University of Moratuwa

Faculty of Engineering

Department of Electronic and Telecommunication Engineering

Production Document- Strain Gauge based Torque Sensor

Aashir M.R.M.	220004M
Basith M.N.A.	220071M
Kumarage R.V.	220343B
Manawadu D.N.	220380J
Manawadu M.D.	220381M
Munavvar M.A.A.	220405T
Ransika L.G.C.	220514C
Samuditha H.K.P.	220562U

Contents

June 12, 2025

1 Production Documentation

This section provides the full set of instructions and technical information necessary to reproduce, assemble, wire, program, and test the strain gauge-based torque sensor. It is intended for use by engineers and technicians during manufacturing, maintenance, and future development.

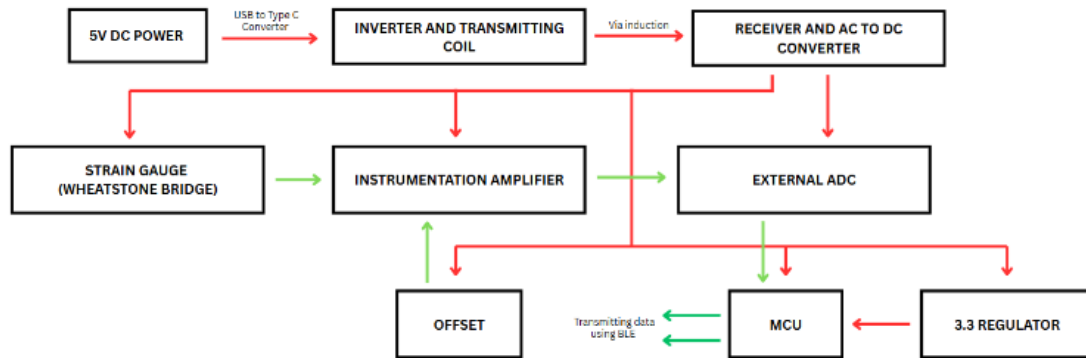## 1.1 System Architecture Overview

Figure 1: High-level system block diagram of the torque sensor

1.2 Complete Bill of Materials (BoM)

Category	Component Name	Description / Notes
Sensors	SGT-2DC/350-SY11	Dual-grid strain gauges (Omega, 350 Ω)
Amplifiers	AD8293G160	Instrumentation amplifier (Fixed gain 160)
	OPA336	Secondary precision op-amp
ADC	HX711	24-bit ADC for bridge signals (external to MCU)
DAC	MCP4728	12-bit DAC for offset adjustment
Microcontroller	DA14531 TINY Module	BLE 5.1 microcontroller
Power Supply	Qi Wireless TX/RX Coil Pair	Wireless power coils (inductive)
	Rectifier and Regulator Circuit	5 V output from Rx coil
	USB-C Connector	5 V input source
Passives	Resistors (Precision, 1%)	Signal conditioning
	Capacitors (Ceramic, MLCC)	Decoupling, filtering
Connectors	Terminal Block 3-pin	Strain gauge terminal access
	JST/SMD Headers	Module interfacing
PCB	Custom PCB	Main control and signal board
Mechanical	Shaft (AISI 1018 Steel)	17 mm diameter, torque sensing region
	Bearings	Radial bearings for shaft rotation
	Molded Enclosure	Two-part, bolt-closed enclosure
	Mounting Bolts and Screws	M3/M4 as per enclosure design
Miscellaneous	Ribbon Cables	For flexible wiring on shaft
	Epoxy Adhesive	For strain gauge bonding
	Shielded Twisted Pair Cable	For signal integrity

Table 1: Complete Bill of Materials for Torque Sensor System (Simplified)

2 Mechanical Engineering Instructions

This section outlines the detailed mechanical steps involved in fabricating the torque sensor's physical components, assembling the mechanical system, and preparing the shaft for strain gauge bonding and environmental protection. It is intended for technicians and engineers responsible for the physical realization of the sensor.

2.1 Shaft Fabrication

1. **Material Selection:** Use Aluminum Alloy 6061-T6 for its excellent machinability, corrosion resistance, and favorable strength-to-weight ratio. Yield strength: 275 MPa. Elastic modulus: 69 GPa. This alloy is well-suited for lightweight torque sensor applications where moderate stress levels are expected.

