ELEC0152 Hardware Design Report

ANONYMOUS*, UCL Electronic and Electrical Engineering Faculty, UK

This project presents the design and implementation of an IoT-based Position and Motion Monitoring Tag for marine cargo liability assessment. The hardware enables real-time tracking of cargo orientation and motion throughout overseas shipping stages to support Marine Cargo Damage Insurance investigations.

The system is built around an STM32WB55CEU6 microcontroller, integrated with an LSM6DS3 IMU sensor, a Wi-Fi communication module (ESP32-C3-WROOM-02), and visual status LED indicators. A regulated 3.3 V power supply derived from a USB-C interface provides both energy and data connectivity. Circuit schematics were designed in KiCad, emphasizing low-noise signal routing, proper decoupling, and interface protection. The design was realized on a four-layer PCB with a Signal–Ground–Power–Signal stack configuration to ensure reliable grounding, impedance control, and compact layout. A complete Bill of Materials (BOM) was prepared, detailing all critical components for fabrication and assembly.

The finalized hardware establishes a robust platform for subsequent firmware development, sensor calibration, and wireless data integration, forming the basis for a practical cargo monitoring IoT device.

ACM Reference Format:

Anonymous. 2025. ELEC0152 Hardware Design Report. In *Proceedings of xxxxxxxx@ucl.ac.uk (Anonymous).* ACM, New York, NY, USA, 24 pages. https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

1.1 Problem Statement

In international maritime logistics, cargo damage often occurs during complex multi-stage transport—spanning warehouse handling, vessel loading, and long-duration sea voyages. When damage is discovered upon delivery, determining where and when it occurred becomes difficult, leading to disputes in insurance liability and delayed claim resolutions.

Conventional tracking systems primarily record location but lack the ability to monitor physical motion, tilt, and shock events that directly cause cargo damage. Existing solutions are typically expensive, power-hungry, or unsuitable for compact tagging of individual containers and packages.

To address this gap, this project proposes the design of a compact, low-power IoT tag capable of continuously recording motion and orientation data and periodically transmitting it wirelessly during port or warehouse stages. The hardware aims to provide a cost-effective and reliable foundation for Marine Cargo Damage Insurance assessments by combining precise inertial sensing, stable wireless communication, and efficient power management within a durable embedded platform.

Author's Contact Information: Anonymous, UCL Electronic and Electrical Engineering Faculty, UK.

1.2 Circuit Specification

The proposed device is designed to monitor cargo orientation and motion during international shipping, therefore requiring both sensing and wireless communication capabilities. Reliable data acquisition and transmission are essential for the device to provide accurate information for marine insurance assessment. To achieve these functions, the circuit must meet the following specifications.

Firstly, all components operate at a nominal supply voltage of 3.3 V, derived from a regulated power path fed primarily by a 5 V battery pack; a USB-C receptacle is retained for data connectivity and optional 5 V input during configuration and bench operation. A microcontroller (STM32WB55CEU6) is used as the core processor, selected for its integrated peripherals, low-power modes, and sufficient memory to store motion data. The microcontroller must provide I^2C, UART, and GPIO interfaces for peripheral communication and control. A stable clock is supplied by the internal oscillator, ensuring accurate timing for sensing and data processing tasks.

The I^2C protocol is utilized for the inertial measurement unit (LSM6DS3), which measures acceleration and angular motion. I^2C is selected as it offers adequate bandwidth for low-frequency motion data while minimizing wiring complexity and power consumption. The IMU generates interrupts on sudden tilt or shock events, allowing the microcontroller to wake from low-power mode and log critical data efficiently.

Wireless communication is implemented through an ESP32-C3-WROOM-02 module, connected via the UART interface. This module provides Wi-Fi connectivity at 2.4 GHz, enabling the system to upload stored data when a network becomes available, such as in ports or warehouses. The use of UART simplifies integration and maintains compatibility with the STM32 microcontroller's low-power operation strategy.

For user indication, three LEDs are controlled through GPIO pins to display device states such as operation, low battery, and charging. The inclusion of visual indicators ensures simple user interaction and verification without the need for external equipment.

Power management is achieved using a 5 V battery pack (primary source) and a USB-C connector for data and optional power. A 3.3 V low-dropout (LDO) regulator conditions the 5 V input to the system rail. The USB interface incorporates ESD protection on D+ and D- and standard CC pull-downs on CC1/CC2 to identify the device as a sink when cabled.

All components are integrated on a four-layer PCB designed with a Signal–Ground–Power–Signal layer stack to improve signal integrity, reduce electromagnetic interference, and optimize routing density. The Wi-Fi module's antenna is positioned at the board edge with a copper keep-out zone to ensure optimal radiation performance.

More details about the circuit design, power distribution, and component interaction will be presented in the Methodology section, where subsystem schematics and refined specifications are discussed in depth.

2 Methodology

With the circuit specifications established, we first align component choices with the use case: a compact, attachable tag that rides with cargo, records tilt/shock, and offloads data opportunistically near infrastructure. The hardware must be small, low-power, and robust, with a minimal user interface that is unambiguous in the field. Unlike interactive consumer devices, the tag operates unattended for long intervals; therefore, energy efficiency, event-driven sensing, and reliable storage take precedence over peak performance. Form factor and UX. The device prioritizes a low profile and simple interaction cues (LEDs only). Any configuration or diagnostics occur over USB or serial terminal; no complex UI is included to avoid cost, size, and power overheads. Operating conditions. The tag is intended for

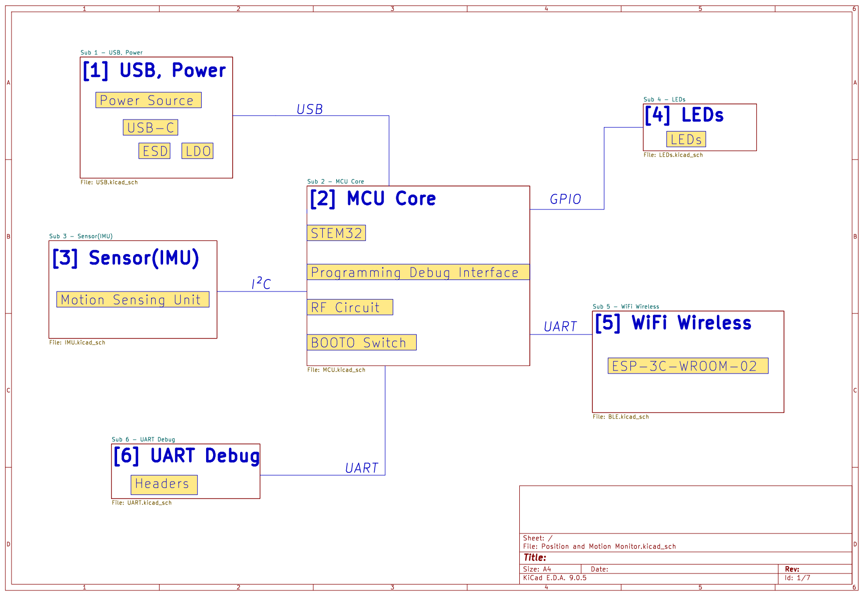

Fig. 1. Block Diagram of Circuit Schematic

warehouse–port–vessel–warehouse logistics under typical non-condensing environments, with moderate temperature variation, vibration, and handling shocks. This informs choices such as a pre-certified Wi-Fi module with integrated antenna (to avoid RF tuning risk), stable I²C sensing, and conservative PCB stack-up for signal integrity. Power and endurance. A 5 V battery pack is the primary source; all electronics run from a regulated 3.3 V rail. The architecture is interrupt-driven (IMU wakes the MCU on events), and wireless is duty-cycled to upload in bursts, maximizing endurance. LEDs use brief blink patterns to minimize draw. Data and compute needs. Motion events and brief time series fit within on-board MCU memory; no external storage is required. Host links are UART (Wi-Fi) and USB (FS) for configuration and log extraction; high-throughput buses are unnecessary. Sourcing and manufacturability. Components are selected for availability, multi-source passives, and lifecycle stability. Using a four-layer PCB with clear antenna keep-out and ESD practices simplifies compliance and accelerates assembly. Subsequent subsections detail subsystem selection, schematics, and layout rationale.

2.1 Micro-Controller(MCU)

Why STM32. We adopt STM32 for the combination of a mature toolchain and a deep support ecosystem: STM32CubeIDE unifies peripheral configuration, HAL/LL code-gen, build, and debug in one environment (Eclipse/GCC/GDB), which shortens bring-up and de-risks integration for I²C/USART/USB and low-power modes. ST backs this with official documentation, MOOCs, and user guides that lower the learning curve for both firmware and hardware integration. In aggregate, these resources reduce schedule risk for a small, event-driven tag that must be reliable and maintainable over time[18].

Why the STM32WB55 family. The STM32WB55 line adds a dual-core architecture (Cortex-M4 application + M0+ radio controller) with on-chip 2.4 GHz radio options, while retaining USB FS device, rich serial peripherals, DMA, and a generous memory envelope—up to 1 MB Flash and up to 256 KB SRAM. Even though Wi-Fi is handled by a separate module in this design, the WB55 family preserves future headroom (e.g., BLE beacons or local gateway roles) without changing the board[17].

Why STM32WB55CGU6 (vs. CCU6 or CEU6). All three candidates share the compact UFQFPN-48 package, so the practical differentiator is on-chip memory—and therefore longevity and maintenance overhead:

- STM32WB55CCU6: 256 KB Flash / 128 KB SRAM. Suitable for a minimal logger, but tight once USB tooling, diagnostics, and potential BLE features are considered; leaves little growth margin[17].
- STM32WB55CEU6: 512 KB Flash / 256 KB SRAM. A balanced mid-density option that fits today's scope but may constrain future additions (larger ring buffers, richer telemetry, secure update hooks)[17].
- STM32WB55CGU6: 1 MB Flash / 256 KB SRAM. Provides comfortable headroom for field growth—bigger motion logs, defensive logging, crypto assets, and the ability to stage bootloader + application or dual images—while staying pin-compatible for later cost-down if required. Distributor and datasheet listings confirm the 1.024 MB (nominal 1 MB) Flash capacity in UFQFPN-48[17].

