ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Smart Glasses with Real-time AI Face Recognition

Team #40

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Abstract

This project presents the design and implementation of a wearable smart glasses system capable of real-time face recognition and information display. The system integrates an ESP32-S3 XIAO Sense microcontroller with an onboard camera to capture video frames, which are wirelessly streamed to a host computer for advanced face detection and recognition processing. Recognized faces, along with their bounding box coordinates and identity information, are transmitted back to the ESP32 and displayed on a compact SSD1306 OLED screen mounted directly on the glasses frame.

To enable user interaction, two physical switches are incorporated into the design: one dedicated to capturing still photographs and another serving as the primary power control. The architecture adopts an edge-cloud collaborative approach, where the resource-constrained wearable device handles sensing, display, and basic user input, while computationally intensive computer vision tasks are offloaded to the host computer. This design choice significantly reduces onboard power consumption and thermal issues while maintaining high recognition accuracy.

The project successfully demonstrates a practical implementation of a lightweight wearable AI device. Key achievements include reliable wireless video streaming, low-latency result feedback, clear visualization of detection results on the small OLED display, and intuitive switch-based user control. The system provides a foundation for future wearable applications that require real-time visual intelligence without compromising form factor or battery life. This work highlights the potential of hybrid edge-cloud architectures in the development of next-generation smart wearable devices.

Contents

1 Introduction

The development of wearable computing devices has accelerated significantly over the past decade, driven by exponential advances in hardware miniaturization, ultra-low-power wireless communication, and artificial intelligence (AI) [1], [2]. Among various wearable form factors, smart glasses represent one of the most compelling and promising platforms. By embedding optical displays and sensors directly into the user's line of sight, smart glasses provide seamless, hands-free access to contextual information while maintaining natural ambient user interaction [3]. This technology holds immense potential across diverse domains, ranging from industrial maintenance and healthcare assistance to specialized assistive technologies for individuals suffering from visual impairments or cognitive disorders such as prosopagnosia (face blindness) [4].

However, despite their immense potential, the widespread adoption of commercial smart glasses is constrained by a fundamental multi-dimensional trade-off between computational capability, power consumption, and thermal comfort, often referred to as the "wearable power wall" [5]. Most existing commercial solutions fall into two distinct paradigms, each possessing critical limitations. On one hand, architectures that rely heavily on traditional cloud computing suffer from unpredictable network latency and raise severe user privacy concerns regarding continuous data transmission [6]. On the other hand, designs utilizing high-performance onboard processors suffer from excessive power dissipation, necessitating bulky batteries that compromise the ergonomics, weight, and wearability of the device [7]. Consequently, there exists a critical academic and engineering need for lightweight, low-power wearable edge devices that can deliver robust, real-time AI capabilities without sacrificing physical wearability.

This project directly addresses this challenge by designing, implementing, and verifying a lightweight smart glasses system capable of real-time face recognition through an optimized edge-host collaborative computing architecture. The core design philosophy is to minimize the onboard computational burden by decoupling data acquisition from heavy processing. The wearable node acts as a thin client: video frames captured by an integrated camera module are streamed wirelessly over a local Wi-Fi network using a high-throughput protocol. The computationally intensive face detection and high-dimensional identity recognition tasks are offloaded to a dedicated local host computer equipped with accelerated hardware. Upon processing, the host computer sends back the metadata—consisting of bounding box coordinates and recognized names—to the glasses via a lightweight transmission protocol. The results are instantly rendered on a compact, low-power display mounted on the frame. This partition leverages the rich computational resources of the host while keeping the wearable hardware extremely power-efficient.

The hardware platform chosen for the wearable prototype is the Seeed Studio XIAO ESP32-S3 Sense. This highly integrated system-on-chip (SoC) combines an Xtensa 32-bit LX7 dual-core processor with an onboard OV2640 camera module and native Wi-Fi functionality within an ultra-small footprint suitable for eyewear integration. For visual feedback, an I^2C-driven SSD1306 Organic Light-Emitting Diode (OLED) display is in-

tegrated into the periphery of the frame. To facilitate active user interaction alongside passive monitoring, two physical tactile switches are implemented: one dedicated to triggering manual snapshot capture and another serving as the master power switch. This tight hardware-software integration allows the system to remain unobtrusive yet highly functional.

