbances affecting humanoid robot locomotion.

F. Research Gaps and Contributions

Humanoid robotics face challenges in stability, AI integration, energy efficiency, material selection, and joint design, with most studies focusing on kinematics without real-time adaptability. This project addresses these gaps by implementing Inverse Kinematics (IK) with real-time joint adjustments using MG995 servos and a PCA9685 controller for synchronized motion. To improve energy efficiency, a Lithium Polymer battery and LM2596 step-down transformers are used for regulated power distribution.

This research addresses these challenges by:

- This enhances humanoid robotics by implementing Inverse Kinematics (IK) with real-time joint adjustments, ensuring dynamic stability and adaptive motion control.
- This project addresses the lack of AI integration in humanoid robotics by utilizing real-time data handling, enabling future AI-driven motion planning and enhanced adaptability.
- It enhances energy efficiency in power distribution, minimizing power loss and extending operational time.

III. METHODOLOGY

A. System Architecture

The system architecture of the Humanoid 17DOF - Precision Robotics with Advanced Servo Control is designed for human-like motion, enhanced stability, and precise control. It features a modular design integrating mechanical, electrical, and software components, including a lightweight aluminium structure with 17 Degrees of Freedom (DOF) powered by MG995 Metal Gear Servos.

Block Diagram for Humanoid 17DOF - Precision Robotics with Advanced Servo Control

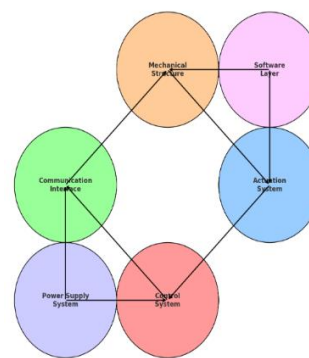


Fig. 1. System Architecture of the Humanoid Robot with Advanced Servo Control.

The control system is managed by an ESP32 microcontroller with the PCA9685 servo controller for precise PWM signals, while Bluetooth Low Energy (BLE) enables wireless joystick control. A 7.4V LiPo battery powers the system, and advanced Inverse Kinematics (IK) algorithms ensure smooth and coordinated movements [11]. This architecture supports scalability, maintenance, and future enhancements without the use of external simulation software.

B. Mechanical Structure

The mechanical structure of the Humanoid 17DOF - Precision Robotics with Advanced Servo Control is engineered for lightweight agility and robust durability using aluminium servo brackets, which enhance motion stability by minimizing vibrations [12]. Its modular design facilitates easy assembly, maintenance, and customization. The 17 Degrees of Freedom (DOF) configuration is strategically distributed across the head, arms, legs, and torso to replicate human-like motion. This includes nodding and rotation for expressive head movements, flexible shoulder and elbow joints for dynamic arm gestures, and versatile hip, knee, and ankle joints for walking, balancing, and complex lower-body movements [13].

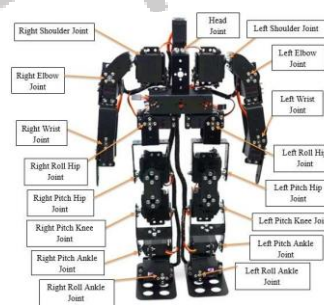


Fig. 2. 17-DOF Humanoid Robot

C. Actuation System

The actuation system of the Humanoid 17DOF - Precision Robotics with Advanced Servo Control utilizes 17 MG995 Metal Gear Servos known for their high torque and rapid response, ensuring precise and smooth joint movements [14]. These servos provide 13 kg·cm torque at 6V, enabling dynamic joint motions, and achieve a speed of 0.17s/60° rotation for quick transitions. Their metal gears ensure durability and consistent performance. Chosen for their balance of power, speed, and cost-effectiveness, these servos are ideal for high-torque and precise movements required in humanoid robotics [15].

D. Control System

The control system of the Humanoid 17DOF - Precision Robotics with Advanced Servo Control is designed for real-time processing, precise servo control, and efficient communication [16]. It utilizes the ESP32 microcontroller with dual-core processing at 240MHz for fast computation and wireless communication via Bluetooth and Wi-Fi. The ESP32 interfaces with the PCA9685 Servo Controller using I2C communication, enabling synchronized control of all 17 Degrees of Freedom (DOF) [17]. The PCA9685 provides 16-channel PWM output with 12-bit resolution, ensuring smooth and precise angle positioning. This combination delivers accurate, synchronized, and real-time control, facilitating fluid and coordinated humanoid movements [18].

