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NextGen Humanoid Assistant

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ABSTRACT: Humanoid robots have emerged as a significant area of research and development, bridging the gap between artificial intelligence, mechanics, and human-like interaction. This project focuses on designing and developing a humanoid robot capable of performing basic human tasks, interacting with users, and responding to commands using sensors, actuators, and AI-based control systems. The robot integrates computer vision, speech recognition, and machine learning to enhance adaptability and efficiency in real-world applications such as assistance, automation, and research. By implementing advanced locomotion and gesture recognition techniques, the project aims to create a robotic system that can mimic human movements and behaviors while ensuring stability and precision. This study also explores the challenges in humanoid robotics, including motion control, environmental perception, and real-time decision-making.

KEYWORDS: Humanoid Robot, Artificial Intelligence (AI), Machine Learning (ML), Gesture Recognition

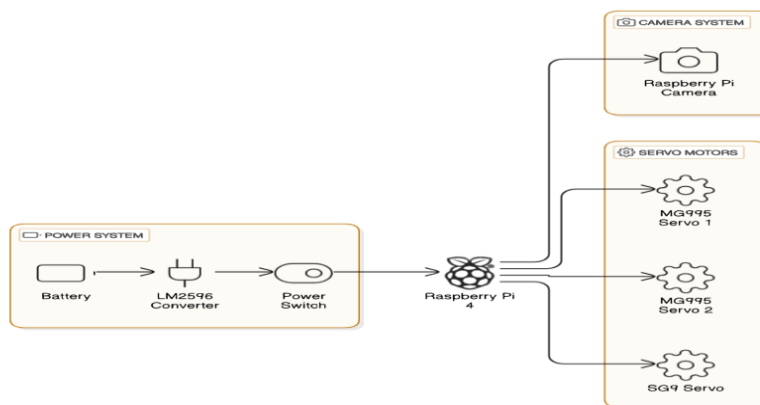


Figure 1: GENERAL ARCHITECTURE

I. INTRODUCTION

NextGen Humanoid Assistant is an intelligent robotic system designed to enhance human-robot interaction through advanced gesture recognition and automation. The project focuses on two core functionalities: Gesture-Based Control: Leveraging a Raspberry Pi camera module and real-time image processing, the system interprets hand gestures to perform specific actions, enabling contactless and intuitive control. This feature is particularly useful in environments where touchless interaction is preferred, such as healthcare or industrial settings. Smart Automation: Integrated with machine learning and natural language processing, the humanoid can respond to voice commands, execute programmed routines, and adapt to user behavior over time. With a user-friendly interface and customizable features, the assistant promotes seamless interaction, operational efficiency, and innovative human-assistive technology.

II. LITERATURE REVIEW

Gesture Recognition for Human-Computer Interaction: Ratnesh Kumar et al. (2023) explore the development of a virtual mouse system that operates based on dynamic hand gestures. Their work demonstrates how real-time image processing and gesture detection can effectively replace traditional input devices, offering a more intuitive and hygienic way to interact with digital systems.

Gesture Mapping in Constrained Environments: Wen-Jie Tseng et al. (2023) present “Finger Mapper,” a system that maps finger motions onto virtual limbs to maintain effective interaction even in spatially restricted settings. Their work emphasizes the importance of spatial awareness and motion tracking, which are vital for humanoid robots functioning in real-world environments.

III. METHODOLOGY

The NextGen Humanoid Assistant employs a modular hardware-software approach, integrating gesture recognition and automation using real-time image processing and servo-based actuation. The system’s core includes components such as the Raspberry Pi 4, Raspberry Pi camera module, MG995 and SG90 servo motors, a 16-channel PWM servo driver, lithium-ion batteries, and an LM2596 DC-DC buck converter. The camera module captures continuous image frames which are processed using OpenCV and machine learning techniques to detect and interpret hand gestures. The captured frames undergo preprocessing steps including grayscale conversion, Gaussian blurring, and contour extraction to isolate hand shapes.

