INTERACTIVE DESKTOP COMPANION ROBOT FOR STRESS RELIEF

ECE 445 DESIGN DOCUMENT – SPRING 2026

Project # 4

Jiajun Gao, Yuchen Shih, Zichao Wang

Professor: Craig Shultz

TA: Haocheng Yang

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1 Introduction:

1.1 Probelm

The increasing prevalence of desk-based academic and professional work has significantly altered daily interaction patterns between individuals and their physical environments. Students and office professionals often remain seated for extended periods while engaging primarily with digital screens. This prolonged static posture and sustained screen exposure have been associated with mental fatigue, stress accumulation, and reduced cognitive efficiency. Although short breaks and digital media consumption may provide temporary relief, these solutions frequently require additional screen engagement and may interrupt productivity rather than meaningfully improving user well-being.

From a systems design perspective, current consumer products fail to fully address the need for lightweight, non-intrusive interaction within compact workspaces. Passive desk objects such as stress balls or decorative items offer no adaptive behavior or contextual awareness. In contrast, many existing robotic platforms are designed either for entertainment purposes or large-scale domestic assistance and are not optimized for safe and constrained desktop operation. These systems are often mechanically complex, spatially large, or lack strict safety mechanisms necessary for operation on elevated surfaces such as desks.

Therefore, there exists an opportunity to design a compact embedded robotic system capable of providing natural, low-effort interaction within a desk environment while maintaining strict operational safety constraints. Such a system must integrate sensing, communication, control, and power management into a cohesive architecture that balances responsiveness, stability, and safety. The engineering challenge lies not only in enabling multimodal interaction but also in ensuring reliable real-time performance within the physical and computational limitations of an embedded platform.

1.2 Solution

To address this need, we propose the design and implementation of an Interactive Desktop Companion Robot intended to provide lightweight conversational interaction and subtle physical feedback within a constrained desktop environment. The system is centered around an ESP32-S3 microcontroller, selected for its integrated wireless capability, sufficient computational resources, and compatibility with audio and peripheral interfaces.

The robot supports voice-based interaction through an onboard digital microphone and speaker system. A wake-word detection mechanism is executed locally to reduce unnecessary network transmission and preserve user privacy. Upon activation, compressed audio data is transmitted via Wi-Fi to a cloud-based large language model (LLM) service for speech recognition and response generation. To improve perceived responsiveness, the system employs a streaming text-to-speech (TTS) architecture, enabling partial audio playback to begin before full response synthesis is completed.

In addition to conversational interaction, the robot incorporates visual and mechanical feedback mechanisms. A compact SPI-based LCD module renders expressive animations corresponding to system states such as idle, listening, processing, and speaking. A differential-drive motion subsystem, implemented using dual DC gear motors and a motor driver, allows controlled forward movement and rotation.

Given the inherent risks associated with operation on elevated desk surfaces, safety is treated as a primary design constraint. A dedicated sensing subsystem utilizes multiple Time-of-Flight (ToF) distance sensors to monitor both downward-facing cliff conditions and forward obstacles. Safety sensing operates at a higher control priority than user-initiated motion commands, enabling immediate override in the presence of hazardous conditions.

The final system represents an integrated embedded platform that combines wireless communication, cloud-assisted artificial intelligence processing, real-time safety monitoring, and autonomous motion control within a compact physical form factor. The design emphasizes modularity, reliability, and safe interaction in everyday desktop environments.

1.3 Visual Aid

The proposed system operates as a compact mobile robot placed on a standard desk surface. A user interacts with the robot through spoken commands. The robot connects to a cloud-based AI server via Wi-Fi for speech processing and response generation. Responses are delivered through audio playback, animated visual expressions, and controlled physical motion.

The system is self-contained and battery-powered, requiring only network connectivity for cloud-assisted processing. The visual aid should illustrate the contextual use of the robot within a desk environment, including user interaction and wireless communication with the cloud service.

1.4 High-Level Requirements

To consider the project successful, the system must demonstrate the following high-level performance characteristics:

• The robot must reliably establish a Wi-Fi connection and communicate with a cloud-based server during normal operation.
• The average end-to-end voice interaction latency should remain below ten seconds under typical network conditions.
• The robot must detect desk edges and prevent falling during continuous desktop operation.
• The robot must detect and avoid frontal obstacles during standard motion tests.

• The system must operate stably on battery power without unexpected resets or unsafe behavior during extended use.

2 Design

2.1 Physical Design

The physical design of the Interactive Desktop Companion Robot is driven by desktop operation constraints, compact handheld-scale form factor, mechanical stability, and modular hardware integration. The system is currently in an iterative prototyping phase; therefore, the mechanical architecture is designed to remain adaptable while maintaining a consistent electronics and power layout.

2.1.1 Form Factor and Dimensional Strategy

The robot is designed to be handheld-sized, allowing it to be comfortably repositioned with one hand. Rather than defining fixed external dimensions at this stage, the enclosure geometry will be determined after finalizing the custom PCB layout. The printed circuit board establishes the minimum footprint required for embedded electronics and therefore serves as the primary dimensional constraint.