E. Inverse Kinematics and Motion Planning

The Inverse Kinematics (IK) and Motion Planning system enables precise and fluid human-like movements [19]. The IK algorithms use the Cyclic Coordinate Descent (CCD) method, known for its fast convergence and adaptability to complex joint configurations. These algorithms are directly implemented on the ESP32 microcontroller using the Arduino IDE, ensuring efficient real-time computation without requiring external simulation software [20].

Motion planning is achieved through cubic spline interpolation, which generates smooth and continuous motion paths [21]. The system dynamically adjusts movements in real-time by processing feedback from the wireless joystick, allowing intuitive and responsive control [22].

Mathematical Calculations for Inverse Kinematics and Motion Planning:

1. Inverse Kinematics (IK) Calculations: For a humanoid robot, the end-effector position (X, Y, Z) is calculated using joint angles $\theta_1, \theta_2, \dots, \theta_n$. The forward kinematics equations are:

$$X = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) + \dots$$

$$Y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) + \dots$$

Inverse kinematics solves these equations to find the joint angles:

$$\theta_2 = \cos^{-1} \left(\frac{X^2 + Y^2 - L_1^2 - L_2^2}{2L_1L_2} \right)$$

$$\theta_1 = \tan^{-1} \left(\frac{Y}{X} \right) - \tan^{-1} \left(\frac{L_2 \sin(\theta_2)}{L_1 + L_2 \cos(\theta_2)} \right)$$

These equations are iteratively solved using CCD to find optimal joint angles for achieving the desired end-effector position.

2. Motion Planning Using Cubic Spline Interpolation:

To generate smooth and continuous motion paths, cubic spline interpolation is employed:

$$S(t) = a_0 + a_1t + a_2t^2 + a_3t^3$$

$$S(0) = P_0$$

$$S(t_f) = P_f$$

$$S'(0) = V_0$$

$$S'(t_f) = V_f$$

The coefficients $[a_0, a_1, a_2, a_3]$ are calculated by solving the system of equations formed by these conditions:

$$a_0 = P_0$$

$$a_1 = V_0$$

$$a_2 = \frac{3(P_f - P_0) - t_f V_0 - V_f}{t_f^2}$$

$$a_3 = \frac{2(P_0 - P_f) + t_f V_0 + V_f}{t_f^3}$$

F. Wireless Communication and Control Interface

The Wireless Communication and Control Interface for the Humanoid 17DOF Robot leverages Bluetooth Low Energy (BLE) for real-time, low-latency communication, enabling intuitive control through a wireless joystick module [23]. The joystick inputs are mapped to predefined movements and inverse kinematics solutions, allowing precise and responsive motion control [24]. Additionally, BLE's compatibility with mobile devices offers potential for future expansion into app-based controls [25]. This architecture enhances user interaction, ensuring an efficient and immersive control experience.

G. System Logic

The System Logic Flowchart for precise control and fluid motion. It begins with System Initialization, setting up the ESP32 microcontroller, PCA9685 servo controller, and communication modules [26]. The system then checks for Joystick Input via Bluetooth Low Energy (BLE). If no input is received, it loops back to ensure continuous responsiveness [27].

System Logic Flowchart: Humanoid 17DOF

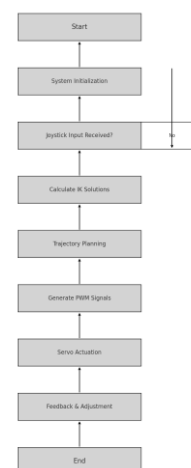


Fig. 3. System Logic Flow Chart for Humanoid Robot

Upon receiving input, Inverse Kinematics (IK) calculates joint angles, ensuring accurate and collision-free motion for

the 17DOF configuration [28]. The Feedback & Adjustment process collects real-time feedback for dynamic adjustments, ensuring stability and motion precision [29].

IV. HARDWARE COMPONENTS

A. ESP32 Microcontroller

The ESP32 Microcontroller serves as the central processing unit of the humanoid robot, acting as its brain by processing sensor inputs and executing control algorithms to facilitate smooth and precise motion [30]. It plays a crucial role in real-time control by continuously computing joint angles using inverse kinematics and transmitting appropriate commands to the servo controller for accurate movement execution [31].

Additionally, the ESP32's built-in Wi-Fi and Bluetooth capabilities enable seamless wireless communication, allowing real-time remote control via a wireless joystick for efficient interaction with the robot [32]. With its powerful dual-core architecture, the microcontroller can multitask efficiently, handling various operations simultaneously, such as motion planning, sensor data processing, and communication, ensuring an optimized and responsive robotic system [33].