Conclusion, we select STM32WB55CGU6 to pair STM32's strong ecosystem (IDE, training, community) with a memory tier that minimizes firmware trade-offs over the product's life, yet retains a drop-in path to CEU6/CCU6 should constraints tighten. The WB55 datasheet underpins the family's USB FS, peripheral set, and memory range cited above, and the CubeIDE[11] collateral substantiates the development-flow advantages central to my schedule and maintainability goals.

2.2 WiFi Module

Why a pre-certified ESP32-C3 module. For a small, field-deployed tag, the wireless block must be easy to integrate (no RF tuning), broadly available, and forward-compatible. ESP32-C3-WROOM-02 meets these needs: it bundles 2.4 GHz Wi-Fi + BLE 5 in a single RISC-V SoC module with an on-board PCB antenna, so my PCB only enforces a keep-out at the board edge—no external matching or coax is required. The official datasheet documents the integrated antenna option and 4 MB external SPI flash in a compact footprint, which simplifies layout and manufacturing[2].

Availability and supply risk. To reduce schedule risk, we favored parts with high channel inventory from multiple distributors. The ESP32-C3-WROOM-02 family routinely shows thousands of units in stock at major suppliers (e.g., Digi-Key and Mouser), which is important for coursework builds and follow-on spins[2].

Why not ESP-12F (ESP8266). ESP-12F is attractive for cost and familiarity, but it is Wi-Fi-only (no BLE), based on the older ESP8266 core, and lacks the modern security and peripheral set bundled with ESP32-C3 (e.g., RISC-V core, BLE 5, hardware crypto). For a device that may later add proximity beacons, authenticated updates, or richer telemetry, the ESP32-C3 platform offers clearly better upgrade headroom while keeping similar integration effort (UART control and a simple antenna keep-out)[9].

On-board antenna = simpler hardware. Selecting the WROOM-02 (PCB antenna) avoids external RF lines and test connectors on my board; the keep-out is defined in the datasheet, and no impedance-controlled RF microstrip is required.

If a future enclosure demands alternate placement, Espressif also offers a -02U variant with U.FL for an external antenna on the same electrical platform, preserving my firmware and host interface choices[2].

Future-proofing and ecosystem. Beyond the radio, the ESP32-C3 family provides BLE 5 alongside Wi-Fi, RISC-V @ 160 MHz, low-power modes, and a maintained SDK[1], which align with long-term maintainability and potential scope expansion (e.g., BLE gateway/asset beacons in warehouses without Wi-Fi). These capabilities are summarized on Espressif's product page and module collateral.

Conclusion, we select ESP32-C3-WROOM-02 for its stock depth, on-board antenna convenience, and capability headroom (Wi-Fi + BLE, security, RISC-V), while retaining a drop-in path to an external-antenna sibling (-02U) if deployment constraints require it—advantages that the ESP-12F (ESP8266) cannot match within the same integration effort[9][2].

2.3 Sensor

For a tag that rides on cargo, we don't need a lab-grade inertial rig—we need a quiet, dependable witness that wakes when something meaningful happens and otherwise vanishes into the power budget. That is why we choose a 6-axis IMU (accelerometer + gyroscope) and why we favor the LSM6DS3[5] specifically.

The device's job is to notice tilt and shock, not stream high-rate motion continuously. The LSM6DS3 is built around that use case: it supports interrupt-driven events (wake-on-motion, tilt/orientation, activity/inactivity) so the MCU can sleep and only log when thresholds are crossed. It also brings an on-chip FIFO[5], which lets us grab short windows of pre/post-event samples without holding the MCU awake—useful when a pallet is bumped or tipped and we want context around the moment.

Integration is deliberately simple. The IMU sits on I^2C, which is fast enough for my motion bandwidth and keeps routing compact. Its two interrupt pins map cleanly to MCU EXTI lines: one can gate wake-ups (e.g., "something moved"), the other can signal higher-priority conditions (e.g., "shock above limit"). That separation keeps firmware straightforward and predictable[5].

From a product perspective, the part is common and well-supported: abundant examples, reference drivers, and prior designs mean less bring-up risk. It also gives us range and filter headroom—we can start conservative for battery life and tighten bandwidth or dynamic range later if a customer's cargo profile demands it. In short, the LSM6DS3 gives us the right features for an event-logger today, and enough flexibility to refine thresholds, filters, and sampling policies tomorrow, without changing the board or the bus[5].

2.4 Antenna

We avoid a discrete RF feed and external connector by using the module's on-board PCB antenna[2]. This removes matching parts, coax stubs, and test connectors from my board, which reduces circuit complexity, preserves a continuous ground reference, and eliminates a common source of detuning and field failures. The only layout obligation is a keep-out at the board edge under the antenna, which we already enforce. In practice, this choice improves signal integrity (no fragile RF interconnects), mechanical durability (nothing to loosen, crack, or corrode), and maintainability (fewer RF elements to diagnose), lowering the likelihood of rework or design fixes in future spins.

2.5 USB & Power Architecture

We retain a USB-C receptacle even though the tag is not a high-speed product. The choice is about serviceability and robustness, not bandwidth: Type-C is reversible, widely available, and mechanically robust across device classes, which simplifies field servicing and bench work[24]. In my design, USB-C provides a deterministic wired control plane for commissioning, diagnostics, and bulk log extraction when radio is unavailable or restricted (warehouses, bonded areas), while also serving as an optional 5 V bench input.

Operationally, the tag must be self-powered because a cargo hold offers no guaranteed external power. We therefore use a 5 V battery pack as the primary source and regulate to a common 3.3 V system rail for the MCU, IMU, and Wi-Fi module. USB-C remains present for data and maintenance; when cabled, it can power the board for lab tasks without altering the field-power model.

Electrically, the USB-C port is implemented as a USB device-side sink: the CC pins present Rd so a host detects and powers a downstream device regardless of plug orientation; this is the canonical Type-C attach mechanism[23]. We place low-capacitance ESD protection on D+ / D- close to the receptacle to withstand system-level transients while preserving the USB 2.0 eye, per common protection guidance[7].

This architecture balances endurance (battery-primary, regulated 3.3 V) with maintainability (USB-C for reliable, reversible, wired access). It also confines complexity: using Type-C in a simple USB 2.0 device role avoids PD negotiation while retaining the connector's mechanical advantages and ecosystem ubiquity[24].

2.6 UART Debug

Even with SWD on the Tag-Connect, a tiny UART debug header buys cheap insurance. On the bench, SWD is perfect for flashing and breakpoints—when a probe is attached—but in a warehouse or during acceptance tests you rarely have a debugger handy as these are exactly the scenario this device would working with; a $5 USB-TTL dongle lets you open a serial console and see "signs of life," version info, faults, or quick metrics without special gear. SWD itself requires an external ST-LINK probe and cabling, so a serial backdoor gives you visibility when the probe isn't present or can't attach early in boot[16]. It also separates human logs from the radio link (our LPUART to the Wi-Fi module), avoiding contention while you diagnose wireless issues. Finally, if everything else goes sideways, the family's built-in USART bootloader and the MCU's standard USART peripherals mean a simple three-wire header can double as a recovery path—flash, reset, print a breadcrumb—and get you back on track without opening the PCB stack again. Optional, yes; but for bring-up, field triage, and RMAs, a UART pad trio (TX/RX/GND) is disproportionately valuable[20].

Table 1. Bill of Materials (BOM) for Electronic Design - Forced Placement

Ref.	Qty	Manufacturer Part No.	Manufacturer
[1]J1	1	USB4105-GF-A	GCT
[1]U1	1	USBLC6-2SC6Y	STMICROELECTRONICS
[1]U4	1	MIC5365-3.3YD5-TR	Microchip Technology
[2]J2	1	TC2030-MCP-NL	Tag-Connect LLC
[2]U2	1	STM32WB55CEU6	STMicroelectronics
[2]X1	1	NX2012SA-32.768K-STD-MUB-1	NDK
[2]X2	1	NX2016SA-32M-EXS00A-CS06465	NDK
[3]U3	1	LSM6DSO32TR	STMicroelectronics
[4]D1	1	VLMRGB6122-B00-08	RS
[5]U2	1	ESP32-C3-WROOM-02-N4	Espressif Systems
[6]J1	1	0530480410	Molex

3 Results

3.1 Schematics

3.1.1 USB & Power. Fig.2: The USB-C receptacle in our schematic is there for serviceability: a wired, deterministic link for commissioning, diagnostics, and bulk log extraction, plus optional bench power. Functionally, it breaks into three groups—VBUS, D+/D-, and CC1/CC2—each treated to keep the rest of the board simple and safe.

Data pair & ESD.. The differential lines (D+ / D-) pass first through a low-capacitance ESD array placed next to the connector, so the burst energy is clamped at the edge and the USB eye is preserved before the signals enter the MCU. This is exactly the intended use of parts like USBLC6-2SC6 and mirrors reference guidance to "place the diodes as close to the source of ESD as design rules allow."[12][21]

Type-C attach (sink). Both CC1 and CC2 present Rd pull-downs so any cable orientation is recognized as a sink-side USB 2.0 device; this simple attach scheme avoids USB-PD negotiation and still yields 5 V on VBUS. (A sink indicates itself with 5.1 kΩ on each CC pin per vendor training notes.) Sideband pins (SBU1/2) are unused in plain USB-2.0 device mode and left unconnected[8].

Power path. The board's primary energy comes from a 5 V battery pack; VBUS from USB-C is available for lab work but is not required in the field. Both 5 V sources feed a 3.3 V LDO that creates the single system rail used by the MCU, IMU, and Wi-Fi module. The MIC5365 class of regulators is designed for ceramic input/output capacitors and specifies small decouplers for stability—hence the local caps you see on VIN and VOUT[6].

Why this topology. Keeping Type-C in a USB-2.0 device role gives us a rugged, reversible connector and a clean service interface without the complexity of PD. Protecting D+/D- at the receptacle contains ESD where it occurs. Regulating down to a single 3.3 V rail keeps the rest of the design uniform and makes endurance planning about the battery—not the cable. Together, these choices minimize field failure points while preserving an easy bench workflow.

