University of Moratuwa: Electronic Design Realization

NEURAL NEXUS

Advanced 6-DOF Robotic & AI Ecosystems for Precision Automation

Team Neural Nexus

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Abstract

The global industrial robotics market is experiencing unprecedented growth, yet advanced 6-Degree-of-Freedom (DOF) robotic arms remain prohibitively expensive for Small and Medium Enterprises (SMEs) in developing nations like Sri Lanka. This report details the technical development, business strategy, and commercialization roadmap of Neural Nexus: an affordable, high-precision 6-DOF robotic arm engineered for localized manufacturing. Utilizing a distributed control architecture, the system currently employs standard terminal interfaces for command routing, with a dedicated touch-enabled Human-Machine Interface (HMI) slated as a premium future add-on. A sophisticated MATLAB-based Digital Twin leverages a dedicated Inverse Kinematics (IK) model for complex trajectory simulation and collision validation, mitigating operational risks. The validated spatial coordinates are subsequently executed by a custom PCB built around an STM32H743VIT6 Master Control Unit (MCU), which drives all six axes and closes the position loop using AS5047P magnetic absolute encoders read over SPI on every joint. At a total project value of approximately 568,982.27 LKR and a strategic retail price of 1,500,000 LKR, this ecosystem undercuts imported alternatives by over 25–33% while maintaining industrial-grade performance, offering local SMEs a highly lucrative, rapid-ROI pathway to Industry 4.0 automation.

Contents

Chapter 1

Problem Description, Motivation, and Justification

1.1 The Market Gap and Macroeconomic Drivers

The global market for industrial robotics is projected to escalate from $1.2 billion in 2023 to $10.5 billion by 2030, representing a Compound Annual Growth Rate (CAGR) of 36%. Concurrently, post-pandemic supply chain disruptions and persistent labor shortages have driven a 28% increase in Small and Medium Enterprise (SME) automation adoption globally.

However, in developing markets like Sri Lanka, a critical market failure exists driven by severe macroeconomic factors. Severe foreign exchange fluctuations (most recently during the 2022 balance-of-payments crisis), high import taxation, and extended shipping delays (often 6 to 8 months) drastically inflate the landed cost of capital machinery. Currently, entry-level industrial 6-DOF arms cost between $15,000 and $80,000 upfront. Once imported, this Capital Expenditure (CAPEX) becomes entirely inaccessible to local SMEs and academic laboratories, stifling industrial modernization and economic growth.

1.2 Local Market Context: Sri Lanka

Beyond the global figures above, several Sri Lanka-specific indicators sharpen the case for a locally manufactured arm:

- **SMEs are the backbone of the local economy.** Small and Medium Enterprises account for over 75% of all active businesses in Sri Lanka, contribute approximately 52% of GDP, and provide around 45% of national employment. Within the manufacturing sector specifically, small and medium-scale industries make up roughly 96% of industrial units and about 36% of industrial employment—meaning the vast majority of Sri Lanka's manufacturing base is precisely the CAPEX-constrained customer segment Neural Nexus targets, rather than a handful of large conglomerates.
- **The import duty structure compounds against capital machinery.** Imports into Sri Lanka are subject to a stacked tax structure: an 18% Value Added Tax (VAT), a 7.5% Ports and Airports Development Levy (PAL), and a 2.5% Social Security

Contribution Levy (SSCL), applied cumulatively on top of any applicable Customs Import Duty, with VAT calculated last on the full duty-inclusive value. Even where capital machinery qualifies for a concessionary customs duty rate, the PAL/SSCL/VAT stack alone typically adds on the order of 25–30% to the landed cost, on top of freight, insurance, and clearance charges—directly corroborating the CAPEX inflation problem described above.

- **Rising local labor costs strengthen the automation ROI case.** Wage inflation in Sri Lanka's manufacturing sector, alongside statutory contributions (EPF/ETF) and overtime premiums, makes repetitive-task automation an increasingly attractive OPEX trade-off for local factory owners, reinforcing the ROI case built in Chapter 8.
- **Local demand for robotics education already exists—supply does not.** Multiple Sri Lankan universities (including the University of Moratuwa, SLIIT, the Open University of Sri Lanka, and CINEC Campus) already run dedicated Mechatronics or Robotics and Automation degree programmes, confirming strong latent academic demand. However, based on our review of publicly available laboratory facilities, none of these programmes currently have hands-on access to a locally supported, industrial-grade, programmable 6-DOF arm; robotics and automation modules are taught predominantly through simulation software or small hobbyist-grade kits, since the same import-cost barrier described above applies equally to educational procurement budgets. This is the specific gap Neural Nexus's education bundle (Chapter 9) is designed to fill.
- **The local STEM education market is growing quickly, and pre-university demand is already commercial.** STEM enrolment across selected Sri Lankan higher education institutions grew at roughly 10% per year between 2017 and 2023 under the World Bank-backed AHEAD higher-education reform programme, well ahead of the programme's original target. Below the university level, a maturing ecosystem of private robotics and coding academies (e.g. STEM.org-affiliated centres, dedicated kids' robotics institutes, and project-based STEM labs) is already operating profitably across the country, teaching robotics predominantly with imported hobbyist kits—evidence that Sri Lankan families and institutions are already paying for STEM/robotics instruction, just not yet on industrial-grade hardware.

1.3 Market Evidence Summary

The table below consolidates the market and survey indicators that motivate this project, combining global industry figures with the Sri Lanka-specific data above. These figures were gathered from industry growth reports, Sri Lanka Customs' published tariff schedule, national wage statistics, and a review of local university engineering programmes, and are used as supporting evidence for the problem statement rather than a definitive market study.

Indicator	Value
Entry-level imported 6-DOF arm cost	\$15,000 – \$80,000
Global industrial robotics market (2023)	\$1.2 billion
Global industrial robotics market (2030, projected)	\$10.5 billion
Market CAGR (2023–2030)	36%
Increase in SME automation adoption post-pandemic	28%
Global STEM robotics education market (2024)	\$2.8 billion
Sri Lankan SME contribution to GDP	$\sim$52%
Sri Lankan SME share of active enterprises	>75%
Small/medium-scale industry share of manufacturing units (LK)	$\sim$96%
Combined import levy stack on capital machinery (PAL+SSCL+VAT)	$\sim$25–30%
Sri Lankan universities offering mechatronics/robotics degrees (identified)	4+
Of those, with hands-on lab access to a programmable 6-DOF arm	0
Sri Lanka STEM higher-education enrolment growth (2017–2023)	$\sim$10%/year
Typical import lead time for capital machinery	6–8 months

Table 1.1: Key global and Sri Lanka-specific market indicators supporting the Neural Nexus problem statement

The combination of a fast-growing global market, a structurally CAPEX-constrained local SME manufacturing base, a compounding local import-tax burden, rising local labor costs, and unmet local demand for hands-on robotics education together form the central justification for this project.

1.4 Justification for Selection and Value Proposition

While low-cost, hobbyist-grade robotic alternatives exist on the market, they universally sacrifice precision, payload capacity, and software ecosystem capabilities, rendering them useless for industrial compliance. Currently, no reliable, locally supported mid-tier solution exists that offers sub-millimeter repeatability at an accessible price point. Furthermore, as shown above, no Sri Lankan engineering faculty currently has hands-on access to a programmable 6-DOF arm for STEM curriculum, despite several of them already running dedicated mechatronics and robotics degree programmes (a global educational market valued at $2.8B in 2024).

By developing Neural Nexus—a locally manufactured, high-precision robotic arm—we aggressively penetrate this unserved mid-tier market. Our primary value proposition is delivering industrial-grade automation that drastically lowers the capital barrier to entry for local SMEs, completely bypasses severe import delays, and provides the localized, zero-downtime technical support that foreign competitors fundamentally lack.

Chapter 2

Technical Feasibility and Design for Manufacturability (DFM)

The Neural Nexus project is highly technically feasible. All resource requirements and performance targets are reachable using a strategic combination of locally sourced materials, optimized electronic configurations, and a strong emphasis on Design for Manufacturability (DFM).

2.1 Cost-to-Performance Optimization in Hardware

To achieve industrial repeatability without relying on prohibitively expensive $2,000 servo motors, the mechanical structure utilizes rigid aluminum structural components paired with custom 3D-printed parts. This hybrid material approach provides superior structural rigidity under dynamic loads, excellent heat dissipation, and eliminates flex over the 800mm lever arm, all while keeping chassis fabrication costs exceptionally low and insulated from global supply chain shocks.

For actuation, we utilize a highly calibrated combination of open-loop and closed-loop NEMA stepper motors (NEMA 17, 23, and 24). Paired with TMC2209 and CL57T drivers, this drive-train achieves the extreme microstepping required for precise sub-millimeter repeatability. By utilizing closed-loop steppers on the critical load-bearing joints, we guarantee position retention and eliminate step-loss without the exorbitant costs associated with traditional industrial servos, keeping our Cost of Goods Sold (COGS) strictly within budget.

2.2 Control and Software Feasibility

Beyond the mechanical drive-train, feasibility depends on the reliability of the control and software stack:

- **Kinematics:** The MATLAB Digital Twin uses established closed-form and iterative IK solvers (Robotics System Toolbox) that are well within MATLAB's proven capability envelope for a 6-DOF serial-link manipulator, so no unproven algorithmic risk is carried on the critical path.

- **Firmware:** The STM32H743VIT6 (Arm Cortex-M7, up to 480 MHz) has more than sufficient timer, PWM, and SPI resources to generate jitter-free step/direction pulses for six axes simultaneously while polling six SPI-connected absolute encoders for closed-loop position feedback, well inside its documented real-time performance envelope.
- **Computer Vision:** Object detection and pose estimation run on standard camera hardware using established, pre-trained model architectures, avoiding the need for bespoke model development on the critical path.

2.3 Resource Availability and Procurement Feasibility

All electromechanical components (NEMA motors, TMC2209/CL57T drivers, aluminum stock, fasteners, bearings) are available from local or regional (South/South-East Asian) suppliers with lead times of days to a few weeks, rather than the 6–8 month lead times faced by fully assembled imported arms. This significantly de-risks the project schedule and insulates the Bill of Materials (BOM) from long-haul shipping disruptions.

2.4 Performance Target Validation

Target Metric	Design Target	Feasibility Basis
Repeatability	Sub-millimeter	Closed-loop steppers + microstepping drivers
Payload capacity	2 kg	Torque-matched NEMA 17/23/24 selection
Reach	800 mm	Aluminum link rigidity validated against flex limits
Duty cycle	24/7 continuous	Mains-powered, no battery degradation constraint

Table 2.1: Mapping of design targets to feasibility basis

Chapter 3

Product Architecture

Neural Nexus utilizes a highly modular, distributed control architecture to separate high-level trajectory planning from low-level deterministic motor control, ensuring maximum system stability, scalability, and safety.

3.1 System Block Diagram

Figure 3.1 shows the four functional blocks of the system and the direction of data flow between them: command input and simulation (currently PC-terminal driven, with a touch HMI as a future add-on), the MATLAB Digital Twin, the STM32H743VIT6-based real-time firmware, and the physical hardware, with a dashed feedback path returning per-axis absolute encoder position data back up the chain over a dedicated SPI bus.

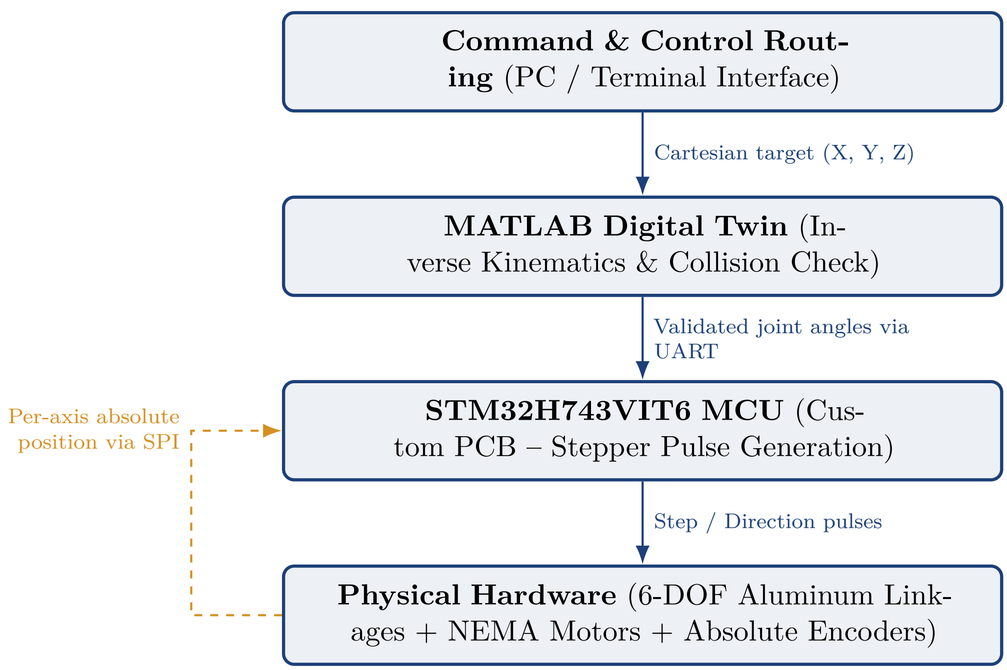


Figure 3.1: Neural Nexus distributed control architecture: command flow (solid) and real-time SPI encoder feedback (dashed).

3.2 Block Descriptions

- **Command & Control Routing:** Currently, user Cartesian targets (X, Y, Z) and operational commands are routed via standard tethered PC interfaces directly into the computational engine. *(Note: A dedicated, physical touch-screen HMI console is planned as a premium, monetizable add-on for enterprise clients, detailed in Chapter 9).*

- **Trajectory Simulation (MATLAB Digital Twin):** The core kinematic calculations have been strategically offloaded to a MATLAB-based Digital Twin, acting as the system's heavy computational engine. This environment runs a sophisticated Inverse Kinematics (IK) model to simulate complex trajectories, verify joint limits, and ensure collision avoidance. From a business perspective, this acts as a critical risk-mitigation tool, preventing costly hardware collisions on the factory floor before any physical motion is executed.