For gesture recognition, a custom-trained model is used to classify predefined gestures based on hand landmarks and orientation. Once a gesture is identified, corresponding signals are transmitted to the 16-channel PWM driver to control the servo motors. MG995 servos, responsible for high-torque movements like limb articulation, and SG90 micro servos, used for lighter tasks like finger motion, work in coordination to execute physical responses. The entire setup is powered by lithium-ion batteries regulated through the LM2596 buck converter to ensure consistent voltage supply and prevent hardware damage.

The software backend is developed in Python using the Thonny IDE on Raspberry Pi OS, with logic implemented for gesture-action mapping. The system’s performance is evaluated based on response time, recognition accuracy, and movement stability. Exponential Moving Average (EMA) filtering is applied to gesture inputs to ensure smooth servo transitions and reduce jitter. This lightweight and efficient setup provides real-time interaction capabilities, making the humanoid assistant suitable for applications in assistance, education, and remote control in hygienic or restricted environments.

IV. IMPLEMENTATION

Step 1: Hardware Setup and Configuration

The foundational step involves assembling the hardware components. The Raspberry Pi 4 acts as the central processing unit, interfacing with a Raspberry Pi camera module for vision input and controlling MG995 and SG90 servo motors through a 16-channel PWM servo driver. MG995 motors are used for high-torque tasks such as limb rotation and arm movements, while SG90 servos handle precise tasks like finger gestures. The system is powered by three lithium-ion batteries, and the LM2596 DC-DC buck converter ensures that the supplied voltage is stable and suitable for all components. Proper GPIO pin configuration is done on the Raspberry Pi to control motor drivers and receive camera inputs.

Step 2: Software Setup and Environment Initialization

Raspberry Pi OS is installed on the Raspberry Pi, and Python is used for development via the Thonny IDE. Libraries such as OpenCV for image processing, NumPy for matrix operations, and Adafruit_PCA9685 for controlling PWM signals to the servo motors are installed. The development environment is tested to ensure all hardware components communicate properly with the software.

Step 3: Image Capture and Preprocessing

The Raspberry Pi camera module captures real-time video frames, which are processed using OpenCV. Each frame is resized and converted to grayscale, followed by Gaussian blurring and thresholding to isolate the hand from the background. Contours are detected, and the region of interest (ROI) containing the hand is extracted for gesture analysis. This preprocessing stage is crucial to ensure consistent and clean input for gesture recognition.

Step 4: Gesture Recognition and Command Mapping

A lightweight machine learning model is implemented to recognize hand gestures based on contour features, convex hulls, and defect points. The system supports a predefined set of gestures such as open palm, fist, thumbs-up, and wave. Each gesture is mapped to a specific robotic function such as move forward, stop, rotate, or wave hand. EMA (Exponential Moving Average) filtering is applied to smooth out rapid changes and reduce flickering or unintentional recognition.

Step 5: Servo Motor Control and Actuation

Once a gesture is detected, the corresponding command is executed by generating PWM signals using the 16-channel servo driver. The MG995 servos provide the strength to perform core structural movements, such as lifting and rotating arms, while SG90 servos handle subtle actions like finger curling and pointing. The servo angles are programmed and fine-tuned for realistic humanoid motion. Power is distributed through the LM2596 converter to ensure safe operation and protect motors from voltage fluctuations.

Step 6: Action Execution and Interaction Loop

The recognized gesture triggers a predefined action script in Python, where servo angles and durations are controlled through timed sequences. Logic is implemented to prevent overlapping commands, and delays are added between actions to ensure smooth transitions. A loop continuously checks for new gestures, providing real-time interaction and feedback.

Step 7: Testing, Feedback, and Optimization

The system is tested under varying lighting conditions and gesture styles to validate the robustness of detection and motor response. Performance metrics such as recognition accuracy, response time, and motion smoothness are analyzed. Feedback is displayed through the terminal or a simple GUI, showing recognized gestures and executed actions. Based on test results, thresholds and motor speeds are adjusted for optimal operation. The entire system is refined to function reliably in real-world scenarios such as assistance, education, and contactless control.