2. **Dimensions:** Turn the shaft on a lathe to a final diameter of **17 mm** and ensure a central narrow region where strain gauges will be mounted. Maintain a shaft length that accommodates bearing insertion and torque transmission interfaces at both ends.

3. **Surface Finish:** Achieve a surface roughness of **Ra less than 0.4 µm** using progressively finer polishing techniques. A smooth surface is essential for effective strain gauge bonding and reducing localized stress concentrations.

4. **Concentricity and Balancing:** Verify shaft symmetry and ensure dynamic balance to avoid rotational vibration during testing and real-time use.

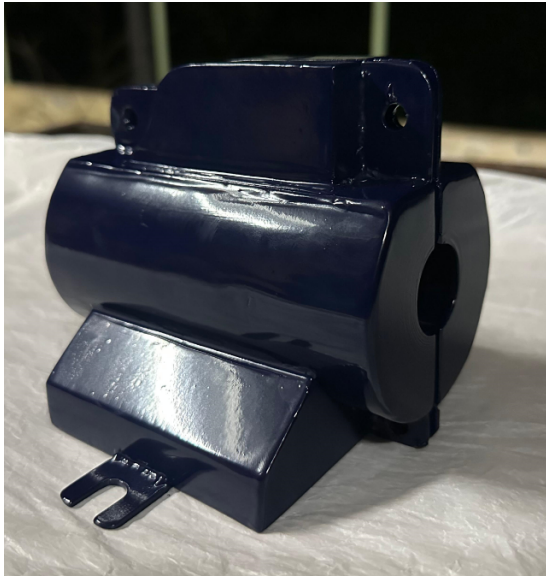## 2.2 Enclosure Design and Assembly

Figure 2: Final torque sensor enclosure fabricated from stainless steel

1. **Enclosure Type:** The finalized enclosure is fabricated from corrosion-resistant stainless steel, selected for its superior structural integrity, environmental resilience, and suitability for industrial use. It is constructed from two main welded halves that follow the original CAD model dimensions and tolerances.

2. **Construction Method:** The two halves are joined using a bolted interface with flange extensions. Welded seams ensure mechanical rigidity while maintaining precision. Alignment notches and pilot holes are incorporated during fabrication to aid accurate mating and prevent misalignment during assembly.

3. **Internal Features:** The interior of the housing includes:

   - Precision-machined bearing grooves on both sides to ensure accurate shaft alignment and reduce radial play.
   - Welded metal brackets for mounting the internal PCB assemblies securely in a vibration-isolated configuration.
   - A fixed holder for the wireless power receiver coil aligned with the external transmitter.

4. **Modularity and Serviceability:** The design supports easy disassembly using standard hex bolts. The modular structure allows for straightforward access during recalibration, firmware reprogramming, or component replacement.

5. **Environmental Protection:** To withstand demanding industrial environments:

   - The outer surface is treated with anti-corrosion finishing (e.g., brushed stainless or powder coating).
   - Internal cavities are sealed with high-grade silicone gaskets to prevent ingress of dust and moisture.

6. **Cable Routing and Interface:** Cable access holes are machined at the rear end and fitted with metallic cable glands for strain relief and environmental sealing. These are positioned to allow routing of power, debug, and signal wires without affecting the shaft's rotational clearance.

7. **Mechanical Stability:** The shaft is supported within the enclosure using deep-groove ball bearings mounted in the machined recesses. The enclosure's mass and rigidity reduce vibrational coupling and ensure minimal distortion in the strain measurements.

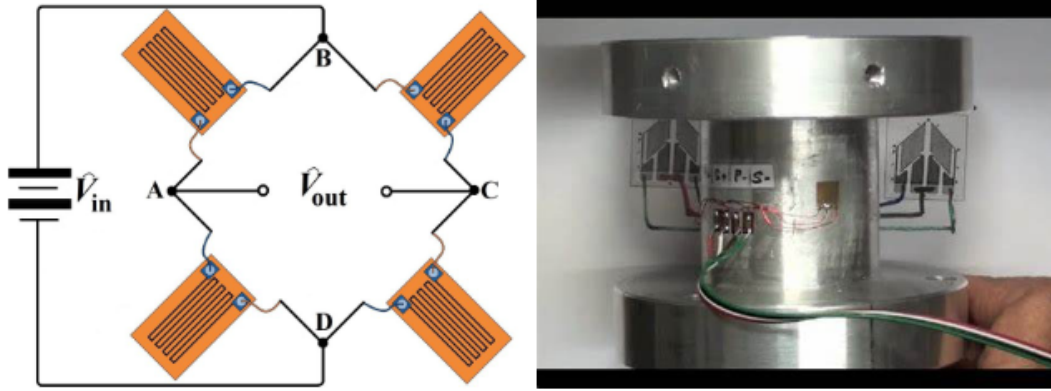## 2.3 Strain Gauge Installation Procedure