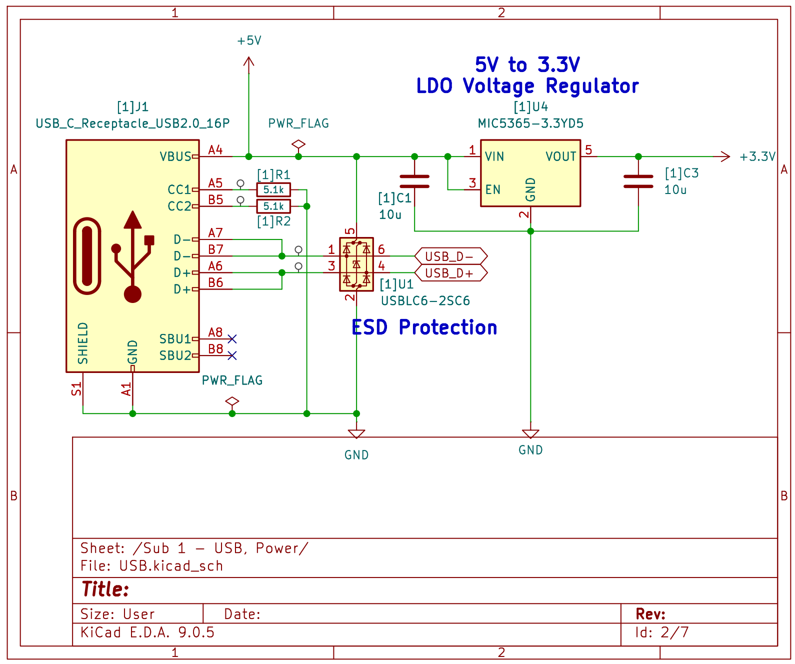

Fig. 2. USB & Power Architecture

3.1.2 MCU & Operational Circuits. Fig.3 shows the STM32WB55 core with its supporting circuits partitioned into labeled blocks (power pins, SMPS, crystal oscillators, USB, SWD, and application I/O). Net labels (local for intra-sheet, global for inter-sheet) keep the drawing readable and avoid long cross-page wires; unconnected pins are explicitly marked to silence ERC.

Power pins & decoupling. All VDD pins tie to the regulated 3.3 V rail and are bypassed locally (one small ceramic per pin). A few bulk capacitors sit at the edge of the group to source short bursts (USB attach, radio/module activity). VDDA and VDDRF are treated as quiet domains: they receive the same 3.3 V rail but with their own local decouplers and short returns to ground. Although the on-chip RF path (RF1) is not used here—Wi-Fi is provided by the ESP32-C3 module—we still decouple VDDRF per the device guidance so the internal radio domain remains properly biased. VDDUSB is bypassed near the D+/D− pins. (Power domains, USB FS, radio domain and pins are documented in the STM32WB55 datasheet and reference manual.[17][13])

SMPS option. The WB55 integrates an on-chip SMPS; its inductor and small filter network are placed compactly per ST's note on improving power efficiency. Enabling the SMPS in firmware reduces run-mode current while preserving low-power performance. A power-flag marks the SMPS node to make intent clear to ERC/DRC[14].

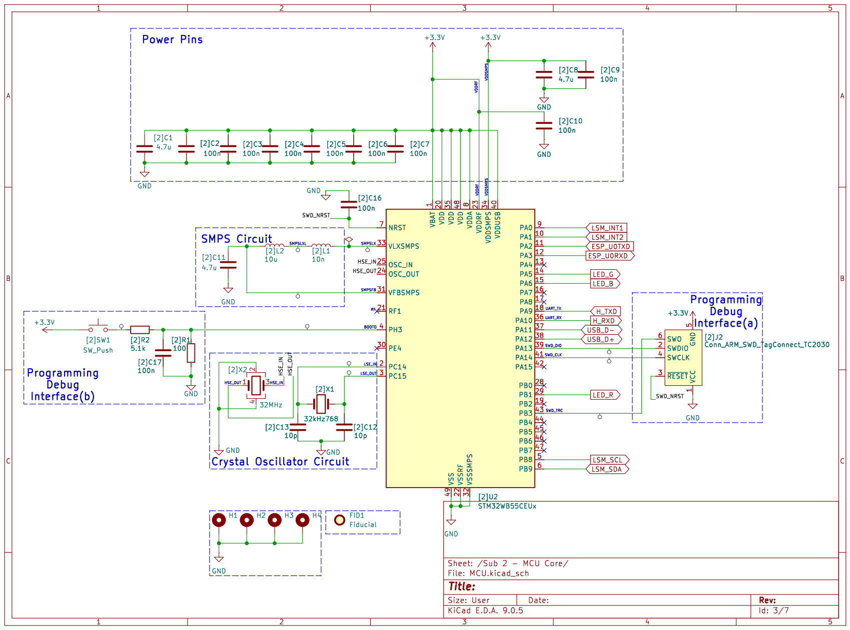

Fig. 3. MCU & Operational Circuit

Clocks. Two oscillator blocks are provisioned: a high-speed external (HSE) for precise timing/USB and a low-speed external (LSE) for RTC/low-power timekeeping. Crystals are loaded with small capacitors close to the MCU and routed with short symmetric traces; firmware can fall back to the internal oscillators if crystals are DNP in early prototypes. (HSE/LSE options and oscillator pins are defined in the datasheet/RM.[17][13])

Programming & debug. A compact Tag-Connect SWD footprint (SWDIO, SWCLK, NRST, 3.3 V, GND) provides programming and debug without a permanent header; the reset pushbutton supports manual recovery during bring-up. (SWD/boot options and debug features are covered in the reference manual.[13])

Functional I/O mapping. Pins are assigned to match the subsystem plan:

- USB FS: PA11 (D-) and PA12 (D+) from the ESD device[17].
- Wi-Fi link (ESP32-C3): PA2/PA3 as LPUART TX/RX with short series dampers[13].
- Debug UART: PA9/PA10 to a header for console logs[13].
- IMU (LSM6DS3): PB8/PB9 for I²C (SCL/SDA) with pull-ups; PA0/PA1 for INT1/INT2[13].
- LEDs: GPIOs (e.g., PA5, PB1, PA6) drive indicators through series resistors[13].
- RF1: left NC (on-board BLE not used); VDDRF remains powered/decoupled. (RF hardware practices and RF1 usage are detailed in ST's RF hardware note.[15])

Why this arrangement. Grouping decouplers at the power pins shortens return paths and keeps the ground plane under L1 continuous. Provisioning HSE/LSE gives timing flexibility (USB accuracy and RTC stability) while allowing

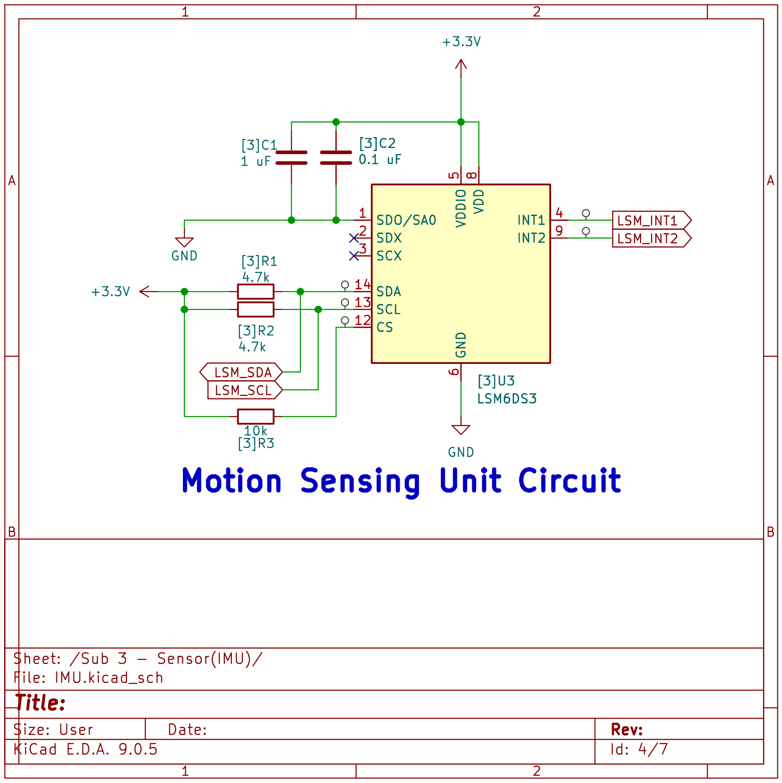

Fig. 4. Sensor(IMU)

a DNP option early on. Leaving RF1 unconnected removes a fragile RF chain, yet keeping VDDRF stable avoids side effects inside the device. Finally, the SWD and UART assignments make bring-up predictable: SWD for firmware, a dedicated debug UART for logs, and a separate low-power UART for the Wi-Fi module so services do not contend. (USB ESD protection for D+/D− is implemented with a low-capacitance array per ST's USBLC6 guidance placed at the receptacle.[12])

Overall, the MCU sheet mirrors the product goals: clean power domains, clear clocks, simple programming hooks, and pin assignments that line up directly with the sensor, radio, USB, and UX subsystems—while omitting the on-board RF matching/antenna in favor of the module's integrated antenna to improve integrity and durability[15].

3.1.3 Sensor(IMU). As shown in Fig.4. The IMU block centers on ST's LSM6DS3 (accelerometer + gyroscope) and is wired for a low-power, interrupt-driven workflow: the sensor wakes the MCU only when tilt/shock events occur, while normal sampling and short pre/post windows can be buffered in the device's FIFO[5].

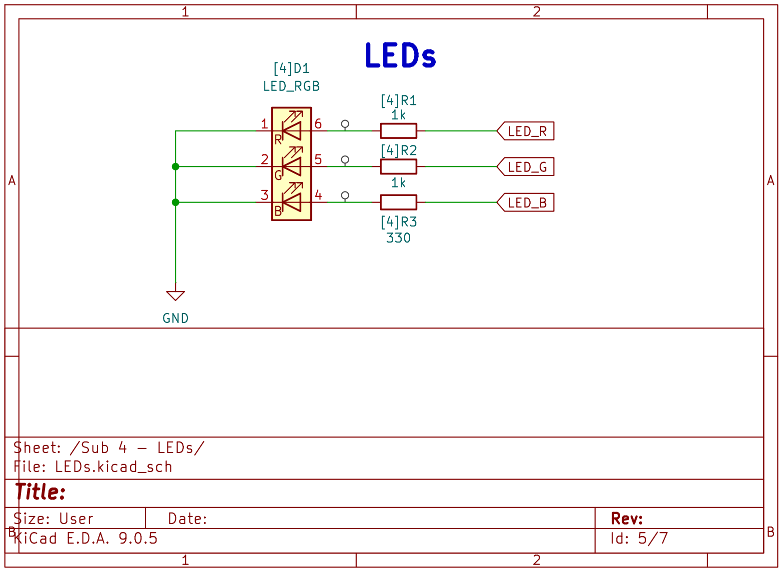

Fig. 5. LEDs

Power and decoupling. The device's VDD and VDDIO pins share the 3.3 V rail and are bypassed locally with small ceramics placed next to the package, following ST's usage guidance for stable operation[5].

