Production Document

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Capacitive Torque Sensor

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1 Objective

The objective of this production report is to document the development, manufacturing process, and performance evaluation of the Capacitive Torque Sensor. This report aims to provide a comprehensive overview of the sensor's design, production stages, quality control measures, and testing results to ensure it meets the required specifications for accuracy, sensitivity, and durability. Additionally, this report serves as a reference for stakeholders, facilitating future improvements, scalability, and compliance with industry standards. By detailing key challenges, solutions, and production efficiencies, this document supports continuous optimization and successful deployment of the torque sensor in its intended applications.

2 System Overview

2.1 Working Principle

When torque (τ) is applied to the shaft, it induces a proportional **angular deflection** (θ) along the axis, governed by:

$$\tau = G \cdot J \cdot \frac{\theta}{L} \tag{1}$$

where G is the shear modulus, J the polar moment of inertia, and L the shaft length.

2.1.1 Capacitance Variation Mechanism

The angular deflection alters the overlapping area (A) between two parallel conductive plates separated by a dielectric (e.g., polyimide film). The capacitance (C) is given by:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{2}$$

where ε_0 is vacuum permittivity, ε_r the dielectric constant, and d the plate separation.

Area Modulation: Radial plate geometry maximizes sensitivity to angular displacement.

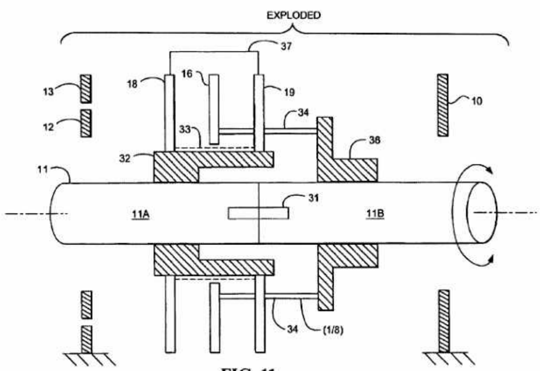

FIG. 11

Figure 1: Internal Arrangement of the Sensor

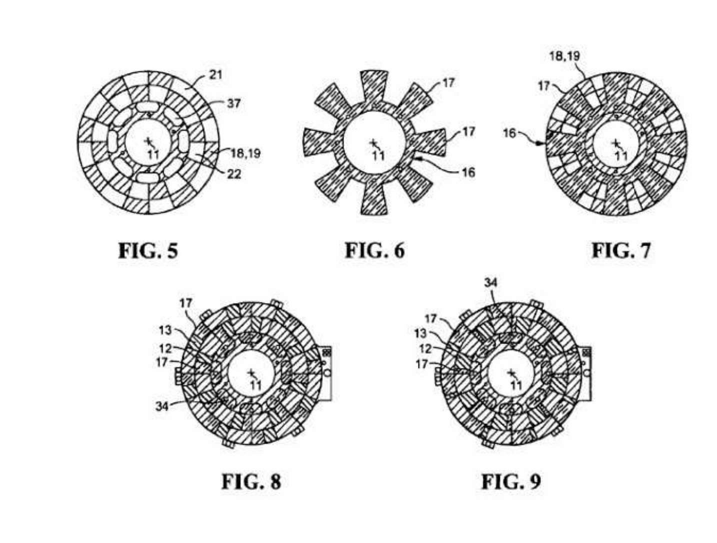

Figure 2: Area modulation in the capacitance measurement

2.1.2 Signal Processing Chain

- **Capacitance-to-Digital Converter (PCAP04)**:
  - 24-bit resolution for ±0.1 fF sensitivity
  - Integrated temperature compensation
  - SPI interface for microcontroller communication
- **Microcontroller (ATmega32U)**:
  - Linearizes data using polynomial calibration curves
  - Outputs data via USB at 1 kSPS