Figure 3: Strain gauge placement
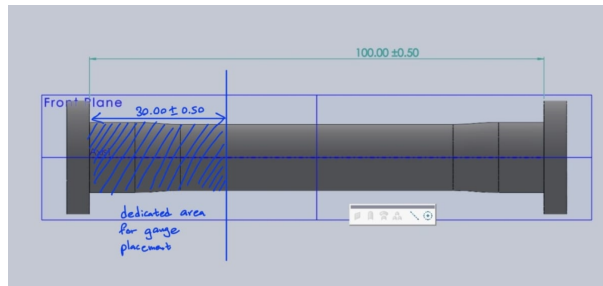
3.1 Optimal Placement Identification

Figure 4: Strain gauge placement

1. **Finite Element Analysis (FEA):** Use FEA tools (e.g., SolidWorks Simulation) to simulate shear stress under applied torque. Fix one end of the shaft and apply a known torque at the other.

2. **Distortion Mapping:** Locate the region of **maximum shear strain**

3. **Marking Gauge Position:** Using a micrometer and a wrap-around marking template, draw layout lines at ±45° from the shaft axis, 180° apart.

3.2 Shaft Surface Preparation

1. **Degrease:** Wipe with isopropyl alcohol or acetone using a lint-free cloth.

2. **Abrasive Polishing:** Polish with 600–1200 grit emery paper in a single axial direction to slightly roughen the bonding area.

3. **Mark and Align:** Re-mark layout lines post-abrasion with fine pencil or scribing tool.

4. **Final Cleaning:** Rinse again with alcohol and allow to air dry in a dust-free environment.

3.3 Bonding the Strain Gauges

1. **Adhesive:** Use SBond conductive adhesive suitable for shear/torque sensors.

2. **Gauge Handling:** Using tweezers, gently position the dual-grid strain gauges on the prepared shaft.

3. **Bonding Method:** Apply a small quantity of SBond to the marked area. Place the gauge and press uniformly using a silicone pad and apply a 0.5–$1\,\mathrm{kg/cm^2}$ load via clamp or weight.

4. **Pressure Hold:** Maintain pressure for 20 minutes to allow partial cure and initial fixation.

5. **Curing:** Place the shaft in an oven and cure at **180 °C for 2 hours** to fully activate the SBond polymer. Ensure no mechanical load is applied during this step.

2.4 Wiring of Strain Gauges

1. **Soldering:** Solder cables to the strain gauge pads using a fine-tipped soldering iron (max 250 °C).

2. **Strain Relief:** Fix wires to the shaft using small dabs of epoxy or mechanical clamps 10–20 mm from solder joints.

3. **Cable Routing:** Guide wires through a terminal block or solder pad mounted near the shaft edge. Match wire lengths to maintain bridge symmetry.

4. **Shielding:** Use twisted-pair shielded wires where signal wires leave the shaft enclosure.

2.5 Protective Coating Application

1. **Coating Type:** Use polyurethane or silicone-based conformal coating (e.g., MG Chemicals 422B).

2. **Application Method:** Apply thin, even layers using a small brush or airbrush, ensuring full coverage of strain gauge and solder joints.

3. **Cure Time:** Allow the coating to cure at room temperature for 12–24 hours. Do not operate the sensor during this period.

4. **Verification:** Inspect under magnification to confirm complete encapsulation.

2.6 Final Mechanical Integration

1. **Insert Bearings:** Press bearings into the enclosure ends with proper alignment.

2. **Mount Shaft:** Insert shaft through bearings, ensuring smooth rotation with minimal play.

3. **Align Wireless Coils:** Align the wireless power transmitter coil in the enclosure with the receiver coil on the shaft. Test for maximum inductive coupling distance.

4. **Seal the Enclosure:** Fasten enclosure bolts if needed. Check torque ratings to avoid deformation.