- **Real-Time Edge Firmware (STM32H743VIT6, Custom PCB):** Once validated by the Digital Twin, spatial coordinates are streamed via high-speed UART to a bespoke control board built around an **STM32H743VIT6** microcontroller (Arm Cortex-M7 core, up to 480 MHz, 2 MB Flash, 1 MB RAM, LQFP-100 package). The MCU acts as the deterministic execution layer, translating the calculated joint angles into jitter-free stepper pulses on its dedicated motor-control timer channels. In parallel, it polls a dedicated **SPI bus** to read back absolute position data from a AS5047P magnetic absolute encoder mounted on each of the six axes, closing the position loop entirely on-board without relying on the host PC or the Digital Twin for real-time feedback. The Cortex-M7's headroom (well above what six simultaneous step-pulse trains and six polled SPI encoder channels require) leaves comfortable margin for future features such as on-board safety interlocks or local trajectory smoothing.

- **Physical Hardware:** The execution layer consists of the 6-DOF aluminum linkages driven by the NEMA stepper array, with each axis fitted with a AS5047P magnetic absolute encoder that reports true joint position back to the STM32H743VIT6 over SPI, independent of step-count tracking.

3.3 Deviations from Original Plan

Initially, the Digital Twin and Inverse Kinematics calculations were planned to be executed entirely on a Raspberry Pi edge device. However, during development, we determined that simulating complex 6-DOF kinematics required more robust computational modeling to guarantee industrial safety and precision.

Strategic Pivot: We transitioned the Digital Twin and core IK modeling to run natively on **MATLAB**. This deviation was highly successful. MATLAB's extensive kinematics libraries allowed for far superior trajectory smoothing, error-checking, and visualization compared to our initial embedded approach, resulting in a much more reliable and robust end-product for the consumer.

Interim Mid-Evaluation Architecture: At the mid-evaluation stage, the demonstrator used a fully integrated touch-screen HMI performing on-edge IK directly on a generic STM32 development board alongside the UART/USB control link, to showcase the end-to-end concept on a single self-contained rig. Following the pivot above, the finalized architecture deliberately separates these responsibilities: IK and collision-checking now run on the more computationally capable MATLAB Digital Twin rather than on the MCU, and the touch HMI has been repositioned from a standard included component to a premium add-on (Chapter 9), which also simplifies the base unit's cost structure without removing the option for enterprise customers.

MCU and Feedback Upgrade: The generic development-board STM32 used at mid-evaluation was replaced with a custom PCB built around the **STM32H743VIT6**, selected for its higher timer count, larger SRAM/Flash headroom, and larger number of hardware SPI peripherals. This directly enabled the second key hardware deviation: swapping simple limit-switch-only feedback for **per-motor AS5047P magnetic absolute encoders read over SPI**, giving true closed-loop joint-position awareness on every axis (rather than only end-of-travel detection), which is what ultimately underpins the sub-millimeter repeatability target validated in Chapter 2.

Chapter 4

PCB Design

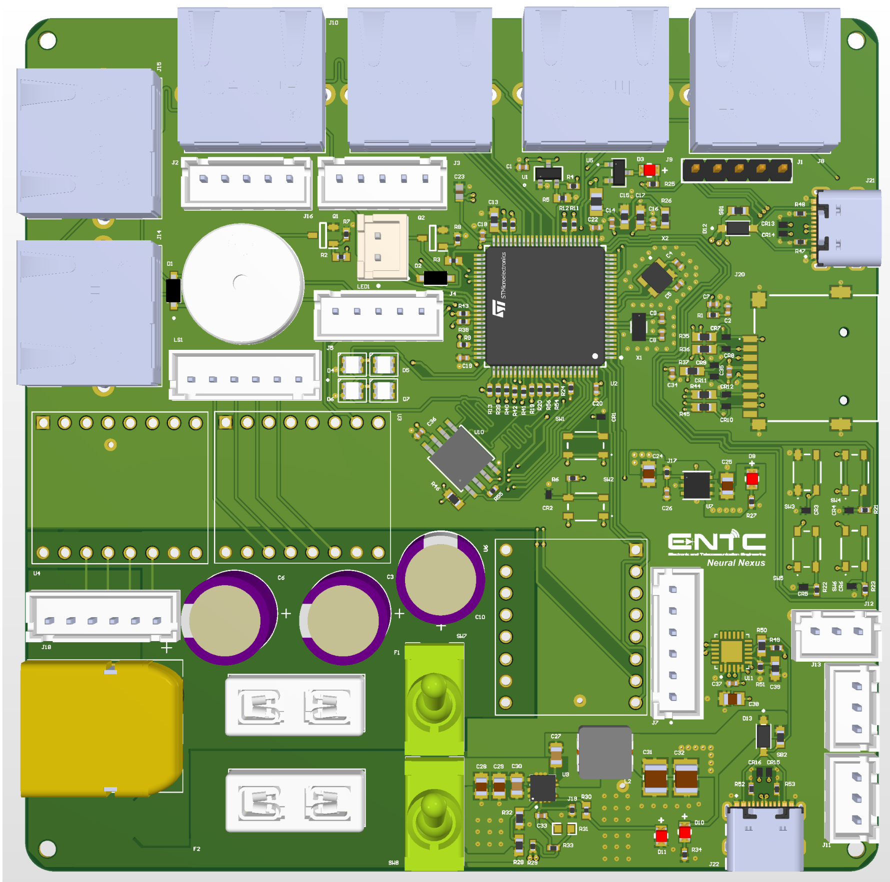


Figure 4.1: Neural Nexus custom control board — 3D render, top (component) side. The STM32H743VIT6 MCU is visible at center, flanked by the RJ-connector bank for the six per-axis SPI absolute encoder / motor driver harnesses (top), USB-C and barrel power input (right), and status LEDs / user switches (bottom right).

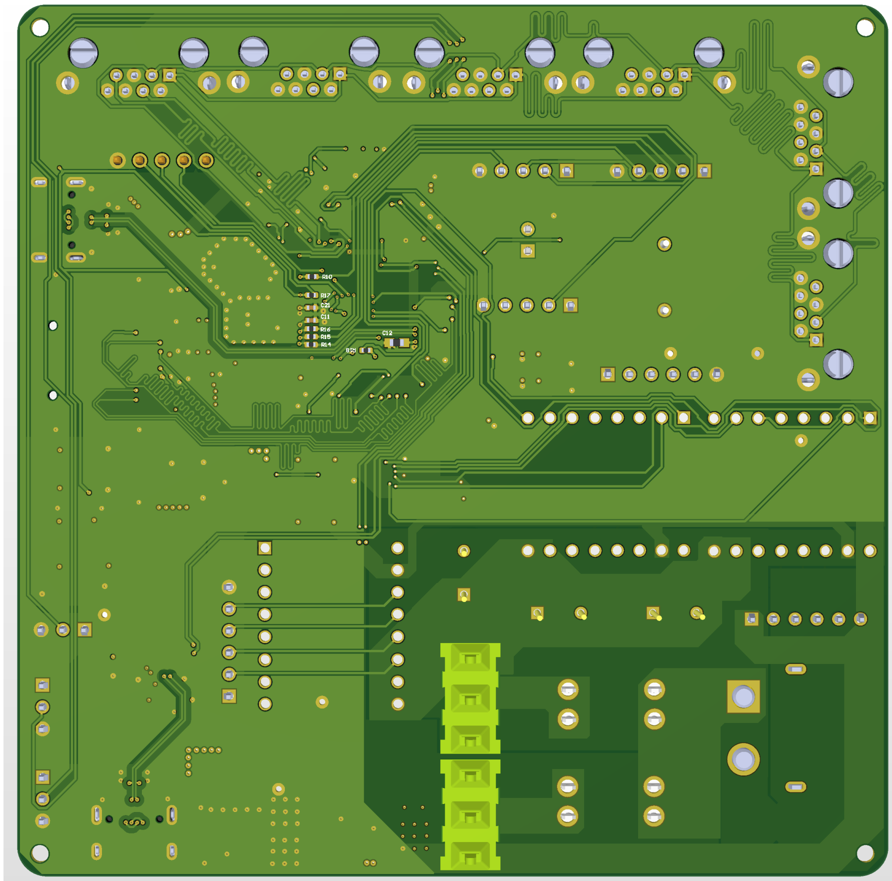


Figure 4.2: Neural Nexus custom control board — 3D render, bottom (routing) side, showing the high-current motor driver copper pours (bottom right, highlighted) kept physically separated from the logic and SPI routing above them.

4.1 Master Control Unit (MCU): STM32H743VIT6

The custom PCB is built around an **STM32H743VIT6** as the Master Control Unit (MCU), replacing the generic development board used at the mid-evaluation stage. As shown in Figure 4.1, the MCU is placed centrally on the board with the six RJ-style motor/encoder harness connectors run along the top edge, minimizing average trace length from the MCU's SPI and timer pins to each axis connector. Key selection and layout considerations:

- **Compute headroom:** The Arm Cortex-M7 core (up to 480 MHz, with FPU and DSP extensions) comfortably services six simultaneous hardware-timer step/direction pulse trains while concurrently polling six SPI encoder channels, and provides the floating-point math throughput needed to support on-board inverse-kinematics routines, with substantial margin left for future features (e.g. local trajectory smoothing or safety interlocks) without a redesign.

- **Memory and peripheral count:** 2 MB of dual-bank Flash and 1 MB of RAM comfortably house the firmware, motion-control lookup tables, and communication buffers, while the device's multiple hardware SPI, UART, and Timer peripherals allow every joint's step generation and encoder polling to be assigned dedicated hardware resources rather than being time-multiplexed in software.

- **Package and footprint:** The LQFP-100 package was chosen over larger BGA H7 variants specifically for hand-solder and low-cost PCBA compatibility during the prototype-to-volume transition described in Chapter 7, avoiding the need for X-ray inspection or specialized reflow profiles associated with BGA assembly.

4.2 Core Component Architecture

Beyond the MCU itself, the logic and control domains of the board are built around high-performance processing and precise absolute feedback, summarized below.

Absolute Position Encoders: AS5047P

Each of the six axes is fitted with an **AS5047P** magnetic absolute position sensor for closed-loop feedback, communicating with the STM32H743VIT6 over a dedicated high-speed SPI bus rather than relying solely on open-loop step counting or end-of-travel limit switches. This has direct layout consequences for the PCB:

- **Bus topology:** Each AS5047P is wired to a shared SPI clock and data pair with an individual chip-select (CS) line per axis, allowing the MCU to address each of the six encoders independently on a single physical bus while keeping the harness wire count low.
- **Signal integrity:** Because the AS5047P's SPI link operates in the electrically noisy environment created by nearby stepper motor switching, strict signal integrity practices — impedance-controlled routing, ground-plane referencing, and physical separation from motor phase traces — are required to ensure position data is not corrupted in transit; see Section 4.4 for the specific routing techniques used.
- **Closed-loop benefit:** Because absolute encoders report true joint position rather than accumulated step count, the system inherently self-corrects for any missed microsteps on the open-loop NEMA 17/23 joints, which is central to meeting the sub-millimeter repeatability target validated in Chapter 2 without paying for closed-loop steppers on every axis.

Motor Drivers: Hybrid On-board and External Topology

The board supports a **hybrid driver topology**: onboard **TMC2209** drivers provide localized, compact control for the smaller NEMA 17 joints, while dedicated **opto-isolated headers** break out step/direction/enable signals for external industrial drivers such as the **CL57T** used on the higher-torque NEMA 23/24 joints. The opto-isolation on the external headers galvanically separates the MCU's 3.3 V logic domain from the higher-current, higher-voltage external driver stage, protecting the STM32H743VIT6 from transients generated by the larger closed-loop motors.

Power Delivery and Protection

The board's Power Delivery Network (PDN) steps down and regulates supply voltage in stages: a **12 V** main input feeds a **5 V buck** converter for intermediate rails and peripheral power, which in turn feeds **3.3 V** regulation for the MCU and digital logic. USB-sourced power is combined with the main supply using diode-OR'ing built around the **1N5819HW-7-F** Schottky diode, chosen for its low forward-voltage drop and fast switching to provide reverse-current protection without materially reducing the available USB power budget.

Timing: External HSE Crystal

An external **8 MHz quartz crystal** oscillator (HSE, High-Speed External) drives the STM32H743VIT6's Phase-Locked Loop (PLL), which multiplies this reference up to the clock rates needed for accurate USB Full-Speed communication (48 MHz) and precise step-pulse generation. Matched load capacitors on the crystal legs are selected to the manufacturer's specified load capacitance to ensure reliable startup and frequency accuracy; see Section 4.4 for the associated layout precautions.

