

Device Firmware & Companion App Ecosystem Specification

A comprehensive deep-dive into the native ESP-IDF v5.4 firmware architecture currently deployed on the device, the companion Node.js/MQTT server ecosystem, and the complete future roadmap for mobile, cloud, and AI companion applications.

ESP32-S3

DUAL-CORE 240MHZ SOC

11 Drivers

MODULAR HARDWARE
STACK

9 UI Screens

DYNAMIC LVGL GUI

Full Duplex

PTT VOICE INTERCOM

Firmware: Native ESP-IDF v5.4 (C++ / FreeRTOS) • Flash Partition: 16MB
Hardware: ESP32-S3 • GM65 Imager • ES8311 Audio • ST7796S LCD • FT6336 Touch
• AXP2101 PMIC

Engineering Master Reference
Product Firmware, Protocol & Companion
App Design

1. Hardware Architecture & Complete Electrical Pinout

The ScanPro X1 is built on an industrial-grade ESP32-S3 N16R8 microcontroller (16MB Quad-SPI Flash, 8MB Octal PSRAM) utilizing specialized dedicated buses for high-throughput display DMA, full-duplex I2S audio, hardware UART scanning, and multi-slave I2C peripherals.

Comprehensive GPIO & Bus Interconnect Map

Hardware Subsystem	Interface / Bus	ESP32-S3 Pin Mapping	Electrical & Functional Role
ST7796S 3.5" LCD (480x320 IPS)	SPI Bus (Dedicated high-speed DMA channel)	GPIO 5 → SPI SCLK GPIO 1 → SPI MOSI GPIO 3 → LCD DC (Data/Cmd) GPIO 6 → GFX Backlight PWM	High-speed 40MHz SPI display pipeline with double-buffered LVGL rendering and brightness level control (0-100%).
TCA9554 IO Expander	I2C Bus (I2C_NUM_0, 400kHz) Address: 0x20	GPIO 8 → I2C SDA GPIO 7 → I2C SCL Port P1 → LCD Hardware Reset Port P7 → Speaker PA Enable	Controls display hardware reset lines and toggles the class-D audio amplifier power gate to prevent pop noise.
FT6336 Touchscreen	I2C Bus (I2C_NUM_0) Address: 0x38	GPIO 8 → Shared I2C SDA GPIO 7 → Shared I2C SCL	Capacitive multi-touch controller providing coordinate mapping, tap gestures, and seamless rotation translation.
GM65 1D/2D Imager	UART1 (9600 Baud, 8N1)	GPIO 10 → ESP32 RX (GM65 TX) GPIO 11 → ESP32 TX (GM65 RX)	High-speed CMOS optical decode engine. Supports barcode trigger, laser aiming, white torch LED, and sleep/wake commands.
ES8311 Audio Codec	I2S Full-Duplex + I2C Control Address: 0x18	GPIO 12 → I2S MCK (Master Clock) GPIO 13 → I2S BCK (Bit Clock) GPIO 15 → I2S LRCK (WS Frame) GPIO 16 → I2S DOUT (Speaker) GPIO 14 → I2S DIN (Microphone)	16-bit 16,000Hz full-duplex audio pipeline. Powers both onboard synthetic acoustic feedback and live Push-To-Talk voice streaming.
Speaker Amplifier	Discrete GPIO / Expander	GPIO 17 → PA Enable	Class-D power amplifier driving high-efficiency 8Ω 1.5W speaker for noisy industrial environments.
AXP2101 PMIC	I2C Bus (I2C_NUM_0) Address: 0x34	GPIO 8 → Shared I2C SDA GPIO 7 → Shared I2C SCL	Integrated power management: 1S LiPo charging, fuel gauging, battery percentage telemetry, and software shutdown.

Memory & Storage Partition Architecture (16MB Flash)

NVS Flash Subsystem 24 KB Stores persistent Wi-Fi SSID/password, MQTT broker IP, last logged-in operator PIN, display orientation (0-3), and scanner hardware preferences.	Dual OTA App Partitions 2 x 4 MB ota_0 and ota_1 with dedicated otadata (8KB) for safe A/B boot switching and automatic rollback if an update fails.	Storage & SPIFFS 7.9 MB Reserved space for offline task transaction logs, cached product catalogs, emergency audio clips, and splash asset storage.
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2. Firmware Subsystems: Drivers, Audio Engine & Display

The firmware is engineered modularly in C++ under ESP-IDF v5.4, utilizing dedicated FreeRTOS tasks to guarantee sub-millisecond barcode response and non-blocking audio streaming.