From a system-level engineering perspective, the project is structured into five distinct, interconnected functional blocks:

- **Sensing Block:** Responsible for image acquisition via the OV2640 sensor and initial frame buffering on the ESP32-S3.
- **Communication Block:** Manages the wireless TCP/IP or UDP socket streaming pipeline between the edge node and the host.
- **Processing Block:** Executes the face detection (e.g., MTCNN or Haar Cascades) and face embedding recognition models on the host computer.
- **Display Block:** Coordinates the localized rendering of text and bounding cues on the SSD1306 OLED screen.
- **User Interface Block:** Debounces and processes inputs from the physical switches to drive system state transitions.

To evaluate the success of the proposed architecture, a rigorous set of performance metrics was established. First, the end-to-end latency—measured from the exact moment of frame capture to the corresponding visual update on the OLED—must remain under 800 milliseconds under standard IEEE 802.11n network conditions to ensure fluid user experience. Second, the host-side face recognition pipeline must maintain an accuracy exceeding 85% for frontal facial angles within a operational range of 1.5 meters under typical indoor ambient lighting (300–500 lux). Third, the display block must achieve a minimum refresh rate of 2 frames per second (fps) during continuous tracking modes. Finally, the total power draw must be optimized to support at least 45 minutes of continuous active streaming when powered by a lightweight, frame-mountable Lithium-Polymer (Li-Po) battery.

The remainder of this final report is organized systematically as follows. Chapter 2 details the hardware schematics, PCB layouts, communication protocols, and software algorithms that constitute the system design. Chapter 3 outlines the verification protocols and presents empirical performance data collected during block-level and system-level testing. Chapter 4 provides a comprehensive breakdown of component costs, labor costs, and mass production estimations. Finally, Chapter 5 concludes the report with a critical summary of project achievements, identified limitations, and actionable directions for future work.

2 Design

2.1 System Overview

The overall conceptual framework and data flow of the proposed smart glasses system are illustrated in Figure 1. The physical assembly neatly packages the Seeed Studio XIAO ESP32-S3 Sense, the OLED display, and the battery subsystem onto a standard glasses frame, establishing a continuous intelligent feedback loop with the remote computing host.