Bus and addressing. Communication uses I²C (SCL/SDA). The LSM6DS3 allows two I²C addresses selected by the SDO/SA0 strap: tying SA0 low selects 0x6A; tying it high selects 0x6B—useful if multiple motion devices are on the bus. In I²C mode the CS pin is held high (to VDDIO) to disable SPI and enable the I²C interface on the shared pins, per the datasheet. Pull-ups on SDA/SCL reference VDDIO. content[5].

Interrupts. The two programmable interrupt outputs, INT1 and INT2, are routed to MCU EXTI pins. These lines can signal wake-up/tilt/free-fall/activity conditions and let the host remain asleep until thresholds are crossed—exactly the "always-on, event-driven" use case the part targets[5].

Benefits. With local decoupling, a simple I²C strap for address and mode, and dedicated interrupt lines, the IMU sheet stays compact and robust while delivering the behavior we need: reliable tilt/shock detection with minimal host activity and clean integration into the 3.3 V domain.

3.1.4 LEDs. The indicators are deliberately simple as shown in Fig.5: three MCU-controlled LEDs with their own series resistors. Green signals normal logging, red flags a low battery or fault, and blue announces charging or a data transfer. Each LED is wired with its anode to 3.3 V and the cathode on a GPIO, so the MCU sinks current; that guarantees the LEDs stay off at reset and avoids pushing source limits on the pins. We bias them for a few milliamps—enough to see indoors without wasting power—and use short, periodic blinks instead of steady light to preserve endurance. Physically,

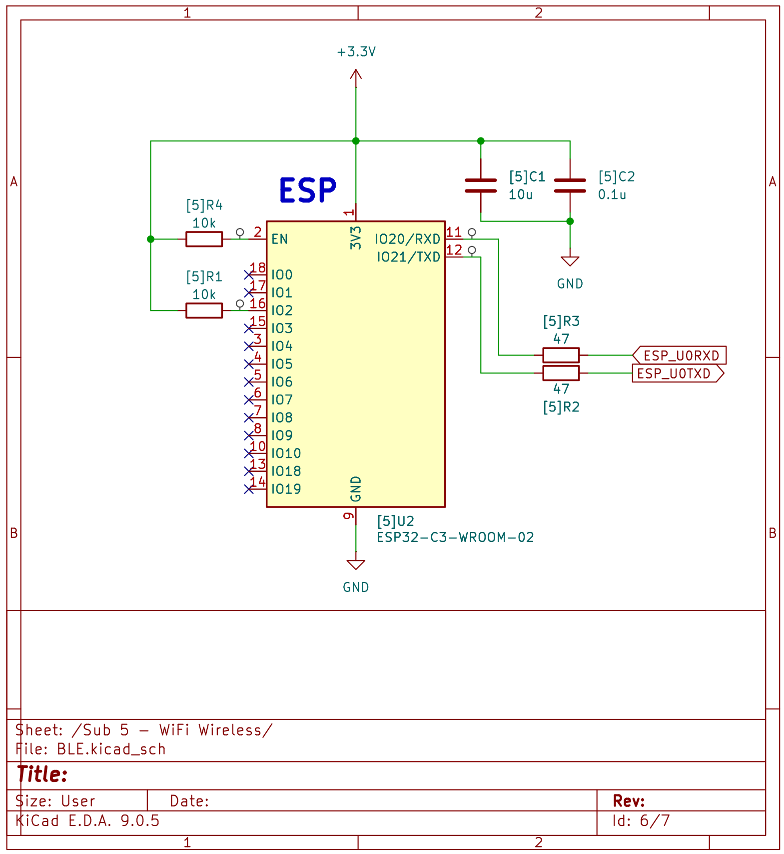

Fig. 6. WiFi Module

the LEDs sit at the board edge for visibility with clear polarity marks on the silkscreen, and the traces are kept short with local ground to keep this little UI quiet and dependable.

3.1.5 WiFi Module. The wireless link is built around ESP32-C3-WROOM-02 as shown in FIg.6, used purely as a UART-controlled uplink so the MCU can keep its radio off at sea and push logs when infrastructure is available. In the schematic, the module's UART0 pins are brought out as U0RXD (GPIO20) and U0TXD (GPIO21) to the STM32's LPUART through short 47 Ω series dampers for edge-rate control; this pin mapping is the module's default assignment for UART0[2].

Power is tied to the common 3.3 V rail with local input/output decoupling beside the module pads, and the EN pin is held high through a pull-up so the radio is enabled after reset (Espressif explicitly cautions not to leave EN floating)[3].

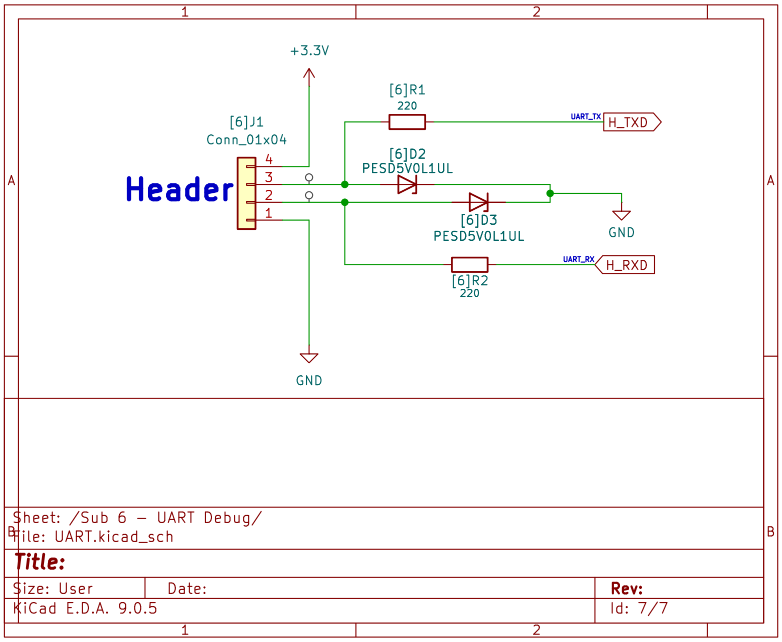

Fig. 7. UART Debug

Because the WROOM-02 variant includes an on-board PCB antenna, the board only enforces a keep-out at the module edge—there is no RF feed, matching network, or coax on our PCB. If a future enclosure demands an external antenna, the footprint remains compatible with WROOM-02U (same platform, U.FL connector[2]).

Finally, the C3 family's strapping/boot pins are respected per the datasheet so the module comes up in normal SPI-boot; no special wiring is needed beyond keeping EN stable during reset. (Espressif documents GPIO8/9 strapping behavior and EN timing/hold.[2])

Net effect. The module integrates the RF, flash, and antenna so our sheet stays compact: one 3.3 V supply with local caps, a clean UART pair to the MCU, and a mechanical keep-out for the antenna—minimal risk, easy bring-up, and headroom to migrate to an external-antenna sibling if deployment conditions require it.

3.1.6 UART Debug. The debug port in Fig.7 is a simple three-wire UART (TX, RX, GND) that gives us a console without needing a probe. In the schematic, PA9/PA10 are assigned to USART1 TX/RX, broken out to a small header near the board edge.

Signals are 3.3 V TTL level, intended to plug straight into a USB-to-UART cable/dongle; no level shifting is required, only the usual cross-over (MCU-TX → adapter-RX, MCU-RX → adapter-TX).Short 47 Ω series resistors at the MCU pins tame edge rates and reduce stub ringing on a flying lead. Ground is provided on the adjacent pin so field techs can clip a dongle with minimal fuss.

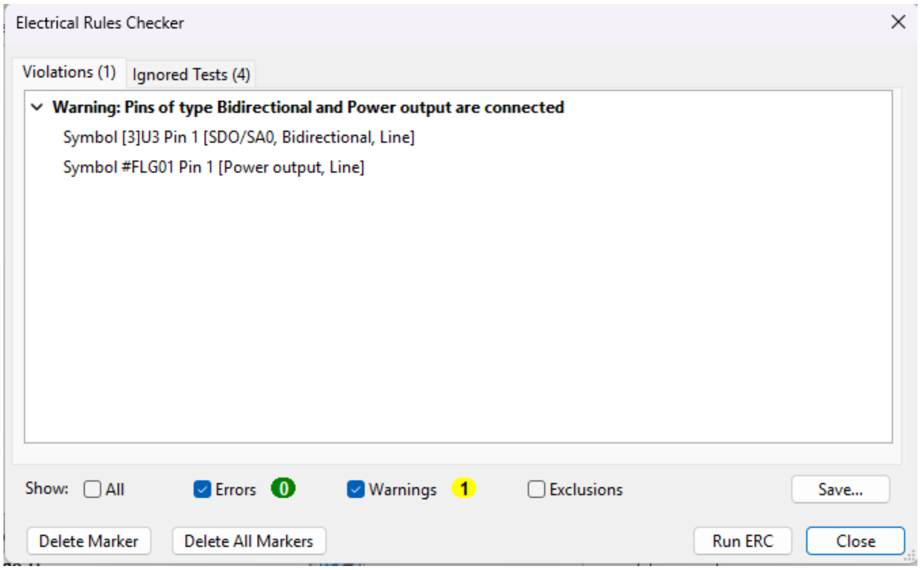

Fig. 8. Schematic ERC Result

This header is optional—SWD already handles programming and breakpoints—but it is valuable insurance: when a board is on a pallet or at a warehouse bench, engineers can still read boot banners, firmware versions, fault codes, or interact with a tiny CLI using only a $5 UART adapter. If recovery is ever needed, STM32 devices expose a ROM bootloader that supports USART; keeping a UART pad trio means we always have a documented path to re-flash or interrogate a misbehaving unit without opening the PCB stack[20][19].

For robustness, the header is receive-only by default during normal operation (logs on TX), with RX enabled for service commands; the net is labeled clearly, pads are test-probe friendly, and no power is exported on the header to avoid accidental back-feeding.

