Design and Development of a Desktop Companion Robot with Social Intelligence and Human-Like Interaction

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ABSTRACT

"The Design and Development of a Desktop Companion Robot with Social Intelligence and Human-like Interaction" presents the development of a 17 Degree-of-Freedom (DOF) humanoid desktop companion robot designed to offer intelligent, safe, and emotionally engaging interactions. This innovative robot is equipped with 17 Degrees of Freedom (DOF), providing it with the flexibility to replicate various human movements and serve as a surveillance tool [1]. The types and structures of control and sensor systems, and the energy efficiency of the robots. Terrain roughness recognition systems using different sensor systems based on light detection and ranging or multiple cameras are introduced[3]. The robot integrates facial recognition for user identification, an expressive digital face using OpenGL, and edge detection sensors to ensure safe operation on elevated surfaces. Its core interaction capabilities are powered by speech-to-text (Whisper API) and text-to-speech (ElevenLabs) systems, enabling real-time voice communication. Emotional understanding is achieved through pretrained emotion classification models, which guide the robot's responses and facial expressions. The system's intelligence is driven by Large Language Models (LLMs) via the Groq API, allowing for personalized, context-aware dialogue. The robot maintains a user profile database using SQLite to support memory-based interactions. A modular backend built with FastAPI, along with a secure Next.js admin panel, manages chat history, API control, and emotion tracking. The robot's physical behaviour is driven by 17 servo motors controlled via Arduino Mega, enabling dynamic gestures such as head movement, arm waving, and posture shifts. Future extensions include MQTT-based control for

gesture synchronization. The proposed system provides a compact, intelligent solution for personal companionship and interaction in desktop environments.

I.INTRODUCTION

Robotics is a multidisciplinary field at the intersection of computer science, engineering, and mathematics, focusing on the design, construction, operation, and use of robots[1], especially when it comes to personal assistants and companion devices. This research introduces a compact humanoid robot designed to sit on a desktop and interact intelligently, emotionally, and safely with users in both personal and professional settings. With 17 degrees of freedom, the robot moves in lifelike ways using servo motors controlled by an Arduino Mega. The lightweight aluminium frame ensures durability, while a Lithium Polymer battery supports extended operation. LM2596 step-down transformers regulate power, ensuring stable performance[2]. It uses facial recognition to identify users and personalize interactions. These profiles are stored in a local SQLite database, allowing the robot to learn and improve over time. One of its standout features is an expressive digital face that displays dynamic emotions using OpenGL and Pygame, helping create a more natural and engaging connection with users. The robot communicates through emotionally aware, context-sensitive conversations, powered by Large Language Models accessed via the Groq API. Voice input is processed using Whisper for speech-to-text, and responses are spoken through ElevenLabs' text-to-speech engine, with backup options for offline use. Safety is also a priority, with edge detection sensors preventing the robot from falling off tables or other elevated surfaces. The system runs on a modular FastAPI backend that manages all core functions, while a user-friendly admin dashboard built with Next.js allows for easy monitoring and control. The design is built to scale, with future plans for MQTT-based gesture and motor control. By combining movement, emotional intelligence, and real-time communication, this robot takes an important step toward creating practical and engaging desktop companions.

1.2 Objective of the project

This project aims to build a smart, compact desktop robot that does more than just respond—it forms a real connection with users. With 17 degrees of freedom, the robot can move in lifelike ways and express emotions through a digital animated face. It recognizes individual users using facial recognition . Using speech-to-text, emotion detection, and advanced language models, the robot can engage in natural, meaningful conversations. It's designed to be more than just a device it's meant to be a thoughtful, responsive companion. Edge detection sensors help keep it safe on desks or tables. Its expressive screen adds emotional depth to interactions, while its ability to learn from past conversations helps it grow and adapt over time. Overall, the goal is to create a robot that draws people in and keeps them engaged through intelligent, human-like behaviour.

II.LITERATURE SURVEY

The fusion of robotics and artificial intelligence has opened up exciting possibilities for creating intelligent robots that can respond emotionally and adapt to individual users. In recent years, humanoid robots have been increasingly used in environments centred around people—with the aim of improving user interaction, offering help, and supporting emotional well-being. This review looks at past research that informs the development of compact, desktop humanoid robots with movable parts (degrees of freedom), social awareness, and the ability to personalize interactions.