2.2 Block Diagram

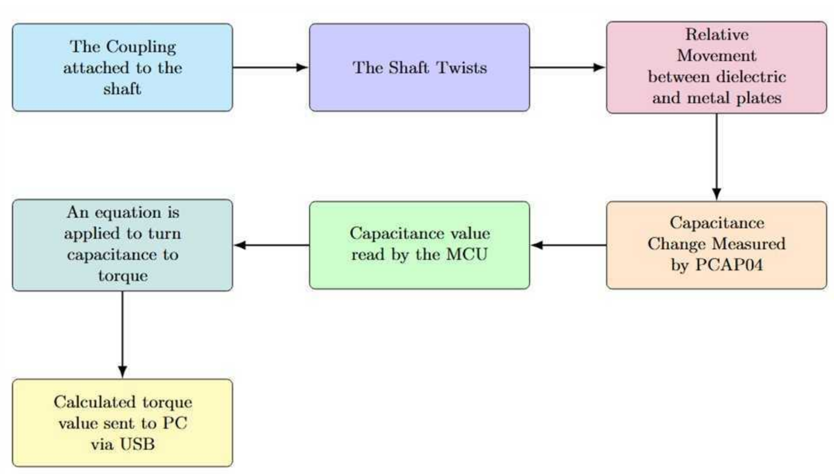

Figure 3: Block diagram of the system

3 Mechanical Design

The mechanical design of the capacitive torque sensor consists of two primary components: the enclosure, which provides robust protection and structural integrity, and the internal structure, which houses the sensitive capacitive elements and ensures precise torque measurement.

3.1 Enclosure Overview

The enclosure is constructed from anodized aluminum to provide corrosion resistance and electromagnetic shielding. Its design includes mounting flanges for secure attachment to rotating shafts, and it houses the capacitive sensing elements while maintaining environmental protection.

Figure 4: Enclosure of the Sensor

3.1.1 Parts of the enclosure

The enclosure consists of a middle body, 2 outer lids and 2 bearings.

3.2 Internal structure Overview

Internal mechanism of the sensor consists of a shaft,2 metal disks, 1 dielectric disk, holders of the disks.

3.2.1 Assembly of Internals

1. Begin by attaching the first metal disk to the holder.
2. Place the dielectric disk over the first metal disk, ensuring proper alignment.

Figure 5: Middle part of the enclosure made of aluminium

Figure 6: Outer lids of the sensor made of steel.

Figure 7: Aluminium shaft machined using a lathe.

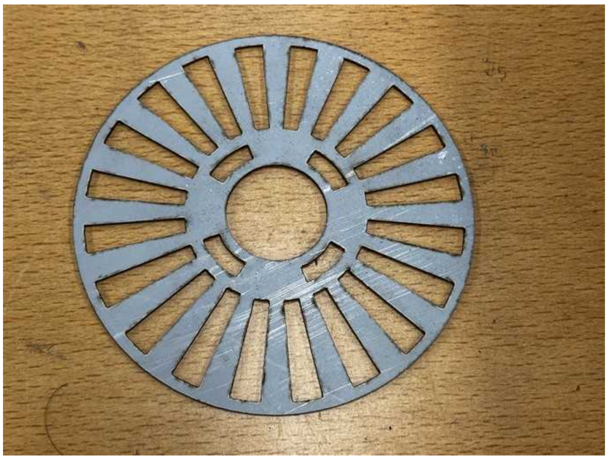

Figure 8: Metal disks made of nickel-coated steel, cut using CNC machining

Figure 9: Dielectric disk cut using laser cutting.

Figure 10: Holders that connect metal and dielectric disks to the shaft.

3. Attach the second metal disk on top of the dielectric disk using the same holder.
4. Secure the assembled holder to the shaft.
5. assemble the dielectric with the second holder.
6. Attach the second holder to the shaft.
7. Finally, mount the shaft onto the bearings to complete the assembly.