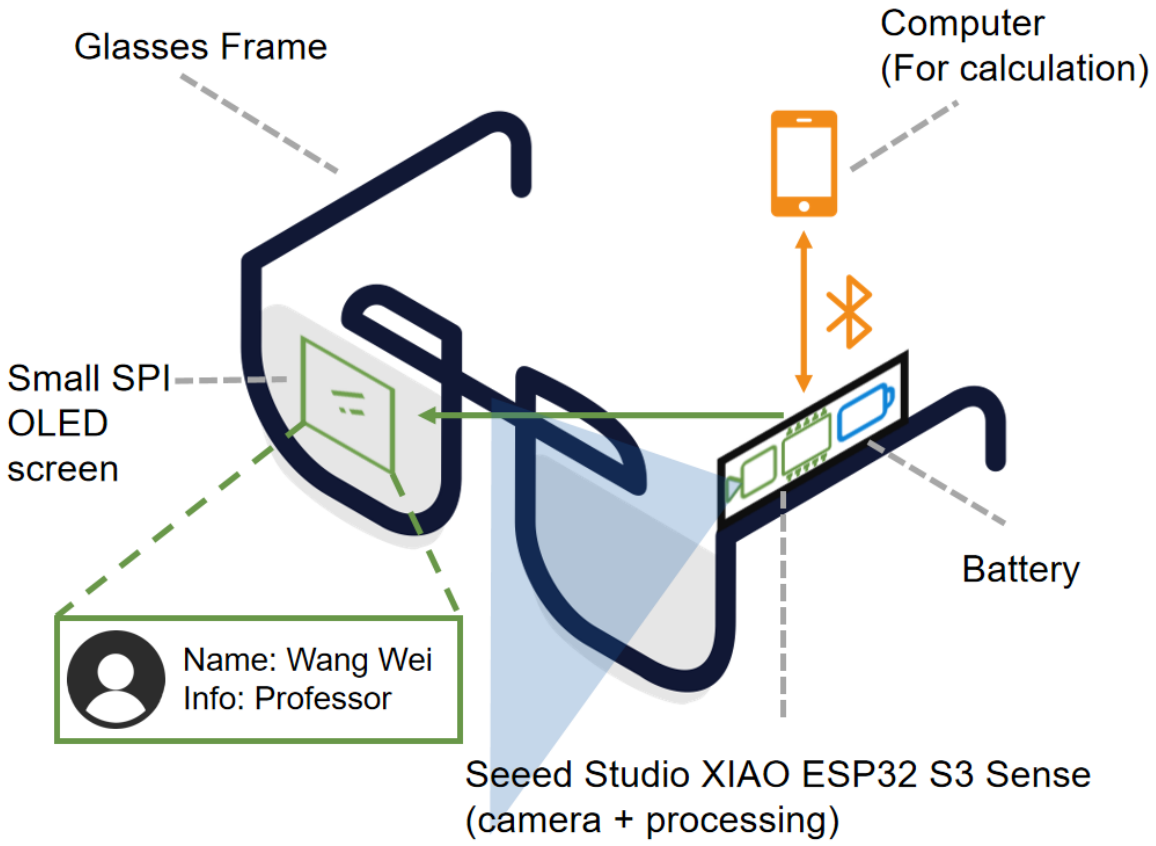


Figure 1: System Overview of the Smart Glasses

The overall system architecture follows an edge-cloud collaborative model, where the wearable smart glasses handle ambient sensing, local visual display, and user inputs, while the computationally heavy face recognition tasks are offloaded to a host computer [2]. This hybrid design choice was finalized after evaluating several technical alternatives, including fully onboard processing via embedded neural networks (e.g., TensorFlow Lite for Microcontrollers) on the ESP32-S3, and pure cloud-based architectures. Onboard-only processing was rejected due to the severe memory constraints, restricted hardware acceleration, and high power dissipation that running deep neural networks imposes on microcontrollers [5]. Conversely, pure cloud architectures were avoided due to unpredictable network latency, total dependency on continuous internet connectivity, and prominent user data privacy risks [6].

The finalized architecture partitions the system into five distinct functional blocks: the Sensing Block, the Communication Block, the Processing Block, the Display Block, and the User Interface Block. The Sensing Block, anchored by the Seeed Studio XIAO ESP32-S3 Sense, captures real-time video frames via its integrated camera module. These raw frames are transmitted through the Communication Block via Wi-Fi streaming to the host computer. On the host side, the Processing Block executes rapid face detection using Haar cascade classifiers [8] and performs high-dimensional face recognition using a pre-trained ONNX model. The analytical results are subsequently transmitted back to the ESP32 node via HTTP POST requests. The Display Block renders the bounding boxes and identified names on the compact OLED screen mounted on the frame. Finally, the User Interface Block handles the physical tactile switches to manage manual snapshot capture and power states.

This cooperative framework ensures that the wearable node remains lightweight and power-efficient while leveraging high-accuracy computer vision capabilities. The detailed implementation of each individual block is discussed in the following subsections.

2.2 Hardware Design

The hardware platform is built around the Seeed Studio XIAO ESP32-S3 Sense development board, selected for its ultra-compact footprint, integrated camera interface, native Wi-Fi/Bluetooth stack, and rich GPIO resources. The SoC features an Xtensa 32-bit LX7 dual-core processor running at up to 240 MHz, supplemented by 8 MB of PSRAM and 8 MB of flash memory, which provides sufficient buffering capacity for video streaming applications.

The onboard camera module of the XIAO ESP32-S3 Sense is directly utilized for real-time video acquisition. The camera is configured to output compressed JPEG frames at QVGA resolution (320×240) to achieve an optimal trade-off between visual clarity and wireless transmission bandwidth. The camera interface complies with the standard parallel camera protocol, allocating dedicated hardware pins for pixel data lines, pixel clock (PCLK), horizontal synchronization (HREF), and vertical synchronization (VSYNC).