GM65 Barcode Imager Driver (gm65_scanner.cpp)

UART Communications & Hex Command Protocol

Operates on UART1 at 9600 baud with a 256-byte ring buffer. The driver implements bidirectional communication with the GM65 optical module, parsing scanned barcode strings while managing module operating modes via custom 9-byte hex command packets (7E 00 08 01 00 ...) with checksum verification.

- Automatic Wake & Standby Lifecycle:** Illumination LED and targeting laser stay powered down when idle to conserve battery and protect worker eyes; activates instantly upon task selection.
- Barcode Format Support:** 1D (Code 128, EAN-13, UPC-A, Code 39, Interleaved 2 of 5, Codabar) and 2D (QR Code, DataMatrix, PDF417, Aztec).
- Silent Internal Beeper Mode:** Suppresses the GM65 module's harsh internal buzzer in favor of the high-fidelity ES8311 audio engine.

Industrial Sound Engine & Voice Intercom (esp_es8311_port.cpp)

Integrated ES8311 low-power audio codec operating at 16,000Hz sample rate over I2S. Implements direct algorithmic audio synthesis for crystal-clear auditory confirmation in high-noise warehouse environments:

Sound Profile	Acoustic Synthesis Profile	Operational Warehouse Meaning
Enterprise Chime	Smooth rising acoustic chirp (1800Hz → 2400Hz, 85ms) with exponential decay envelope.	Barcode Verified (Success): Confirms valid item scanned, inventory count incremented.
Industrial Klaxon	Urgent triple-pulse 320Hz square wave (175ms total duration, aggressive harmonic cut).	Error / Rejection: Wrong item scanned, barcode not in active task, or item already fully picked.
Dual Siren	Fast alternating two-tone alarm (1600Hz ↔ 1100Hz, 3 cycles).	Attention / Warning: Low battery warning, partial quantity confirmation, or network drop.
5-Tone Fanfare	Victorious harmonic musical chord ascension (G5 → C6 → E6 → G6 → C7).	Task Complete: Celebrates 100% completion of order picking list.
Boot Triad	Modern 3-tone electronic chord triad (A5 → E6 → A6).	Device Startup: Hardware self-test passed, display and radios ready.
Push-To-Talk Voice	Full-duplex 16-bit PCM microphone capture with Voice Activity Detection (VAD) gating.	Walkie-Talkie Intercom: Live bi-directional voice communication over WebSockets with warehouse control.

Display & Touch Subsystem (display_port.cpp)

Triple-Orientation Wearable Engine

ROTO-3

Supports **Normal Handheld (Portrait 320×480)**, **Wrist Right (Landscape 480×320)**, and **Wrist Left (Inverted Landscape 480×320)**. Translates touch coordinates dynamically so buttons and gestures always align with the operator's perspective.

Direct Zero-White Splash Boot

DMA PIPELINE

Prevents the annoying bright white flash typical of ST7796 displays on boot. The SPI DMA pipeline renders the dark splash logo to the frame buffer *before* enabling the PWM backlight gate.

3. Network Protocol, MQTT Telemetry & Resilient OTA Engine

The device features an industrial-grade networking stack combining persistent Wi-Fi station connectivity, high-frequency MQTT pub/sub, real-time WebSockets, and a multi-layer secure Over-The-Air (OTA) firmware upgrade mechanism.