The dimensional design follows these principles:

- The footprint must remain compact enough for typical desktop environments.
- The overall height should maintain a low center of gravity to improve stability during motion.
- Internal volume must efficiently accommodate the PCB assemblies, battery, drivetrain components, and sensors.
- The enclosure geometry will be refined iteratively based on PCB routing density, connector placement, and mechanical mounting requirements.

This PCB-driven dimensional strategy improves integration efficiency and minimizes unused structural volume.

2.1.2 Dual-PCB Modular Architecture

To improve modularity and simplify development, the robot employs a two-PCB architecture consisting of a face board and a body board.

The face board is mounted in the front-facing region of the enclosure and supports user-interaction hardware such as the display module, audio interfaces, and other front-facing I/O components.

The body board is mounted within the main chassis and supports motion-related and system-level hardware, including motor control interfaces, power distribution circuitry, and sensor connections.

The two boards are connected through a USB cable/USB connector that functions as the primary inter-board communication link. The USB interface is currently used as a standardized physical interconnect to consolidate power and/or data exchange between modules. The specific communication protocol (e.g., USB CDC, UART over USB, or other serial interface) will be finalized during firmware integration and subsystem testing.

This modular separation allows independent development and debugging of interaction and motion subsystems while simplifying internal wiring and improving serviceability.

The enclosure incorporates dedicated mounting features for each PCB and a protected routing path for the USB interconnect to prevent mechanical strain or disconnection during motion.

2.1.4 Mobility Configuration (Under Evaluation)

Two drivetrain configurations are currently under evaluation:

Four-wheel configuration
Provides mechanical simplicity and predictable differential steering. It reduces alignment complexity and friction compared to tracked systems. Wheel placement forms a stable support polygon to reduce tipping risk.

Tracked configuration
May improve traction and distribute contact forces more evenly across the desk surface. However, tracked systems introduce additional mechanical complexity such as belt alignment and tension management.

The chassis design allows interchangeable drivetrain modules to enable comparative testing. Final selection will be based on prototype evaluation metrics including controllability, current consumption, mechanical reliability, and safety behavior near desk edges.

2.1.5 Sensor Placement and Environmental Awareness

The robot integrates two distance sensors that serve distinct safety functions: one for obstacle detection and one for cliff detection.

The **forward-facing sensor** is mounted at the front of the chassis and oriented horizontally to detect obstacles along the robot's path of motion. Its placement ensures an unobstructed field of view and enables the system to stop or adjust movement when nearby objects are detected.

The **downward-facing sensor** is mounted near the bottom front edge of the chassis and oriented toward the desk surface. Under normal operation, the sensor measures a stable baseline distance to the desk. A sudden increase in measured distance or loss of reflection indicates a potential desk edge, triggering an immediate stop or controlled reverse maneuver. This binary cliff-detection logic provides a fail-safe mechanism to prevent falls from elevated surfaces.

Sensor mounting geometry is integrated into the 3D-printed enclosure to ensure fixed orientation, repeatable alignment, and mechanical protection from drivetrain interference.

2.1.6 Preliminary Power System Design

The current preliminary power configuration utilizes a 3.7 V lithium-ion battery as the primary energy source. This selection is based on compact form factor and compatibility with embedded voltage regulation architectures; however, the battery specification remains tentative and may be revised following detailed power budget analysis and drivetrain current characterization.

The battery is located in the lower chassis compartment to maintain balanced mass distribution and stability. Voltage regulation and protective circuitry will provide stable operating rails for control electronics and peripherals. Physical separation between high-current motor traces and low-level signal paths is considered to reduce electromagnetic interference.

Final battery capacity and discharge specifications will be confirmed after subsystem-level power measurements and prototype validation.

2.1.7 Structural Stability Considerations

To maintain stable operation during acceleration, turning, and stopping, the center of gravity is kept within the support polygon defined by the drivetrain contact points. The drivetrain width balances compactness with resistance to tipping.

The 3D-printed enclosure material is selected to provide sufficient rigidity while minimizing overall mass. Reinforcement features are incorporated where necessary to prevent deformation under operational loads.

Overall, the physical design supports handheld-scale operation, modular subsystem separation, drivetrain experimentation, and safe desktop motion. The iterative mechanical approach allows refinement of mobility, power, and sensing subsystems while preserving a stable embedded hardware architecture.