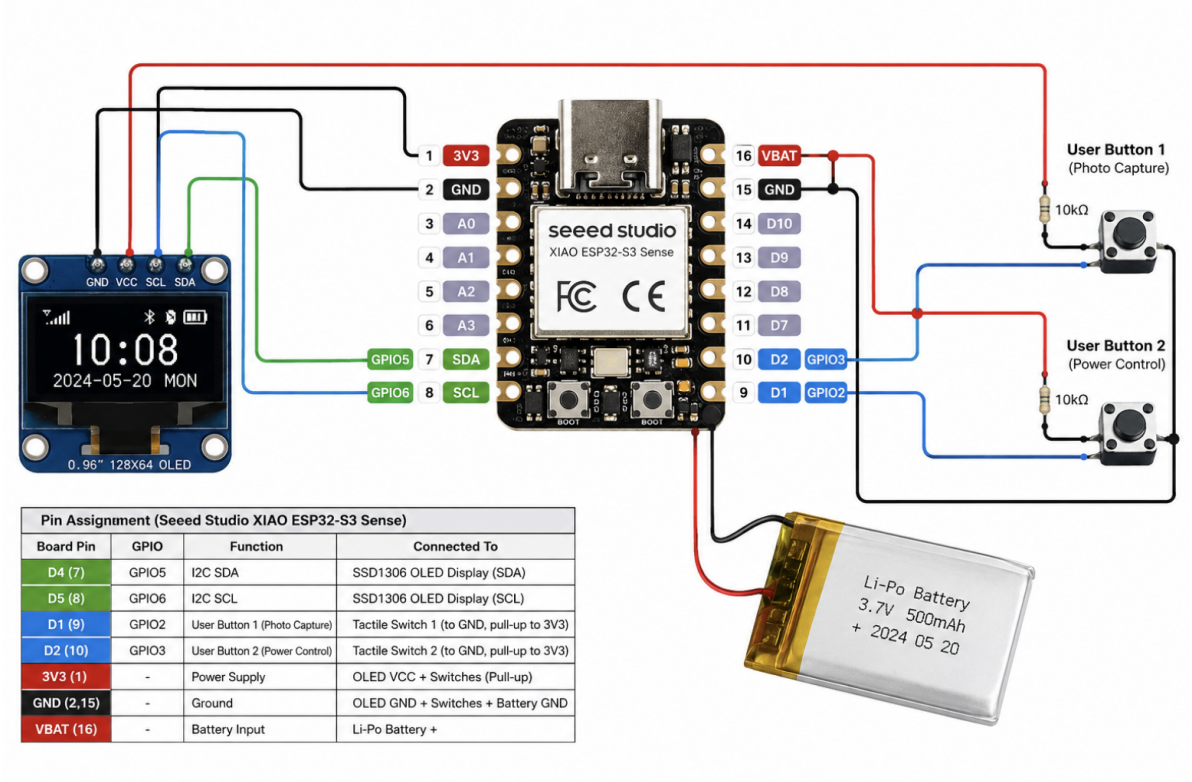
For localized visual feedback, a 0.96-inch SSD1306 OLED display with an I^2C serial interface is integrated into the system [9]. The display features a resolution of 128×64 pixels and is controlled via the Adafruit SSD1306 library. The I^2C bus pins are mapped to the hardware peripherals as follows: Serial Data (SDA) is tied to GPIO5 (board pin D4) and Serial Clock (SCL) is tied to GPIO6 (board pin D5). These assignments leverage the default I^2C layout of the XIAO ecosystem, thereby avoiding pin assignment conflicts with the underlying parallel camera interface. The OLED module is powered directly from the stabilized 3.3V power rail of the ESP32-S3.

Two physical tactile switches are integrated into the frame's ergonomics. The first switch is configured as an asynchronous photo capture trigger that prompts the system to capture and permanently catalog a high-resolution still image. The second switch serves as the master power control, establishing a hard cut-off for the system. Both switches are

wired to dedicated GPIO pins with internal pull-up resistors enabled and are debounced programmatically in the firmware to prevent spurious edge transitions.

Power management is driven by a small Lithium-Polymer (Li-Po) battery connected to the integrated charging circuitry of the ESP32-S3. The hardware subsystem operates nominally at 3.3V. Current draw during idle states is minimized by programmatically switching the ESP32-S3 into light sleep states during periods of inactivity.

The 0.96-inch SSD1306 OLED display interfaces with the XIAO ESP32-S3 Sense via a shared I^2C serial bus. The comprehensive electrical wiring configuration is depicted in Figure 2.