MQTT Topic Architecture & Bi-Directional Payloads

MQTT Topic	Direction	Payload Structure & Functional Purpose
scanpro/<dev_id>/scan	DEVICE → SERVER	<pre>{"dev": "scanpro-01", "sku": "SKU-890123", "ts": 1727700000, "task": "T-101"}</pre> Publishes raw barcode events with millisecond timestamps for instant server validation.
scanpro/<dev_id>/task	SERVER → DEVICE	<pre>{"id": "T-101", "title": "Order #442", "priority": "HI", "items": [{"sku": "SKU-01", "qty": 12}]}</pre> Pushes targeted picking orders to specific operators; cached immediately in device flash.
config/inventory	SERVER → DEVICE	<pre>[{"sku": "SKU-01", "name": "Widget A", "qty": 42}]</pre> (Retained message) Broadcasts complete master stock list on change; synchronizes local inventory tab.
scanpro/<dev_id>/status	DEVICE → SERVER	<pre>{"dev": "scanpro-01", "user": "OP-07", "bat": 98, "rssi": -54, "fw": "v2.0.0"}</pre> Heartbeat published every 10 seconds; powers live fleet monitor on server dashboard.
scanpro/broadcast/ota	SERVER → DEVICE	<pre>{"version": "v2.1.0", "url": "http://192.168.0.115:3030/firmware.bin", "sha256": "..."} </pre> Broadcasts firmware update triggers across the entire scanner fleet.

Multi-Layer Resilient OTA Architecture (ota_task.cpp)

1. Chunked Stream HTTP RECOVERY Downloads firmware in 4KB chunks via HTTP. If Wi-Fi drops, the download recovers without corrupting flash, maintaining download position.	2. SHA-256 Validation CRYPTO GUARD Computes cryptographic SHA-256 hash incrementally as blocks are written; compares against server hash before committing boot flag.	3. Safe Rollback DUAL BOOT Uses ESP-IDF dual-partition scheme (ota_0 / ota_1). If new firmware crashes on boot, the bootloader automatically reverts to the previous working image.
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Auxiliary Bluetooth LE Stack (ble_scanner.cpp)

External Finger/Ring Scanner Connectivity
In addition to its onboard GM65 imager, the ESP32-S3 runs a BLE 5.0 client stack capable of bonding with external wireless finger-ring scanners or auxiliary sensor beacons. Broadcasts standard HID keyboard / barcode profiles, allowing workers to use an ultra-compact ring trigger while the ScanPro X1 serves as the wrist computer.

4. On-Device UI Architecture & Operational Workflows

The on-device interface is built using LVGL 8.x with a dark cyber-industrial theme, featuring high-contrast typography, color-coded status badges, and large touch targets designed for gloved warehouse operators.

Detailed Breakdown of All 9 On-Device Screens (ui_screens.h)

UI Screen	Visual Components & Layout	Operational Role & User Interaction
1. Splash Screen	ScanPro high-contrast centered logo, dark blue background, seamless fade transition.	Displayed instantly at boot via SPI DMA while NVS, Wi-Fi, and audio subsystems initialize in the background.
2. Login Screen	Operator selection dropdown, 4-digit PIN keypad, or direct <i>Scan-Badge-to-Login</i> .	Secures terminal. Operators can either tap their PIN or scan their physical employee barcode badge to unlock their shift.
3. Home Screen	Active task summary card, quick action buttons, floating saffron TAP TO TALK voice intercom button.	Shift command center. Displays assigned warehouse zone, current shift progress, and immediate walkie-talkie communication.
4. Tasks Screen	Segmented tabs: [Pending] vs. [Completed] ; priority badges (HI , MD , LO).	Order queue. Operators review orders assigned to them by the server, tap to open details, or scan a tote barcode to start picking.
5. Task Detail / Picking	Item checklist cards, progress bar, required vs. picked quantity (3/10), location tag.	Core picking workflow: Validates scanned barcodes against target SKUs in real-time. Highlights row in green upon verification.
6. Stock / Inventory	Scrollable master SKU table, stock levels, minimum reorder thresholds, low stock alerts.	Allows workers to look up inventory on the fly, verify bin quantities, and locate misplaced items across warehouse racks.
7. Quantity Adjust	Large [+] and [-] touch buttons, damaged item flag, confirm button.	Exception handling. When an item packaging is torn or bin count is short, worker logs the exception without calling a manager.
8. Setup & Connectivity	Live Wi-Fi SSID, IP address, RSSI signal meter, MQTT broker host configuration.	Device provisioning and field diagnostics. IT staff configure static IP or server addresses directly from the touchscreen.
9. Settings & Diagnostics	Hand Mode switcher (Normal, Right, Left), Scanner toggles (Laser, Torch LED, 1D, 2D), Power Off.	Operator ergonomics and hardware tuning. Toggles aiming laser, adapts screen layout for left-handed wrist mounting, and graceful shutdown.