3.2 ERC

No Error as shown in Fig.8.

3.3 PCB

The PCB uses a four-layer stack: Signal – Ground – Ground – Signal. Outer copper is 0.035 mm, inner planes 0.0152 mm. Dimensions and impedance targets were derived using the manufacturer's (JLCPCB) stackup calculator. Annular rings follow:

$$\textbf{annularring} = \frac{\textbf{paddiameter} - \textbf{drilldiameter} + \textbf{safety margin}}{\textbf{2}} \tag{1}$$

Routing classes. Signal traces are 0.19-0.20 mm; power traces are 0.30 mm (3.3 V) and 0.50 mm (5 V) to limit IR drop and improve thermal spreading. USB D+/D- are routed as edge-coupled microstrip to the calculator's differential-impedance targets; single-ended controlled-impedance runs use the corresponding widths from the same stack.

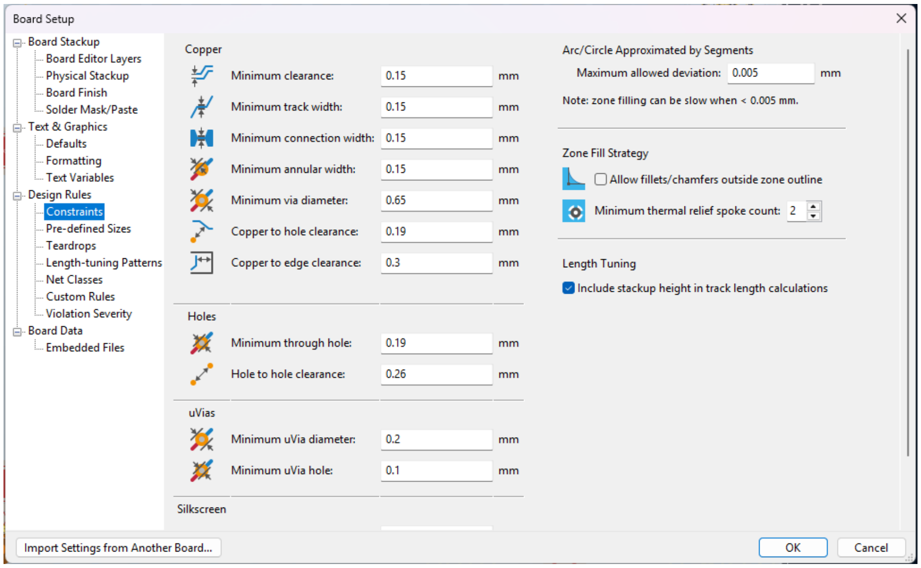

Fig. 9. PCB Design Physical Constraints

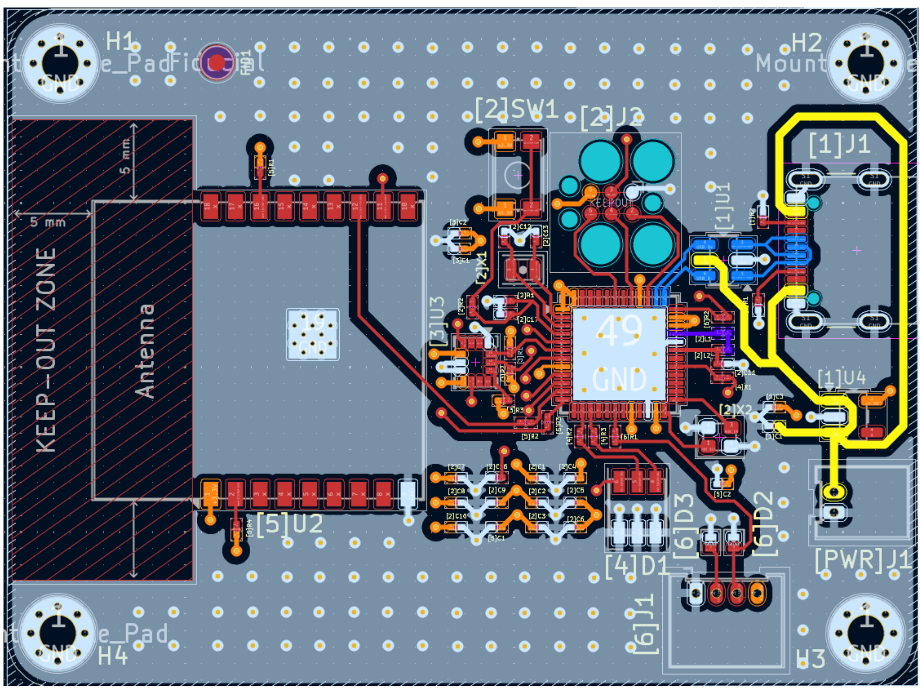

Fig. 10. PCB Design Top Layer View

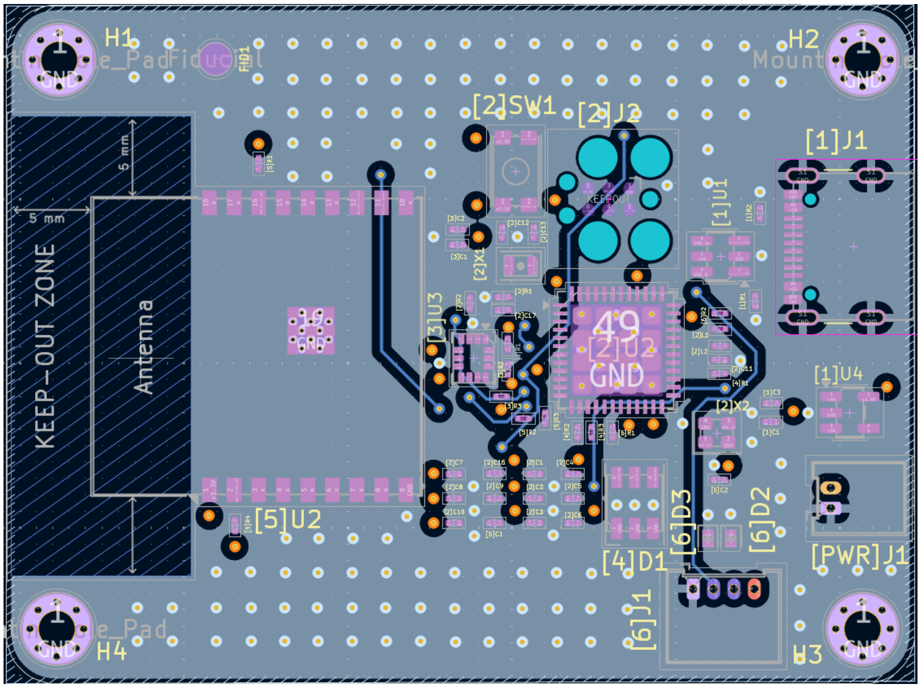

Fig. 11. PCB Design Bottom Layer View

Grounding strategy. A continuous L2/L3 ground core is maintained; signal layers reference these planes without splits. Unused copper on signal layers is poured to GND and stitched with frequent vias. Dense stitching (typ. 2–5 mm pitch, higher near I/O, clocks, and along the ESP32-C3 antenna keep-out boundary) (i) shortens high-frequency return paths and lowers ground AC impedance, (ii) reduces loop area and EMI (emissions and susceptibility), (iii) limits common-impedance coupling between subsystems (USB, clocks, IMU, radio), (iv) damps plane resonances on larger copper regions, and (v) improves thermal spreading from hot devices into the ground core. Stitching remains outside the antenna keep-out to avoid detuning while a via "fence" at its edge helps contain return currents.

Mechanical & assembly features. Four corner mounting holes provide mechanical anchoring, limit board flex, and offer optional chassis-to-ground tie points. Fiducials (global and local) support pick-and-place vision alignment, improving placement accuracy for fine-pitch parts and the RF module.

Vias & manufacturability. The minimum via uses a 0.60 mm pad / 0.25 mm drill, chosen to stay within standard, low-cost fabrication. Vias are used to transition congested routes between outer layers while preserving continuous planes on the inner layers.

Overall, the stack and rules prioritize clean return paths, predictable impedance, and factory-friendly fabrication while meeting the USB and RF placement constraints.

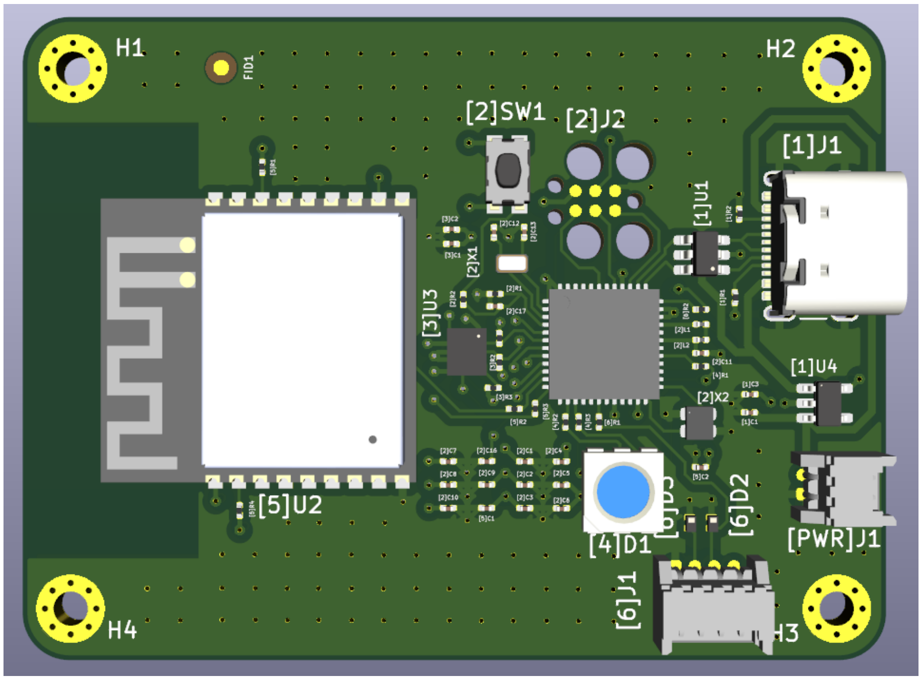

Fig. 12. PCB 3D Model Front View

3.4 3D Model

The 3D PCB model of the IoT device is presented in both front & back views in Fig.12 & Fig.13. All components have corresponding 3D representations, either sourced from the KiCad 3D model library or obtained from verified online libraries[4][10][22].