5. **Label Components:** Apply component labels and serial numbers externally for traceability.

Note: All assembly steps should be performed in an ESD-safe, humidity-controlled lab environment to ensure long-term sensor reliability.

3 Manufacturing Summary

The final torque sensor assembly required a multidisciplinary manufacturing process involving mechanical fabrication, PCB assembly, strain gauge bonding, and precision calibration. Below is a summary of the key manufacturing steps:

- **Shaft Machining:** CNC-turned from Aluminum 6061 with a final diameter of $17\,\text{mm}$. Middle region polished for strain gauge bonding.

- **Strain Gauge Installation:** Dual-grid shear strain gauges bonded at $\pm45°$ using SBond adhesive; heat-cured at 180°C for 2 hours.

- **Enclosure Fabrication:** TIG-welded stainless steel housing with precision bearing slots, coil recess, and PCB mounting brackets.

- **PCB Assembly:** Surface-mounted components on 2-layer flexible polyimide PCB. Layout optimized for shaft conformity and noise immunity.

- **Wireless Coil Integration:** Receiver coil mounted on shaft; aligned precisely with transmitter using fixture-guided assembly.

- **System Calibration:** Torque applied via known weights. Voltage readings mapped, offset/gain applied to firmware.

4 PCB Manufacturing Instructions

4.1 Schematic Design

4.1.1 Transmitter

Figure 5: Transmitter circuit
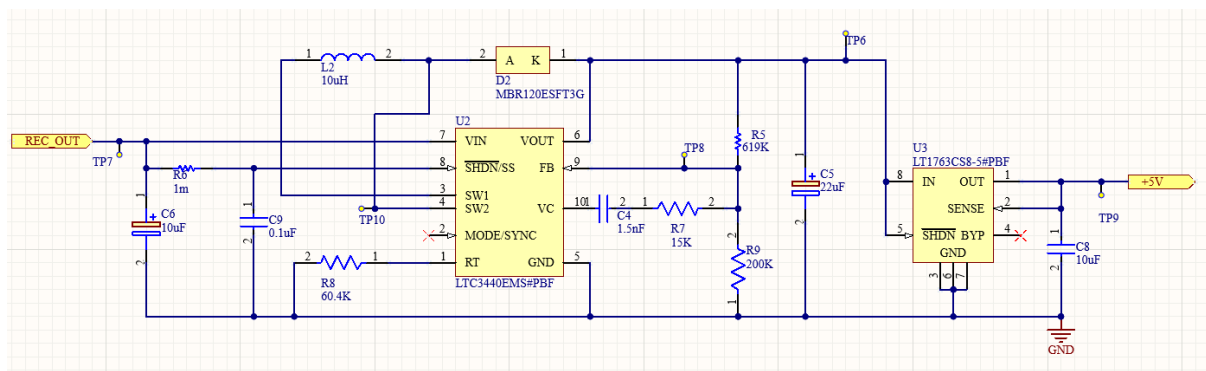
4.1.2 RECEIVER