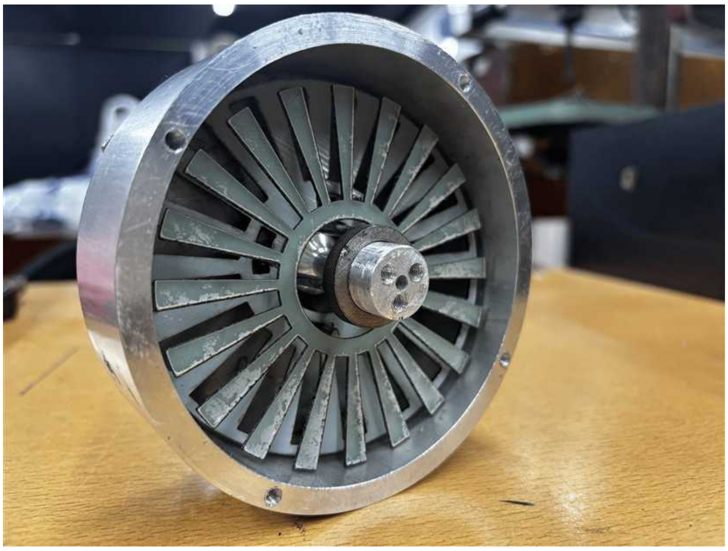

Figure 11: Complete internal assembly.

4 Schematic Circuit Design

4.1 MCU Circuit

- **Core Components**:
  - ATmega32U4 microcontroller
  - Key functions:
    - Reads capacitance via SPI
    - Computes torque using calibration equation
    - Manages USB communication
- **Power Management**:
  - 5x V_{CC} pins with decoupling capacitors
  - AVCC pin filtered via ferrite bead
- **Clock**: ECS-8FMX-160-TR 16MHz oscillator for USB timing
- **UI**: Reset button, 3x LEDs (USB/SPI/status)