3.5 DRC

No Error as shown in Fig.14.

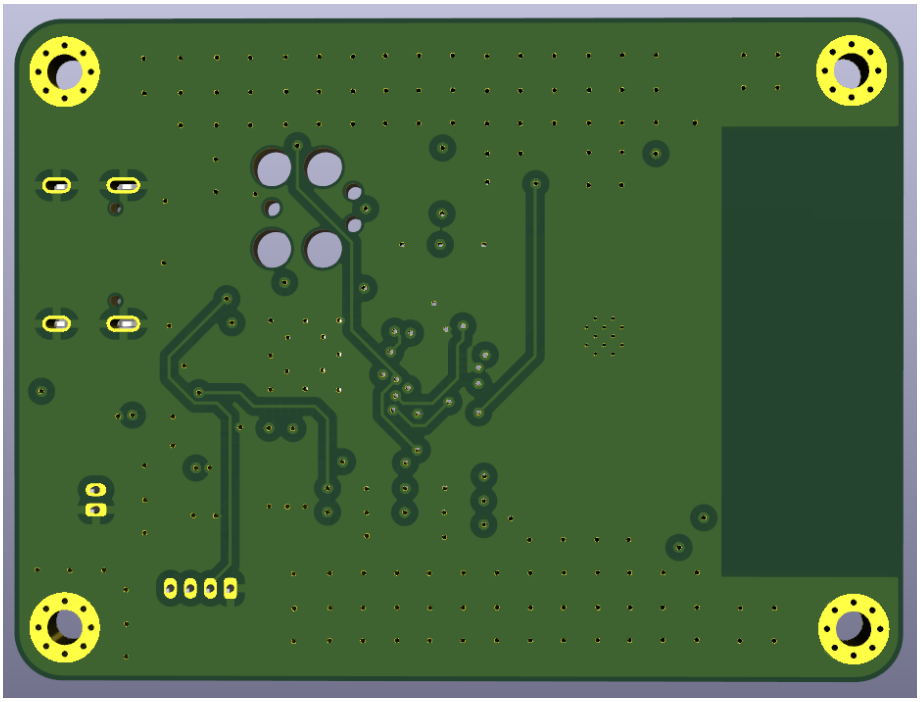

Fig. 13. PCB 3D Model Back View

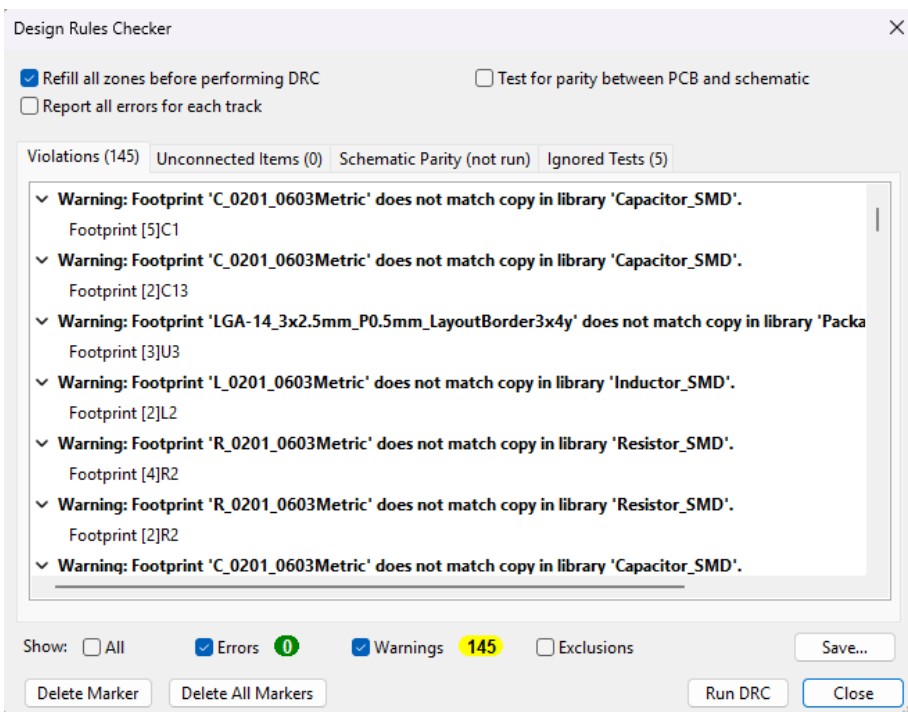

Fig. 14. PCB DRC Result

3.6 BOM

As the screenshot of the BOM in Fig.15 cannot display all the detailed information contained in the BOM .xlsx file, the complete .xlsx file has been included in the project's .zip archive to allow clear and comprehensive viewing.

Reference	Qty	Manufacturer Part Number	Manufacturer	Footprint	Value	Distributor Link
[1]C1,[1]C3,[5]C1	3	ZRB18AR61E106ME01L	MURATA	Capacitor_SMD:C_0201_0603Metric	10u	https://cpc.farnell.com/murata/zrb18ar61e106me01l/
[1]J1	1	USB4105-GF-A	GCT	Connector_USB:USB_C_Receptacle_GCT_USB4105-xx-A_16P_TopMnt_Horizonta	USB_C_Receptacle_USB2.0_16P	https://www.mouser.co.uk/ProductDetail/GCT/USB41
[1]R1,[1]R2,[2]R2	3	CR0603-FX-5101ELF	BOURNS	Resistor_SMD:R_0201_0603Metric	5.1k	https://cpc.farnell.com/bourns/cr0603-fx-5101elf/res
[1]U1	1	USBLC6-2SC6Y	STMICROELECTRONICS	Package_TO_SOT_SMD:SOT-23-6	USBLC6-2SC6	https://cpc.farnell.com/stmicroelectronics/usblc6-2sc
[1]U4	1	MIC5365-3.3YD5-TR	Microchip Technology	Package_TO_SOT_SMD:TSOT-23-5	MIC5365-3.3YD5	https://www.mouser.co.uk/ProductDetail/Microchip-T
[2]C1,[2]C8,[2]C11	3	C1608X7S1A475K080AC	TDK	Capacitor_SMD:C_0201_0603Metric	4.7u	https://cpc.farnell.com/tdk/c1608x7s1a475k080ac/ca
[2]C2,[2]C3,[2]C4,[2]C5,[2]C6,[2]C7,[2]C9,[2]10,[2]C16,[2]:	10	C0603X5R1E104K030BB	TDK	Capacitor_SMD:C_0201_0603Metric	100n	https://cpc.farnell.com/tdk/c0603x5r1e104k030bb/ca
[2]C12,[2]C13	2	GRM0335C1E100JA01D	MURATA	Capacitor_SMD:C_0201_0603Metric	10p	https://cpc.farnell.com/murata/grm0335c1e100ja01d/
[2]J2	1	TC2030-MCP-NL	Tag-Connect LLC	Connector:Tag-Connect_TC2030-IDC-FP_2x03_P1.27mm_Vertical	Conn_ARM_SWD_TagConnect_TC	https://www.digikey.co.uk/en/products/detail/tag-co
[2]L1	1	0603HP-10NXGLW	COILCRAFT	Inductor_SMD:L_0201_0603Metric	10n	https://uk.farnell.com/coilcraft/0603hp-10nxglw/indu
[2]L2	1	7447610410	Wurth Elektronik	Inductor_SMD:L_0201_0603Metric	10u	https://www.mouser.co.uk/ProductDetail/Wurth-Elekt
[2]R1	1	183-9504	RS PRO	Resistor_SMD:R_0201_0603Metric	100	https://uk.rs-online.com/web/p/surface-mount-resist
[2]SW1	1	KMR232NG ULC LFS	C&K	Button_Switch_SMD:SW_Push_1P1T_NO_CK_KMR2	SW_Push	https://www.mouser.co.uk/ProductDetail/CK/KMR232
[2]U2	1	STM32WB55CEU6	STMicroelectronics	Package_DFN_QFN:QFN-48-1EP_7x7mm_P0.5mm_EP5.6x5.6mm	STM32WB55CEUx	https://www.digikey.co.uk/en/products/detail/stmicro
[2]X1	1	NX2012SA-32.768K-STD-MUB-1	NDK	Crystal:Crystal_SMD_2012-2Pin_2.0x1.2mm	32kHz768	https://www.mouser.co.uk/ProductDetail/NDK/NX201
[2]X2	1	NX2016SA-32M-EXS00A-CS06465	NDK	Crystal:Crystal_SMD_2016-4Pin_2.0x1.6mm	32MHz	https://www.mouser.co.uk/ProductDetail/NDK/NX201
[3]C1	1	KAM03CT70G105MH	KYOCERA AVX	Capacitor_SMD:C_0201_0603Metric	1 uF	https://www.mouser.co.uk/ProductDetail/KYOCERA-A
[3]C2	1	02016C104KAT2A	KYOCERA AVX	Capacitor_SMD:C_0201_0603Metric	0.1 uF	https://www.mouser.co.uk/ProductDetail/KYOCERA-A
[3]R1,[3]R2	2	183-9527	RS PRO	Resistor_SMD:R_0201_0603Metric	4.7k	https://uk.rs-online.com/web/p/surface-mount-resist
[3]R3,[5]R1,[5]R4	3	RC0201FR-0710KL	Yageo	Resistor_SMD:R_0201_0603Metric	10k	https://uk.farnell.com/yageo/rc0201fr-0710kl/res-10k
[3]U3	1	LSM6DSO32TR	STMicroelectronics	Package_LGA:LGA-14_3x2.5mm_P0.5mm_LayoutBorder3x4y	LSM6DS3	https://www.mouser.co.uk/ProductDetail/STMicroelec
[4]D1	1	VLMRGB6122-B00-08	RS	LED_SMD:LED_RGB_PLCC-6	LED_RGB	https://uk.rs-online.com/web/p/leds/0637771?cm_m
[4]R1,[4]R2	2	RC0201FR-071KL	YAGEO	Resistor_SMD:R_0201_0603Metric	1k	https://uk.farnell.com/yageo/rc0201fr-071kl/res-1k-1
[4]R3	1	RG0603P-331-D-T10	Susumu	Resistor_SMD:R_0201_0603Metric	330	https://www.digikey.co.uk/en/products/detail/susumu
[5]C2	1	06031C104KAT2A	KYOCERA AVX	Capacitor_SMD:C_0201_0603Metric	0.1u	https://cpc.farnell.com/kyocera-avx/06031c104kat2a/
[5]R2,[5]R3	2	RC0201FR-0747RL	Yageo	Resistor_SMD:R_0201_0603Metric	47	https://www.digikey.co.uk/en/products/detail/yageo/
[5]U2	1	ESP32-C3-WROOM-02-N4	Espressif Systems	RF_Module:ESP32-C3-WROOM-02	ESP32-C3-WROOM-02	https://www.mouser.co.uk/ProductDetail/Espressif-Sy
[6]D2,[6]D3	2	PESD5V0L1UL	EVVO	Diode_SMD:D_SOD-882	PESD5V0L1UL	https://www.digikey.co.uk/en/products/detail/evvo/P
[6]J1	1	530480410	Molex	Connector_Molex:Molex_PicoBlade_53048-0410_1x04_P1.25mm_Horizontal	Conn_01x04	https://www.digikey.co.uk/en/products/detail/molex/
[6]R1,[6]R2	2	RC0201FR-07220RL	Yageo	Resistor_SMD:R_0201_0603Metric	220	https://uk.rs-online.com/web/p/surface-mount-resist