4.3 The PCB Stackup

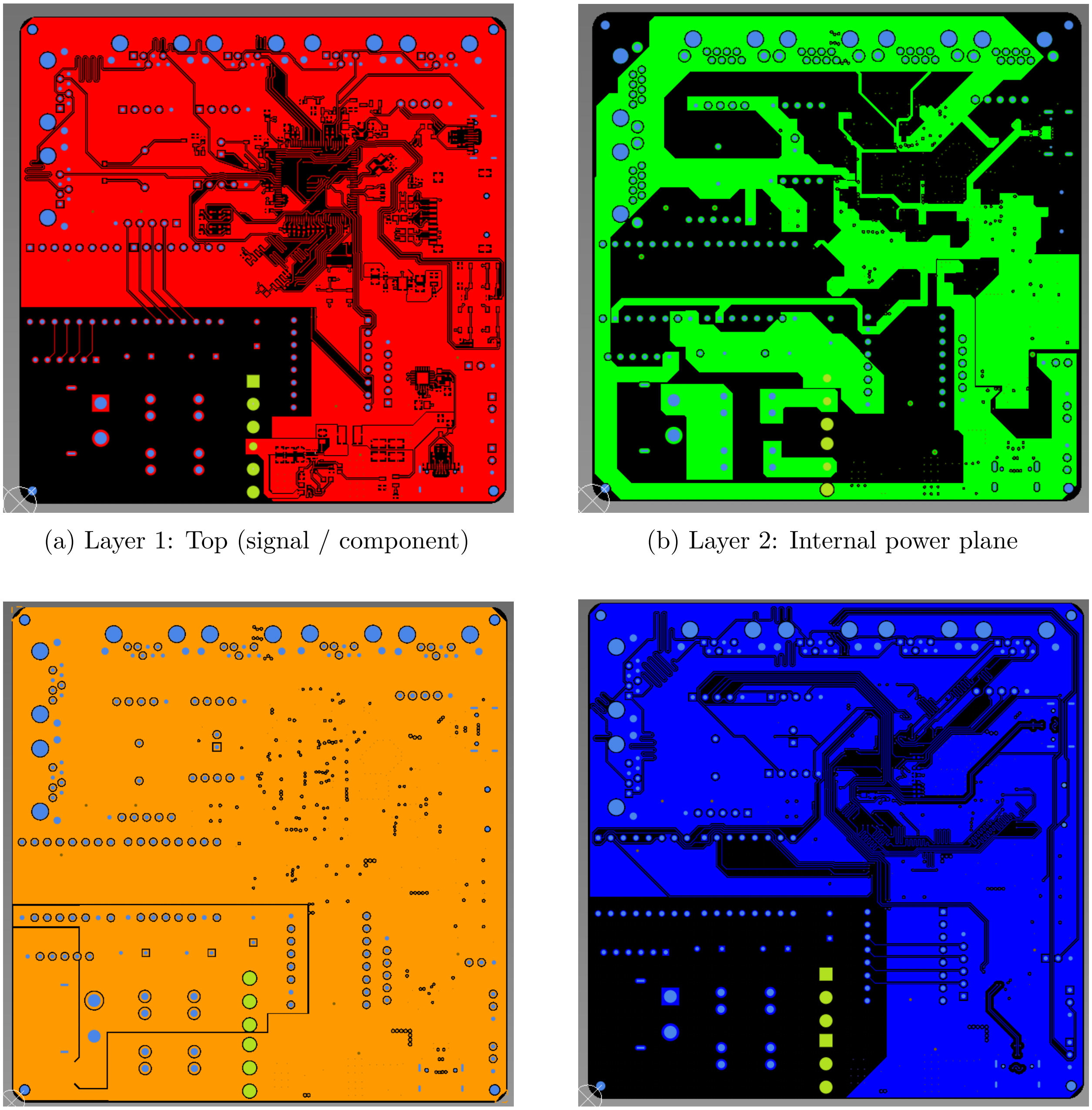
The board is designed in **Altium Designer** using a standard **4-layer stackup**. Driving heavy inductive loads (the NEMA stepper motors) mere millimeters away from sensitive 3.3 V digital logic and high-speed SPI lines requires strict physical separation that a 2-layer board cannot provide, so the 4-layer stackup is used for the current design rather than treated as a future-only upgrade path. The stackup delivers three concrete benefits:

- **Power Delivery Network (PDN) optimization:** Dedicated internal power and ground planes provide a low-impedance return path for the high-current 12 V transients generated by the stepper motors, preventing ground bounce that could otherwise destabilize or crash the STM32H743VIT6.

- **Signal Integrity (SI):** Ground planes placed directly adjacent to signal layers allow tightly coupled return currents, containing electromagnetic interference (EMI) and preventing the fast di/dt switching noise of the motor drivers from coupling into the AS5047P SPI lines.

- **Thermal dissipation:** The internal copper planes act as distributed heatsinks, drawing thermal energy away from the onboard TMC2209 drivers and the power regulator stages.

Figure 4.3 shows the routed copper on all four layers of the board, extracted directly from the Altium Designer layout.



(a) Layer 1: Top (signal / component)

(b) Layer 2: Internal power plane

(c) Layer 3: Internal ground plane

(d) Layer 4: Bottom (signal / routing)

Figure 4.3: Neural Nexus control board, all four copper layers of the 4-layer stackup. The internal power (b) and ground (c) planes sandwiched between the top (a) and bottom (d) signal layers are what provide the low-impedance PDN return path and the EMI-shielding signal-integrity benefit described above.

4.4 Major Routing Strategies

The routing methodology prioritizes high-speed logic stability and mechanical reliability across the board.

- **Impedance-controlled routing:** High-speed communication lines — specifically the USB differential pair (D+/D–) and the SPI buses to each AS5047P encoder — are routed as controlled-impedance traces referencing the continuous internal ground plane, preventing signal reflection that could corrupt encoder reads or USB enumeration.
- **Optimized polygon pours:** Ground planes and copper pours follow strict clearance design rules to avoid manufacturing defects such as localized short-circuits that could inadvertently ground an active signal (an early revision surfaced exactly this risk around the SPI Flash and a motor direction pin, which the current clearance rules are designed to prevent from recurring).
- **Parasitic capacitance mitigation:** Traces connecting the 8 MHz HSE crystal to the MCU's oscillator pins are routed as short and symmetrically as possible, avoiding vias and adjacent high-speed switching lines. This minimizes stray capacitance (C_{stray}), ensuring the crystal starts up reliably and the PLL remains locked at exactly 48 MHz for USB enumeration.
- **Mechanical integration:** The board layout incorporates specific mechanical mounting holes, a custom board outline, and cutouts (visible around the connector edges in Figures 4.1 and 4.2) to physically mate the PCB securely to the robotic arm chassis.

4.5 Additional Layout Considerations

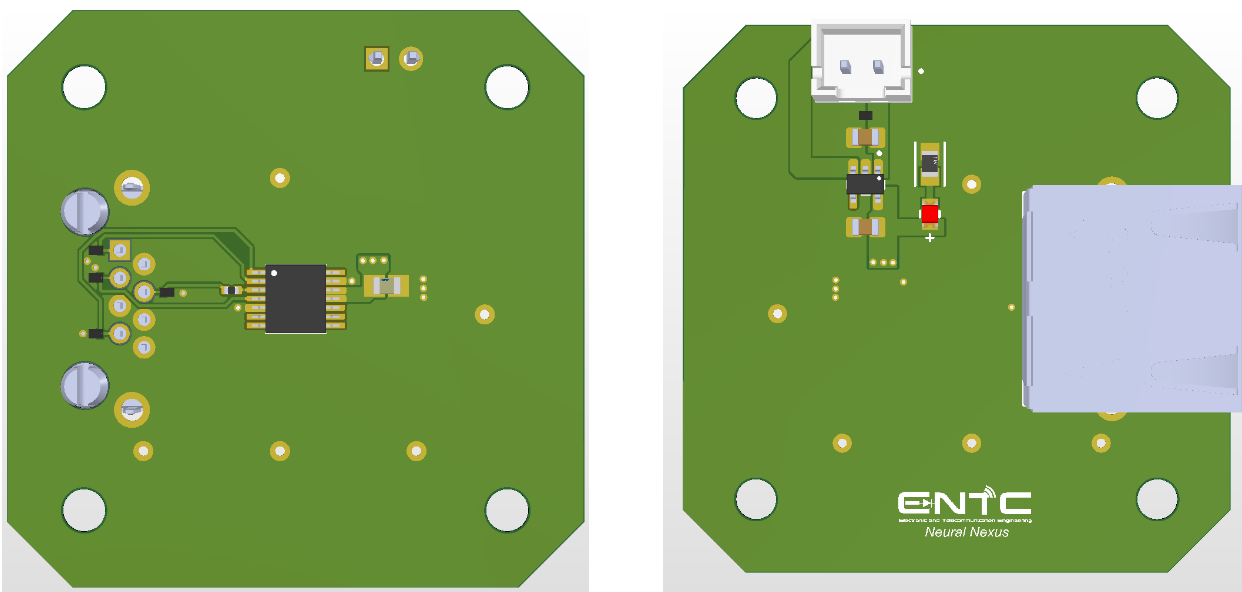
- **Power and signal separation:** High-current motor driver traces (TMC2209 / CL57T supply and phase lines) are routed on wider copper pours and physically separated from low-voltage logic, UART, and SPI signal traces to minimize EMI coupling into the control and encoder-feedback lines. This is visible in Figure 4.2, where the highlighted high-current motor driver pours are kept clear of the logic and SPI routing above them.
- **Grounding strategy:** A unified ground plane pour is used beneath the MCU, logic, and communication sections (including the SPI encoder bus) to reduce ground-loop noise, with star-point grounding back to the main power entry for the motor driver stages.
- **Connector selection:** Locking, keyed RJ-style connectors are specified for the motor, limit-switch, and per-axis SPI encoder harnesses (top edge of Figure 4.1) to prevent field mis-wiring during assembly or maintenance — an important reliability consideration for a product intended for continuous industrial duty.
- **Design for Automated Assembly (DFM/DFA):** Component footprints, spacing, and fiducial placement follow standard pick-and-place tolerances so that the board can transition directly to a Turnkey PCBA process at volume without redesign, reducing manual labor costs during scaling (see Chapter 7).

4.6 Full Schematic Capture

[This section is reserved for the full net-level schematic capture (Altium Designer schematic print, all sheets), to be merged in as a standalone PDF insert. The 3D layout renders in Sections 4.2–4.5 above reflect the current board design; the schematic pages that follow provide the corresponding net-level detail.]

4.7 Per-Axis Encoder Daughterboards (Motor-Specific Variants)

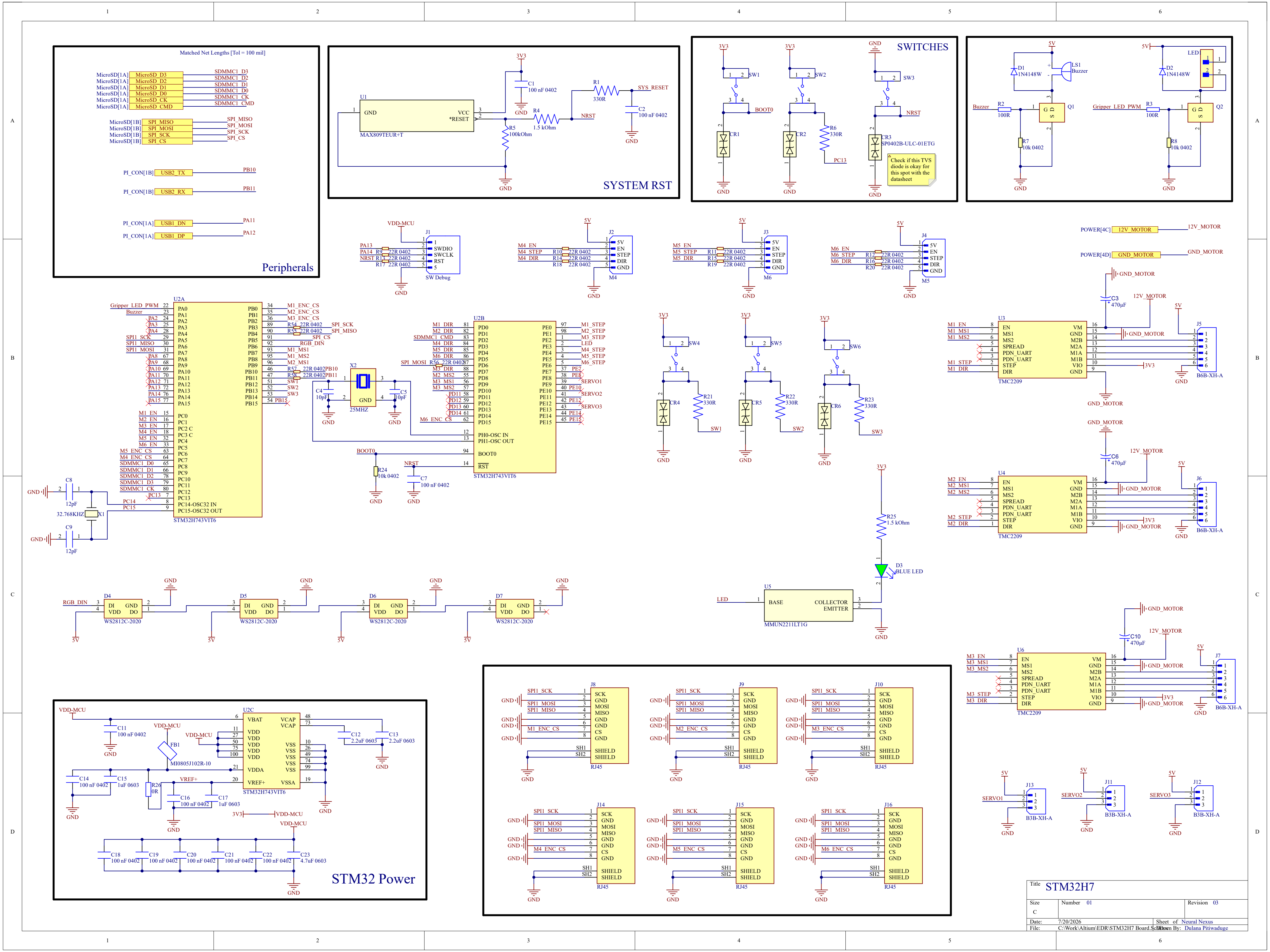
In addition to the main control board (Figures 4.1–4.3), each joint carries a small **encoder daughterboard** mounted directly on its motor, hosting that axis's AS5047P and its local signal conditioning close to the magnet target for the shortest possible sense-to-ADC path. Since the six joints use three different NEMA frame sizes (Chapter 6), the daughterboard outline and mounting-hole pattern are adapted per motor size while the sensor circuit itself — AS5047P, decoupling, protection diode, and the JST/RJ harness pair back to the main board — stays identical across variants for BOM commonality. Four board variants are currently in use.