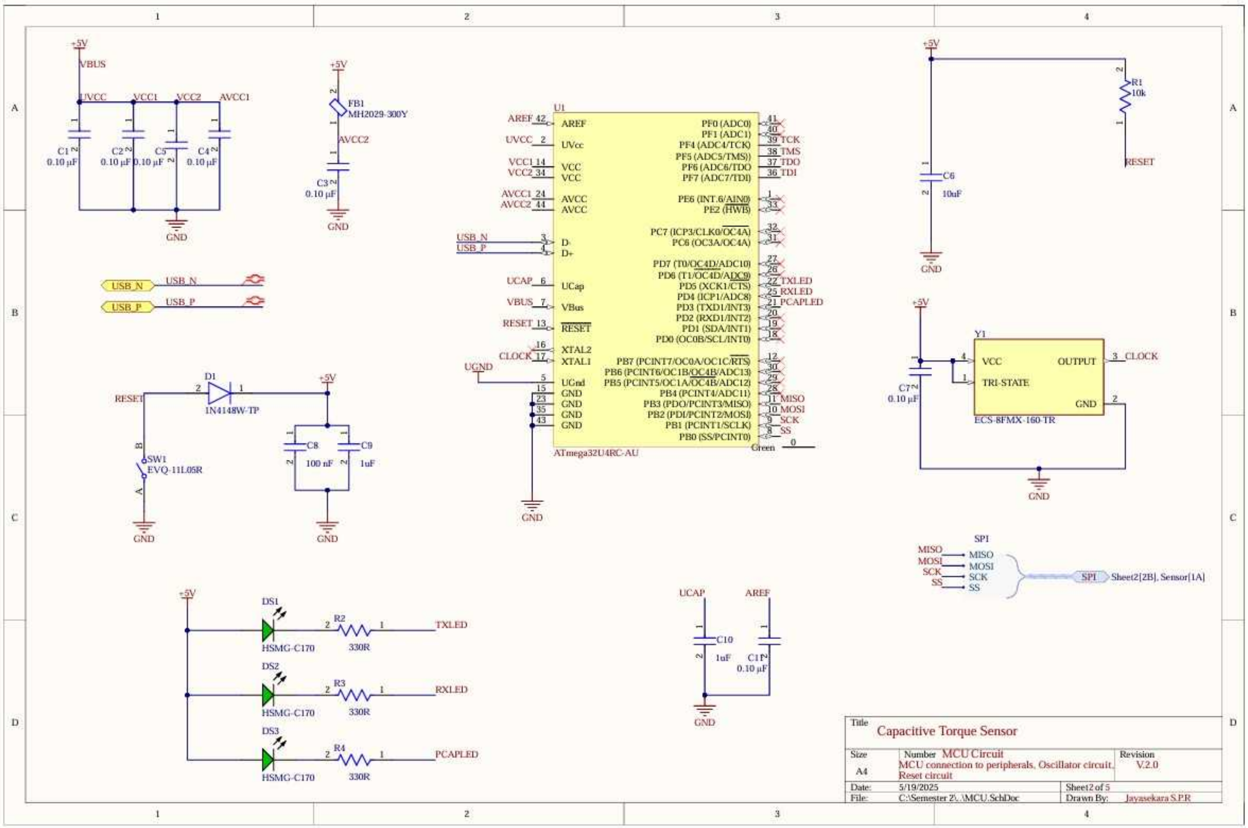

Figure 12: MCU Schematic

4.2 USB Circuit

- Provides **data transmission** and **power supply** (+5V via VBUS).
- **ESD Protection**:
  - +D/-D lines connected to ground through **varistors**.
- **Grounding**:
  - USB ground (UGND) and main ground linked via **ferrite bead** for:
    - High-frequency noise filtering
    - Prevention of ground loops
- **Power Line Protection**:
  - Resettable fuse for overcurrent protection
  - Capacitor C12 for ripple smoothing
  - LED DS4 as power indicator