Fig. 15. Bill of Materials

4 Conclusion

This work presented the hardware design of a compact, low-power marine cargo motion tag that records tilt/shock events and offloads logs opportunistically. The system integrates an STM32WB55 MCU, LSM6DS3 IMU on I²C, a UART-controlled ESP32-C3-WROOM-02 for Wi-Fi backhaul, and simple GPIO LED indicators, all powered from a 5 V battery pack regulated to a unified 3.3 V rail. A USB-C port provides a deterministic wired path for configuration, diagnostics, and bench power; a SWD Tag-Connect and UART debug header support bring-up and field priority. The electronics are realized on a four-layer S-G-P-S PCB with a continuous ground core, differential routing for USB, antenna keep-out for the on-module radiator, and dense ground stitching for EMC and thermal performance.

The design meets the coursework requirements (USB data + power path available, multiple serial protocols, wireless link, sensor, actuator) while emphasizing manufacturability and extensibility: common footprints, DNP options (e.g., crystals), and pin-compatible paths (e.g., external-antenna module variant) reduce re-spin risk.

Planned next steps are firmware implementation (interrupt-driven logging, duty-cycled uploads, health reporting), sensor calibration and threshold tuning, power profiling to validate endurance targets, and environmental tests (vibration/shock/temperature). Future work may add secure update/boot, BLE beacons for warehouse proximity, battery management for rechargeables, and enclosure-level sealing and certification. Together, the platform provides a robust hardware foundation for objective, field-ready cargo handling evidence in marine insurance workflows.

References

[1] Espressif Systems. 2025. ESP32-C3: Single-core Wi-Fi and Bluetooth 5 (LE) RISC-V SoC. Product Webpage. https://www.espressif.com/en/products/socs/esp32-c3 Accessed: November 9, 2025.

[2] Espressif Systems. 2025. ESP32-C3-WROOM-02 Datasheet. Datasheet. https://documentation.espressif.com/esp32-c3-wroom-02_datasheet_en.pdf Document Version 1.6.

[3] Federal Communications Commission. 2022. Grant of Equipment Authorization, FCC ID: 2AC7Z-ESPC3WROOM. FCC Report. https://fcc.report/FCC-ID/2AC7Z-ESPC3WROOM/5875713.pdf FCC ID: 2AC7Z-ESPC3WROOM Pre-release v0.1.

[4] GrabCAD. 2025. GrabCAD Community Library. Online CAD Repository. https://grabcad.com/library Accessed: November 10, 2025.

[5] LSM6DS3TR-C. 2017. LSM6DS3TR-C: iNEMO inertial module always-on 3D accelerometer and 3D gyroscope. Datasheet. https://www.st.com/en/mems-and-sensors/lsm6ds3tr-c.html#documentation DocID030071 Rev 3.

[6] Microchip Technology. 2013. MIC5365 150 mA, Low-Noise, Ultra-Fast, Low-Dropout Regulator. Datasheet. https://ww1.microchip.com/downloads/en/DeviceDoc/mic5365.pdf Document DS20005798A Revision 3.1.

[7] Nexperia. [n. d.]. N-channel Trench MOSFETs in SOT223-3 and SOT404 Packages. Application Note. https://assets.nexperia.com/documents/application-note/AN10753.pdf AN10753.

[8] Renesas. 2025. USB Power Delivery 03: What are the main features of USB PD? Engineer School / Web Tutorial. https://www.renesas.com/en/support/engineer-school/usb-power-delivery-03 Accessed: November 9, 2025.

[9] Shenzen Ai-Thinker Technology CO., Ltd. 2018. ESP-12F Datasheet. Datasheet. https://www.quick-teck.co.uk/Management/EEUploadFile/1548298650.pdf Document Version V1.

[10] SnapEDA. 2025. SnapEDA: Search Engine for Electronic Components. Website. https://www.snapeda.com/home/ Accessed: November 9, 2025.

[11] STMicroelectronics. 2021. STM32CubeIDE. Data Brief. https://www.st.com/resource/en/data_brief/stm32cubeide.pdf Document DB3871 Rev 6.

[12] STMicroelectronics. 2021. USBLC6-2: Low capacitance ESD protection to IEC 61000-4-2 for USB and high speed buses. Datasheet. https://www.st.com/resource/en/datasheet/usblc6-2.pdf Document DS4260 Rev 7.

[13] STMicroelectronics. 2022. STM32WB55xx Microcontrollers Reference Manual. Reference Manual. https://cdn.sparkfun.com/assets/1/6/c/b/b/STM32WB55xx_Reference_Manual.pdf RM0434 Rev 10.

[14] STMicroelectronics. 2023. How to use SMPS to improve power efficiency on STM32WB MCUs. Application Note. https://www.st.com/resource/en/application_note/an5246-how-to-use-smps-to-improve-power-efficiency-on-stm32wb-mcus-stmicroelectronics.pdf AN5246 Rev 4.

[15] STMicroelectronics. 2024. How to develop RF hardware using STM32WB microcontrollers. Application Note. https://www.st.com/resource/en/application_note/an5165-how-to-develop-rf-hardware-using-stm32wb-microcontrollers-stmicroelectronics.pdf AN5165 Rev 10.

[16] STMicroelectronics. 2024. ST-LINK/V2 in-circuit debugger/programmer for STM8 and STM32. User Manual. https://www.st.com/resource/en/user_manual/um1075-stlinkv2-incircuit-debuggerprogrammer-for-stm8-and-stm32-stmicroelectronics.pdf UM1075 Rev 10.

[17] STMicroelectronics. 2024. STM32WB55xx STM32WB35xx - Multiprotocol wireless 32-bit MCU Arm. Datasheet. https://www.st.com/resource/en/datasheet/stm32wb55cc.pdf Document DS11929 Rev 17.

[18] STMicroelectronics. 2025. Official Website. Web Page. https://www.st.com/content/st_com/en.html

[19] STMicroelectronics. 2025. STM32 microcontroller system memory boot mode. Application Note. https://www.st.com/resource/en/application_note/an2606-stm32-microcontroller-system-memory-boot-mode-stmicroelectronics.pdf AN2606 Rev 68.

[20] STMicroelectronics. 2025. USART protocol used in the STM32 bootloader. Application Note. https://www.st.com/resource/en/application_note/an3155-usart-protocol-used-in-the-stm32-bootloader-stmicroelectronics.pdf AN3155 Rev 20.

[21] Texas Instruments. 2024. ESD and Surge Protection for USB Interfaces. Application Report. https://www.ti.com/lit/an/slvaf82b/slvaf82b.pdf SLVAF82B.

[22] TraceParts. 2025. Engineers and Designers Portal: 3D Models and CAD Data. Web Portal. https://info.traceparts.com/designers/engineers-and-designers/ Accessed: November 10, 2025.

[23] USB Implementers Forum. 2019. USB Type-C Specification, Release 2.0. Technical Standard. https://www.usb.org/sites/default/files/USB%20Type-C%20Spec%20R2.0%20-%20August%202019.pdf Version Release 2.0.

[24] USB Implementers Forum. 2021. USB Type-C Cable and Connector Specification. Technical Standard. https://www.usb.org/usb-type-cr-cable-and-connector-specification Accessed: November 9, 2025.

Attached with screenshots proof of components remain in-stock status in JLCPCB.