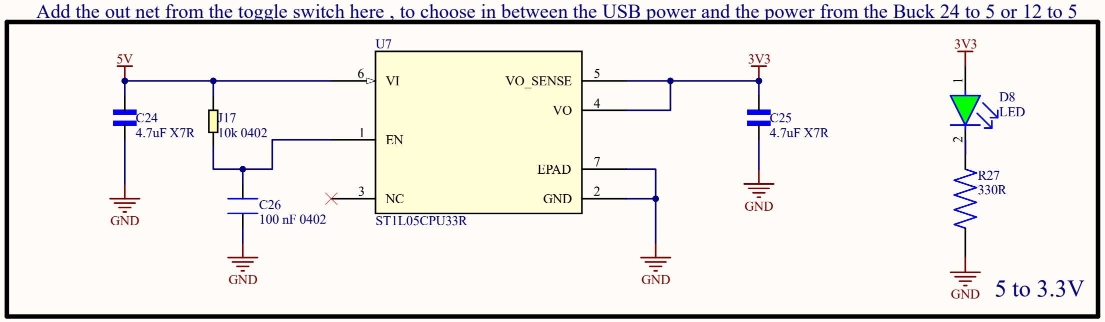


(a) Component side: AS5047P encoder IC and local decoupling/pull-up passives

(b) Connector side: JST power/data connector, protection diode, and RJ-style SPI harness header back to the main control board

Figure 4.4: Standard NEMA17 variant, used on the open-loop NEMA17 joints. The octagonal outline and four mounting holes allow it to be secured directly to the rear of the motor housing, keeping the AS5047P concentric with the shaft-mounted diametric magnet.


Peripherals
Matched Net Lengths [Tol = 100 mil]
SYSTEM RST
SWITCHES
SW Debug
STM32H743VIT6
TMC2209
WS2812C-2020
MMUN2211LT1G
BLUE LED
STM32 Power
Title STM32H7
Size C
Number 01
Revision 03
Date: 7/20/2026
Sheet of Neural Nexus
File: C:\Work\Altium\EDR\STM32H7 Board.SchDoc
Drawn By: Dulana Pitiwadugge



Splitting the 12V line is only half the battle; you must also manage the ground return paths.

When those three motors pull 6A, that 6A has to flow back to the battery through the ground plane. If that 6A flows underneath or through the ground copper near your STM32 or your TPS56637 feedback resistors, it will raise the local ground voltage, causing your microcontroller to read false button presses, corrupt SPI data, or trigger a brown-out reset.

How to route it in Altium:

Do not use one massive, uniform ground pour for the whole board.

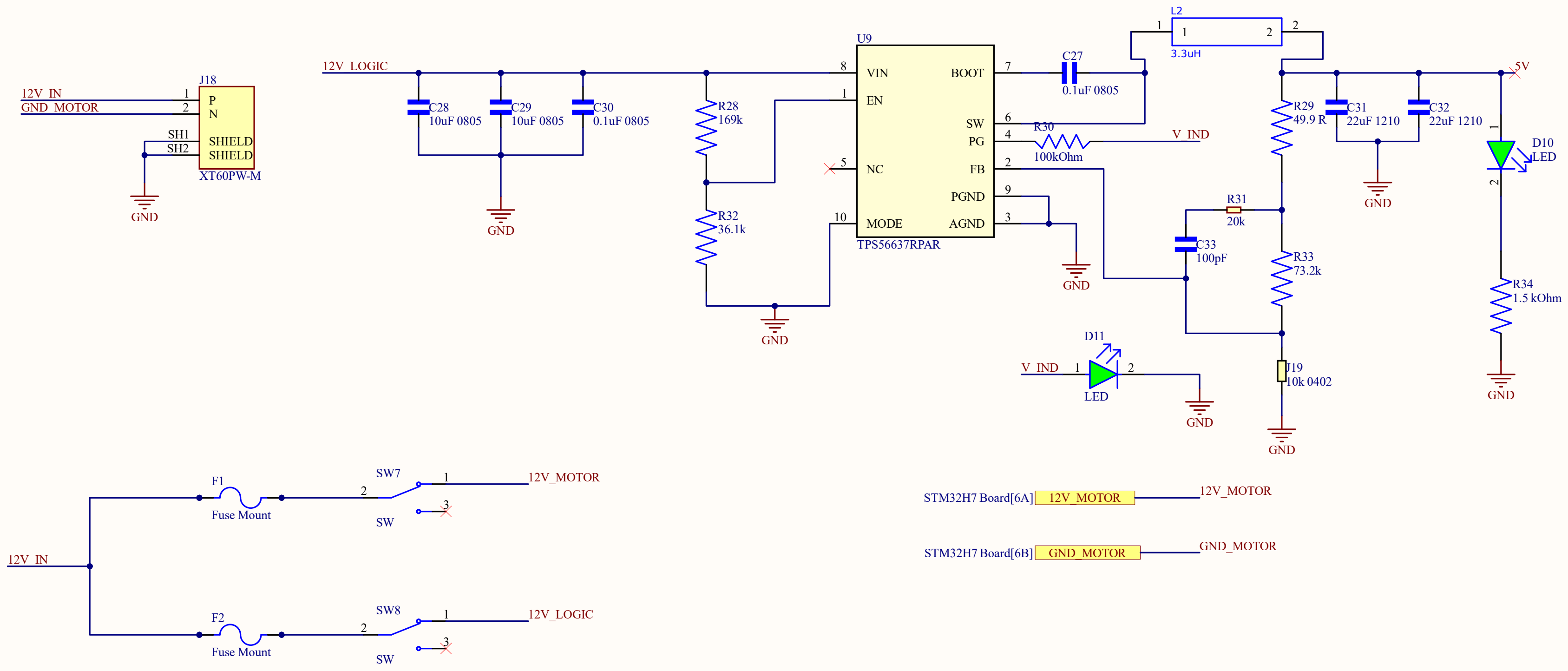
Create a specific, thick ground trace (or dedicated polygon pour) that connects the GND pins of the three TMC2209s directly back to the PGND pin of the XT60 connector.

Keep this motor ground return path physically away from your STM32 and analog sensors.

Your logic ground (PGND and AGND from the buck converter, and the STM32 ground) should meet the motor ground at exactly one single point: the physical solder pad of the XT60's negative pin.

3. Don't Forget the Bulk Capacitors!

As a final reminder, because you are running 3 motors from this 12V line, you absolutely must place a large aluminum electrolytic capacitor (e.g., 220uF to 470uF, rated for 35V or 50V) on the 12V_MOTORS net right next to the TMC2209 drivers. Without it, the inductive flyback from three simultaneous 2A motors will easily spike the 12V rail past 30V and detonate your chips.



Title	POWER		
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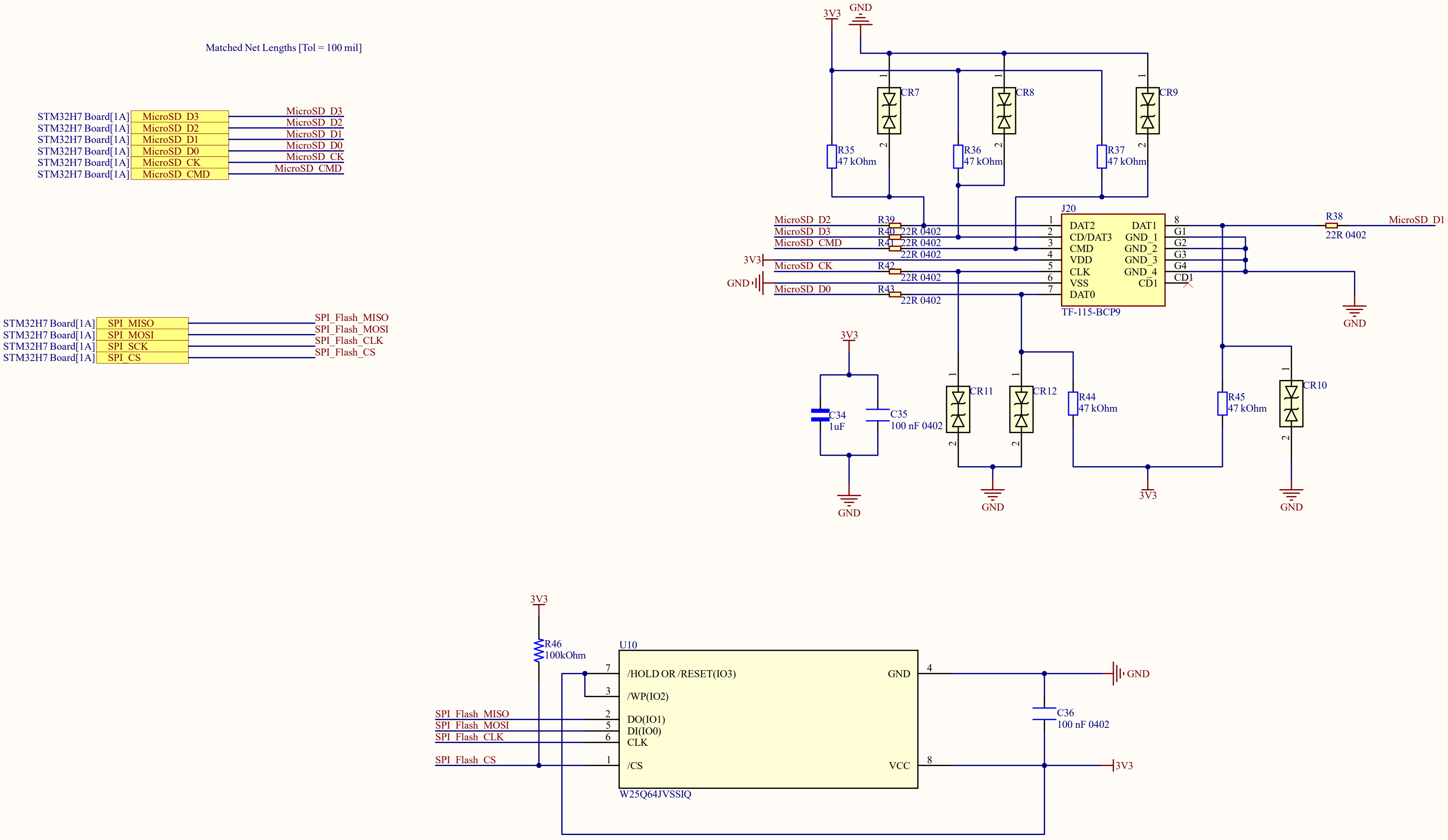

Title	MicroSD & SPI FLASH		
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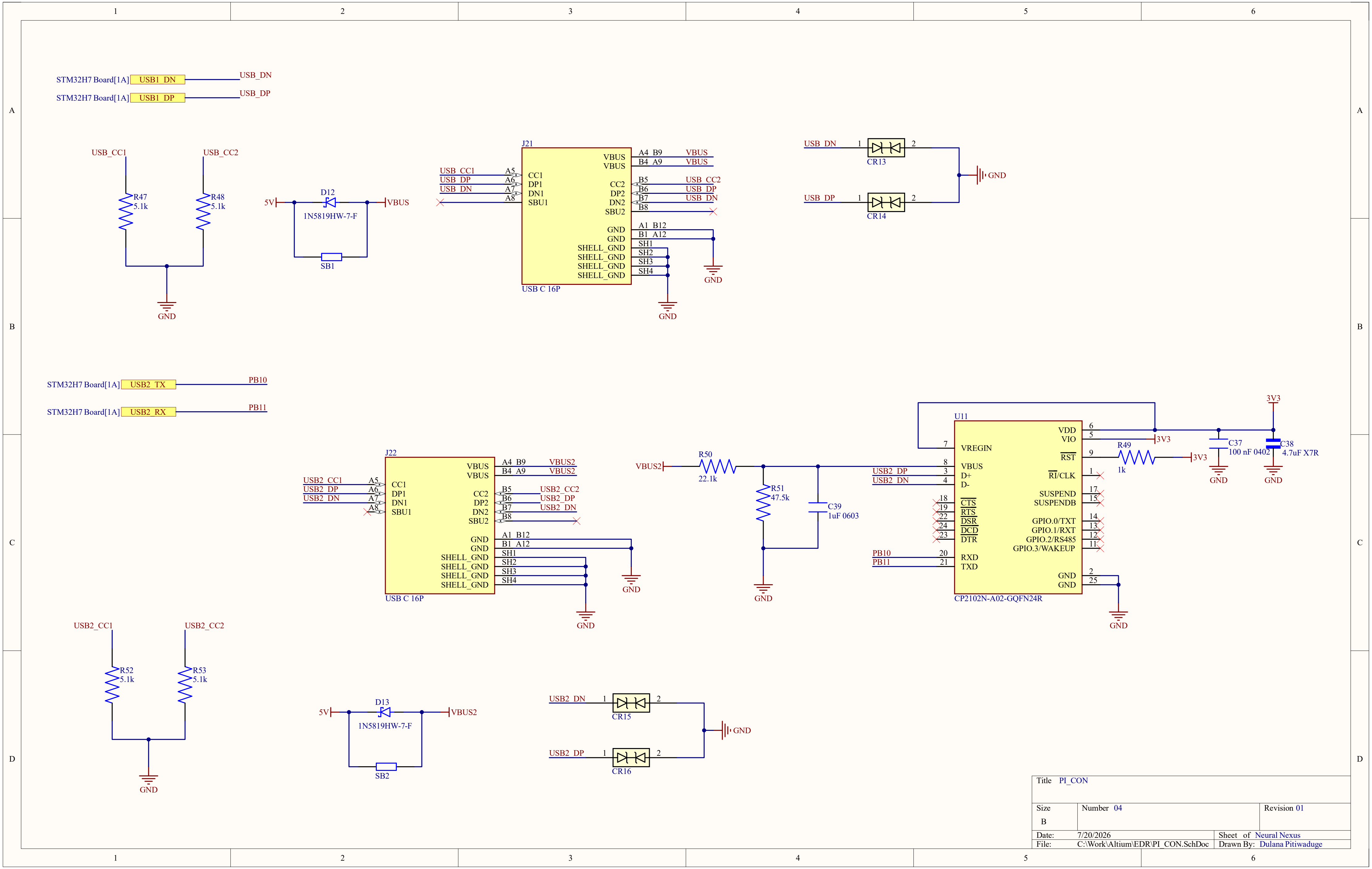