One study introduced a socially assistive robot that uses facial recognition to identify and interact with users. Its ability to remember individuals and adjust its behaviour accordingly helps create a more personal connection. This directly supports our project's goal of using facial recognition to build a database that enables custom interactions with users. Another key aspect is the robot's expressiveness. Robots that feature digital facial displays—like a screen for a face—can simulate emotions and provide visual cues. These features significantly boost user engagement and emotional connection. Our robot adopts a similar approach, using an expressive screen to enhance non-verbal communication. Safety is also a major focus, especially for desktop robots. Sensors like ultrasonic or infrared detectors can identify edges or sudden drops, which helps prevent falls. Research shows these sensors are effective for ensuring safe movement , and we've integrated this into our design. The use of Large Language Models (LLMs), such as GPT, is also transforming how robots communicate. In our project, LLMs power the robot's real-time conversation skills and help it learn continuously from interactions. Another important factor is the robot's Degrees of Freedom (DOF), which determine how much it can move and express itself. Studies show that having 17 or more DOFs lets a robot perform complex gestures like nodding, waving, or leaning—making interactions feel more lifelike . Our design includes a 17 DOF framework to support these movements. Finally, the work by Guni Ganesh and colleagues introduced a desktop companion robot with all the features we aim to include: 17 DOFs, emotional expression, facial recognition, and fall prevention. Their research highlights how powerful social robots can be in everyday life—especially in limited spaces like desks—reinforcing our vision for a smart, engaging desktop companion.

III.HARDWARE DESCRIPTION

ARDUINO MEGA 2560

The Arduino Mega 2560, powered by the ATmega2560, offers 54 digital I/O pins (15 with PWM), 16 analogue inputs, and 4 serial ports, along with 256 KB of flash memory, 8 KB of SRAM, and 4 KB of EEPROM. In the desktop companion robot, it serves as the main controller, operating 17 servo motors for precise movements and processing data from ultrasonic and infrared sensors for environmental awareness. Its multiple serial ports enable smooth integration with facial recognition and display systems, while its high I/O capacity and processing power ensure dependable multi-tasking for complex robotic function. Arduino board and IDE software are the reference versions of Arduino and currently progressed to new releases.[1]

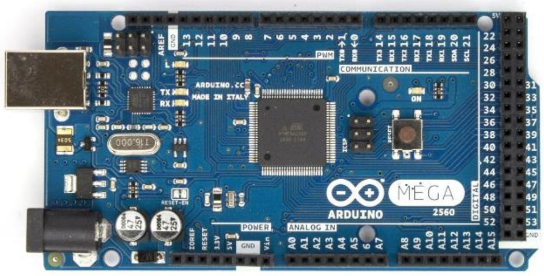

Fig1: Arduino MEGA 2560 Board

SERVO MOTOR

The TowerPro MG995 metal-gear servo motors provide the actuation system for all 17 degrees of freedom in the desktop companion robot. These compact servos (40×20×41 mm, 55g) deliver substantial torque output of 9.4-12 kg·cm at 4.8-6.6V operating voltage, enabling stable execution of complex humanoid gestures and movements. Key performance characteristics include a 180° rotation range, rapid response times (0.16-0.20 seconds per 60°), and Their high torque capability is crucial for maintaining stability and executing dynamic movements with precision[2]. MG995 Servo Motor is a heavy-duty reliable servo motor. It is a low-power, cost-effective motor.[1] The servos' power efficiency (4.8-7.2V operating range) and standardized control interface facilitate centralized coordination through a PCA9685 driver board.

Fig2:MG995 Servo Motor

LITHIUM POLYMER BATTERY

The robot utilizes a Bonka 7.4V, 3300mAh lithium-polymer (Li-Po) battery in 2S configuration, providing 14.42Wh energy capacity for extended autonomous operation. The battery delivers substantial power output with a continuous 25C discharge rate (82.5A, ~610W) and peak 50C capability for handling transient loads during high-demand operations such as multi-servo coordination and sensor processing. Key specifications include compact dimensions (135×44×14mm) optimized for mobile robotics integration, JST-XH balance connector for safe charging protocols, and high-current XT60 discharge connector ensuring reliable power delivery. This feature is essential for executing dynamic movements like walking, balancing, and complex gestures[2]. The Li-Po chemistry provides consistent voltage output throughout the discharge cycle, ensuring stable performance of servo motors and electronic components during complex robotic tasks and autonomous behaviours.