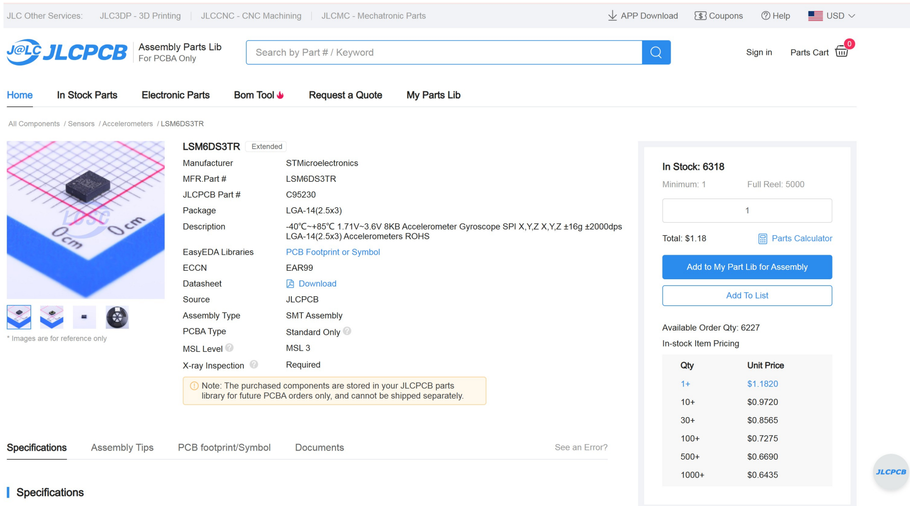

Fig. 16. Motion Sensor Stock

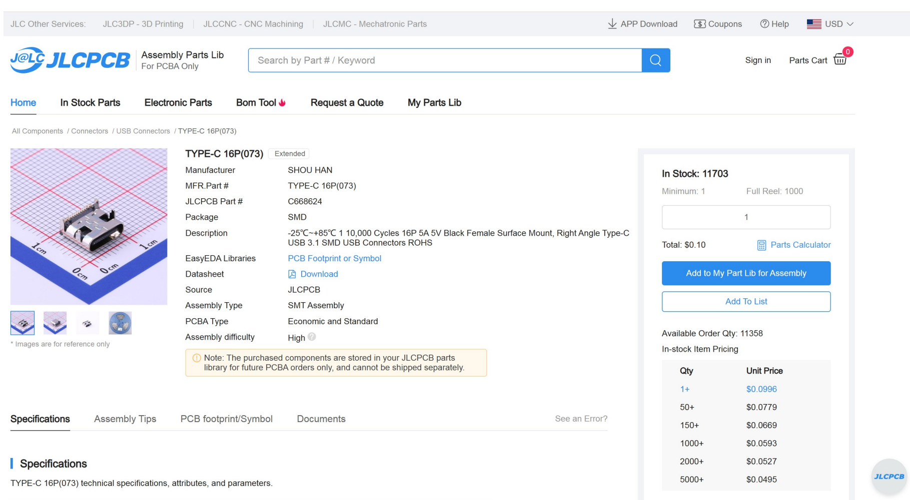

Fig. 17. USB-C Port Stock

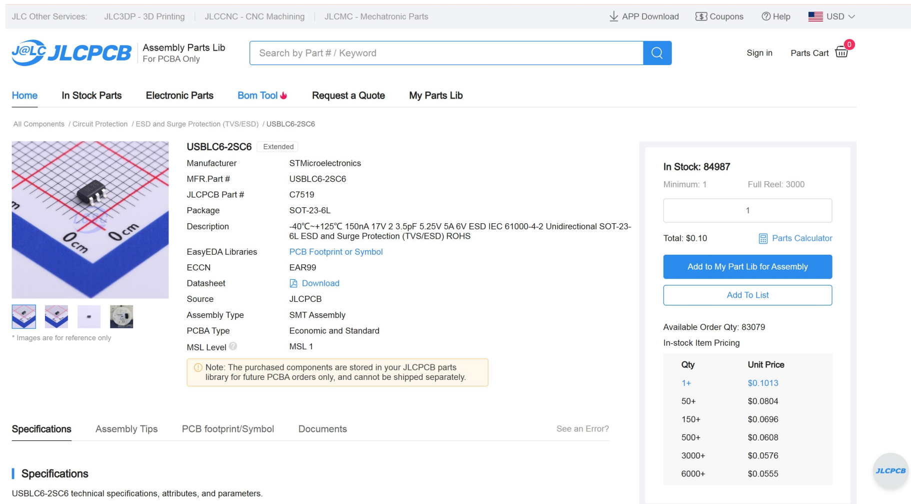

Fig. 18. ESD Stock

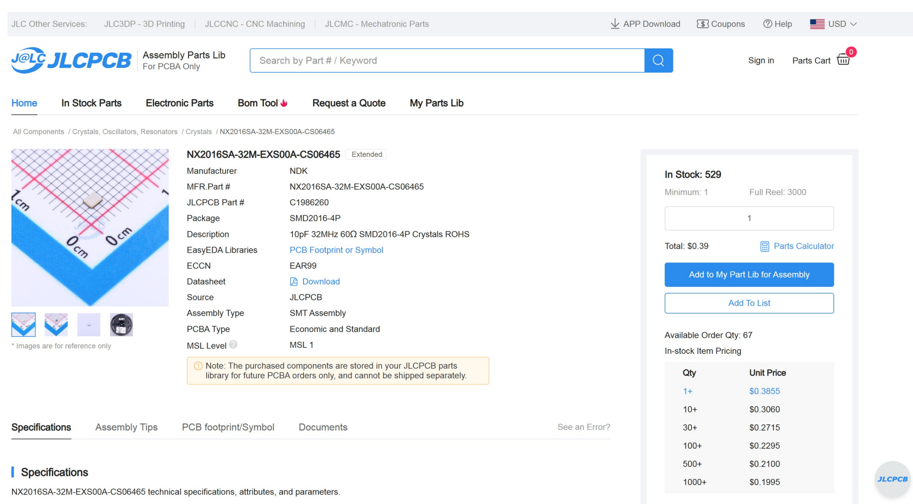

Fig. 19. Crystal Stock

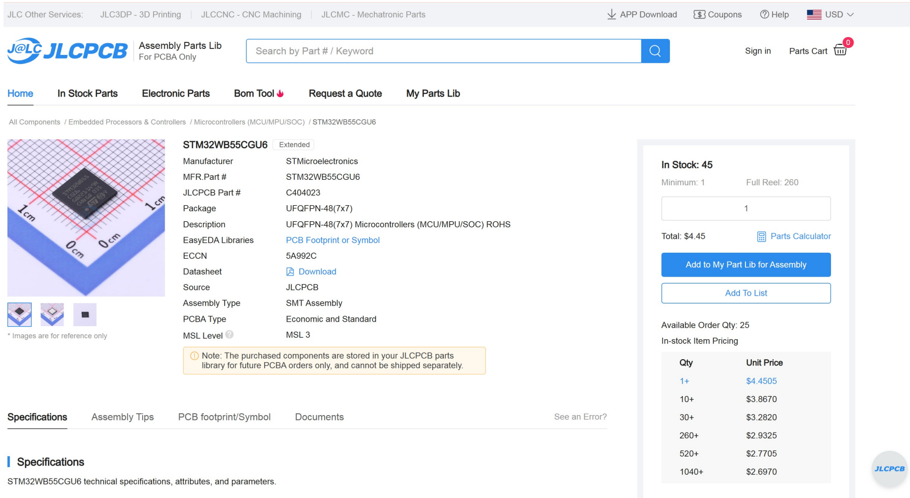

Fig. 20. MCU Stock

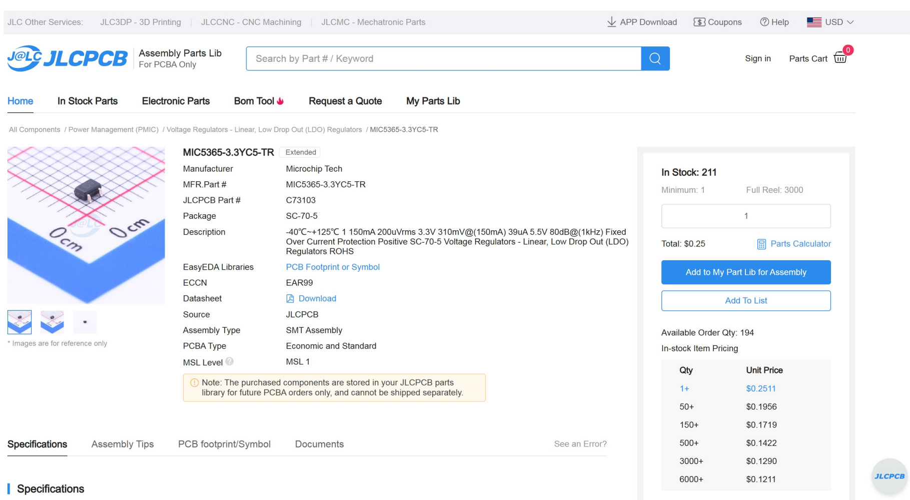

Fig. 21. LDO Stock

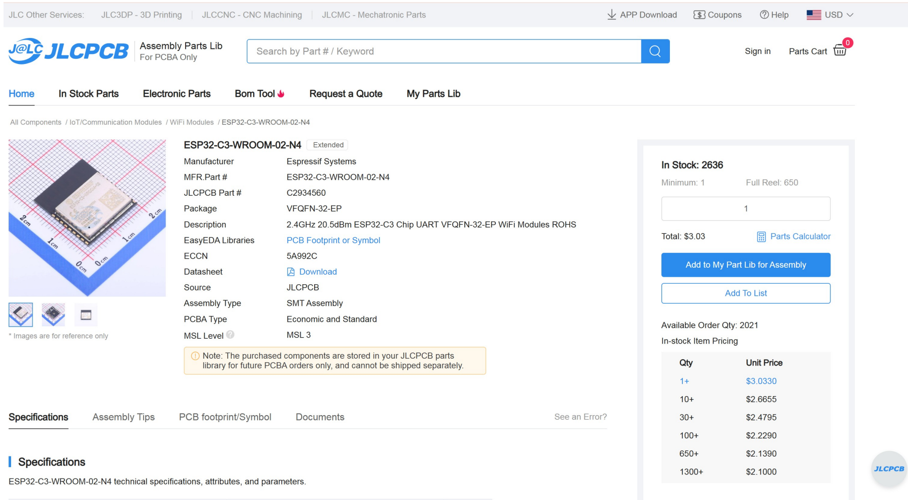

Fig. 22. WiFi Module Stock

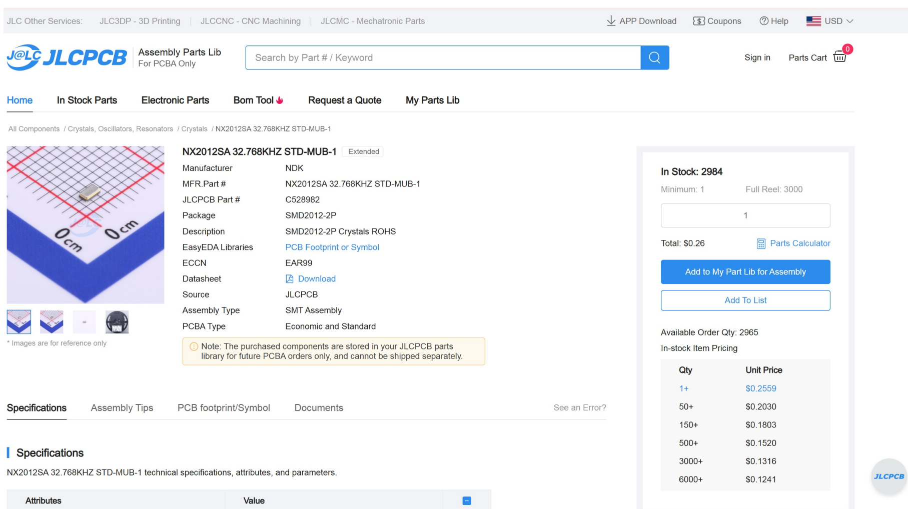

Fig. 23. Crystal Stock