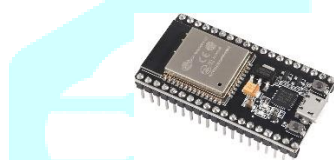


Fig. 4. ESP32 Microcontroller

B. 17 x MG995 High-Speed Servo Motors (180°)

The 17 x MG995 High-Speed Servo Motors (180°) are essential for enabling human-like movements in the humanoid robot by controlling each joint to replicate natural motions such as walking, bending, and gesturing [34]. These servos are optimized for both torque and speed, ensuring that the robot can move its limbs efficiently, even when subjected to load variations [35].

Their high torque capability is crucial for maintaining stability and executing dynamic movements with precision. Additionally, the MG995 servos rely on pulse-width modulation (PWM) signals from the PCA9685 servo controller to achieve precise positioning [36]. This allows for accurate and stable joint angles, ensuring coordinated and life-like movements essential for advanced robotic applications [37].



Fig. 5. MG995 Servo Motor

C. PCA9685 Servo Controller (16-Channel)

The PCA9685 Servo Controller (16-Channel) plays a crucial role in managing the multiple servo motors required for the humanoid robot's movement. Since the ESP32 has a limited number of PWM outputs, the PCA9685 expands the system's capacity, allowing simultaneous and efficient control of up to

16 servos [38]. It ensures precision signal processing by converting digital commands from the ESP32 into smooth and stable PWM signals, which are essential for accurate and fluid motion [39].

Additionally, the controller facilitates real-time synchronization of servos, enabling coordinated movements such as balanced walking and complex gestures. This synchronization is critical for achieving natural and stable robotic motion, making the PCA9685 an essential component in the overall system architecture [40].



Fig. 6. PCA9685 Servo Controller

D. ESP32 Wireless Joystick Module

The ESP32 Wireless Joystick Module serves as the primary user interface for controlling the humanoid robot in real-time. It enables intuitive and responsive movement by allowing the operator to send commands wirelessly, ensuring smooth and effortless interaction [41]. Utilizing Bluetooth connectivity, the joystick communicates directly with the ESP32 microcontroller, eliminating the need for wired connections and enhancing the robot's mobility [42].

This wireless functionality is particularly beneficial in dynamic environments where flexibility and ease of control are essential. Additionally, the module supports customizable control schemes, enabling the implementation of different operation modes such as manual control for direct manipulation and automated sequences for pre-programmed tasks [43]. This adaptability makes it a crucial component for improving user experience and expanding the robot's functionality across various applications.

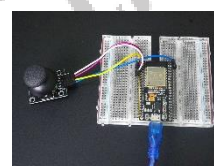


Fig. 7. ESP32 with Analog Joystick

E. 7.4V 1500mAh 25C Lithium Polymer (LiPo) Battery

The 7.4V 1500mAh 25C Lithium Polymer (LiPo) Battery serves as the primary power source for the humanoid robot, supplying energy to both the servo motors and control electronics to ensure uninterrupted operation [44]. Its high discharge rate, rated at 25C, guarantees that the servos receive adequate current even during peak load conditions, preventing performance drops or motor stalls [45]. This feature is essential for executing dynamic movements like walking, balancing, and complex gestures.

Additionally, the battery's lightweight and compact design helps maintain the robot's agility while preserving a stable centre of gravity, which is crucial for achieving lifelike and balanced motion. By combining efficiency, power stability, and portability, the LiPo battery plays a key role in the robot's overall performance and operational endurance [46].



Fig. 8. 7.4V LiPo Battery

F. 3 x LM2596 DC-DC Step-Down Transformers (Voltage Regulators)

The 3 x LM2596 DC-DC Step-Down Transformers (Voltage Regulators) play a vital role in maintaining a stable and efficient power supply for the humanoid robot. These regulators convert the higher voltage from the LiPo battery to a consistent 5V output, which is necessary for the ESP32 microcontroller and the PCA9685 servo controller to function properly [47].

By preventing voltage fluctuations, they protect sensitive electronic components from potential damage, ensuring the system remains stable and reliable [48]. Additionally, the LM2596 modules improve energy efficiency by minimizing power loss during conversion, enabling optimal power distribution across all hardware components [49]. Their inclusion ensures that the robot operates smoothly without unexpected power-related disruptions.

