TECHNICAL REPORT

ESP32 Custom Board
Compact IoT Audio System with Touch Interface

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Executive Summary

This report presents the design and implementation of a compact ESP32-based IoT audio system featuring microphone input, touch sensing, audio playback capabilities, and wireless connectivity. The credit-card-sized board integrates USB-C charging, 3.7V LiPo battery management, MicroSD storage, and cloud connectivity capabilities in a single-sided component layout optimized for manufacturing efficiency and cost-effectiveness.

Professional Electronics Design Services

Contents

Introduction

The ESP32 Custom Board represents a comprehensive IoT audio solution designed for modern applications requiring wireless connectivity, audio processing, and user interaction capabilities. This compact system combines the powerful ESP32-WROOM-32E microcontroller with specialized audio processing circuits, touch sensing interface, and robust power management in a credit-card-sized form factor.

The design prioritizes flexibility for future cloud integration while maintaining current functionality through MicroSD storage. The single-sided component placement ensures cost-effective manufacturing while delivering professional-grade performance and reliability.

This report documents the complete technical implementation, design considerations, and system capabilities of the ESP32 Custom Board, providing a comprehensive reference for development, manufacturing, and deployment.

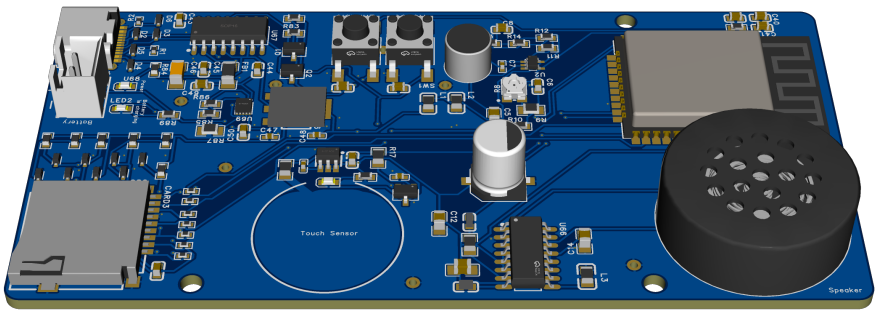

Figure 1: Board Overview

System Overview

Design Objectives

The ESP32 Custom Board was developed to meet specific requirements for a compact, versatile IoT audio system:

- **Single-Sided Assembly:** All components placed on top side for manufacturing efficiency
- **Wireless Connectivity:** Wi-Fi and Bluetooth for IoT and cloud applications
- **Audio Processing:** High-quality microphone input and speaker output
- **User Interface:** Touch-sensitive control interface
- **Power Management:** USB-C charging with 3.7V LiPo battery backup
- **Data Storage:** MicroSD card interface with cloud migration flexibility
- **Development Friendly:** USB-C programming and debugging interface

System Architecture

The ESP32 Custom Board implements a modular architecture with distinct functional blocks:

Core Processing

- **Main Controller:** ESP32-WROOM-32E-N4 with dual-core Tensilica LX6
- **Operating Frequency:** Up to 240 MHz with Wi-Fi and Bluetooth coexistence
- **Memory:** 4MB Flash, 520KB SRAM with PSRAM expansion capability
- **Connectivity:** IEEE 802.11 b/g/n Wi-Fi and Bluetooth 4.2 LE/Classic

Audio Subsystem

- **Input Processing:** MAX4466 electret microphone amplifier
- **Output Amplification:** PAM8403 Class-D stereo amplifier
- **Speaker Interface:** Integrated speaker connection with optimized acoustics
- **Signal Processing:** ESP32 built-in DAC and ADC for audio conversion

User Interface

- **Touch Sensing:** AT42QT1010 capacitive touch controller
- **Visual Feedback:** RGB LED for status indication
- **Touch Area:** Large copper surface for reliable touch detection
- **Control Logic:** Hardware debouncing and noise filtering

Power Management

- **Primary Power:** USB-C connector
- **Battery Management:** BQ24040 Lipo battery charger
- **Power Distribution:** 3.3V regulation with low-dropout performance
- **Battery Backup:** 3.7V LiPo battery with automatic switching