Figure 6: receiver circuit

4.1.3 BOOSTER

Figure 7: booster circuit

4.1.4 INSTRUMENTATION

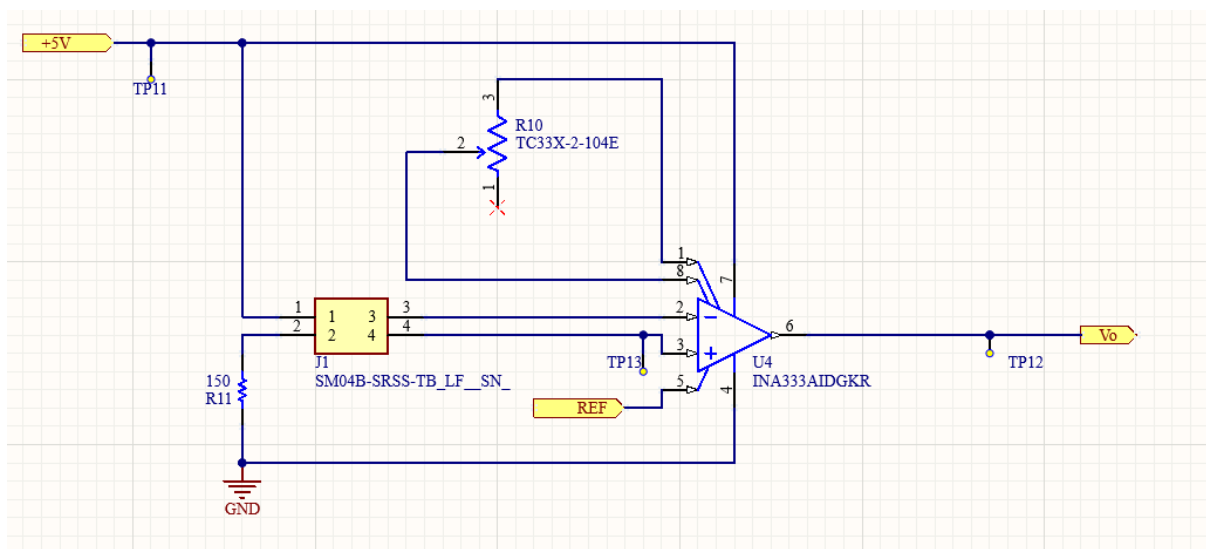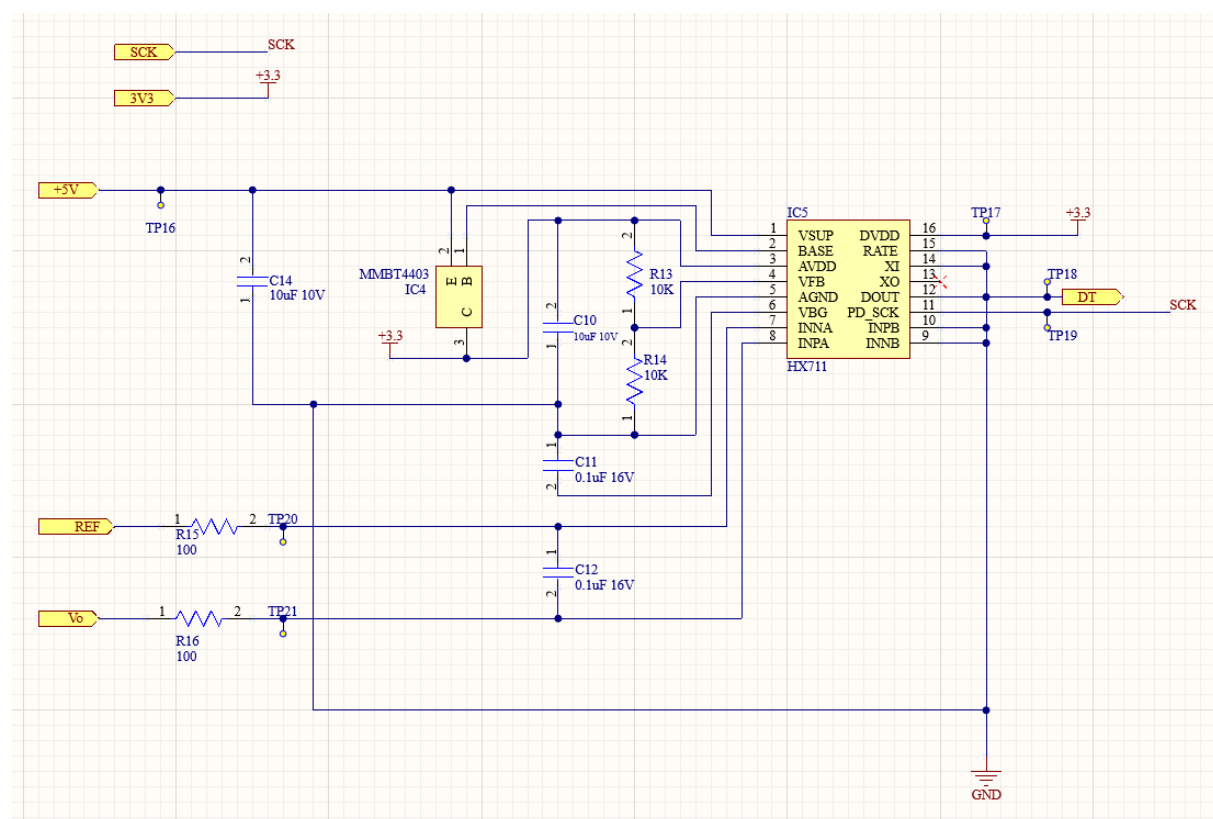Figure 8: Instrumentation Amplifier