STM32H7 Board[1A] USB1_DN USB_DN
STM32H7 Board[1A] USB1_DP USB_DP
USB_CC1
USB_CC2
R47 5.1k
R48 5.1k
GND
5V
D12
1N5819HW-7-F
VBUS
SB1
J21
USB_CC1 A5 CC1
USB_DP A6 DP1
USB_DN A7 DN1
A8 SBU1
VBUS A4_B9 VBUS
VBUS B4_A9 VBUS
CC2 B5 USB_CC2
DP2 B6 USB_DP
DN2 B7 USB_DN
SBU2 B8
GND A1_B12
GND B1_A12
SHELL_GND SH1
SHELL_GND SH2
SHELL_GND SH3
SHELL_GND SH4
USB C 16P
USB_DN 1 CR13 2
USB_DP 1 CR14 2
GND
STM32H7 Board[1A] USB2_TX PB10
STM32H7 Board[1A] USB2_RX PB11
J22
USB2_CC1 A5 CC1
USB2_DP A6 DP1
USB2_DN A7 DN1
A8 SBU1
VBUS A4_B9 VBUS2
VBUS B4_A9 VBUS2
CC2 B5 USB2_CC2
DP2 B6 USB2_DP
DN2 B7 USB2_DN
SBU2 B8
GND A1_B12
GND B1_A12
SHELL_GND SH1
SHELL_GND SH2
SHELL_GND SH3
SHELL_GND SH4
USB C 16P
VBUS2
R50 22.1k
R51 47.5k
C39 1uF 0603
U11
7 VREGIN
8 VBUS
USB2_DP 3 D+
USB2_DN 4 D-
18 CTS
19 RTS
22 DSR
24 DCD
23 DTR
PB10 20 RXD
PB11 21 TXD
VDD 6
VIO 5
RST 9
RI/CLK 1
SUSPEND 17
SUSPENDB 15
GPIO.0/TXT 14
GPIO.1/RXT 13
GPIO.2/RS485 12
GPIO.3/WAKEUP 11
GND 2
GND 25
CP2102N-A02-GQFN24R
R49 1k
3V3
C37 100 nF 0402
C38 4.7uF X7R
USB2_CC1
USB2_CC2
R52 5.1k
R53 5.1k
5V
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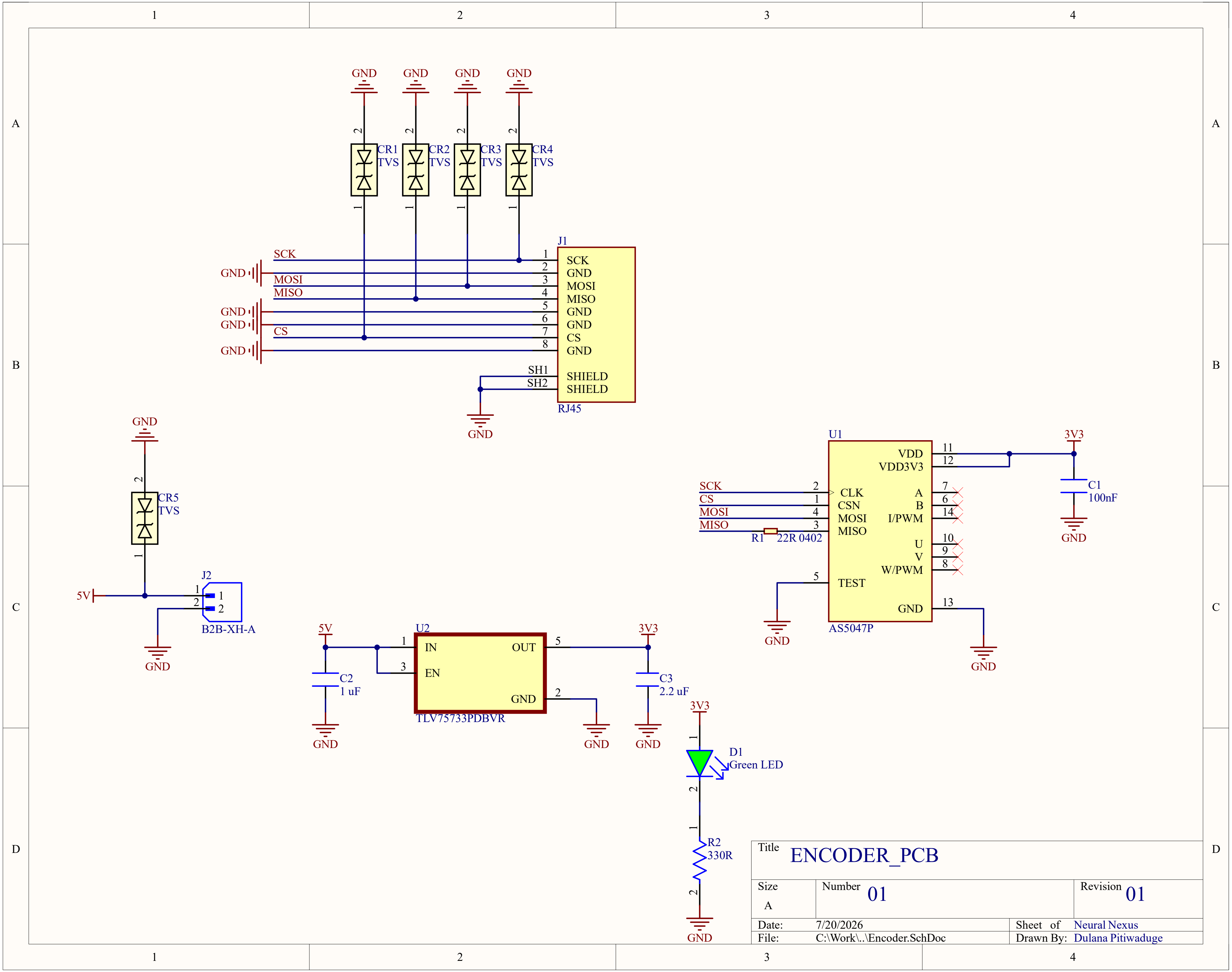
Drawn By: Dulana Pitiwaduge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J1
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MISO
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GND
CS
GND
SHIELD
SHIELD
SH1
SH2
RJ45
CR5 TVS
5V
J2
B2B-XH-A
U1
VDD
VDD3V3
CLK
CSN
MOSI
MISO
A
B
I/PWM
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V
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C3 2.2 uF
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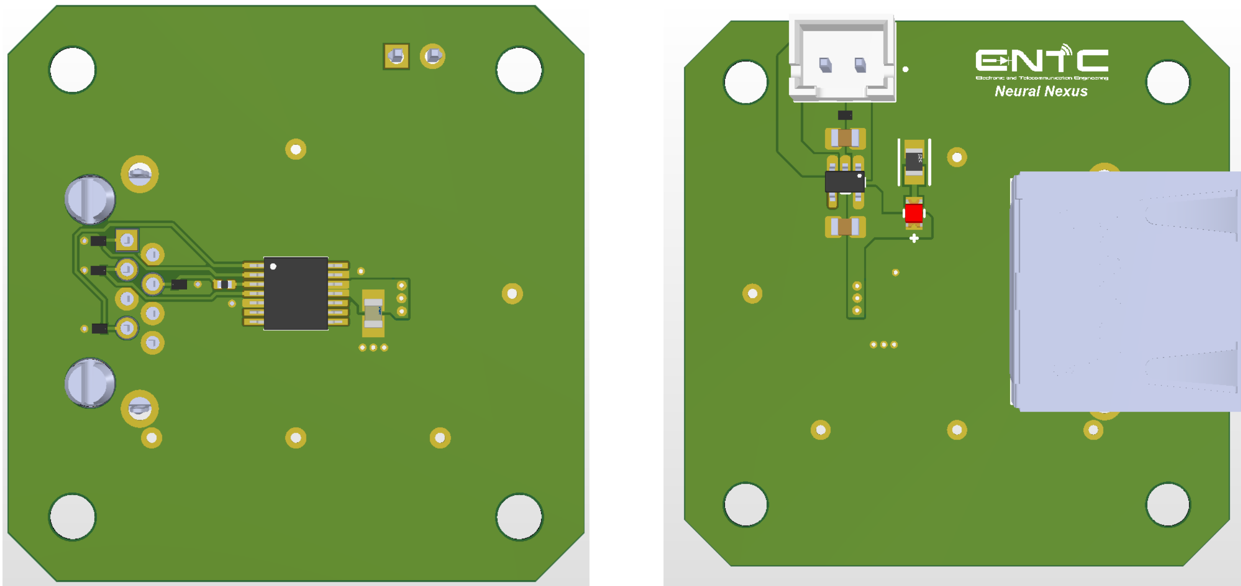
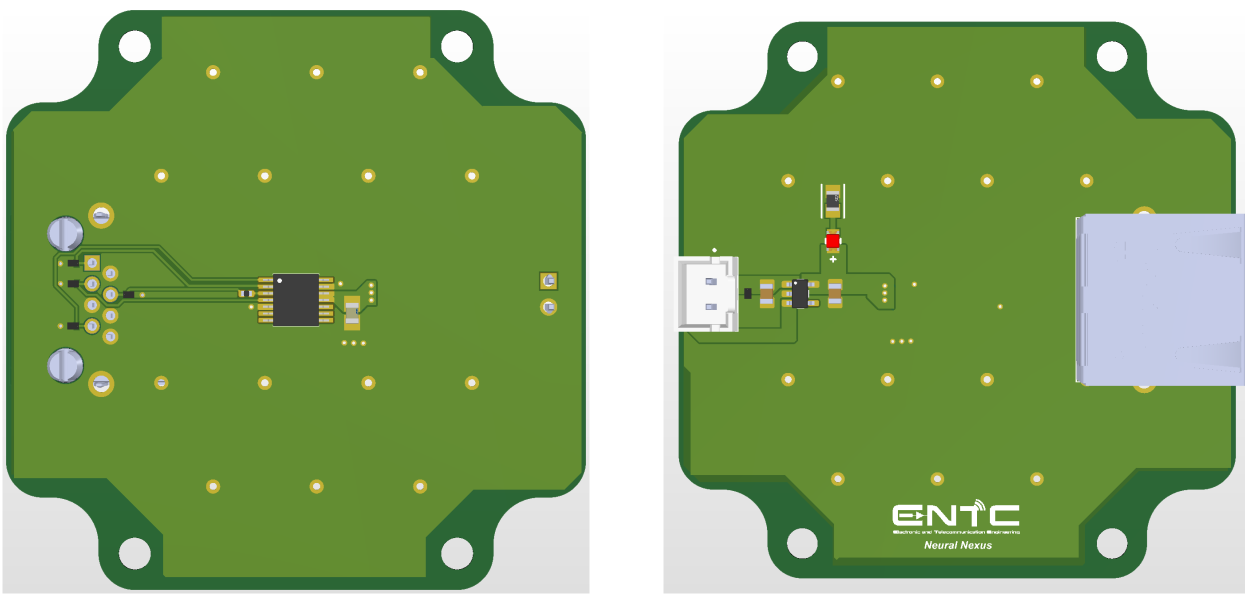


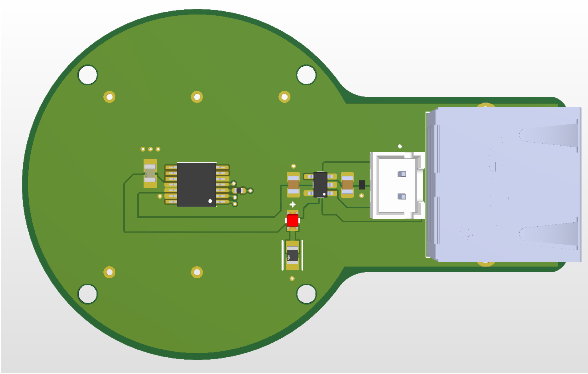
(a) Component side (b) Connector side

Figure 4.5: NEMA17 Pancake variant, sharing the same octagonal mounting pattern and sensor circuit as the standard NEMA17 board above, adapted for the shorter-bodied pancake motor used on the closed-loop NEMA17 joint.

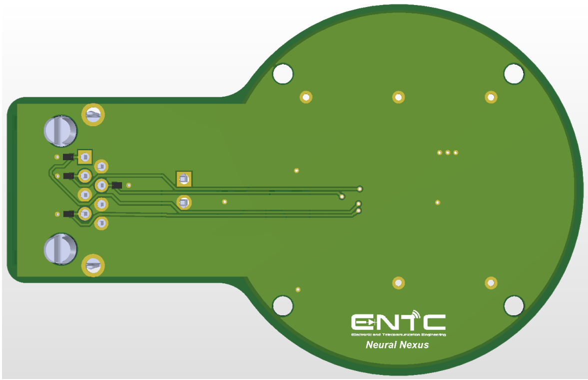


(a) Component side (b) Connector side

Figure 4.6: NEMA23 variant, used on the open-loop NEMA23 joint. The scalloped square outline matches the larger NEMA23 face-mount bolt pattern while retaining the same AS5047P sensor circuit.



(a) Component side



(b) Connector side

Figure 4.7: NEMA24 variant, used on the two closed-loop NEMA24 joints. The extended "lollipop" outline places the sensor circuit on a larger circular head to clear the NEMA24 motor's wider diametric-magnet target, with the same JST/RJ harness pair as the other variants.

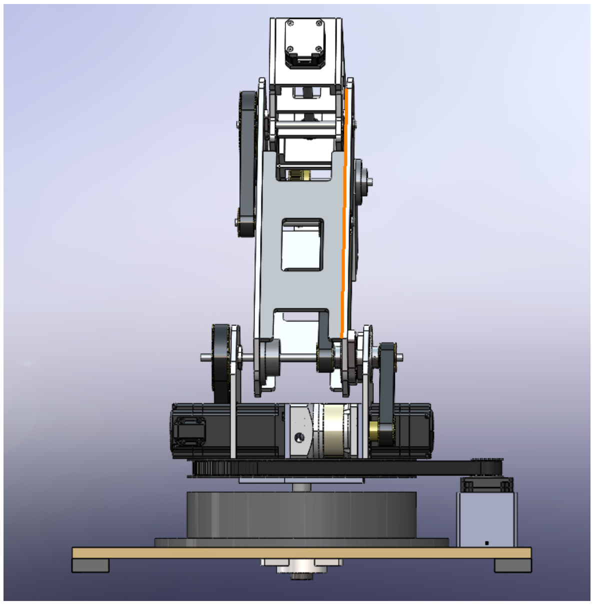
Because these daughterboards sit physically close to each motor's own switching noise, their short JST harnesses back to the main board's RJ-style encoder headers (Section 4.5) are the first and most exposed leg of the SPI signal path described in Section 4.2, which is why the impedance-controlled routing and physical separation practices in Section 4.4 are applied consistently across all four board variants and the main control board alike.