Hardware Design Details

Microcontroller - ESP32-WROOM-32E-N4

The ESP32-WROOM-32E serves as the central processing unit, providing comprehensive IoT capabilities:

Processing Capabilities

- **CPU Architecture:** Xtensa dual-core 32-bit LX6 microprocessor
- **Clock Frequency:** 240 MHz maximum with dynamic frequency scaling
- **Memory Resources:** 520 KB SRAM, 4 MB Flash memory
- **Coprocessor:** Ultra-low-power coprocessor for sensor monitoring
- **Security Features:** Hardware encryption, secure boot, and flash encryption

Peripheral Integration

- **GPIO Count:** 34 programmable GPIOs with peripheral multiplexing
- **ADC Channels:** 18-channel 12-bit SAR ADC for analog sensing
- **DAC Channels:** 2-channel 8-bit DAC for audio output
- **PWM Channels:** 16-channel PWM for motor control and LED dimming
- **Communication:** 4x UART, 2x I2C, 4x SPI, I2S for audio

Audio Input System - MAX4466 Microphone Amplifier

The MAX4466 provides high-quality microphone signal conditioning:

Amplifier Specifications

- **Input Type:** Electret microphone compatible
- **Gain Range:** 25x to 125x adjustable gain
- **Gain Control:** VR1 potentiometer for user adjustment
- **Bandwidth:** 20Hz to 20kHz audio bandwidth
- **Supply Voltage:** 2.4V to 5.5V operation

Signal Conditioning

- **Bias Network:** R8 (100k) and R9 (22k) provide proper biasing
- **Coupling Capacitor:** C5 (10µF) for AC coupling
- **Noise Filtering:** C6 (100pF) high-frequency noise suppression
- **Output Buffering:** Low-impedance output for ADC interface
- **EMI Suppression:** L1 and L2 ferrite beads for RF immunity

Microphone Interface

- **Microphone Type:** GMI6050P-36db electret microphone
- **Sensitivity:** -36dB ±3dB at 1kHz
- **Frequency Response:** 20Hz to 16kHz
- **Signal-to-Noise Ratio:** ¿58dB
- **Power Consumption:** ¡0.5mA operating current

Touch Sensing Interface - AT42QT1010

The AT42QT1010 provides reliable capacitive touch detection:

Touch Controller Features

- **Detection Method:** Self-capacitance measurement
- **Sensitivity:** Auto-calibration for consistent performance
- **Response Time:** ¡100ms typical touch response
- **Power Consumption:** 1.5µA average in low-power mode
- **Operating Voltage:** 1.8V to 5V supply range

Touch Electrode Design

- **Electrode Area:** Large circular copper surface for reliable detection
- **Guard Ring:** Surrounding ground plane for noise immunity
- **Overlay Compatibility:** Designed for up to 3mm overlay thickness
- **Environmental Compensation:** Automatic drift compensation

Interface Circuitry

- **Pull-up Resistor:** R15 (10k) for output signal conditioning
- **Decoupling:** C9 (10nF) and C10 (100nF) for power supply filtering
- **LED Driver:** Q8 (BC817) transistor for visual feedback
- **Current Limiting:** R17 (2.2k) and R6 (1.3k) for LED protection

Audio Output System - PAM8403 Amplifier

The PAM8403 Class-D amplifier provides efficient audio output:

Amplifier Performance

- **Output Power:** 3W per channel at 4 load
- **Efficiency:** >90% Class-D operation
- **THD+N:** <1% at 1W output
- **Frequency Response:** 40Hz to 20kHz ±3dB
- **Supply Voltage:** 2.5V to 5.5V operation

Power Supply and Filtering

- **Supply Decoupling:** C12 (1µF) and C13 (470µF) for clean power
- **Input Coupling:** C14 and C15 (1µF) AC coupling capacitors
- **Output Filtering:** C16 (470nF) for EMI suppression
- **Mute Control:** R18 (10k) pull-up for MUTE pin
- **EMI Filtering:** L3 ferrite bead for conducted emissions