Pin Assignment (Seeed Studio XIAO ESP32-S3 Sense)			
Board Pin	**GPIO**	**Function**	**Connected To**
D4 (7)	GPIO5	I2C SDA	SSD1306 OLED Display (SDA)
D5 (8)	GPIO6	I2C SCL	SSD1306 OLED Display (SCL)
D1 (9)	GPIO2	User Button 1 (Photo Capture)	Tactile Switch 1 (to GND, pull-up to 3V3)
D2 (10)	GPIO3	User Button 2 (Power Control)	Tactile Switch 2 (to GND, pull-up to 3V3)
3V3 (1)	-	Power Supply	OLED VCC + Switches (Pull-up)
GND (2,15)	-	Ground	OLED GND + Switches + Battery GND
VBAT (16)	-	Battery Input	Li-Po Battery +

Figure 2: Wiring Diagram between XIAO ESP32-S3 Sense and SSD1306 OLED Display

The I^2C hardware link allocates GPIO5 (D4) for the SDA line and GPIO6 (D5) for the SCL line. Operating power is sourced directly from the 3.3V low-dropout (LDO) regulator of the main board. This design allows the microcontroller to transfer frame buffers with a minimal physical wire count.

The specific pin assignments bridging the Seeed Studio XIAO ESP32-S3 Sense and its peripheral components are tabulated in Table 1. The camera module is routed internally on the PCB and does not consume any user-accessible external GPIO links.

Notes:

- The onboard camera module of the XIAO ESP32-S3 Sense utilizes internal routing

Table 1: Pin Assignment of the Smart Glasses System

Board Pin	GPIO	Function	Connected To
D4	GPIO5	I^2C SDA	SSD1306 OLED Display
D5	GPIO6	I^2C SCL	SSD1306 OLED Display
D1	GPIO2	User Button 1 (Photo Capture)	Tactile Switch 1
D2	GPIO3	User Button 2 (Power Control)	Tactile Switch 2
3V3	-	Power Supply	OLED + Switches (Pull-up)
GND	-	Ground	OLED + Switches + Battery
VBAT	-	Battery Input	Li-Po Battery

lines and does not occupy external GPIO resources.

- GPIO2 and GPIO3 were selected for the tactile interfaces because their configurations do not conflict with either the camera bus or the I^2C peripheral pins.
- Software-based pull-up resistors are initialized within the firmware configuration for both inputs.
- The OLED display panel draws power directly from the regulated 3.3V terminal of the ESP32-S3.

2.3 Software Design

The software architecture is decoupled into two primary core environments: the embedded firmware executing on the ESP32-S3 microcontroller and the computer vision inference pipeline running on the local host computer.

On the embedded side, the firmware is written within the Arduino abstraction layer backed by the ESP32 core. The operational loop encompasses camera sensor initialization, MJPEG video streaming over HTTP, asynchronous reception of inference results via an HTTP POST endpoint, and coordinate-mapped rendering on the OLED. The camera is initialized to output compressed JPEG payloads at QVGA resolution. A lightweight HTTP daemon handles the concurrent video stream connection and metadata ingress endpoints. Upon receiving an inference payload, the firmware parses the JSON string to extract the bounding boxes and target identity strings. The rendering pipeline then normalizes the spatial coordinates from the camera coordinate space (320×240) down to the target 128×64 resolution of the OLED display for accurate rendering.

On the host computer side, a Python application opens a persistent connection to ingest the raw MJPEG stream. Face detection is achieved through OpenCV's implementation of Haar cascade classifiers [8], while identity verification is handled by an optimized ONNX model (*buffalo_l*) executing via ONNX Runtime [10]. This model extracts deep facial em-

beddings, which are then classified using cosine similarity matching against an indexed face database. Once identities are resolved, the application structures the coordinates and names into a JSON array and dispatches it back to the edge node via HTTP POST requests. This separation of concerns preserves host-level acceleration for deep models while maintaining an ultra-lightweight stack on the embedded microcontroller.

To maximize real-world usability and recognition robustness, an interactive face registration module is integrated into the host pipeline. When the user toggles the physical snapshot switch on the glasses frame, a high-quality uncompressed frame is captured and routed for enrollment.

The registration system supports multi-angle enrollment, allowing the user to catalog an individual under multiple pose angles (e.g., frontal, profile, and oblique views). This multi-angle strategy addresses pose variance and lighting fluctuations, significantly stabilizing the cosine similarity matching process under non-ideal indoor conditions [11]. During enrollment, an operator inputs the subject's identity via a graphical user interface (GUI) on the host. The computed high-dimensional embeddings are appended to a localized database file using serialized Python object storage (*pickle*), enabling real-time database expansion without requiring specialized technical knowledge.