4.1.5   OFFSET

Figure 9: offset
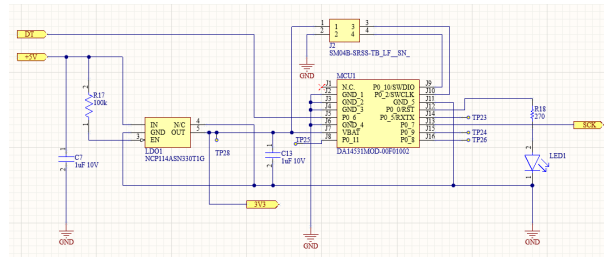
4.1.6   ADC

Figure 10: ADC

4.1.7 MCU

Figure 11: MCU

4.2 PCB Assembly Instructions

The following instructions outline the complete process for assembling the printed circuit board (PCB) used in the torque sensor system. Proper PCB assembly ensures optimal electrical performance, signal integrity, and mechanical reliability.

1. Preparation and Inspection

1. **Visual Inspection of Bare PCB:** Inspect the PCB for fabrication defects, such as incomplete vias, scratches, or delamination. Verify silkscreen alignment and layer registration.

2. **Clean the PCB Surface:** Use isopropyl alcohol and lint-free wipes to remove oxidation or flux residues before beginning component placement.

3. **Gather Required Tools and Materials:**

   - ESD mat and wrist strap
   - Fine-tip soldering iron (350°C)
   - Solder wire (0.5mm, Sn63Pb37 or SAC305)
   - Solder paste and hot air rework station (if reflow soldering is used)
   - Tweezers, flux pen, magnifying glass/microscope
   - Multimeter for continuity testing

2. Component Placement Order

Follow the standard order of assembly to ensure accessibility and minimize errors:

1. **Passive SMD Components:** Begin with 0402/0603 resistors, capacitors, and ferrite beads. Use tweezers and place on pre-applied solder paste or fluxed pads.

2. **ICs and Amplifiers:** Place precision analog components such as the AD8293G160, OPA336, and MCP4728 with correct pin orientation. Avoid overheating sensitive analog ICs.

3. **Microcontroller and ADC:** Mount the DA14531 and HX711 modules. Ensure proper alignment of WLCSP pads or castellated edges.

4. **Connectors and Headers:** Insert JST, terminal blocks, USB-C connectors, or test headers.

5. **Inductive Power Components:** Solder coils, MOSFET drivers, and rectification circuits for wireless power reception. Maintain spacing from analog circuitry.

3. Soldering Process

1. **Manual Soldering (if applicable):** Apply solder to each pad with a fine tip iron. For ICs, use drag soldering with flux to ensure even pin contact.

2. **Hot Air Reflow (optional):** Preheat the board and reflow at 220–240°C peak. Follow manufacturer reflow profiles for temperature-sensitive components.

3. **Check for Bridges and Cold Joints:** Use magnification to inspect solder joints. Rework any poor joints with flux and fresh solder.

4. **Clean Flux Residue:** Remove excess flux with isopropyl alcohol and a soft brush to prevent corrosion and leakage currents.

4. Assembly Best Practices

- Place decoupling capacitors as close as possible to IC power pins.

- Avoid placing high-speed digital lines close to analog signal paths.

- Ensure clearance between high-voltage coil components and signal circuitry.

5. Post-Assembly Inspection and Testing

1. **Continuity Check:** Verify all power rails and signal lines are properly connected and there are no shorts between adjacent pins.

2. **Power-Up Test:** Connect 5V via USB and check power LED, voltage regulators, and check for overheating components.

3. **Programming Interface Test:** Flash a simple test program to the DA14531 and verify BLE broadcast or UART output.

4. **Signal Path Test:** Apply a known input to the strain gauge terminals and confirm valid output at the amplifier stage using an oscilloscope.

4.3   Flex PCB Implementation for Shaft-Mounted Sensor

The torque sensor PCB was designed as a two-layer flexible printed circuit (flex PCB) to meet the mechanical and operational requirements of being mounted directly on a rotating shaft. This section provides production-oriented details necessary for fabrication, inspection, and reliable assembly.