Chapter 5

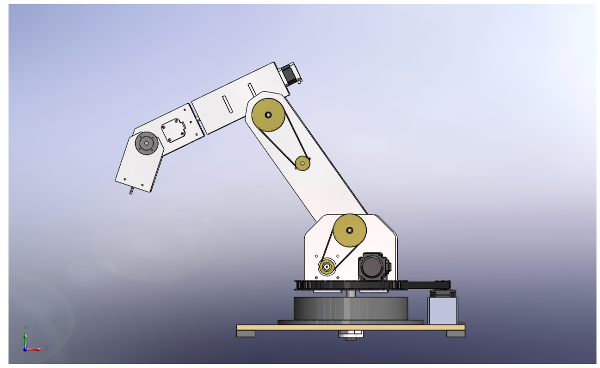
Product Enclosures and Sketches

5.1 Initial CAD Design Iterations

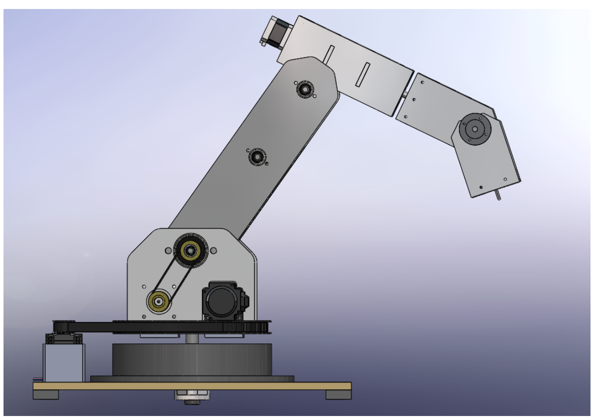
Figure 5.1 shows the early full-assembly CAD models used to block out the arm's joint envelopes, motor placement, and belt/pulley transmissions before any physical fabrication began.



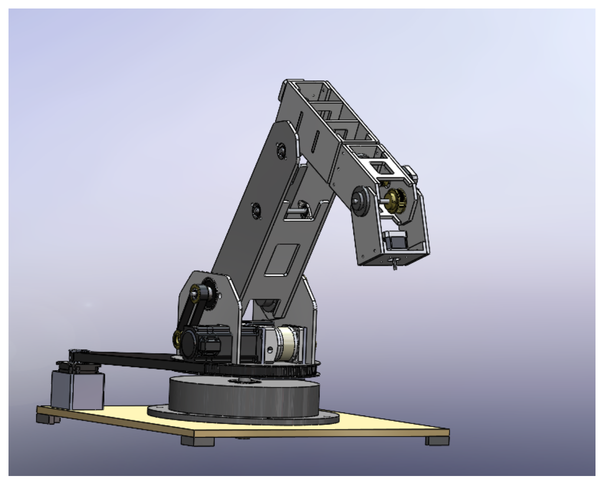
(a) Front elevation with the critical drive-belt path highlighted (orange), showing the shoulder pulley train and internal linkage detail



(b) Side elevation, full arm in a raised working pose



(c) Side elevation, matte render of the finalized link geometry



(d) Isometric view, full assembly on the mounting baseplate

Figure 5.1: Neural Nexus initial full-assembly CAD design iterations, showing the belt-and-pulley shoulder/elbow transmission and NEMA motor placement arrived at before fabrication.

Figures 5.2 and 5.3 focus in on the base/shoulder motor cluster, where the majority of the mechanical design iteration took place.

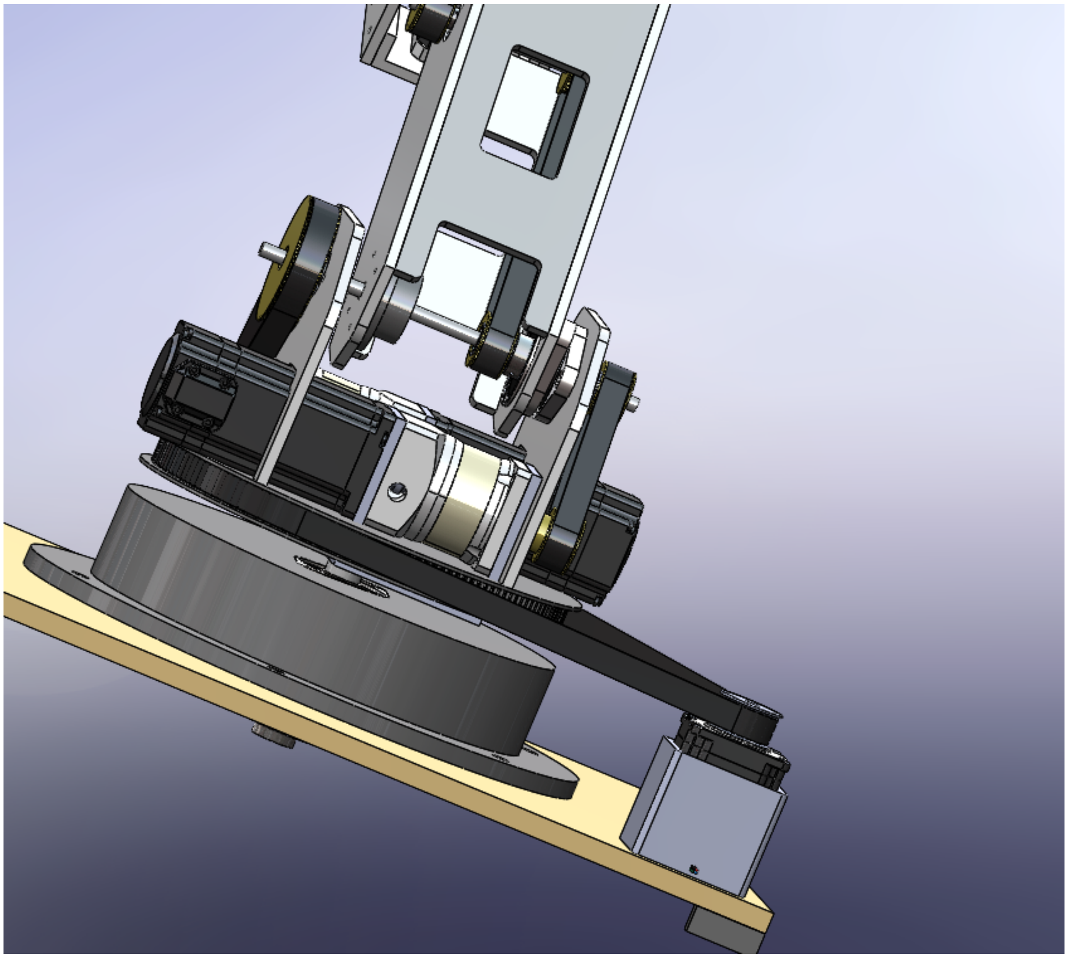


Figure 5.2: Close-up of the base and shoulder motor cluster, showing the paired NEMA motors either side of the shoulder pulley and the large slewing ring at the base rotation joint.

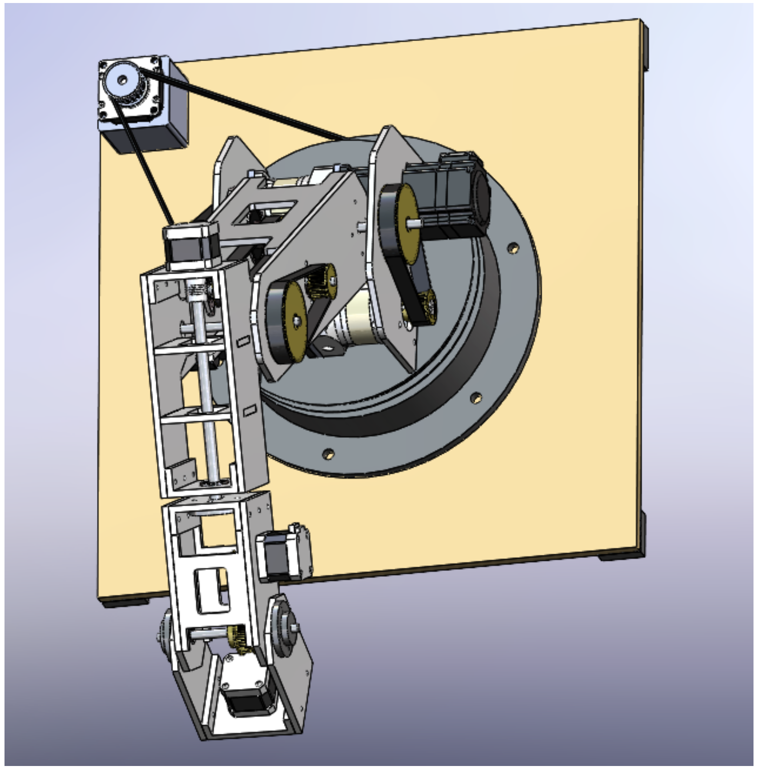
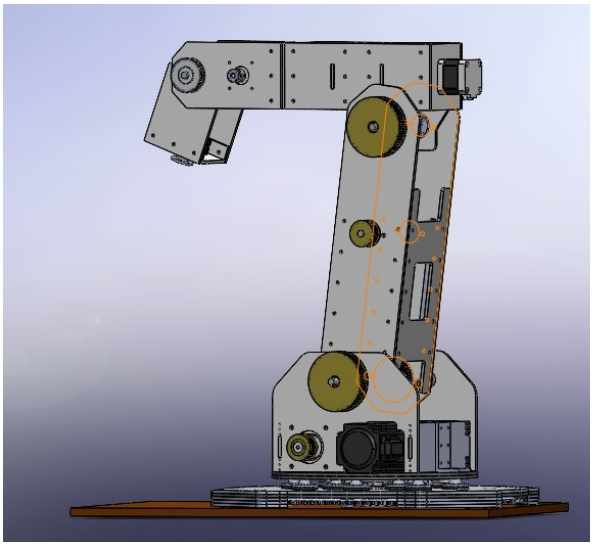


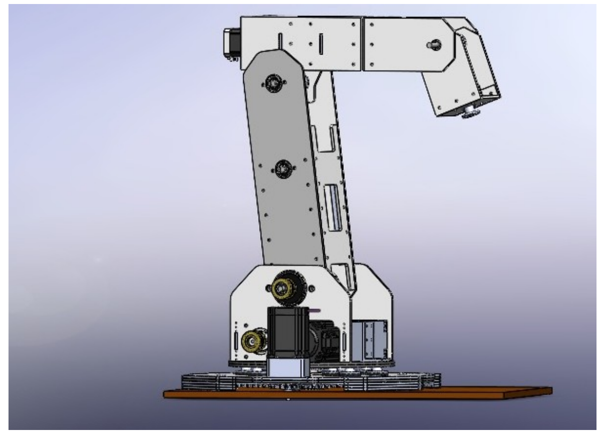
Figure 5.3: Rear-angled view of the base rotation assembly, mounted against its plywood test fixture panel, showing the belt routing between the base-mounted motor and the shoulder joint.

5.2 Finalized CAD Design

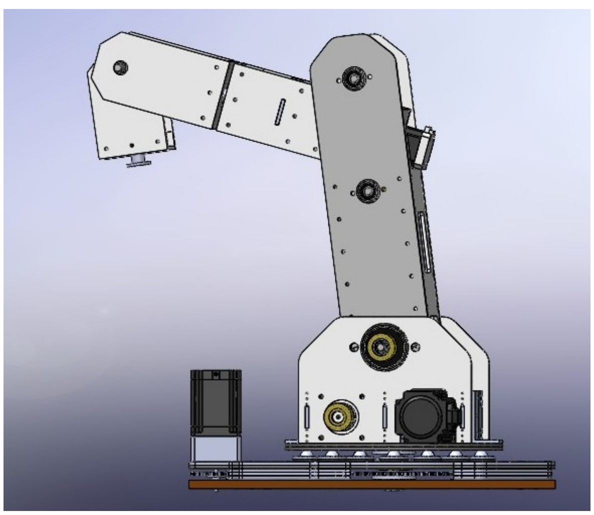
Following the initial iterations above, the design was finalized with three key mechanical revisions: a redesigned base gear and mounting plate, finalized motor placement fully secured with screws throughout (rather than the loosely positioned motors of the earlier iterations), and additional structural integrity supports between the shoulder link plates. Figure 5.4 shows the finalized assembly from four viewpoints.



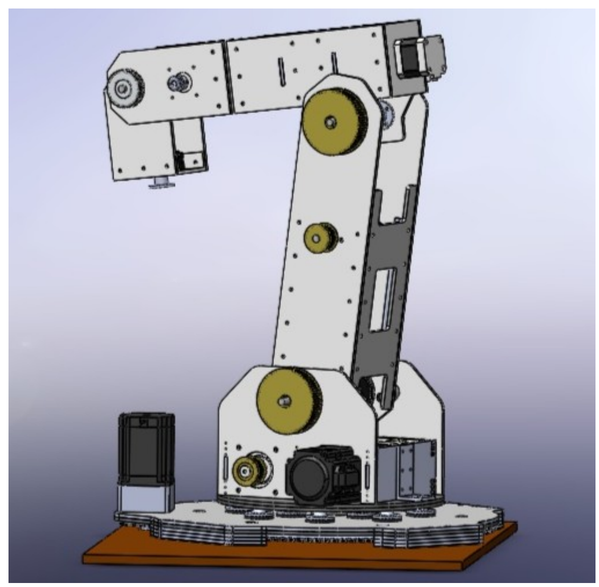
(a) Side elevation with the drive-belt path highlighted, on the finalized base assembly



(b) Front elevation, finalized motor placement secured with screws throughout



(c) Side elevation, finalized arm assembly



(d) Isometric view, finalized assembly on the redesigned base plate

Figure 5.4: Neural Nexus finalized full-assembly CAD design, incorporating the redesigned base gear/plate, fully-screwed motor mounts, and added structural supports.

Figure 5.5 shows the redesigned base gear and mounting plate in detail, and Figure 5.6 shows the added structural integrity supports visible in a fully raised pose.