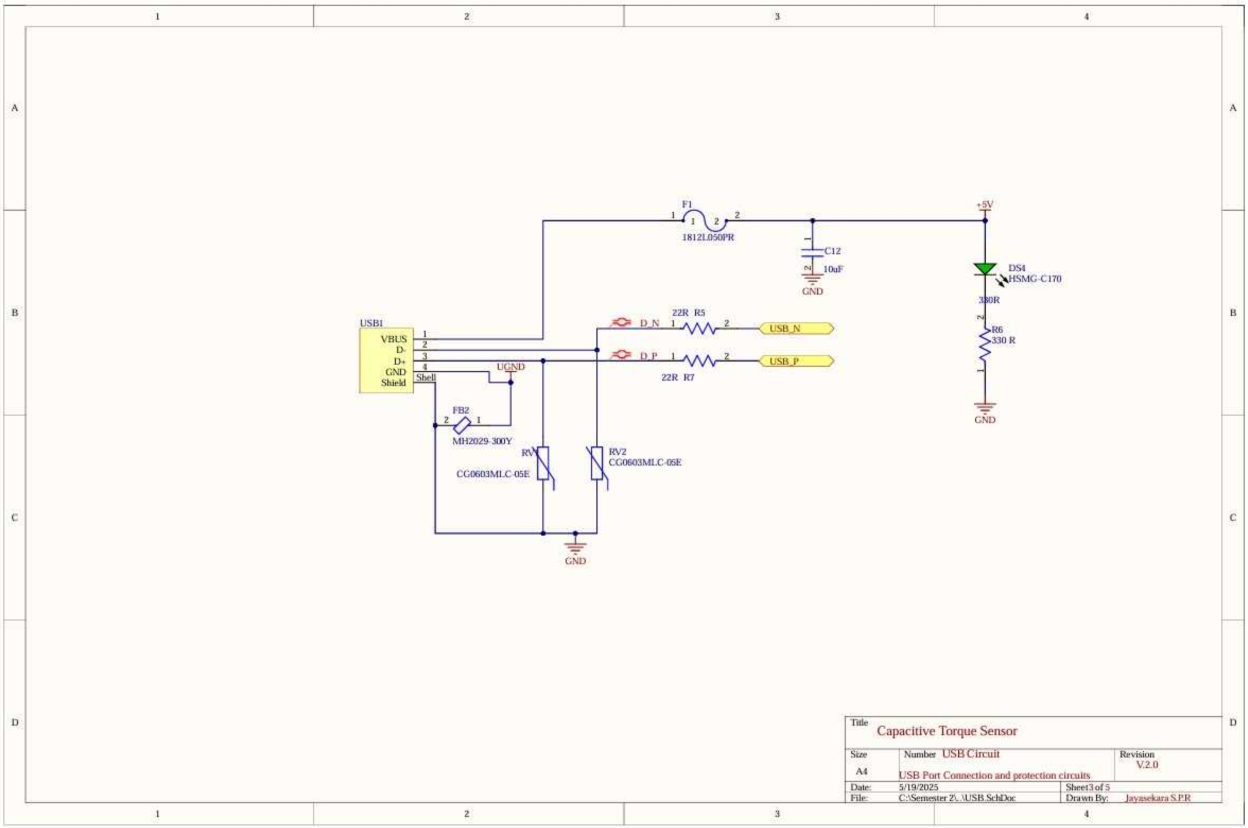

Figure 13: USB Schematic

4.3 Power Circuit

- Generates regulated voltages:
  * **+3.3V** and **+1.8V** for PCAP04 CDC
- **Design Features**:
  * Enable pins tied to V_{CC} for continuous operation
  * Input/output capacitors for:
    · High-frequency noise filtering
    · Ripple reduction

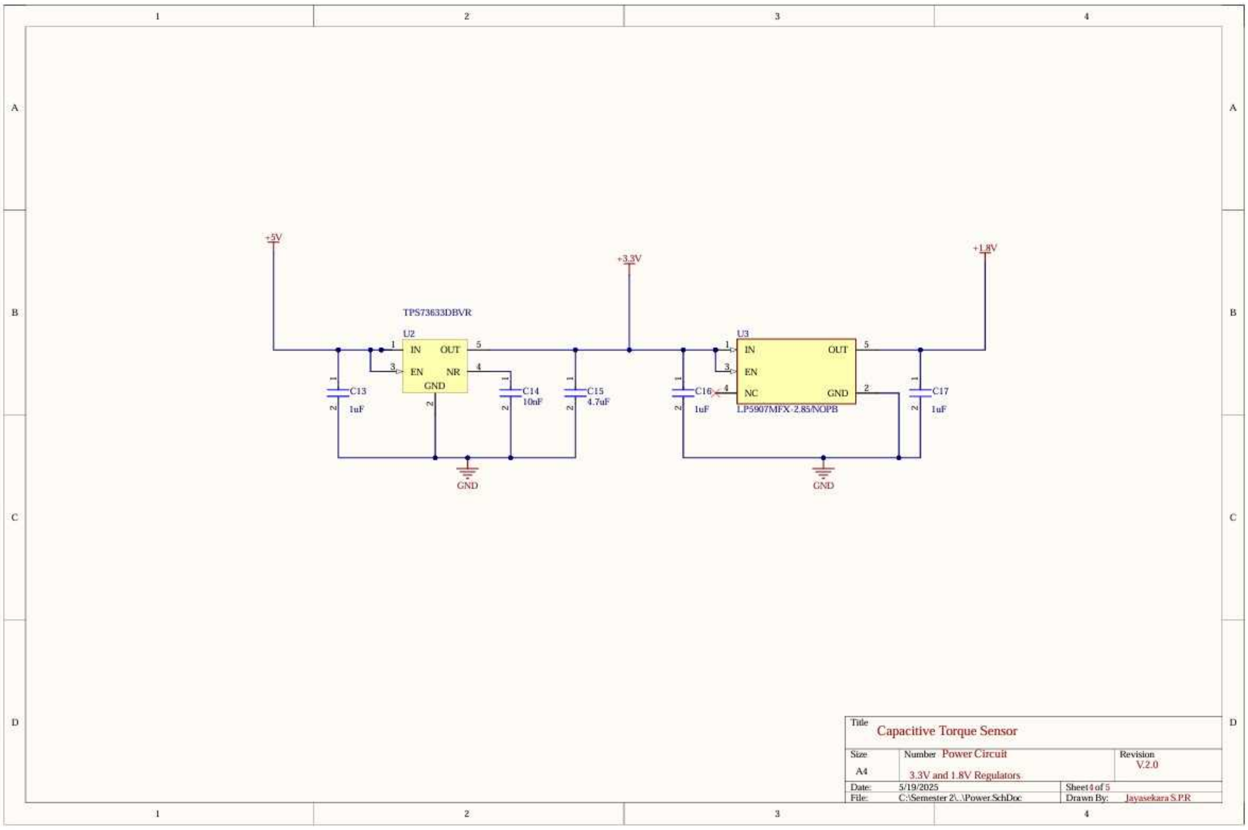

Figure 14: Power Supply Schematic

4.4 Sensor (CDC) Circuit

- **Capacitance-to-Digital Converter (PCAP04)**:
  - Powered by +3.3V (digital) and +1.8V (analog)
  - PC1 pin connected to sensor plates via 2-wire JST connector
  - Operates in **differential capacitance mode**
  - SPI communication with MCU
- **MOSFET Level Shifters**:
  - Converts MCU's +5V signals to +3.3V for CDC
  - Replaced TXB0104PWR IC due to low drive current
  - Used for SPI lines (SCK, MOSI, MISO, CS)