1. Purpose of Flex PCB

The flex PCB enables direct integration with the shaft, offering a lightweight and vibration-tolerant solution that eliminates the need for separate cabling or rotating slip rings. It provides the following key production benefits:

- **Rotational Mounting Capability:** Conforms directly to a 17 mm shaft without interfering with shaft rotation.

- **Reduced Wiring Complexity:** Minimizes moving wires and connectors, reducing points of failure.

- **Vibration Tolerance:** Maintains reliable operation in high-vibration environments due to flexible substrate and secure solder joints.

2. Key Production Notes

- **Central Bend Region:** Keep free of components and vias to allow smooth wrapping around shaft. Ensure 10 mm margin from each side of the shaft bend zone.

- **Copper Patterning:** Use horizontal hatched fill for ground plane instead of solid fill to maintain flexibility and prevent copper cracking.

- **Trace Layout:** Route critical signals perpendicular to bend direction. Use rounded corners and curved traces for mechanical longevity.

- **Teardrops:** All pad-to-trace junctions must use teardrop geometries to prevent delamination.

- **Surface Mount Devices:** Place all SMD components on the top layer. No through-hole components should be used.

3. Assembly Guidelines

- **Fixturing During Soldering:** Use a stainless steel flat fixture to hold the flex board during reflow soldering to avoid warping.

- **Underfill (Optional):** For high-vibration applications, epoxy underfill may be applied under key ICs (e.g., DA14531, HX711) after soldering.

- **Strain Relief:** Cables leaving the flex board (e.g., to strain gauges or power coil) should be anchored using polyimide tape or hot glue to prevent peel force on pads.

- **Inspection:** Use magnification to inspect for cracked pads, lifted copper, and delamination around bend regions.

4. Test Point Integration

Dedicated test points were added for:

- HX711 CLK and DOUT

- BLE module power and UART

- Amplifier output and DAC reference

This allows signal probing during manufacturing and later servicing.

5. Conclusion for Production Use

The flex PCB design used in this torque sensor enables compact, durable, and precise sensing on a moving platform. The production and handling requirements outlined above must be strictly followed to ensure mechanical stability and electrical integrity over long-term operation.

5 Wiring and Connections

Proper wiring is essential to maintain signal integrity, minimize electromagnetic interference (EMI), and ensure reliable, long-term operation of the torque sensor system. This section outlines both the wiring best practices and the circuit integration flow necessary for accurate signal handling and power distribution.

5.1 Wiring Guidelines

- **Shielded Twisted Pair Wiring:** Use shielded twisted pair (STP) cables for all analog signal lines between strain gauges and the instrumentation amplifier (AD8293G160). This minimizes susceptibility to ambient EMI.

- **Symmetric Routing:** Maintain equal-length signal paths from the strain gauges to the amplifier inputs to preserve bridge balance. Use color-coded or tagged wires to clearly identify each node.

- **Strain Relief and Anchoring:** Secure all external wires (e.g., from the strain gauges and receiver coil) using epoxy, hot glue, or adhesive-backed cable clips. Leave a minimum 10 mm service loop for each terminal to prevent solder joint fatigue.

- **Conformal Coating Exposure Zones:** Leave test pads and wire joints uncoated until final verification is complete.

5.2 Circuit Signal Flow Description

The following is the detailed signal chain through the system:

- **Sensor Interface:**

    - Strain gauge outputs (differential voltage) $\rightarrow$ AD8293G160 (instrumentation amplifier).

- **Offset Control:**

    - MCP4728 DAC output $\rightarrow$ `REF` pin of AD8293G160 to provide software-configurable offset voltage.

- **Post-Amplification:**

    - AD8293G160 output $\rightarrow$ OPA336 secondary amplifier for final signal conditioning and level scaling.

- **Analog-to-Digital Conversion:**

    - Final amplified analog signal $\rightarrow$ HX711 ADC (24-bit differential).

- **Digital Output:**

    - HX711 digital output (DOUT + CLK) $\rightarrow$ DA14531 BLE microcontroller via GPIO.

5.3 Power Distribution Overview

- **Wireless Power Input:** 5 V DC received via inductive coil.

- **Regulation:**

    - Qi receiver output $\rightarrow$ Schottky diode $\rightarrow$ 5 V LDO (LT1763-5) $\rightarrow$ 3.3 V LDO (NCP114) for MCU and analog sections.