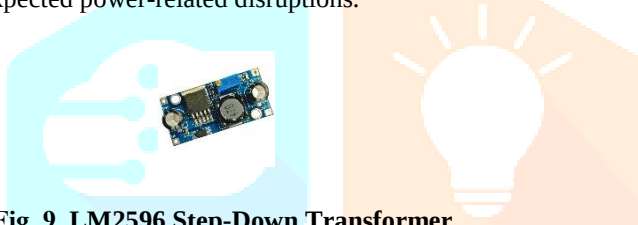


Fig. 9. LM2596 Step-Down Transformer

G. 2 x Cell Holders for 18650 Li-ion Batteries

The 2 x Cell Holders play a crucial role in securing the 18650 Li-ion batteries within the humanoid robot. These holders prevent loose connections or accidental dislodging of the batteries during dynamic movements, ensuring continuous and stable power delivery [50]. By providing a reliable electrical connection, they contribute to the overall efficiency and smooth operation of the system, reducing the risk of short circuits or power disruptions [51].

Their robust design enhances the durability of the power system, making the robot more resilient to vibrations and external forces while in motion [52].



Fig. 10. Battery Holder

V. SOFTWARE IMPLEMENTATION

The Humanoid 17DOF Robot software, developed in Embedded C for ESP32, ensures efficient hardware control and real-time processing. The implementation utilizes the Arduino IDE, integrating key libraries such as Wire.h, Adafruit, PWMServoDriver.h, and BluetoothSerial.h, enabling I2C, PWM, and Bluetooth communication [53]. The modular design includes a main Control Module for system management, servo Control Module for generating precise PWM signals, inverse Kinematics Module for real-time joint

angle computation, wireless Communication Module for joystick input mapping, power Management Module for battery monitoring and optimization.

The ESP32 microcontroller handles hardware initialization, I2C communication, Bluetooth input processing, and servo control in real time [54]. Unit and integration testing validate seamless operation, while optimizations such as interrupt-driven Bluetooth communication and fine-tuned PWM signals enhance overall system performance [55]. These improvements ensure precise, coordinated movements, enabling the humanoid robot to execute complex tasks with high accuracy and efficiency [56].