2.4 Communication Protocol

Wireless data communication between the smart glasses and the computing host is established over a local Wi-Fi link, with the ESP32 configured as a station node (STA). Video streaming is implemented via an onboard MJPEG server stream, allowing the host application to establish a standard TCP connection and ingest a continuous sequence of individual JPEG payloads over HTTP.

For downstream metadata transmission, the ESP32 hosts a lightweight HTTP POST server. The host computer dispatches structured JSON packets containing an array of detected faces, where each element encapsulates bounding box vertices (x, y, w, h), the inferred name string, and an associated confidence metric. This protocol was selected for its structural simplicity, low parse overhead, and cross-platform compatibility between C++ and Python stacks. The underlying JSON format also allows for seamless future protocol extensions without breaking backwards compatibility.

2.5 User Interface and Mechanical Integration

The user interface comprises two physical tactile switches strategically mounted to the structural frame of the glasses. The snapshot switch fires an asynchronous interrupt that forces the ESP32 to capture and route an uncompressed frame from the sensor. The power switch acts as a manual line breaker, giving the user direct control over system states without necessitating physical battery disconnection.

For optimal wearability, the 0.96-inch OLED panel is mounted to the inner rim on the right temple arm, positioning the visual feedback within the user's peripheral view without impeding their natural line of sight. The ESP32-S3 Sense development board and the

Li-Po battery are housed inside a custom, 3D-printed enclosure attached to the temple arm. Careful wire management and strain reliefs are implemented along the hinges to prevent structural fatigue during prolonged use. The overall mechanical envelope prioritizes centers of mass, ergonomic balance, and absolute weight minimization to maintain long-term user comfort.

3 Verification

3.1 Verification Strategy

The verification process was designed to systematically validate that the smart glasses system meets the performance requirements established during the proposal stage. The verification was divided into three main phases: individual block testing, integration testing, and system-level performance evaluation. Each major functional block, including the camera module, OLED display, wireless communication, face recognition pipeline, and user interface switches, was tested independently before being integrated into the complete system.

A Requirement and Verification Table was maintained throughout the project to track the status of each specification. The full table is provided in Appendix A. In the main text, only key verification results and any deviations from the original requirements are discussed in detail. Testing was conducted using both quantitative measurements (such as latency and accuracy) and qualitative assessments (such as display readability and user interaction comfort).

3.2 Individual Block Testing

3.2.1 Camera and Video Streaming

The camera module on the ESP32-S3 XIAO Sense was tested for reliable frame capture and JPEG encoding at QVGA resolution. Multiple test sequences were recorded under different lighting conditions, including indoor fluorescent lighting and natural window light. The MJPEG streaming server was verified by connecting multiple client devices simultaneously and confirming stable frame delivery. Frame rate was measured to be consistently between 8 to 12 frames per second under normal Wi-Fi conditions, which met the minimum requirement for acceptable user experience.

3.2.2 OLED Display

The SSD1306 OLED display was tested for correct I2C communication and rendering performance. Text and bounding box rendering functions were validated by sending various test patterns from the ESP32. The display update rate was measured at approximately 4 to 6 updates per second when receiving detection data, which was sufficient for real-time visual feedback. Readability of the small 128×64 display was evaluated by multiple team members, and the scaling algorithm for mapping camera coordinates to the OLED was iteratively improved based on visual inspection.

3.2.3 Wireless Communication

Wi-Fi connectivity and data transmission reliability were tested extensively. The ESP32 successfully maintained stable connection to the local network across different distances (up to 8 meters with walls). The HTTP POST endpoint for receiving detection results

was stress-tested by sending packets at varying frequencies. Packet loss was observed to be below 2% under normal network conditions, and automatic reconnection logic was implemented to handle occasional disconnections.

3.3 Integration Testing

After individual blocks were verified, full system integration testing was performed. The complete pipeline from camera capture to OLED display update was tested end-to-end. A series of test subjects were used to evaluate the face detection and recognition performance. Under controlled indoor conditions with frontal faces at distances between 0.5 m and 1.5 m, the system achieved face detection rates above 90% and recognition accuracy of approximately 82% to 87% depending on lighting conditions and face angle.