Fig3: Lithium Polymer Battery

PCA9685 Module

The PCA9685 is a 16-channel, 12-bit PWM driver that communicates with the Arduino Mega via I²C, allowing centralized servo control without using multiple PWM pins. And allowing simultaneous and efficient control of up to 16 servos[1]. it delivers precise 1–2 ms pulses for full 0–180° positioning. Its design separates logic and power, using an external 5–6 V supply to prevent voltage drops when multiple servos run simultaneously. Scalable via I²C address settings, it can control up to 992 servos (62 modules × 16 channels) on one bus. In the 17-DOF desktop companion robot, it enables synchronized multi-servo operation for complex humanoid movements, walking, and expressive gestures while reducing the Arduino's processing load.

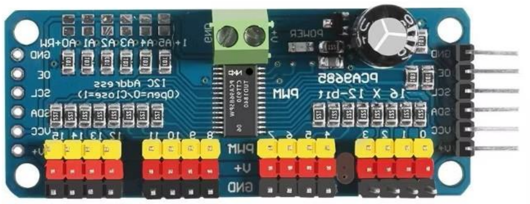

Fig4: PCA9685 Module

LM2596 DC-DC Buck Converter

The LM2596 DC-DC Buck Converter provides highly efficient voltage regulation (>80% efficiency) for robotic systems, converting 4-40V input to adjustable 1.25-37V output with minimal heat generation. This switching regulator significantly outperforms linear regulators in energy conservation and thermal management—critical for battery-powered robotics. Key features include an onboard potentiometer for precise voltage adjustment, status LED, secure screw terminals, and 2-3A current handling capacity. In the desktop companion robot, it steps down 7.4V Li-Po battery power to stable 5V, safely powering the PCA9685 servo controller, sensors, and Arduino Mega. The module's compact design, easy integration, and reliable performance make it ideal for portable robotics where space constraints and power efficiency are essential. Its superior efficiency extends battery life while reducing heat-related component stress, ensuring consistent operation in demanding robotic applications.

Fig5: LM2596 DC-DC Buck Converter

TFT LCD Touch Screen

The 3.5-inch TFT LCD touchscreen (480×320) is the robot's main interface, connected through GPIO and using SPI to avoid the need for HDMI. It shows real-time emotions and animations created with Python tools like Pygame and OpenCV , responding to sensor data and the robot's behaviour. The touch feature lets users interact directly, while its small size and low power use make it ideal for mobile robots. Acting as the robot's "face," it displays emotions such as happiness or surprise, improving communication, engagement, and social acceptance.

Fig6: TFT LCD Touch Screen

RASPBERRY PI 5

The Raspberry Pi 5 (12 GB RAM) serves as the brain of the Desktop Companion Robot, delivering powerful AI capabilities in a compact, energy-efficient package. Its quad-core 2.4 GHz Arm Cortex-A76 processor and 12 GB LPDDR4X RAM enable real-time facial recognition, sensor analysis, and lightweight LLM execution for intelligent human-robot interactions. Key advantages include extensive connectivity (dual 4K HDMI, USB 3.0, PCIe 2.0) for seamless peripheral integration, and native compatibility with essential AI/robotics frameworks like TensorFlow Lite, OpenCV, and ROS. This combination makes it ideal for rapid prototyping and deployment of advanced robotic applications while maintaining cost-effectiveness and accessibility. The Pi 5 handles the robot's cognitive processing, sensory input management, and communication functions, enabling responsive, adaptive interactions that create a personalized user experience.

Fig7: Raspberry Pi 5

IV. PROPOSED SYSTEM

The proposed Desktop Companion Robot features 17 Degrees of Freedom (DOF) for smooth, human-like movements, enabling tasks like walking, grasping, and interacting with its environment. Designed for more than just functionality, it emphasizes social intelligence through facial recognition for personalized responses and an expressive display that conveys emotions. Powered by a Large Language Model (LLM), it engages in natural, context-aware conversations, while a dynamic database of recognized faces ensures continuous learning and evolving personalization.