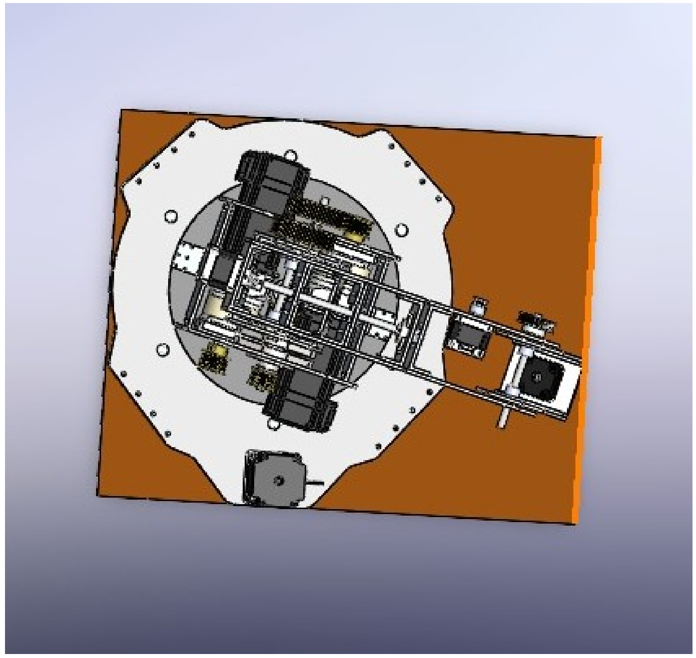


Figure 5.5: Top-down view of the redesigned base gear and mounting plate, showing the scalloped slewing-ring profile and the motor bolt pattern.

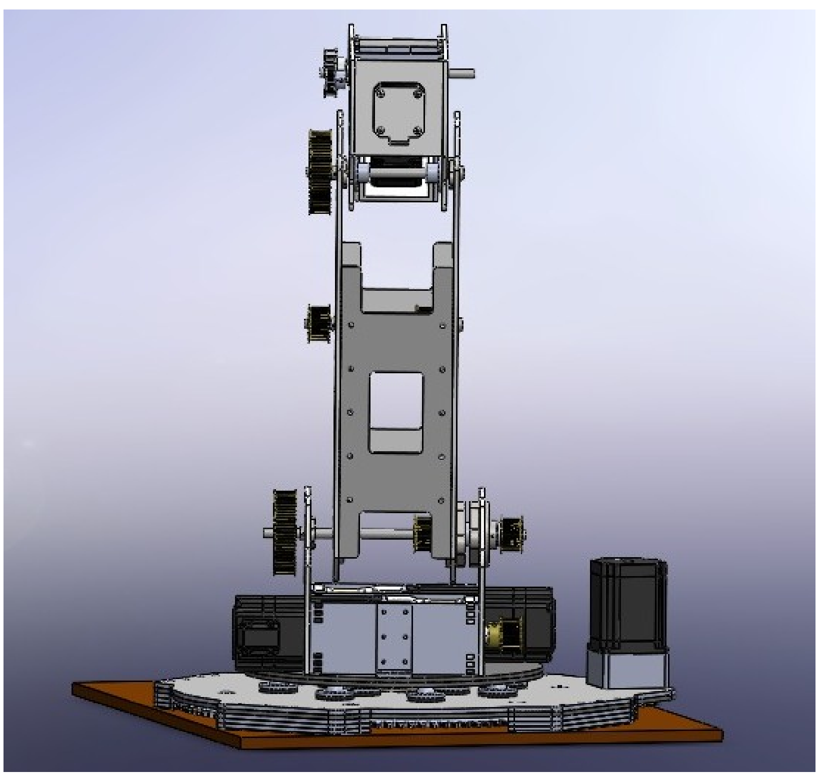


Figure 5.6: Rear elevation in a fully raised pose, showing the added structural integrity supports bracing the shoulder link plates, and the finalized base assembly at the bottom of the stack.

5.3 Electronics Enclosure (Control Box)

In addition to the arm structure itself, the custom control board (Chapter 4) is housed in its own finalized vented enclosure, shown in Figure 5.7. The enclosure is laser-cut/engraved with the *Neural Nexus* branding on the perforated top panel, which doubles as the primary ventilation path directly above the board.

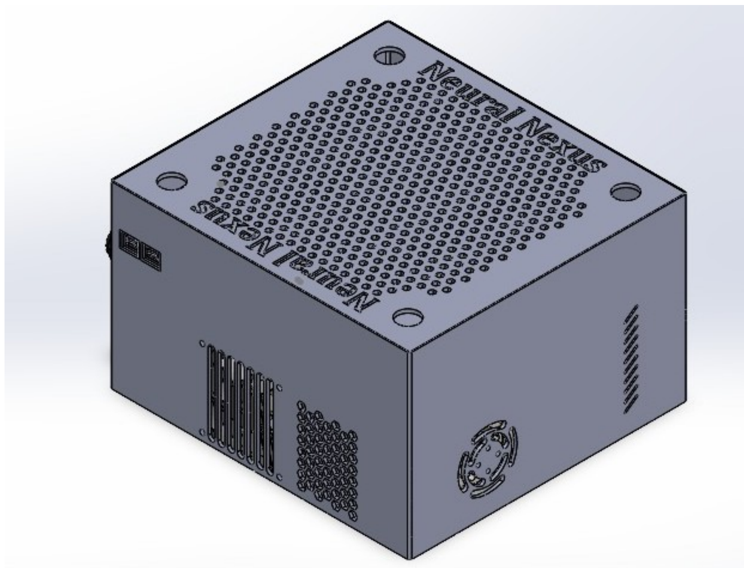


Figure 5.7: Isometric view of the finalized electronics enclosure, showing the perforated top vent panel with the *Neural Nexus* branding, side ventilation slots, a cable-gland cutout on the left face, and the axial fan mount on the front-right face.

Figure 5.8 shows the flattened side-panel layout, including the cable-gland glands for the motor/encoder harnesses leaving the box, the status-indicator cutouts above them, and the combined slot-and-hex ventilation pattern used to balance airflow with EMI shielding on the panel nearest the TMC2209/CL57T driver stage.

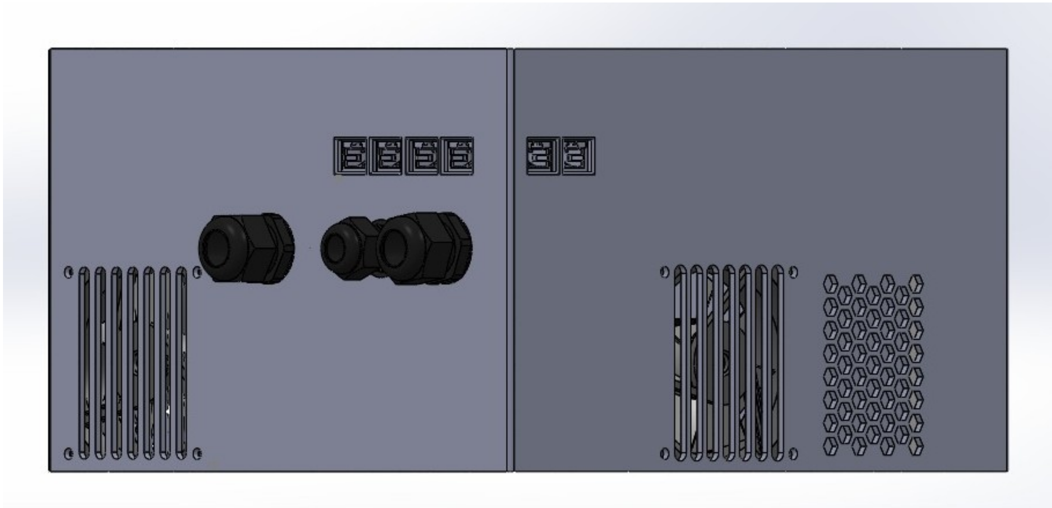


Figure 5.8: Flattened view of the two side panels: cable-gland harness exits and status-indicator cutouts (left panel), and the slot-and-hex ventilation pattern over the driver stage (right panel).

5.4 Design Evolution Notes

The enclosure design progressed through three stages: (1) low-fidelity conceptual hand sketches used to block out joint envelopes and cable routing paths, (2) intermediate CAD models such as those in Figures 5.1–5.3, used to validate motor mounting, bearing seats, and wire-management channels against the aluminum structural frame, and (3) the finalized CAD design in Figures 5.4–5.6, incorporating the redesigned base gear/plate, fully-screwed motor mounts, and structural integrity supports, optimized for 3D-printability at the prototype stage and for future rapid injection molding at volume production. Draft angles, wall thicknesses, and parting lines in the finalized CAD models were selected specifically to ease the eventual transition to injection-molded tooling described in Chapter 7.

Chapter 6

Final Product Details and Operational Value

The Neural Nexus robotic arm is a desktop-sized automation unit capable of complex pick-and-place, assembly, and research tasks.

6.1 Final Product Specifications

- **Degrees of Freedom:** 6 DOF (Enables full 3D workspace with arbitrary end-effector orientation, maximizing factory floor utility and spatial efficiency).
- **Maximum Reach (Arm Span):** 800mm (Optimized specifically to span standard industrial conveyor belts and sorting tables).
- **Payload Capacity:** 2kg (Ideal for SME machine tending, electronics assembly, and lightweight FMCG packaging).
- **Actuation System:** 2 $\times$ NEMA 24 (Closed Loop), 1 $\times$ NEMA 23 (Open Loop), 3 $\times$ NEMA 17 (1 Closed, 2 Open). Torque-matched per joint to reduce moving mass and energy consumption.
- **Master Control Unit (MCU):** Custom PCB built around an STM32H743VIT6 (Arm Cortex-M7, up to 480 MHz, 2 MB Flash, 1 MB RAM, LQFP-100), generating step/direction pulses for all six axes on dedicated hardware timers and closing the position loop via SPI-connected AS5047P magnetic absolute encoders on each joint.
- **Position Feedback:** Six AS5047P magnetic absolute encoders (one per axis), polled over a shared SPI bus with individual per-axis chip-select lines, providing true joint-position feedback independent of step count.
- **Power Consumption & Requirements:** Mains powered (230 V AC). As a high-uptime industrial asset, the system is tethered to ensure 24/7 continuous operational capability without battery degradation concerns. Table 6.1 gives engineering estimates based on manufacturer motor and driver datasheets; these are to be confirmed against bench measurements on the final assembled unit.

- **Modular Upgradability:** The tool-head is designed to be hot-swappable, allowing businesses to adapt the robot from a vacuum gripper to a mechanical claw with minimal downtime, extending the Total Cost of Ownership (TCO) lifespan.

Operating State	**Estimated Draw**	**Notes**
Idle / holding torque	∼80–120 W	All six drivers energized, no motion
Typical operation (single-axis moves)	∼200–300 W	Sequential joint moves, light payload
Peak (coordinated multi-axis move, full payload)	∼500–650 W	All motors near rated current simultaneously

Table 6.1: Estimated power draw by operating state (to be validated by bench measurement)

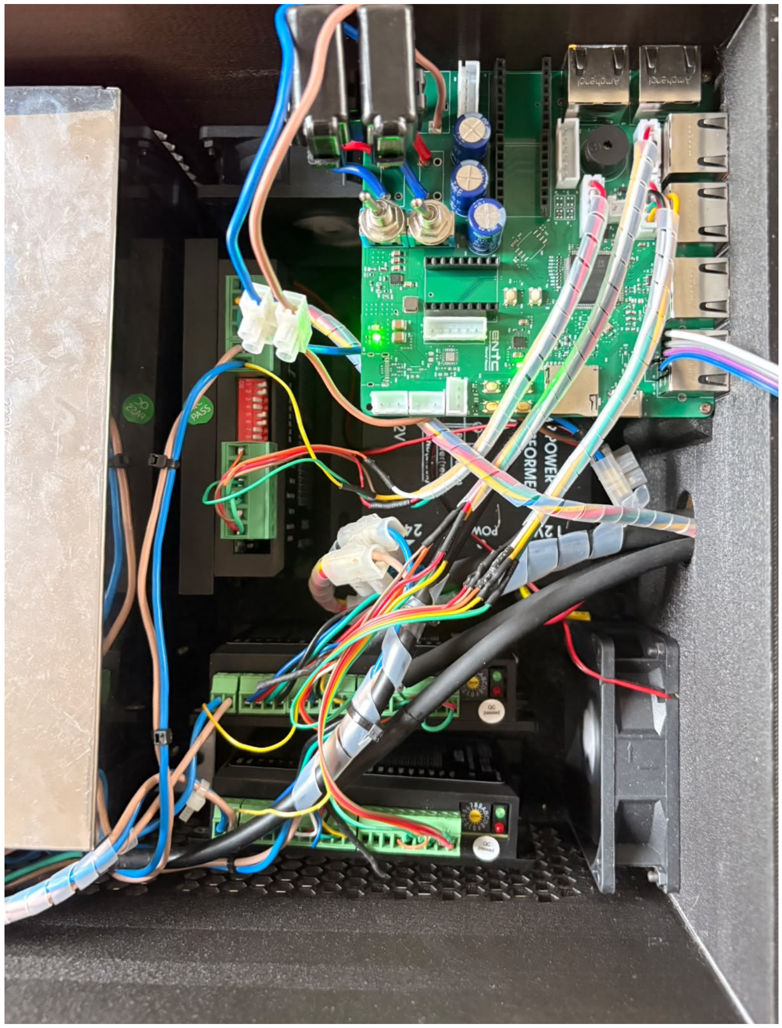
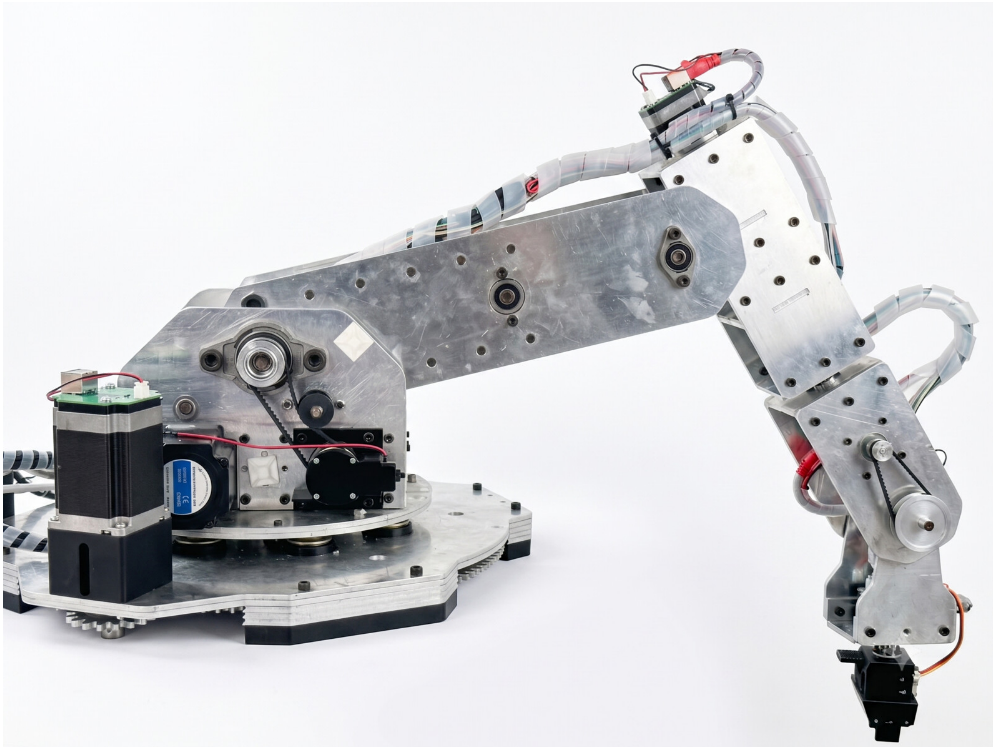


Figure 6.1: Interior of the assembled electronics enclosure (Chapter 5), showing the custom STM32H743VIT6 control board mounted alongside the CL57T driver modules, terminal blocks, cooling fan, and the harness routing described in Chapter 4.