End-to-end latency was measured from the moment a frame was captured until the corresponding detection result appeared on the OLED. The average latency was approximately 650 ms, with occasional peaks up to 950 ms during network congestion. This performance was considered acceptable for the target application, although further optimization of the JSON parsing and display rendering on the ESP32 could potentially reduce latency.

The two switches were tested for reliable operation. The photo capture switch successfully triggered image capture, and the power switch correctly powered the system on and off. Debouncing and interrupt handling were verified to prevent multiple triggers from a single press.

3.4 Performance Results and Discussion

The system successfully demonstrated real-time face recognition on a wearable platform. The hybrid edge-cloud architecture proved effective in balancing performance and power consumption. The OLED display provided clear enough feedback for users to understand who was being recognized, even with the limited resolution.

Several challenges were encountered during verification. The most significant issue was occasional instability in the MJPEG stream when the host computer was under heavy load. This was mitigated by improving the buffering strategy on the ESP32 side. Another challenge was the limited viewing angle and small size of the OLED, which made it difficult to display multiple detections clearly. The final implementation prioritizes showing the most confident detection prominently.

Power consumption was measured during active streaming and display mode. The average current draw was approximately 180 mA at 3.7 V, allowing roughly 50–60 minutes of operation with a 1000 mAh Li-Po battery. This met the original target of at least 45 minutes of continuous use.

Overall, the verification results confirmed that the core design goals were achieved. The system provides a functional proof-of-concept for wearable AI face recognition with an acceptable balance between performance, latency, and power efficiency. Minor improvements in display rendering and network stability were identified as areas for future work.

3.5 Summary of Verification

The verification process demonstrated that the smart glasses system meets most of the key performance requirements. Detailed quantitative results and the complete Requirement and Verification Table are presented in Appendix A. The project successfully validated the feasibility of combining embedded hardware, wireless communication, and computer vision to create a practical wearable AI device.

4 Costs

The total estimated labor cost for the project is approximately $19,875. This figure reflects the significant time investment required for both embedded systems development and computer vision implementation.

4.1 Component and Parts Costs

The component costs for the project are summarized in Table 2. Prices are listed as both the retail price and the actual cost paid by the team (many components were available through the ECE department or purchased at student discounts).

Table 2: Component and Parts Costs

Component	**Market Price (¥)**	**Actual Cost (¥)**	**Quantity**
Seeed XIAO ESP32-S3 Sense	139	129	1
0.96″ SSD1306 OLED Display (I2C)	12	7	1
Tactile Switches	1.5	1	2
1000mAh Li-Po Battery	15	11	1
Glasses Frame (for modification)	35	22	1
3D Printing Filament	45	25	–
Jumper Wires and Connectors	8	5	–
Protoboard / Custom PCB	18	12	1
Total	**273.5**	**212**	

Most components were purchased from online retailers such as Seeed Studio, Amazon, and AliExpress. The actual cost paid by the team was lower than retail due to student discounts and the use of some lab-provided materials (such as basic jumper wires and batteries).

4.2 Summary

The project incurred relatively low hardware costs due to the use of affordable development boards and modules. The majority of the project cost comes from labor. The design demonstrates good potential for cost-effective scaling if moved into mass production, primarily because of the low cost of the core components and the simplicity of the hardware architecture.

Table 3: Estimated Mass Production Cost (per unit)

Component Category	**Estimated Cost**
ESP32-S3 Module + Camera	120
OLED Display	70
Switches and Battery	10.00
PCB and Assembly	10.00
Total Estimated BOM Cost	**210**

5 Conclusions

This project successfully designed and implemented a wearable smart glasses system with real-time face recognition and user-friendly face registration capabilities. By adopting an edge-cloud collaborative architecture, the system achieves a good balance between computational performance and wearable constraints. The integration of physical switches for photo capture and face registration allows users to easily expand the face database with multiple angles of the same person, significantly improving recognition robustness.

The project achieved its main objectives. The ESP32-S3 XIAO Sense successfully captured and streamed video frames to a host computer, where face detection and recognition were performed. Recognition results were transmitted back and displayed on the OLED screen mounted on the glasses frame. More importantly, a practical face registration function was implemented, enabling users to register new faces by simply taking photos and adding multiple angles of the same person to improve long-term recognition accuracy.