2.2 Block Diagram

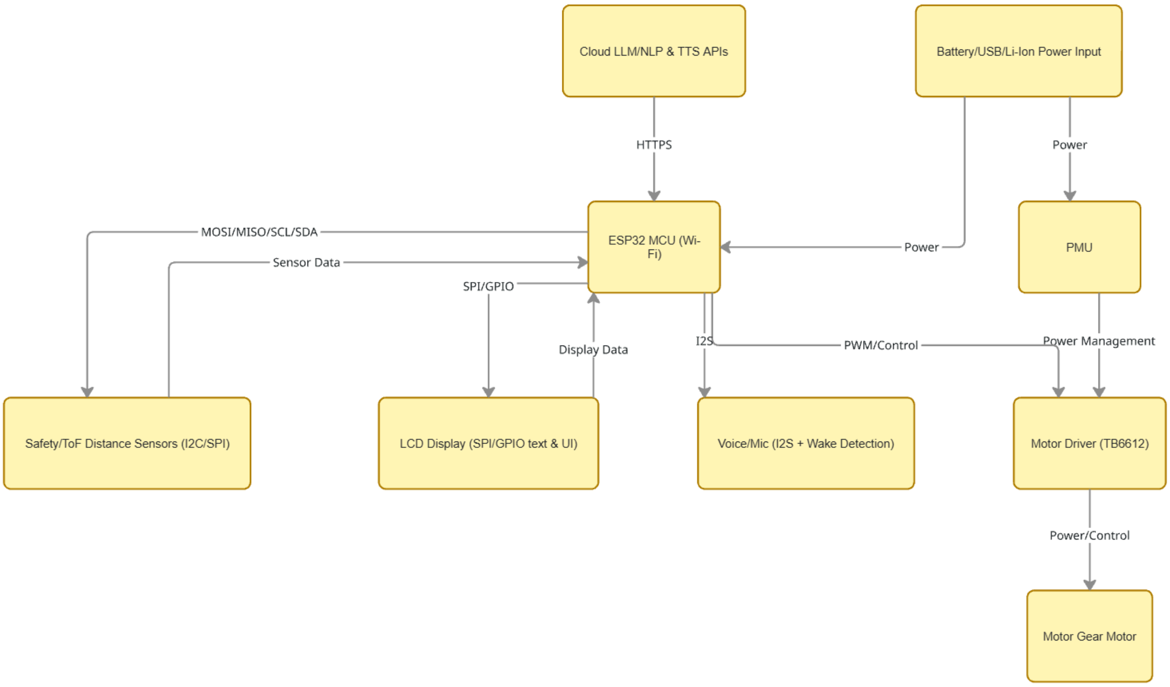

Fig1. Overall Block Diagram

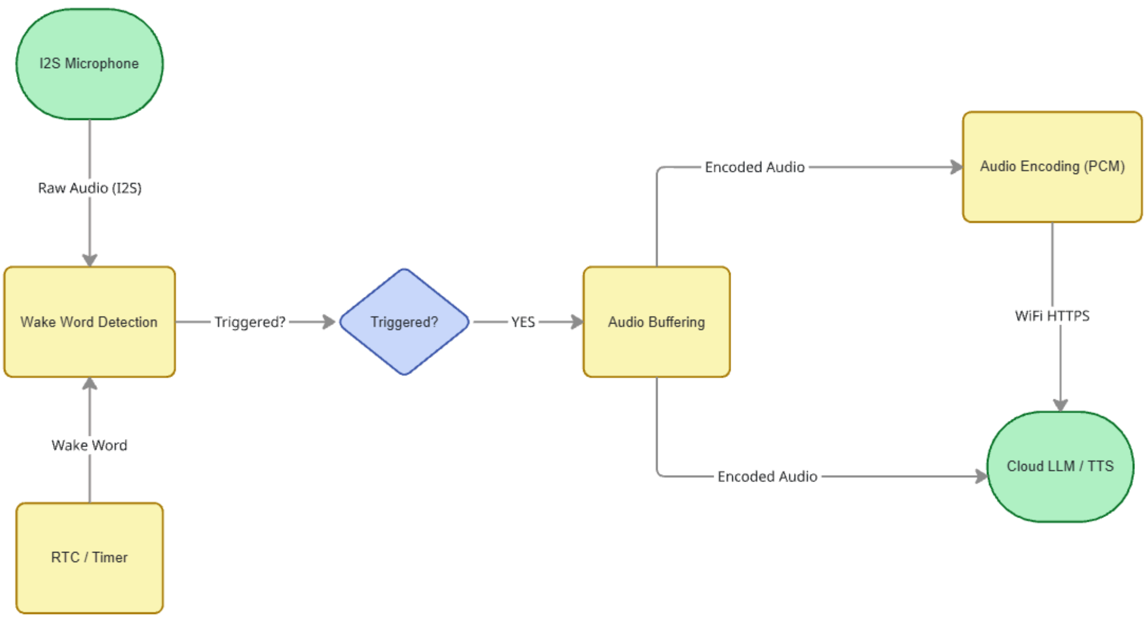

Fig 2. Voice Interaction & Audio Processing Subsystem Block Diagram

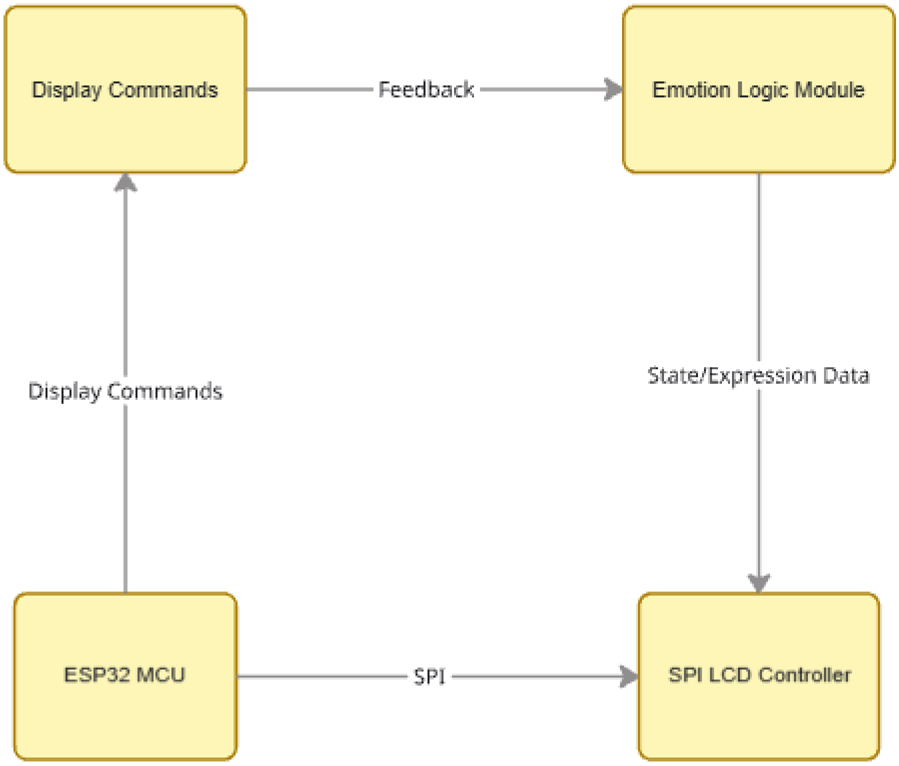

Fig 3. Visual Expression & User Feedback Block Diagram

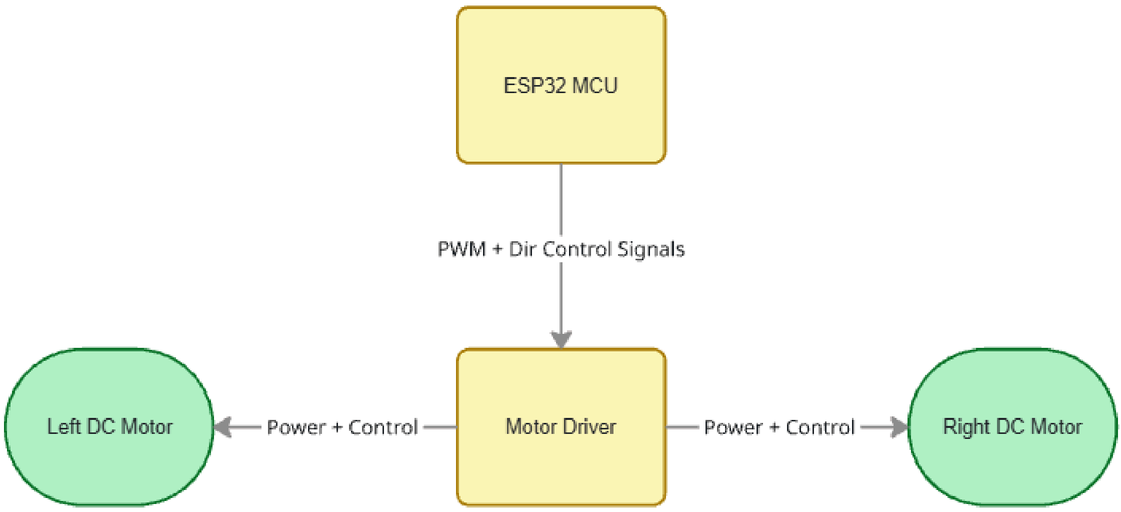

Fig 4. Motion & Actuation Subsystem Block Diagram

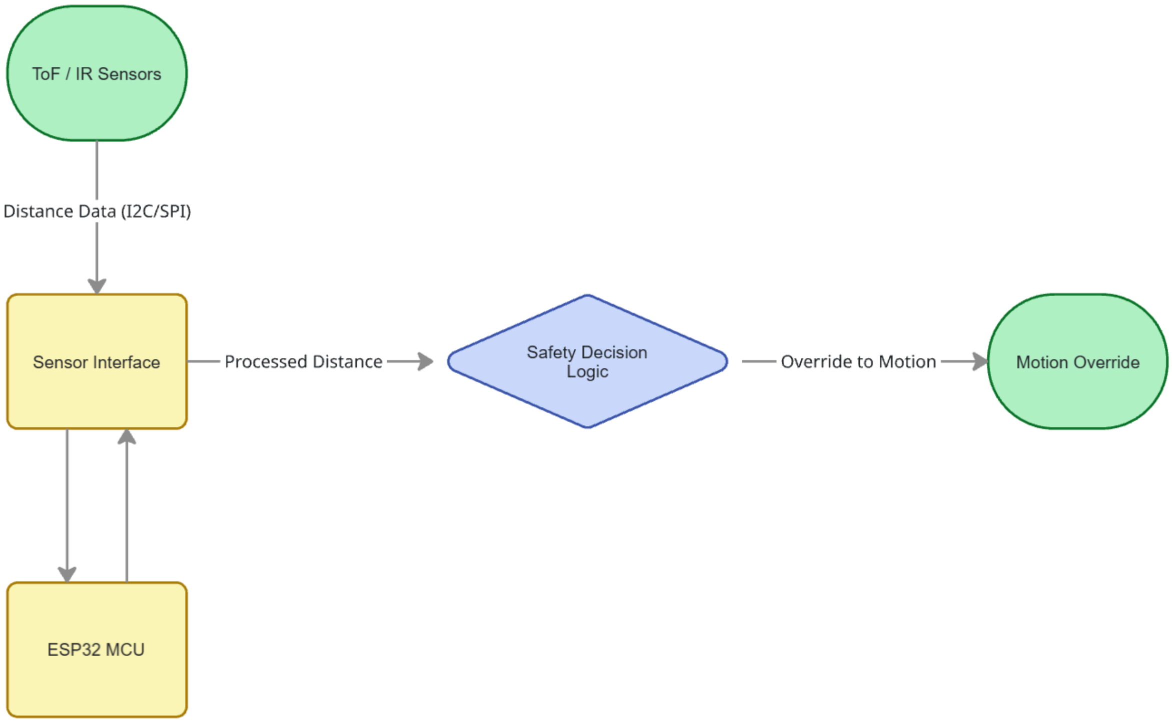

Fig 5. Safety Sensing Subsystem Block Diagram

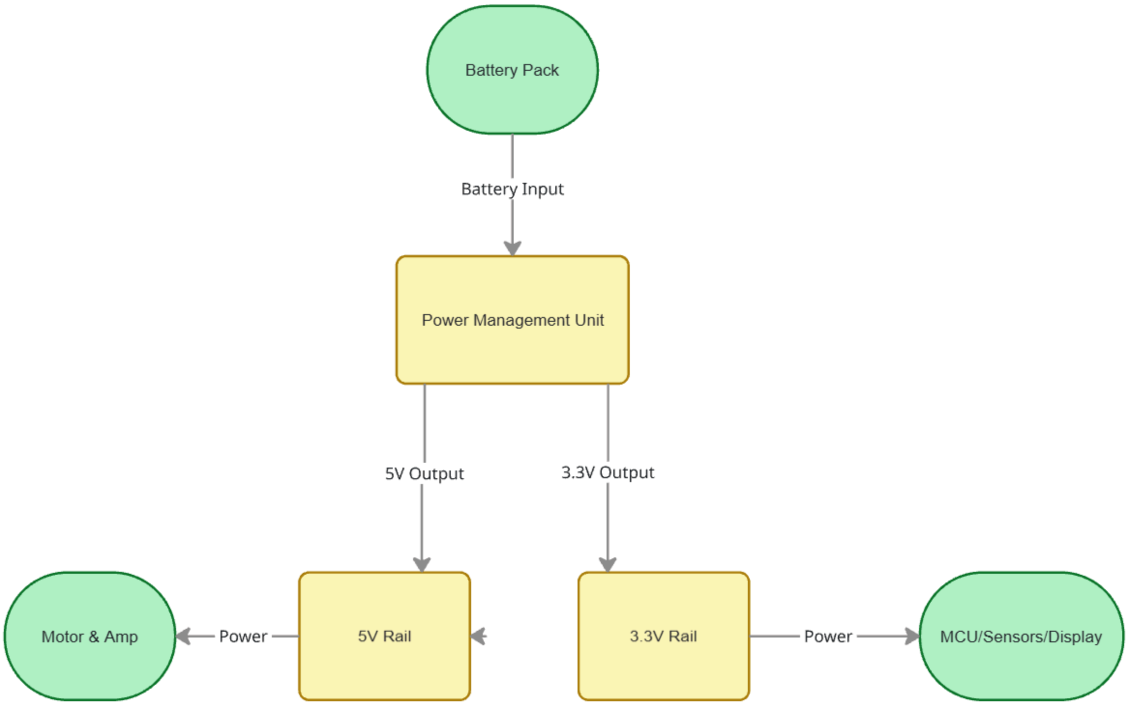

Fig 6. Power Management & Safety Block Diagram

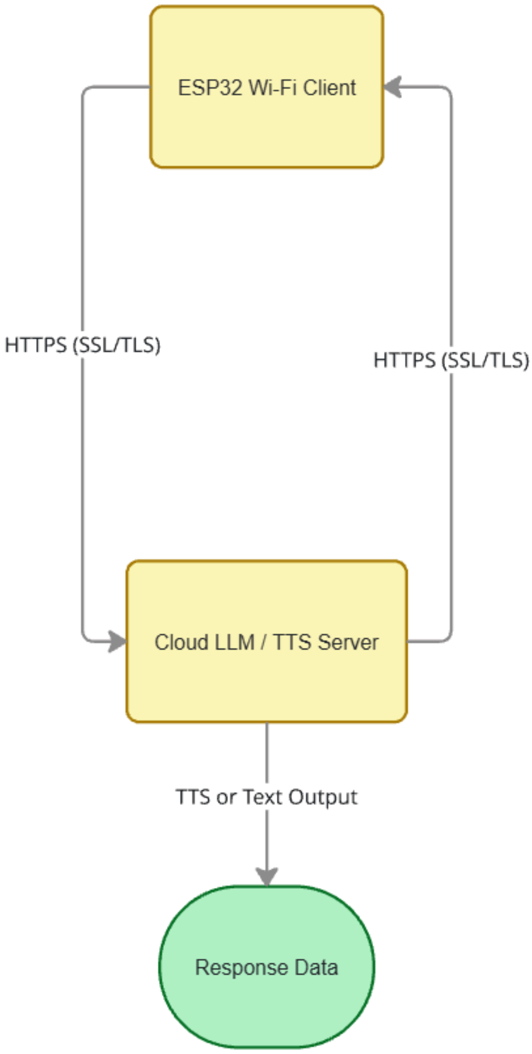

Fig 7. Cloud LLM Interaction Subsystem Block Diagram

2.2 Subsystem Design

2.2.1 Safety Sensing Subsystem (Desk-Edge and Obstacle Detection)

Purpose and Contribution to Project Goals

The Safety Sensing subsystem ensures that the robot satisfies the high-level requirement of **never falling off a desk during a 10-minute continuous motion test** and achieving at least **90% obstacle avoidance success**. This subsystem operates at the highest firmware priority and can override all motion commands. Its function is to detect downward discontinuities (desk edges) and forward obstacles in real time and immediately disable motor outputs when a hazard is detected.

System Architecture and Interfaces

The subsystem consists of multiple Time-of-Flight (ToF) distance sensors connected to the ESP32-S3 via an I2C bus.

Electrical Interface:

- I2C bus frequency: 400 kHz
- Logic level: 3.3 V
- Pull-up resistors: 4.7 kΩ on SDA and SCL
- Supply voltage: 3.3 V ± 5%

Sampling and Timing:

- Minimum sampling frequency: ≥ 50 Hz
- Maximum sampling interval: 20 ms
- Maximum allowed jitter: ±5 ms

Given the maximum robot velocity of 0.10 m/s, the robot travels:

$$d = v \cdot t = 0.10\,\mathrm{m/s} \times 0.020\,\mathrm{s} = 0.002\,\mathrm{m} = 2\,\mathrm{mm}$$

Thus, the robot moves no more than 2 mm between consecutive samples, providing sufficient detection margin before reaching a desk edge.

Hazard Detection Logic

Cliff condition is defined as:

- Downward-facing ToF distance increases above 120 mm for two consecutive samples.

Obstacle condition is defined as:

- Forward-facing ToF distance decreases below 80 mm.

When either condition is met:

- Motor PWM outputs are forced to 0 within 50 ms ± 10 ms.
- Motion task is suspended.
- A recovery maneuver (reverse or turn) is issued.

Failure Mode and Mitigation:

Failure Mode	**Mitigation**
I2C bus stall	Watchdog timer resets sensor task
Sensor returns invalid value	Treated as hazard condition
Firmware crash	Hardware brownout reset + motors default to disabled

2.2.2 Motion and Actuation Subsystem

Purpose and Contribution to Project Goals

The Motion subsystem provides controlled differential drive movement while maintaining safe operation. It supports obstacle avoidance trials and ensures motion is constrained within defined speed limits to maintain sensing reliability.

Electrical Architecture

The subsystem consists of:

- TB6612FNG dual H-bridge motor driver
- Two DC gear motors
- ESP32-S3 PWM outputs

Power Rails:

- Motor supply (VM): 5.0 V ± 5%
- Logic supply (VCC): 3.3 V ± 5%

Motor Control Signals:

- PWM frequency: 20 kHz ± 2 kHz
- PWM resolution: 8-bit minimum
- Direction pins: GPIO digital outputs (3.3 V logic)

Speed Constraint

Maximum allowed forward velocity:

$$v_{\max} = (0.10 \pm 0.01)\,\mathrm{m/s}$$

Velocity is software-limited by constraining PWM duty cycle.

Safety Override Priority

Control hierarchy:

1. Hardware protection (PCM)
2. Safety sensing task
3. Motion control task

4. User interaction task

If safety sensing asserts a hazard flag, PWM duty cycle is immediately forced to zero.

Thermal and Electrical Justification

Motor stall current is estimated at 1.2 A per motor. The TB6612FNG supports:

- 1.2 A continuous
- 3.2 A peak

Transient current is tolerated by bulk capacitors ($\geq$ 470 µF) placed across VM rail.