Chapter 7

Manufacturing Considerations (Volume Production)

Transitioning Neural Nexus from a functioning prototype to volume manufacturing requires strict supply chain management and fabrication standardization to protect our profit margins against local inflation and logistical shocks.

- **Material Sourcing & BOM Resilience:** Bulk sourcing of standardized aluminum sheets ($8' \times 4' \times 4mm$) is critical to keeping chassis costs low. By utilizing raw materials widely available in Sri Lanka, we insulate our Bill of Materials (BOM) from localized price fluctuations and import bans.
- **Automated Fabrication:** Moving from manual prototyping to automated CNC routing and laser cutting for the mechanical linkages will ensure repeatable, industrial-grade tolerances while drastically reducing labor hours (and thus OPEX) per unit.
- **Electronics Assembly:** Transitioning to a Turnkey PCBA (Printed Circuit Board Assembly) manufacturer for volume batches rather than in-house soldering. This reduces defect rates and accelerates production timelines.
- **Quality Assurance (QA) & Calibration:** Implementing a rigorous end-of-line calibration rig using our MATLAB Digital Twin to verify the IK accuracy and payload capacity of every unit before shipping. This step is vital to reducing costly warranty returns and maintaining brand reputation.
- **Supplier Redundancy:** Qualifying at least two suppliers for each critical component category (motors, drivers, aluminum stock) to avoid single-source risk as production scales.

Chapter 8

Costing, Pricing Strategy, and Customer ROI

8.1 Volume Production Costing (COGS)

Based on current batch sourcing and local material procurement, the absolute Cost of Goods Sold (COGS) to manufacture a single prototype unit — taken as the actual total project value tracked in Chapter 10 (pooled contributions, donations, and the member-covered deficit) — stands at **568,982.27 LKR**. As we scale to volume production, economies of scale (e.g., bulk CNC machining and PCBA runs) are expected to drive this material cost down further.

8.2 Determination of Selling Price & Business Justification

The suggested retail price for the base Neural Nexus arm is strategically set at **1,500,000 LKR**.

The Financial Justification: In hardware manufacturing, long-term financial sustainability requires a robust operating buffer. By pricing the arm using an industry-standard $\sim 2.6\times$ multiplier of our component cost, we secure the necessary capital to cover Customer Acquisition Costs (CAC), continuous R&D, marketing overhead, and maintaining a reliable 24/7 after-sales support network.

At this price point, Neural Nexus generates over **931,017.73 LKR in gross profit per unit** (a highly attractive **62.07% Gross Margin**). This robust margin allows us to rapidly scale our software engineering team to develop advanced SaaS features while maintaining a zero-downtime local repair network—a massive competitive advantage over foreign suppliers.

8.3 Total Cost of Ownership (TCO) and Customer ROI

For the SME consumer, the business case is undeniably strong. The baseline for comparable imported models is often over 2,000,000 LKR, *excluding* shipping and the local import levy stack (18% VAT, 7.5% PAL, and 2.5% SSCL, detailed in Chapter 1) that would apply on top if imported directly. By pricing at 1.5M LKR and manufacturing locally, we lower the capital barrier to entry significantly while sidestepping that levy stack entirely.

ROI Example: If a local factory utilizes the Neural Nexus arm to automate a sorting process that previously required two shifts of human labor (saving approximately 100,000 LKR per month in combined wages, statutory contributions, and overtime premiums, alongside reduced defect rates), the factory achieves a complete Return on Investment (ROI) in **under 15 months**. This rapid payback period transitions the purchase from a risky CAPEX to a highly attractive operational upgrade for risk-averse business owners.

Chapter 9

Marketing, Sales, and Beyond

9.1 Product Philosophy: A Precise Automation Skeleton

Neural Nexus is deliberately engineered as a general-purpose **precise automation skeleton** rather than a task-specific machine: a single, sub-millimeter-repeatable 6-DOF mechanical and control platform (Chapters 3–6) onto which a customer- or vertical-specific tool-head and perception stack can be mounted via the hot-swappable tool interface (Chapter 6). The base arm, MATLAB Digital Twin, and STM32H743VIT6 control stack never need to change between customers; only the end-effector and the Computer Vision (CV) model running on top of it are tailored. This philosophy underpins both target markets below and the industrial go-to-market strategy described later in this chapter.

9.2 Target Market

- **Small & Medium Factories:** Ideal for repetitive, high-turnover tasks such as food packaging, garment sorting, and electronics assembly where human error and fatigue are high.
- **STEM Education:** Providing universities, technical colleges, and pre-university STEM academies with an affordable, programmable platform to train students on modern robotics, directly feeding the local engineering talent pool. As described in Chapter 1, this segment is already commercially proven locally (STEM enrolment growing $\sim$10%/year, with an active private robotics-academy market), but is currently served only with imported hobbyist-grade kits.

Anchor STEM Partnership

As proof of the education-market thesis, Neural Nexus has already reached agreement with a major Sri Lankan STEM education institute to deliver hands-on robotics sessions using the physical arm as part of their student programme. This is a deliberate first commercial deployment: it puts the arm in front of a large, recurring student cohort ahead of full-scale production, generates real usage data and testimonials to de-risk the wider education bundle described below, and gives the STEM partner's students the same hands-on programmable 6-DOF access that Chapter 1 shows no other institution in the country currently offers.

9.3 Revenue Streams (The Ecosystem Model)

We are transitioning from a traditional hardware sales model to a highly lucrative "Robotics Ecosystem" model, ensuring both upfront capital and continuous Annual Recurring Revenue (ARR).

- **Tier 1: Base Hardware Sales (CAPEX):** 1,500,000 LKR upfront revenue per arm.
- **Tier 2: Premium Hardware Add-ons:**
  - Bespoke End-Effectors (vacuums, customized grippers) priced between 45,000–85,000 LKR.
  - **Industrial Touch HMI Console:** A ruggedized, standalone Raspberry Pi-driven touch screen interface. This is sold as a premium operational upgrade (estimated at 150,000 LKR) for enterprise clients who require dedicated floor-level control kiosks without tethering a personal computer.
- **Tier 3: SaaS (Software as a Service):** Optional annual subscriptions to unlock advanced Computer Vision models, predictive maintenance analytics, and OTA (Over-The-Air) software updates.
- **Service & Maintenance Contracts:** Paid annual tiers for guaranteed 24/48-hour on-site robotic servicing and hardware checkups.

9.4 Sales Strategy & Go-To-Market

- **Start Small to Prove Value ("Land and Expand"):** We target a single bottleneck in a client's factory, deploy one unit to prove the ROI in under 6 months, and then secure enterprise contracts to automate the rest of their fleet.
- **Flexible Leasing (Robot as a Service):** For businesses lacking the 1.5M LKR upfront capital, we offer a lease model, charging a monthly fee based on machine uptime. This turns a massive CAPEX into a manageable OPEX for the factory owner.
- **Education Bundles:** Providing subsidized starter kits to universities and STEM institutes (building on the anchor partnership above) ensures the next generation of engineers is already trained on, and biased toward, the Neural Nexus ecosystem when they enter the workforce.

Industrial Go-To-Market: The "Trojan Horse" Strategy

Because the current unit is a Proof of Concept (POC) rather than a field-proven industrial product, Neural Nexus deliberately does not attempt to sell a generic, one-size-fits-all industrial arm on day one. Instead, the identical automation skeleton described in Section 9.1 is positioned as the carrier for a narrow, customer-specific solution:

- **The arm is the constant; the head is the offer.** For each pilot industrial customer, only the tool-head (gripper, vacuum end-effector, or custom fixture) and the CV model running the vision pipeline are engineered around that customer's specific part geometry, defect signature, or sorting criterion—the underlying arm, control stack, and Digital Twin are unchanged.
- **Why this is a "Trojan Horse":** The customer evaluates and buys what looks like a narrow, purpose-built solution to their specific bottleneck (e.g. "a machine that sorts these particular garment panels"), which is a far easier and faster sale than an abstract general-purpose robotic arm. Once the unit is installed and trusted on the factory floor, the same underlying skeleton is already capable of being re-tooled and re-trained for adjacent tasks, positioning Neural Nexus for the Land-and-Expand growth path above without a second capital sale.
- **De-risking the POC-to-product transition:** Because each early industrial deployment is scoped narrowly around one tailored head and one CV model, the engineering team can validate reliability and repeatability against a tight, well-defined success criterion per pilot, rather than needing the arm to be simultaneously excellent at every possible task before its first sale.

Chapter 10

Project Budget and Bill of Quantities (BOQ)

The figures below are drawn directly from the team's running project finance tracker as of 18 July 2026, rather than an estimated cost model, and reflect actual funds pooled, donated, and spent to date.

10.1 Project Funding Summary

Item	**Amount (LKR)**
Total money pooled by team members	333,361.00
Total donations received	230,000.00
Combined project value (pooled + donated + member-covered deficit)	568,982.27
Total money expensed to date	338,982.27
Current remaining balance	−5,621.27

Table 10.1: Project funding summary, as of 18 July 2026

The small negative remaining balance indicates that actual expenditure has slightly exceeded the pooled and donated funds; this shortfall has been covered informally, out of pocket, by team members pending final reconciliation.

10.2 Donations Received

Donor	Asset Acquired	Amount (LKR)
Seniors (alumni)	2 × NEMA 24 motors	160,000.00
A colleague	Aluminum sheet stock	30,000.00
A colleague	Raspberry Pi + Pi Camera	40,000.00
Total		**230,000.00**

Table 10.2: External and member-sourced donations, with the specific asset each funded

10.3 Expenditure Summary by Category

Category	Amount Spent (LKR)
Hardware components and sourcing (motors, drivers, bearings, fasteners, laser/rod cutting, 3D printing)	237,856.27
PCB fabrication and components (JLCPCB, LCSC, encoder boards)	72,486.00
Import tax and duties (component and PCB tax lines)	13,730.00
Enclosure materials and cutting (plywood, frame, laser cutting)	3,480.00
Transport and logistics	1,700.00
Software subscriptions, fuel, and miscellaneous	9,730.00
Total Money Expensed	**338,982.27**

Table 10.3: Actual project expenditure to date, summarized by category from the finance tracker

Hardware sourcing and PCB fabrication together account for over 90% of expenditure to date, consistent with the prototype's electronics- and motor-heavy Bill of Materials described in Chapter 2. *[Placeholder: A fully itemized final budget accounting for volume-production pricing, shipping, and projected OPEX — distinct from this prototype-phase actuals tracker — will be provided in the final revision; see Chapter 8 for volume-production COGS estimates.]*

10.4 Future Improvements and Monetization Strategies

To ensure long-term product viability and create new revenue verticals, several strategic improvements are slated for development:

- **Dedicated Touch HMI Console (Premium Add-on):** As detailed in our revenue streams, the current system relies on standard PC/terminal interfaces. Developing a rugged, standalone touch-screen HMI will allow us to immediately upsell enterprise clients who require robust, dedicated floor-level control kiosks.

- **Edge AI Computer Vision Integration:** Currently, real-time object tracking is verified through standard camera detection. We plan to implement the CV pipeline directly into a dedicated edge device (like a Raspberry Pi with an optimized camera module) mounted directly on the arm workspace. This unlocks untethered visual servoing, which will be offered as a premium SaaS tier for advanced quality control and dynamic sorting applications.
- **Fleet Management Dashboard:** A cloud-connected dashboard allowing enterprise customers with multiple units to monitor uptime, cycle counts, and predictive-maintenance alerts across their entire Neural Nexus fleet from a single pane of glass.

Chapter 11

Task Allocation Among Group Members

The execution of the Neural Nexus project relied on specialized, cross-functional collaboration, ensuring all engineering and business deliverables were met on schedule:

- **Lasan Perera (Lead):** Overall project management, systems integration, structural analysis, wiring, and industrial enclosure fabrication.
- **Isitha Dinujaya:** Computer Vision architecture, software integration, and supplementary 3D Design.
- **Dulana Pitiwaduge:** Hardware electronics architecture, component sourcing, custom PCB Design, and financial modeling.
- **Deneth Priyadarshana:** Primary 3D Design, structural analysis, and mechanical tolerancing for manufacturability.
- **Mokshan Colombage:** 3D Design, rendering, soldering, and business strategy alignment.