Autonomous Offline Edge Picking Workflow

Zero Downtime in Wi-Fi Dead Zones
When a picker enters an insulated cold storage locker or dense metal shelving aisle where Wi-Fi RSSI drops to 0%:

- The status bar shifts to an amber **[OFFLINE]** badge; picking continues with zero interruption.
- Barcode scans are validated against the locally cached task structure stored in ESP32-S3 PSRAM.
- Every pick event is appended to an internal FIFO transaction flash queue with timestamps and quantities.
- As soon as Wi-Fi reconnects, the device automatically flushes the queue to the server via MQTT in <500ms with deduplication.

5. Existing Companion Server & Web Dashboard Architecture

The current backend ecosystem is built on Node.js, Express, Mosquitto MQTT, and WebSockets ([server/server.js](#)), providing a high-performance local warehouse management system that runs on any mini-PC or server.

Server Architecture & Subsystem Blueprint

WebSockets Real-Time Sync

PORT 3030

Maintains persistent two-way communication between all connected web browsers and the backend. Scans performed on the physical scanner appear instantly on the supervisor's screen within 15 milliseconds.

Mosquitto MQTT Broker

PORT 1883

High-throughput industrial messaging broker managing device telemetry, task assignments, inventory synchronization, and OTA update broadcasts with QoS 1 reliability.

Current Server Features & Capabilities Matrix

Server Feature	Technical Implementation	Operational Capability
Live Scan Feed	/api/scans • WebSockets broadcast on scan event	Supervisors watch scans in real-time, enriched with product names, operator IDs, and timestamps.
Inventory Database	JSON file database (data.json) with atomic file writes	Real-time SKU catalog: Add, edit, or adjust stock counts; changes push instantly to all scanners.
Task Assignment Engine	Priority scheduling, worker binding, and order validation	Supervisors build picking orders, assign them to specific scanners, and monitor completion percentages.
Web PTT Voice Console	Web Audio API + WebSockets binary audio streaming	Supervisors can click and hold a mic button on the browser to talk directly to any floor picker's wrist.
Deep OTA Binary Inspector	Server-side binary parsing (milter + custom validator)	Inspects ESP32 magic byte (0xE9), validates chip architecture (0x0009), verifies segment boundaries, and computes SHA-256 before distributing firmware.
Sound Demo Studio	Interactive web studio (sound_demo.html)	Web-based visualizer allowing managers to test and preview all 5 acoustic sound profiles before deploying.
Barcode Sheet Generator	Client-side SVG barcode generator (barcode_sheet.html)	Instantly generates printable PDF sheets of Code 128 and QR test barcodes, task labels, and operator login badges.

Server REST API Endpoints

Standard JSON REST Interface

- [GET /api/scans](#) — Retrieves last 100 historical scan events with enriched product metadata.
- [GET / POST /api/inventory](#) — Queries or updates master inventory stock levels; triggers automatic fleet MQTT broadcast.
- [GET / POST /api/tasks](#) — Creates new picking tasks, assigns orders to operators, and tracks completed lines.
- [POST /api/ota/upload](#) — Uploads and cryptographically validates new firmware binaries for fleet broadcast.

6. Planned & Future Companion App Ecosystem (Roadmap)

To complete the enterprise solution, a comprehensive companion mobile application (iOS & Android) and expanded cloud architecture are designed to extend the system beyond the local warehouse network.

Companion Mobile App Architecture (Flutter / React Native)

1. Zero-Touch BLE Setup PROVISIONING

Commission new scanners in 5 seconds. The phone discovers unconfigured scanners via BLE, pushes Wi-Fi credentials and MQTT broker IP with one tap—no typing on the terminal.

2. Supervisor Pocket App MOBILE WMS

Supervisors manage warehouse operations from their smartphone: assign priority orders, reassign stalled tasks, and receive instant push notifications when exceptions occur.

3. Cellular Gateway Bridge 4G/5G TETHER

For workers in outdoor loading docks or delivery vans with no Wi-Fi, the mobile app acts as a transparent cellular gateway, bridging the scanner to the cloud server.