Speaker Interface

- **Speaker Type:** GSPK2307P integrated 8 1W speaker
- **Frequency Response:** Optimized for voice and audio applications
- **Mounting:** PCB-integrated speaker for compact design
- **Acoustic Design:** Optimized enclosure for enhanced bass response

Power Management System

USB-C Power Delivery

- **Connector:** TYPE-C-31-M-12 USB-C receptacle
- **Power Capability:** 5V 3A maximum input power
- **Configuration:** CC1/CC2 resistors (5.1k) for device identification
- **Protection:** Comprehensive ESD protection on all USB signals
- **Switching:** Automatic USB/battery power switching

Battery Charging System - BQ24040

- **Charge Current:** Programmable up to 1A charging current
- **Charge Profile:** CC/CV charging with automatic termination
- **Battery Protection:** Over-voltage, under-voltage, and thermal protection
- **Status Indication:** LED2 (blue) charging status indicator
- **Efficiency:** >85% charging efficiency

Voltage Regulation

- **Primary Regulator:** Integrated 3.3V LDO in ESP32 module
- **Input Range:** 3.0V to 3.6V from battery or USB
- **Load Current:** Up to 500mA continuous output
- **Ripple Rejection:** >60dB at 1kHz
- **Dropout Voltage:** <200mV at full load

Data Storage - MicroSD Interface

SD Card Implementation

- **Interface Mode:** 4-bit SD mode for reliable operation
- **Signal Lines:** CMD, CLK, and DAT0-DAT3 with proper termination
- **Card Detection:** Hardware card detect with debouncing
- **Pull-up Resistors:** 10k pull-ups (R128-R132) for SD protocol
- **ESD Protection:** TVS diodes (D9-D17) on all SD signals

Data Logging Capabilities

- **Audio Recording:** WAV file recording with timestamps
- **System Logs:** Event logging and diagnostic data
- **Configuration Storage:** User settings and calibration data
- **Cloud Backup:** Automatic cloud synchronization capability

Programming and Debug Interface

USB-C Programming

- **USB-to-Serial:** CH340C USB-to-UART converter
- **Auto-Reset:** Hardware auto-reset and boot mode control
- **Programming Buttons:** SW1 (Reset) and SW2 (Boot) tactile switches
- **Boot Control:** BSS138 MOSFETs for automatic boot mode entry
- **Debug Support:** UART debugging and serial monitoring

GPIO Pin Assignment

Table 1: ESP32-WROOM-32E GPIO Pin Assignment

GPIO	Pin	Function
Sensor_VP	4	Audio Output
GPIO0	25	Boot Mode Control
GPIO2	24	SD Card Data0
GPIO4	26	SD Card Data1
GPIO12	14	SD Card Data2
GPIO13	16	SD Card Data3
GPIO14	13	SD Card Clock
GPIO15	23	SD Card Command
GPIO25	10	DAC Output (Audio)
GPIO34	6	SD Card Detect
GPIO35	7	Touch Sensor
RX0	34	UART Receive (Programming)
TX0	35	UART Transmit (Programming)

System Performance Specifications

Electrical Characteristics

Table 2: System Electrical Specifications

Parameter	Minimum	Typical	Maximum
Supply Voltage	3.0V	3.3V	3.6V
Operating Current (Active)	-	160mA	250mA
Operating Current (Sleep)	-	10µA	20µA
Audio Output Power	-	1W	3W
Microphone Sensitivity	-39dB	-36dB	-33dB
Touch Response Time	-	50ms	100ms
Wi-Fi Range (Open Space)	-	50m	100m
Bluetooth Range	-	10m	30m
Battery Life (Typical Use)	6 hours	8 hours	12 hours

Environmental Specifications

Table 3: Environmental Operating Conditions

Parameter	Range
Operating Temperature	-20°C to +70°C
Storage Temperature	-40°C to +85°C
Operating Humidity	10% to 90% RH (non-condensing)
Storage Humidity	5% to 95% RH (non-condensing)
Altitude	0 to 3000m
Vibration	IEC 60068-2-6 compliant
Shock	IEC 60068-2-27 compliant