BLOCK DIAGRAM

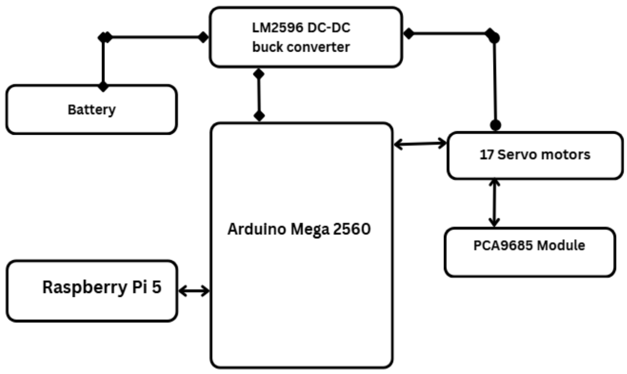

Fig8: Block Diagram

WORKING PRINCIPLE

The Desktop Companion Robot combines its power system, processors, sensors, motors, and interactive modules to deliver intelligent and human-like interactions. It runs on a rechargeable battery, with an LM2596 DC-DC buck converter ensuring a stable voltage for all components.

The Arduino Mega 2560 functions as the main microcontroller, managing low-level hardware tasks and motor control, while the Raspberry Pi 5 handles high-level operations such as facial recognition, emotion display, and natural language processing with a Large Language Model (LLM). For movement, the robot uses 17 servo motors controlled via the PCA9685 Servo Driver Module, providing 17 Degrees of Freedom (DOF) for smooth and natural gestures. An expressive display screen, directed by the Raspberry Pi, serves as the robot's "face," allowing it to show emotions and build stronger social connections.

The facial recognition system maintains a dynamic database of users, enabling the robot to adapt and personalize its responses over time. During operation, sensors and the recognition module collect input, which the Raspberry Pi processes to determine the appropriate response. Commands are then sent to the Arduino, which controls the servo motors and updates the display with matching emotional expressions.

Through this seamless integration of hardware and software, the robot achieves real-time decision-making, natural movement, and adaptive, emotionally intelligent interaction, making it a highly engaging desktop companion.

V. RESULT

Stage-1 Result:

The Desktop Companion Robot successfully achieved the goals of the project. It demonstrated complex, human-like movements using its 17 Degrees of Freedom (DOF). With the Arduino Mega 2560 working alongside the PCA9685 servo driver, the servo motors were precisely controlled to deliver smooth and stable gestures, ensuring accurate and reliable performance. Additionally, the power regulation unit provided a steady voltage supply, which contributed to consistent and dependable operation during testing.

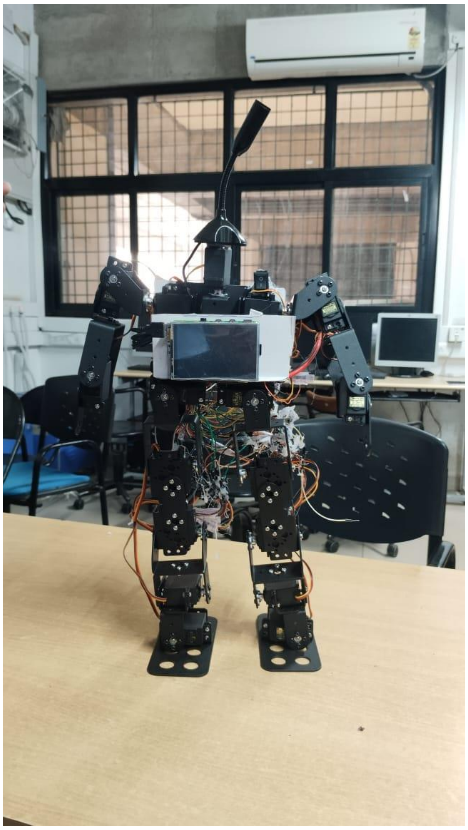

Fig9: stage-1 working model

Stage-2 result:

Testing showed that the robot's interactive and expressive features worked effectively in creating meaningful communication with users. Its expressive display screen acted as a "face," successfully showing a range of emotions that enhanced user engagement. The facial recognition system accurately identified multiple users and maintained a dynamic database for personalized interactions. With the support of a Large Language Model (LLM), the robot held natural, context-aware conversations, while its display synchronized with the dialogue to visually express emotions. Together, these features created a more immersive and emotionally engaging experience for users.

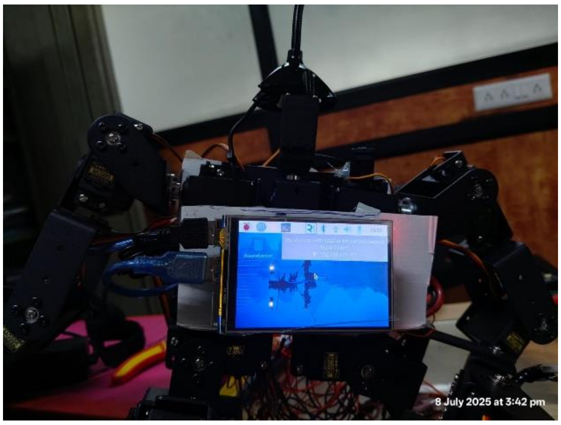

Fig2: stage-2 working model

VI. APPLICATIONS

1.Personal Assistant:

The robot serves as a helpful desktop companion for students and professionals, offering reminders, scheduling help, and interactive support for daily tasks.