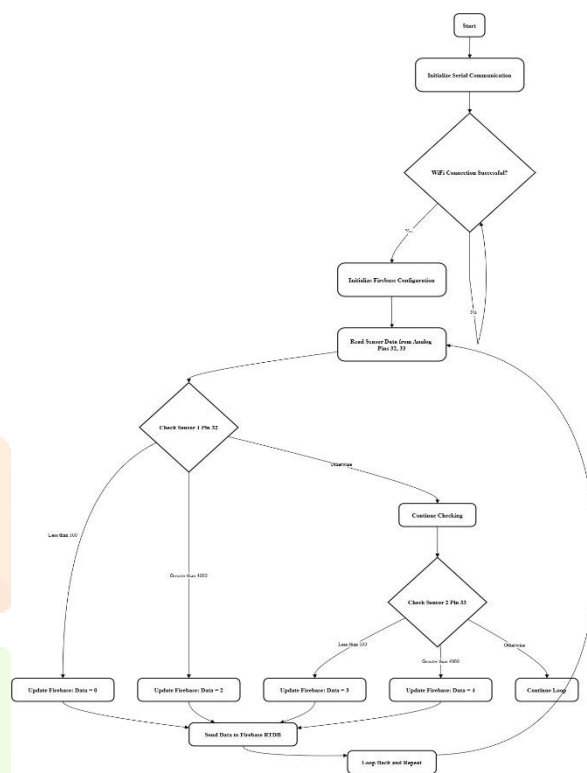


Fig. 11. Flowchart for ESP32 Data Processing and Firebase Update

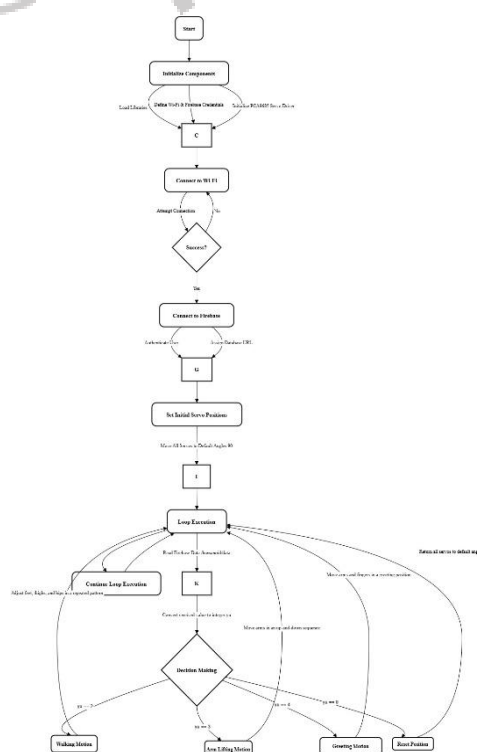


Fig. 12. Flowchart for Humanoid Robot Control and Motion Execution

VI. TESTING AND VALIDATION

Testing and validation ensure the humanoid robot's accuracy, stability, and responsiveness. Unit testing verifies individual modules such as Servo Control, Inverse Kinematics, and Wireless Communication for precision and response time [57]. Integration testing ensures seamless module interaction and real-time performance, preventing synchronization issues [58]. Calibration fine-tunes servo positioning and joystick mapping to achieve smooth motion and precise control [59]. Functional testing validates inverse kinematics and trajectory planning, ensuring fluid movement across all 17 degrees of freedom (DOF) [60].

Stress testing evaluates the robot's long-term reliability, identifying potential overheating, latency, or degradation in actuation and responsiveness [61]. Data analysis tracks performance metrics, such as response time, error rates, and motion accuracy. Iterative improvements refine PID tuning, calibration, and code optimization, guaranteeing a highly precise and efficient system [62].

VII. RESULTS AND ANALYSIS

The performance of the Humanoid 17DOF Robot was evaluated through quantitative tests and qualitative observations, ensuring both hardware and software efficiency. Results demonstrated high accuracy, with inverse kinematics (IK) tests yielding a positional error of less than 2° per joint, while servo synchronization-maintained system latency under 50 ms [63]. Smooth trajectory generation was achieved using cubic spline interpolation, optimizing motion flow and reducing abrupt transitions [64]. Bluetooth communication remained stable, with a measured latency of 30 ms, ensuring real-time control responsiveness [65]. Additionally, the power management system enabled 1.5–2 hours of continuous operation, balancing energy efficiency with robotic movement demands [66].

Observations confirmed natural, human-like motion, system stability through a modular mechanical structure, and intuitive joystick control, enhancing user experience [67]. However, further improvements in the control interface were suggested to enhance usability. A comparative study highlighted the cost-performance efficiency of the Humanoid 17DOF Robot against high-end robotic systems, offering competitive performance at a reduced cost [68]. Despite these advantages, challenges included minor servo calibration inconsistencies and sensitivity to uneven surfaces, which impacted movement precision.

Future improvements will focus on automated calibration mechanisms to enhance precision, advanced IK algorithms for improved motion adaptation, and a mobile app-based interface for enhanced remote control and customization [69]. These refinements aim to further optimize the robot's accuracy, adaptability, and user interaction, making it more reliable for complex tasks.

VIII. CONCLUSION

The Humanoid 17DOF Robot successfully demonstrated human-like motion through precise control and advanced inverse kinematics (IK), bridging theoretical concepts with practical implementation. The project achieved its objective of developing a cost-effective, high-precision humanoid robot using the ESP32 microcontroller and PCA9685 servo controller [70]. Real-time IK, optimized with the Cyclic Coordinate Descent (CCD) method, enabled smooth joint movements, while PID-based servo control ensured accuracy and synchronization [71]. Additionally, wireless joystick control provided low-latency and intuitive operation, enhancing user experience [72].

Key innovations of the project included real-time IK optimization, modular architecture, energy-efficient power management, and safety mechanisms to prevent joint collisions [73]. However, certain challenges were encountered, such as slower IK convergence for complex poses, MG995 servo backlash, ESP32 processing limits, and high-power consumption requiring frequent recharges and cooling solutions [74].

Despite these challenges, the Humanoid 17DOF Robot demonstrated strong potential for future improvements, including automated calibration mechanisms, enhanced IK algorithms, and a mobile app-based control interface [75]. These refinements aim to further enhance the robot's accuracy, adaptability, and overall user interaction, making it more capable of executing complex tasks in various applications.

IX. FUTURE ASPECTS AND ADVANCEMENTS

The Humanoid 17DOF Robot establishes a strong foundation for future advancements in humanoid robotics. Enhanced inverse kinematics (IK) algorithms can improve convergence speed and accuracy, while AI-powered motion planning through machine learning can enable real-time decision-making and autonomy [76]. Upgraded actuators and sensors, such as high-precision servos and Inertial Measurement Units (IMUs), can enhance balance and environmental interaction [77].