PCB Design Considerations

Board Dimensions and Layout

Physical Specifications

- **Board Size:** 100mm x 50mm
- **PCB Thickness:** 1.6mm standard FR4
- **Layer Count:** 2-layer stackup for signal integrity
- **Component Placement:** Single-sided assembly on top layer
- **Mounting:** 3x mounting holes for mechanical attachment

Signal Integrity Design

- **Ground Plane:** Continuous ground plane on both layers.
- **Via Stitching:** Regular via stitching for layer connectivity
- **EMI Considerations:** Proper component placement for EMC compliance

Thermal Management

Heat Dissipation Strategy

- **Component Placement:** Heat-generating components spread for airflow
- **Thermal Vias:** Strategic thermal via placement under power components
- **Copper Pour:** Maximum copper coverage for heat spreading
- **Critical Components:** ESP32 module and audio amplifier thermal analysis

Manufacturing Considerations

Assembly Requirements

- **Component Sizes:** Minimum 0603 passive components for hand assembly
- **Pick and Place:** Single-sided placement for automated assembly
- **Soldering:** Reflow soldering profile optimization
- **Testing:** Test points for in-circuit testing
- **Rework Access:** Component spacing for rework operations

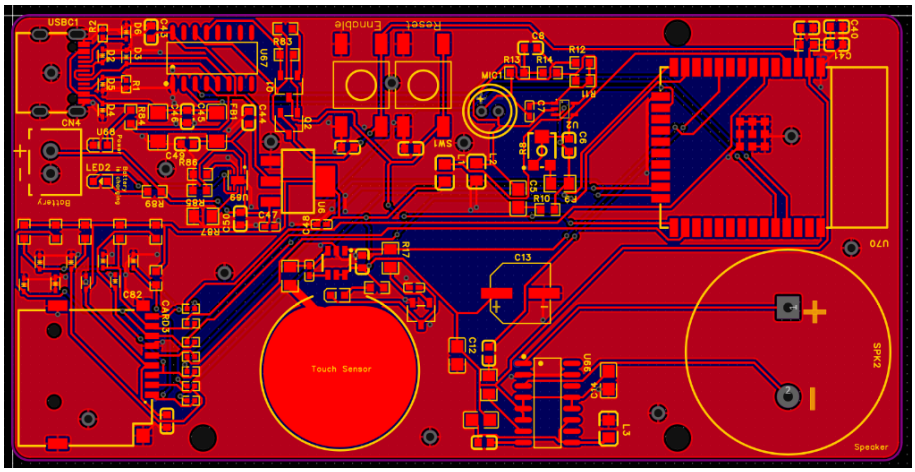

Figure 2: PCB Layout

Software Framework and Development

Development Environment

Supported Platforms

- **Arduino IDE:** Simplified development with ESP32 board package
- **ESP-IDF:** Professional development framework
- **PlatformIO:** Advanced IDE with library management
- **MicroPython:** Rapid prototyping capability

Key Software Libraries

- **Audio Processing:** ESP32 Audio libraries for recording/playback
- **Wi-Fi/Bluetooth:** Native ESP32 connectivity libraries
- **File System:** SPIFFS and SD card file system support
- **Touch Interface:** Capacitive touch processing libraries
- **Cloud Integration:** AWS IoT, Google Cloud, Azure IoT libraries

Firmware Architecture

Real-Time Tasks

- **Audio Processing:** High-priority audio sampling and playback
- **Touch Handling:** Responsive touch event processing
- **Network Communication:** Wi-Fi/Bluetooth data handling
- **Power Management:** Battery monitoring and power optimization

Application Framework

- **Event-Driven Architecture:** FreeRTOS-based task management
- **State Machine:** System state management for different modes
- **Configuration Management:** Non-volatile settings storage
- **OTA Updates:** Over-the-air firmware update capability

Future Enhancement Capabilities

AI/ML Integration

- **Edge AI:** TensorFlow Lite for ESP32 implementation
- **Voice Recognition:** Wake word detection and command processing
- **Audio Classification:** Sound event detection and analysis
- **Predictive Analytics:** Usage pattern analysis and optimization