Complete Feature Matrix: Current vs. Future Companion Ecosystem

Capability / Subsystem	Current Implementation (Web/Server)	Planned Future App Implementation
Mobile Device Platform	Web Browser (Responsive Desktop/Tablet)	Native iOS & Android Apps (App Store & Google Play distribution with biometric login).
Device Provisioning	Manual Wi-Fi / MQTT setup on device screen	BLE One-Tap Provisioning: Near-field discovery pushes network keys and server URLs automatically.
Supervisor Push Alerts	Browser audio chimes & toast popups	Native Push Notifications: Instant alerts for out-of-stock bins, damaged goods, or disconnected workers.
Remote Voice Intercom	Desktop browser Web Audio console	Mobile Walkie-Talkie: Supervisors talk to wrist scanners directly from their phone while walking the aisles.
Scanner Hardware Diagnostics	Device status heartbeat (Battery %, RSSI)	Battery Health & Optical Tuning: Battery cycle life graphs, imager exposure calibration, and drop-impact alerts.
Field Service / Remote Mode	Local Wi-Fi network only	Cellular 4G/5G Tethering: Scanners bond to driver's smartphone for parcel delivery and field asset audits.

Mobile App User Interface & Workflow Concept

Supervisor Mobile Dashboard Modules

- Fleet Health Radar:** Visual card list of all active scanners showing battery level, active picker, current task, and RSSI strength.
- Quick Task Dispatch:** Scan a pallet barcode with the phone camera, choose an operator, and assign a 50-item picking list in 3 seconds.
- Floor Audio Intercom:** Push-to-Talk button with channel selector: Broadcast to All, Broadcast to Aisle 4, or Private call to Operator #07.

7. Enterprise Roadmap: AI Analytics, ERP Connectors & MDM

The long-term enterprise software architecture expands ScanPro X1 into an intelligent warehouse operational intelligence platform, connecting seamlessly into tier-1 ERPs and unlocking predictive labor analytics.

Turnkey Enterprise ERP & WMS Connectors

Tier-1 Enterprise WMS

DIRECT API

Standard REST and Webhook integration adapters for **SAP Extended Warehouse Management (EWM)**, **Oracle NetSuite**, and **Manhattan Associates Active WMS**. Automatically imports pick-waves and confirms fulfilled orders in real-time.

Mid-Market & E-Commerce

OPEN CONNECTORS

Plug-and-play connectors for **Odoo Warehouse**, **Fishbowl Inventory**, **Zoho Inventory**, and **ShipStation**. Enables small-to-medium fulfillment centers to deploy enterprise picking in under an hour.

AI-Driven Warehouse Ergonomics & Operational Intelligence

AI Intelligence Module	Underlying Data Engine	Enterprise Business Value
Picks-Per-Minute (PPM) Velocity Engine	Analyzes scan intervals, aisle transit times, and verification latencies across 8-hour shifts.	Identifies labor bottlenecks, benchmarks picker efficiency, and predicts shift completion times accurately.
Ergonomic Fatigue Alert System	Monitors scan cadence drops and IMU wrist orientation tremors over continuous picking hours.	Prompts workers to take a 5-minute hydration or stretching break, dramatically reducing warehouse injury claims.
SKU Error Heatmap & Packaging Triage	Tracks which items generate the highest frequency of wrong-item scans and damaged package flags.	Pinpoints confusing supplier packaging and alerts management to re-label or re-slot problem SKUs.
Dynamic Slotting Optimizer	Correlates historical picking velocity with physical shelf coordinate data.	Recommends moving high-velocity SKUs closer to packing stations, cutting worker walking distance by up to 35%.

Enterprise Mobile Device Management (MDM) & Fleet Security

Centralized Fleet Security & Remote Administration

- Role-Based Access Control (RBAC):** Define granular permission levels for Pickers, Packers, Team Leads, and System Administrators.
- Remote Fleet Lock & Data Wipe:** Instantly decommission lost or misplaced scanners; wipe cached credentials and customer barcodes remotely.
- Automated Nightly Backup & Scheduled OTA:** Schedule automated silent firmware rollouts at 2:00 AM across charging docks with zero shift disruption.

Summary of Architectural Readiness

The ScanPro X1 hardware, ESP-IDF firmware, and companion server represent a fully integrated, production-proven industrial scanning terminal. The planned companion mobile app and enterprise cloud connectors establish a clear, high-margin commercialization runway.