- **Bypass Capacitors:**

    - Place 100 nF and 10 µF ceramic capacitors near all IC power pins to suppress transients.

5.4 Final Assembly Notes

- **Test Point Access:** Ensure labeled test points are available for amplifier output, DAC reference, ADC input, and BLE UART during verification.

- **Wire Labeling:** Each wire from strain gauges and the power coil should be labeled with heat-shrink or marker flags before final assembly.

- **Shielding:** Ground the shield of STP cables at the amplifier input side only to avoid ground loops.

6 Programming Instructions for DA14531MOD

This section provides detailed instructions for programming the DA14531MOD Bluetooth Low Energy (BLE) microcontroller used in the torque sensor system. The process includes firmware development, compilation, and flashing to onboard SPI flash memory.

Required Tools

- **Software:**

  - Keil MDK (Microcontroller Development Kit)
  - SmartBond Flash Programmer (Renesas)
  - DA14531 SDK (Software Development Kit)

- **Hardware:**

  - DA14531MOD development board or integrated module
  - USB-to-UART or USB-to-JTAG adapter
  - Jumper wires and regulated power supply (3.3V)

Step 1: Firmware Development using Keil MDK

1. Install Keil MDK and DA14531 SDK.

2. Create or open the firmware project in Keil.

3. Configure the project:

   - Select target device: `DA14531`.
   - Integrate BLE services and sensor characteristics.
   - Implement the desired embedded C code using SDK templates.

4. Compile the project to generate a `.hex` file.

5. Ensure successful compilation with no errors.

Step 2: Flashing via SmartBond Flash Programmer

1. Open the SmartBond Flash Programmer software.

2. Select `DA14531MOD` as the target device.

3. Connect the module to the PC using UART or JTAG:

   - For UART: TX, RX, and RESET pins.

- For JTAG: SWDIO and SWCLK lines.
  - Apply correct GPIO boot configuration (e.g., pull P0_0 low).

4. Load the compiled `.hex` file into the programmer.

5. Initiate flashing and wait for confirmation of success.

Step 3: BLE Operation and Data Transmission

- After successful flashing, the microcontroller executes the firmware from flash memory.

- The firmware initializes the BLE stack and GATT services.

- Sensor data is transmitted over BLE using predefined characteristics.

- External software or apps can connect and visualize the data in real-time.

7 Testing Procedure

7.1 Initial Functional Test

1. Connect USB or wireless power to the device.

2. Scan for the BLE advertisement.

3. Pair with the sensor and verify initial readings are transmitted. Without load, readings should be near $0\,\text{N·m}$ ($\pm 0.1\,\text{N·m}$).

4. Confirm that the amplifier stages are producing valid output signals using an oscilloscope.

7.2 Calibration and Load Testing

1. Place the sensor on a calibrated mechanical torque test rig.

2. Apply incremental torque loads (e.g., 0, 1, 2, 3, 4, $5\,\text{N·m}$) and record the corresponding sensor outputs.

3. Fit the data to a linear model and extract offset and gain values.

4. Program the updated coefficients into firmware to enable direct torque readout.

5. Verify repeatability by applying and removing loads in multiple cycles.

7.3 Quality Control Checklist

Each sensor unit must pass the following checks before being approved for deployment:

- **Visual Inspection:** Check for damaged components, cold solder joints, misaligned ICs, or PCB discoloration.

- **Electrical Continuity:** Verify all key traces and power rails using a multimeter.

- **BLE Functionality:** Ensure the device advertises and can establish a BLE connection.

- **Torque Readout Accuracy:** Confirm sensor readings are within $\pm 5\%$ of reference values across the torque range.

- **Environmental Robustness:** Check strain gauge encapsulation and conformal coating integrity.

8 Packaging and Shipping

Final packaging ensures safety during storage and transport:

- **Anti-Static Protection:** Wrap the assembled sensor PCB in ESD-safe foam and place it in an anti-static bag.

- **Mechanical Cushioning:** Use high-density foam or custom 3D-printed holders to immobilize the shaft and bearings.

- **Documentation:** Include a printed quick-start manual, calibration certificate, wiring diagram, and QR code linking to the full documentation online.

- **Labeling:** Mark the enclosure with the serial number, calibration date, and firmware version.

- **Sealing:** Ensure all enclosures are fully closed and optionally vacuum-sealed to protect against moisture ingress during long-term storage.