Hardware Expansion Options

Additional Sensors

- **Environmental Sensors:** Temperature, humidity, pressure sensing
- **Motion Detection:** Accelerometer and gyroscope integration
- **Light Sensor:** Ambient light sensing for display control
- **Air Quality:** VOC and particulate matter sensing

Connectivity Enhancements

- **External Antenna:** U.FL connector for improved range
- **LoRaWAN:** Long-range low-power communication
- **Cellular Connectivity:** 4G/5G module integration
- **Mesh Networking:** ESP-MESH implementation

Manufacturing and Production

Assembly Process

PCB Fabrication

- **Substrate:** FR4 1.6mm thickness
- **Copper Weight:** 1oz (35µm) base copper
- **Surface Finish:** HASL or ENIG for component soldering
- **Solder Mask:** Green solder mask with white silkscreen
- **Testing:** Electrical test and impedance verification

Component Assembly

- **SMD Placement:** Automated pick-and-place for precision components
- **Reflow Soldering:** Temperature-controlled reflow profile
- **Through-Hole:** Hand soldering for connectors and switches
- **Quality Control:** AOI (Automated Optical Inspection)
- **Functional Testing:** In-circuit testing and programming

Production Testing

Automated Test Equipment

- **Bed-of-Nails:** In-circuit testing for component verification
- **Functional Test:** Audio, touch, and wireless functionality
- **Programming:** Factory firmware loading via USB-C
- **Calibration:** Audio gain and touch sensitivity adjustment
- **Final QC:** Complete system validation before packaging

Regulatory Compliance and Certifications

Required Certifications

Wireless Certifications

- **FCC Part 15:** USA wireless device certification
- **CE Marking:** European Conformity marking
- **IC Certification:** Industry Canada wireless certification

- **Wi-Fi Alliance:** Wi-Fi CERTIFIED program compliance
- **Bluetooth SIG:** Bluetooth qualification process

Safety and EMC

- **IEC 62368-1:** Audio/video equipment safety standard
- **IEC 61000-6-3:** Generic EMC emission standard
- **IEC 61000-6-1:** Generic EMC immunity standard
- **RoHS Compliance:** Restriction of Hazardous Substances
- **WEEE Compliance:** Waste Electrical and Electronic Equipment

Conclusion

The ESP32 Custom Board represents a comprehensive IoT audio solution that successfully integrates multiple complex subsystems into a compact, credit-card-sized form factor. The design achieves all primary objectives while maintaining flexibility for future enhancements and cloud integration.

Key Achievements

The project delivers several significant technical accomplishments:

Design Excellence

The single-sided component placement strategy enables cost-effective manufacturing while maintaining professional-grade functionality. The modular architecture ensures that each subsystem operates independently while contributing to the overall system performance.

Technical Innovation

The integration of high-quality audio processing, responsive touch interface, and robust power management in such a compact form factor demonstrates advanced PCB design techniques and component selection expertise.

Manufacturing Readiness

The design prioritizes manufacturability with standard component sizes, automated assembly compatibility, and comprehensive testing strategies that ensure consistent quality in volume production.

Future Development Path

The ESP32 Custom Board provides a solid foundation for evolution toward cloud-based audio applications. The flexible architecture supports seamless migration from MicroSD storage to cloud services while maintaining backward compatibility.

The available GPIO pins and expansion capabilities ensure that the platform can adapt to emerging requirements in IoT audio processing, AI integration, and advanced connectivity features.

Final Recommendations

For successful deployment of the ESP32 Custom Board, the following recommendations should be prioritized:

- Complete comprehensive audio characterization testing across all environmental conditions
- Implement robust cloud integration architecture with proper security protocols
- Establish qualified supply chain relationships for critical components
- Develop comprehensive user documentation and support materials
- Plan for regulatory compliance testing early in the production timeline

The ESP32 Custom Board design demonstrates the successful integration of complex IoT audio functionality into a compact, manufacturable form factor that meets all specified requirements while providing a strong foundation for future enhancements and applications.

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