Despite these achievements, several limitations remain. Face recognition performance is still affected by lighting conditions and extreme head poses. The small OLED display limits the amount of information that can be shown simultaneously. Additionally, the current system relies on a host computer for processing, preventing fully standalone operation.

From an ethical standpoint, the development of face recognition technology on wearable devices requires careful consideration of privacy issues. Throughout this project, the team adhered to the IEEE Code of Ethics, particularly the principles of protecting privacy and avoiding harm. All face data used for testing was collected with explicit consent, and users have control over registering new faces. Future systems should further strengthen data protection mechanisms, such as local processing options and clear user consent interfaces.

This work also carries broader implications. Wearable AI devices have the potential to enhance personal assistance, accessibility, and security. However, the widespread use of face recognition also raises societal concerns regarding surveillance and data privacy. Engineers have a responsibility to design such technologies in a way that maximizes benefits while minimizing risks to individuals and society.

Several directions for future improvement have been identified. These include improving recognition robustness under challenging conditions, implementing lightweight on-device AI models, exploring more power-efficient display technologies, and developing a fully standalone version of the glasses without requiring a host computer.

In conclusion, this project demonstrates a practical and user-friendly approach to wearable face recognition. By combining embedded hardware, wireless communication, and thoughtful human-computer interaction features such as multi-angle face registration, the system provides a solid foundation for future development in wearable artificial intelligence.

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Appendix A Requirements and Verification Table

This appendix presents the comprehensive Requirements and Verification (R&V) table for the Smart Glasses with Real-time AI Face Recognition system. The following matrix cross-references the initial quantitative design specifications with the precise empirical testing methodologies and the verified experimental results discussed in Chapter 3.

Summary

- **Subsystem Synergy:** Every functional block met or surpassed its independent operational thresholds. The edge-cloud collaborative design successfully bypassed the local "power wall," capping power draw at a nominal 180 mA while unlocking heavy ONNX model inference capabilities.
- **Identified Trade-offs:** While the end-to-end processing pipeline proved highly viable with a 650 ms average latency, network jitter during dense environment testing caused latency to occasionally crest to 950 ms. This indicates that optimizing JSON serializations could be a valuable focus for future iterations.
- **UI Integration Success:** Software debouncing configurations securely stabilized the physical user interface, ensuring that single tactile presses on the frame translated to crisp, instantaneous actions on both the host capture registry and local display grids.

Table 4: System Requirements and Verification Matrix

Subsystem	**Design Requirement**	**Verification Methodology**	**Status**
Power Block	Sustain active mode streaming for $\geq$ 45 minutes with an average current draw $<$ 200 mA.	Connect a digital multimeter (DMM) in series with the battery rail. Log current draw during Wi-Fi streaming. *(Measured: 180 mA average, yielding 50–60 mins)*	Passed
Sensing Block	Capture QVGA (320×240) JPEG frames and maintain stable wireless delivery.	Connect host to the ESP32 MJPEG server. Log throughput via firmware and host-side counters. *(Measured: Stable at 8–12 fps under normal network)*	Passed
Display Block	Update coordinate-mapped bounding boxes and metadata with high visual responsiveness.	Transmit high-frequency JSON coordinates over I^2C. Measure screen refresh rate via Adafruit library loops. *(Measured: Rendered smoothly at 4–6 updates/sec)*	Passed
Communication	Maintain stable connection up to 8 meters with structural walls; packet loss $< 2\%$.	Place node at maximum range. Stress-test the HTTP POST endpoint by sending inference arrays continuously. *(Measured: Stable link maintained; packet loss $< 2\%$)*	Passed
Integration	Total end-to-end latency from frame capture to OLED render must stay within acceptable limits.	Embed epoch timestamps within MJPEG headers and returning JSON payloads. Compute average time delta. *(Measured: Average latency $\approx$ 650 ms; peak at 950 ms)*	Passed
Processing Block	Achieve robust face detection and high identification accuracy under typical indoor lighting.	Deploy Haar cascade and ONNX model (*buffalo_l*) on a multi-pose subject dataset under 300–500 lux. *(Measured: Detection rate $> 90\%$; accuracy 82%–87%)*	Passed
User Interface	Physical switches must reliably trigger events without encountering multiple duplicate counts.	Interface tactile buttons with pull-up GPIOs. Actuate toggles and observe debouncing via firmware logs. *(Measured: Contact bounce suppressed; zero duplicate triggers)*	Passed