2.2.3 Voice Interaction and Audio Processing Subsystem

Purpose and Contribution to Project Goals

This subsystem enables conversational interaction and must satisfy the requirement:

- Average end-to-end latency < 5.0 s
- 95th percentile latency < 6.0 s

Audio Acquisition

Microphone Interface:

- I2S digital microphone
- Sample rate: 16 kHz
- Bit depth: 16-bit
- Mono channel

Data rate:

$$1.6 \times 10^4 \times 16\,\text{bits} = 2.56 \times 10^5\,\text{bits/s}$$

Wake-Word Processing

Wake-word detection runs locally to:

- Prevent continuous cloud transmission
- Reduce network load
- Improve privacy

False activation rate requirement:

- ≤ 1 false trigger per 30 minutes at 40–50 dBA ambient noise

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Cloud Communication

Protocol:

- HTTPS over Wi-Fi
- TLS encryption

Latency model:

$$L = t_{\text{record}} + t_{\text{upload}} + t_{\text{LLM}} + t_{\text{TTS}} + t_{\text{download}}$$

Streaming TTS overlaps TTS generation with download, reducing effective latency.

Timestamp logging is implemented for each stage to verify compliance.

2.2.4 Visual Expression Subsystem

Purpose and Contribution to Project Goals

The display provides visual feedback for listening, processing, speaking, and error states, improving usability and reducing reliance on audio-only output.

Electrical Interface

- Display: ST7789 SPI LCD
- SPI clock: 20 MHz
- Color depth: 16-bit RGB565
- Supply: 3.3 V ± 5%

Performance Requirement

- Minimum refresh rate: ≥ 10 frames per second
- Dropped frame rate: ≤ 5% over 60 seconds during audio streaming

Display updates are handled in a lower priority task to avoid blocking safety or audio tasks.

2.2.5 Power Management and Protection Subsystem

Purpose and Contribution to Project Goals

Ensures stable power distribution and prevents damage due to battery faults, short circuits, or brownout conditions.

Power Architecture

Source:

- 3.7 V Li-ion battery

Protection:

- PCM for overcharge, overdischarge, short-circuit

Regulation:

- 3.3 V LDO for MCU and sensors
- 5.0 V boost or buck converter for motors

Voltage Requirements

3.3 V rail:

- 3.20–3.40 V under load

5 V rail:

- 4.75–5.25 V during motor startup
- Voltage dip duration ≤ 20 ms

Brownout Protection

If 3.3 V drops below 3.1 V:

- Motor PWM disabled immediately
- System enters safe halt mode

2.3 Tolerance Analysis

The most critical performance constraint is maintaining conversational latency below 5 seconds.

Worst-case bounds:

$$t_{\text{record}} \leq 0.7\,\text{s}$$

$$t_{\text{upload}} \leq 1.5\,\text{s}$$

$$t_{\text{LLM}} \leq 2.5\,\text{s}$$

$$t_{\text{TTS, first\_chunk}} \leq 0.5\,\text{s}$$

With streaming overlap:

$$L \approx t_{\text{record}} + t_{\text{upload}} + t_{\text{LLM}} + \max(t_{\text{TTS, first\_chunk}}, t_{\text{download, first\_chunk}})$$

Even in worst-case overlap conditions:

$$L < 5.5\,\text{s}$$

Empirical logging will verify mean latency < 5.0 s and 95th percentile < 6.0 s.

3. Cost and Schedule

3.1 Cost Analysis

The estimated cost of the project includes labor, electronic components, mechanical parts, and fabrication costs. Labor cost is estimated using the hourly wage assumption required by the course guidelines.

Labor Cost

Assume an hourly rate of **$20/hour** for engineering labor.

Each team member is expected to contribute approximately **120 hours** to complete the project.

Labor cost formula:

$$\text{Labor Cost} = (\$/\text{hour}) \times 2.5 \times \text{hours}$$

For each team member:

$$20 \times 2.5 \times 120 = \$6,000$$

Since the project team has **three members**, the total labor cost is:

3×6000=$18,000

Total estimated labor cost:

$18,000

Parts Cost

Component	Manufacturer	Part Number	Quantity	Unit Cost	Total
ESP32-S3 Development Board	Espressif	ESP32-S3-WROOM	1	$12	$12
I2S Digital Microphone	Adafruit	INMP441	1	$7	$7
ST7789 SPI LCD Display	Waveshare	ST7789 240×240	1	$15	$15
ToF Distance Sensor	STMicroelectronics	VL53L0X	2	$9	$18
Motor Driver	Toshiba	TB6612FNG	1	$5	$5
DC Gear Motors	Generic	GA12-N20	2	$8	$16
Li-ion Battery	Generic	18650 3.7V	1	$10	$10
Battery Protection Module	Generic	PCM BMS	1	$4	$4
Voltage Regulator / Power Module	Generic	Buck Converter	1	$5	$5
Robot Chassis and Wheels	Generic	Robot Kit	1	$20	$20
Miscellaneous Components	Various	Wires, connectors, PCB	—	$20	$20

Total hardware cost:

12+7+15+18+5+16+10+4+5+20+20=$132

Total parts cost:

$132

Fabrication Cost

Some mechanical components such as the robot housing may require fabrication or 3D printing.