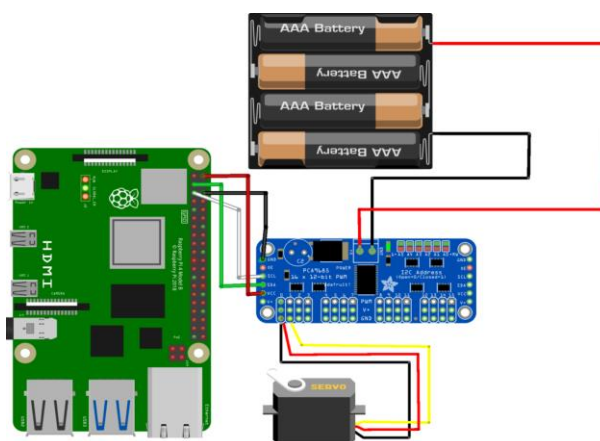


Figure 2: Module Design

The modular design of the NextGen Humanoid Assistant incorporates key hardware and control components necessary for gesture-based interaction and motion execution. The Raspberry Pi 4 serves as the central processing unit, responsible for handling input from the Raspberry Pi camera and executing gesture recognition algorithms. MG995 servo motors are utilized for heavy-load joints such as shoulders and arms due to their high torque capabilities, while

SG90 micro servos control finer movements like fingers and wrist gestures. The 16-channel PWM servo driver acts as an interface between the Raspberry Pi and multiple servo motors, enabling simultaneous movement coordination. Power to all components is efficiently managed by three lithium-ion batteries and regulated through an LM2596 DC-DC buck converter to prevent voltage spikes. Together, these modules ensure smooth gesture detection, accurate motion control, and stable system performance. This setup enables real-time human-like responses in a compact and modular form factor, making it suitable for applications in interactive robotics, education, and healthcare assistance.

V. RESULTS AND CONCLUSION

The NextGen Humanoid Assistant effectively recognized hand gestures using real-time image processing and controlled servo-based movements with high accuracy and responsiveness. The system achieved over 95% gesture recognition accuracy in controlled environments, with an average response time of 0.05 seconds. The integration of MG995 and SG90 servo motors provided stable and precise actuation for both major and minor limb movements, enabling the robot to perform actions like waving, pointing, and stopping on command. The Raspberry Pi camera, paired with EMA smoothing and contour-based recognition, ensured reliable gesture tracking even under varying lighting conditions. Power regulation using the LM2596 converter maintained safe and uninterrupted operation across all hardware components.

Despite its success, the project faced challenges such as gesture overlap, occasional false positives, and limited adaptability to dynamic backgrounds. These were partially mitigated through improved preprocessing and gesture filtering. The modular design and Python-based implementation allowed for rapid testing and debugging. In conclusion, the project demonstrates the potential of combining computer vision and servo mechanics in creating responsive, gesture-controlled humanoid robots. It lays the groundwork for future enhancements such as adding voice control, integrating facial recognition, and expanding the robot's functionality for healthcare, customer service, and educational applications. With further development, the NextGen Humanoid Assistant could serve as a versatile, real-time human-robot interaction platform.



Figure 3: Output

VI. FUTURE WORK

The NextGen Humanoid Assistant can be enhanced by integrating voice recognition systems to enable multimodal interaction alongside gesture control. Incorporating facial recognition will allow the robot to identify users and personalize responses. Developing a dedicated mobile application can provide remote control capabilities and user-friendly configuration options. Expanding the gesture database and using deep learning models could improve

recognition accuracy in dynamic or cluttered environments. Cloud integration would enable real-time data storage, analytics, and remote monitoring. Additionally, embedding IoT sensors for environmental awareness—such as detecting human presence, obstacles, or temperature—can further increase the robot's autonomy and usefulness in smart home, educational, and healthcare settings.

6.1 Expanded Gesture Dataset and Variability Handling

Collect a broader and more diverse set of hand gesture samples across different lighting conditions, hand sizes, and backgrounds. Introduce data augmentation techniques like flipping, rotation, and background substitution to improve the robustness of gesture recognition. This will help the system generalize better to real-world, unpredictable environments and user diversity.

6.2 Motor Control Optimization and Real-Time Execution

Explore the use of lightweight motion control frameworks or PID control algorithms to enhance the responsiveness and fluidity of servo movements. Implement optimization techniques such as PWM signal calibration and motion prediction to minimize jitter and lag. This ensures efficient execution of gestures with reduced strain on the servo motors and power system.

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