2.Educational Tool:

It acts as an engaging platform for learning robotics, artificial intelligence, and programming, using its expressive display and responsive behaviour to make lessons more interactive.

3.Healthcare Support:

Designed to provide companionship, it can engage elderly individuals or patients in meaningful conversations, give medication reminders, and track basic activity patterns to support their well-being.

4.Entertainment and Emotional Support: With natural conversations, expressive gestures, and emotional interactions, the robot offers comfort, entertainment, and helps reduce feelings of loneliness.

5.Research and Development Platform: It serves as a flexible platform for experimenting with advanced human-robot interaction techniques such as emotion recognition, adaptive learning, and gesture control.

6.Smart Home Integration:

The robot can also be connected to smart home devices, allowing users to control lights, appliances, and even monitor environmental conditions through simple voice commands.

VII. ADVANTAGES

1.Human-like Mobility with High Precision:

The robot features 17 Degrees of Freedom (DOF), powered by an Arduino Mega 2560 and a PCA9685 servo driver, enabling smooth, precise, and natural movements. This allows for lifelike gestures that make interactions feel more human and expressive.

2. Personalized and Emotionally Engaging Interaction:

Its expressive display acts as the robot’s “face,” showing emotions that help build stronger social connections with users. This emotional expressiveness can reduce loneliness and improve overall well-being.

3. Adaptive User Recognition and Continuous Learning:

Advanced facial recognition, combined with a constantly updated database, allows the robot to recognize individual users and adapt to their preferences over time, resulting in more personalized and engaging interactions.

4. Natural Language Understanding with Conversational AI

With a built-in Large Language Model (LLM), the robot can hold context-aware conversations, making its dialogue coherent, adaptive, and natural for an improved user experience.

5. Emotional and Social Support: As a desktop companion, the robot provides emotional comfort and companionship, helping to ease stress, loneliness, and social isolation—whether at home or in the workplace.

6. Efficient Human–Robot Interaction Design:
Its human-like appearance and behavior encourage intuitive interaction, making engagement easier and more natural compared to standard voice-only or touchscreen interfaces.

CONCLUSION

The proposed Desktop Companion Robot combines advanced technology to provide both practical assistance and emotional engagement. With 17 Degrees of Freedom (DOF) powered by an Arduino Mega 2560 and PCA9685 servo driver, it moves smoothly and naturally. Its expressive display screen serves as a "face," visually showing emotions to strengthen user connection, while facial recognition and a dynamic face database enable personalized interactions. A Raspberry Pi 5 running a Large Language Model (LLM) allows the robot to hold natural, context-aware conversations and adapt its responses over time.

Testing confirmed that the robot can perform precise movements, accurately recognize users, and maintain coherent, emotionally engaging conversations. These results highlight its potential as a future socially intelligent companion.

Overall, the project demonstrates how precise motor control, expressive design, and conversational AI can be integrated into a compact desktop robot. It lays the groundwork for future improvements such as touch feedback, advanced emotion detection, and richer multimodal interaction, contributing to the development of emotionally intelligent and interactive robotics.

FUTURE SCOPE

Looking forward, the Desktop Companion Robot offers significant potential for further development and wider use. Future versions could integrate voice recognition and speech synthesis for smoother multimodal interaction, creating more natural and engaging communication. Adding tactile sensors and haptic feedback would allow touch-based interaction, enhancing both emotional connection and practical functionality. Improved emotion recognition through computer vision and affective computing could help the robot better understand and respond to human emotions, enabling more empathetic engagement. From a computational perspective, adopting edge AI accelerators or cloud-based inference could boost processing efficiency, supporting more advanced LLM capabilities without compromising responsiveness. Expanding the design with modular add on such as manipulators, environmental sensors, or IoT connectivity could extend the robot's role beyond desktop use, transforming it into a versatile platform. These enhancements would not only increase adaptability and user experience but also open opportunities for applications in education, healthcare, personalized assistance, and other domains.

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