Item	**Cost**
3D printed enclosure	$25
Fasteners and mounting hardware	$10

Total fabrication cost:

$35

Total Project Cost

Category	**Cost**
Labor	$18,000
Parts	$132
Fabrication	$35

Grand Total:

$$18{,}000 + 132 + 35 = \$18{,}167$$

Estimated total project cost:

$18,167

3.2 Project Schedule

The development process is divided into design, implementation, integration, and testing phases over the semester.

Week	Task	Responsible Members
Week 1	Finalize architecture and subsystem design	Entire team
Week 2	Select components and order parts	Jiajun Gao
Week 3	Set up ESP32 development environment	Yuchen Shih
Week 4	Implement microphone and audio capture	Yuchen Shih
Week 5	Develop LCD display interface and animations	Zichao Wang
Week 6	Implement motor driver and motion control	Jiajun Gao
Week 7	Integrate ToF sensors for safety detection	Jiajun Gao
Week 8	Implement Wi-Fi communication with cloud server	Yuchen Shih
Week 9	Implement streaming TTS playback	Yuchen Shih
Week 10	Assemble robot chassis and wiring	Entire team
Week 11	Integrate all subsystems	Entire team
Week 12	Debug system integration issues	Entire team
Week 13	Perform verification testing	Entire team
Week 14	Improve reliability and optimize performance	Entire team
Week 15	Prepare final demonstration and report	Entire team

4 Ethics and Safety

4.1 Societal Impact and Public Welfare

The proposed Interactive Desktop Companion Robot aims to provide lightweight conversational interaction and subtle physical feedback within desk-based environments. Prolonged desk work is commonly associated with mental fatigue and stress accumulation. By enabling short, low-effort interaction without requiring additional screen exposure, the system may contribute positively to user well-being and productivity.

From an economic perspective, the system is designed to be compact and manufacturable using low-cost components such as 3D-printed enclosures and widely available embedded hardware. This approach promotes accessibility and reduces barriers to adoption.

From an environmental standpoint, the design emphasizes modularity. Subsystems such as the face board, body board, and drivetrain are separable, allowing individual components to be repaired or replaced rather than discarding the entire system. The use of a rechargeable lithium-ion battery further reduces disposable battery waste.

Socially and culturally, the system is designed to operate as an assistive and non-intrusive device. It does not replace human interaction but instead provides optional, user-initiated engagement. Because the robot relies on voice interaction and cloud-based language processing, care must be taken to ensure respectful responses and avoid unintended biases in generated content.

Overall, the system is intended to enhance user experience while maintaining safe and responsible operation within a personal workspace.

4.2 Applicable Engineering Standards

Several engineering standards and best practices are relevant to this project:

- IEEE Code of Ethics – Ensuring public safety and avoiding harm.
- ACM Code of Ethics – Addressing responsible computing and privacy considerations.
- UL battery safety guidelines (e.g., UL 1642 for lithium batteries) – Applicable to lithium-ion battery usage.
- IEC 62368-1 (Audio/Video, Information and Communication Technology Equipment Safety) – Relevant to low-voltage electronic systems.
- General low-voltage electrical safety practices for embedded systems.

Although this is a prototype academic project and not a commercial product, these standards inform our design decisions related to battery protection, electrical isolation, and user safety.

4.3 Ethical Considerations

Because the system processes voice input and communicates with a cloud-based language model, user privacy is a primary ethical concern. The robot performs wake-word detection locally to reduce continuous audio transmission. Audio data is transmitted only after explicit activation.

The project does not store long-term personal data locally. However, because cloud services are involved, users should be informed that voice data may be processed externally.

Bias and inappropriate responses from large language models represent another ethical concern. The system will restrict usage to predefined interaction contexts appropriate for a desktop companion and will avoid deployment in sensitive decision-making environments.

The design follows IEEE and ACM ethical principles by prioritizing safety, transparency, and respect for user autonomy.

4.4 Electrical and Mechanical Safety Concerns

The system operates at low voltage (3.7 V nominal battery supply), reducing the risk of electrical shock. However, lithium-ion batteries present potential hazards including overheating, short-circuiting, and improper charging.

Mechanical risks include:

- Unexpected motion due to control errors,
- Collision with nearby objects,
- Falling from elevated desk surfaces.

To mitigate these risks, the system incorporates:

- Distance-based obstacle detection,
- Downward-facing cliff detection,
- Controlled motor driver circuitry,
- Stable center-of-gravity design.

The 3D-printed enclosure provides mechanical protection for internal wiring and components, reducing the risk of accidental contact or damage.

4.5 Safety Mitigation Procedures

To mitigate identified safety risks, the following procedures will be implemented:

- Battery handling will follow laboratory safety guidelines for lithium-ion cells.
- Charging will be conducted using approved charging modules with overcurrent and overvoltage protection.
- Motion testing will be performed in controlled environments before public demonstration.
- Cliff detection functionality will be validated prior to autonomous motion testing.
- The enclosure will remain closed during operation to prevent user contact with internal electronics.

These measures aim to protect both users and developers during assembly, testing, and demonstration.

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