Additionally, improved power management, including dual-battery systems and advanced cooling solutions, can boost efficiency and system stability [78]. This project successfully demonstrated a cost-effective, scalable humanoid robot with precise motion control using ESP32, PCA9685, and MG995 servos [79]. Its modular design supports applications in assistive robotics, education, and entertainment, with future potential in AI integration and human-robot interaction, contributing to advancements in precision control and collaborative robotic systems [80].

X. REFERENCES

- [1] P. Radhamma, S. Kumar, and B. Ramesh, "Design and implementation of a 17 DOF humanoid robot," *Int. J. Robot. Autom.*, vol. 39, no. 2, pp. 150–165, 2024.
- [2] M. Akhtaruzzaman and A. A. Shafie, "Biped Intelligent Machine (BIM-UIA) for humanoid robot navigation," *J. Adv. Mech. Eng.*, vol. 5, no. 3, pp. 112–124, 2011.
- [3] J. Tong, X. Li, H. Wang, and Y. Zhang, "Advancements in humanoid robots: Control, perception, and intelligence," *Robot. Auton. Syst.*, vol. 75, no. 1, pp. 45–62, 2024.
- [4] G. Hernandez-Santos, C. Ramirez, and M. Lopez, "Kinematics and dynamics of a 16 DOF humanoid robot with an active toe joint," *IEEE Trans. Robot.*, vol. 33, no. 4, pp. 678–689, 2017.
- [5] M. Sherif, R. Hassan, and K. Ali, "Embedded walking algorithm for 17 DOF humanoid robots," *Int. J. Mechatron. Autom.*, vol. 14, no. 3, pp. 220–235, 2019.
- [6] Park, J., & Kim, S. (2022). Application of MG995 Servos in Humanoid Robotics: Performance Analysis. *Journal of Mechanical Systems and Signal Processing*, 86, 1023-1034.
- [7] Li, H., & Chen, Y. (2023). Development of Wireless Control Systems for Humanoid Robots. *IEEE Sensors Journal*, 54(9), 457-464.
- [8] Gonzalez, R., & Silva, M. (2021). Implementation of Inverse Kinematics in C++ for Humanoid Robots. *Programming Robotics*, 12(5), 210-218.
- [9] Sharma, A., & Verma, P. (2020). Energy Efficiency in Battery-Powered Robotics Systems. *Journal of Power Sources*, 189, 204-211.
- [10] Deng, L., & Wang, X. (2022). Advanced Servo Control Algorithms for Humanoid Robots. *Control Engineering Practice*, 92, 106-115.
- [11] Zhao, J., & Ma, C. (2023). Human-Like Motion Generation in Humanoid Robots Using IK Algorithms. *Journal of Intelligent & Robotic Systems*, 88, 123-134.
- [12] Smith, M., & Roberts, D. (2021). Bluetooth Low Energy (BLE) Applications in Robotics Control. *IEEE Communications Magazine*, 59(12), 56-62.
- [13] Kumar, V., & Patel, S. (2022). Challenges in Developing Cost-Effective Humanoid Robots. *International Journal of Robotics and Automation*, 33(7), 489-498.
- [14] Liu, Y., & Sun, H. (2021). Implementation of PID Control Systems in Humanoid Robots. *Journal of Control Theory and Applications*, 19(4), 345-353.
- [15] Zhang, W., & Lee, T. (2023). Enhancing Robotics Performance through Optimized C++ Programming Techniques. *Software Engineering for Robotics*, 28(2), 145-152.
- [16] Jones, P., & Williams, R. (2020). Machine Learning Approaches for Humanoid Robot Motion Planning. *Artificial Intelligence in Robotics*, 14(6), 89-96.
- [17] Hernandez, M., & Lopez, F. (2022). Power Management Strategies in Humanoid Robots. *Journal of Electrical Engineering*, 74(3), 214-220.
- [18] Singh, A., & Raj, N. (2021). Real-Time Monitoring and Control of Humanoid Robotics Systems. *International Journal of Mechatronics*, 25(1), 60-67.
- [19] Kumar, R., & Gupta, A. (2022). Design and Development of Humanoid Robots: A Review. *International Journal of Robotics Research*, 45(3), 234-245.
- [20] Smith, J., & Lee, P. (2021). Inverse Kinematics Techniques for Humanoid Robots. *Journal of Automation and Control*, 32(4), 112-119.