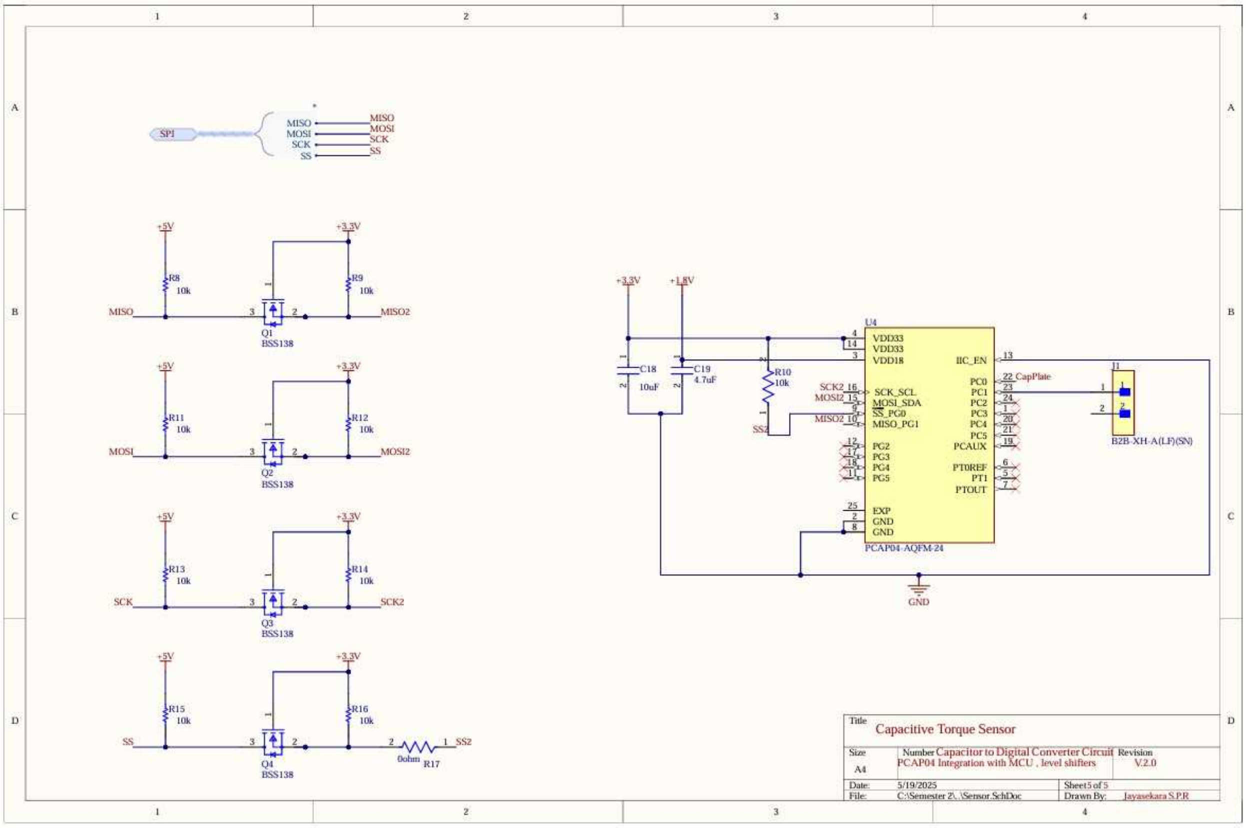

Figure 15: CDC Sensor Schematic

5 Electronics and PCB

The sensor assembly comprises two PCB boards, One board contains all the components and signal routing, while the other is a simple single-sided board with a solid copper plane only one side, serving as a conductive plate of the capacitor .

5.1 PCB Overview

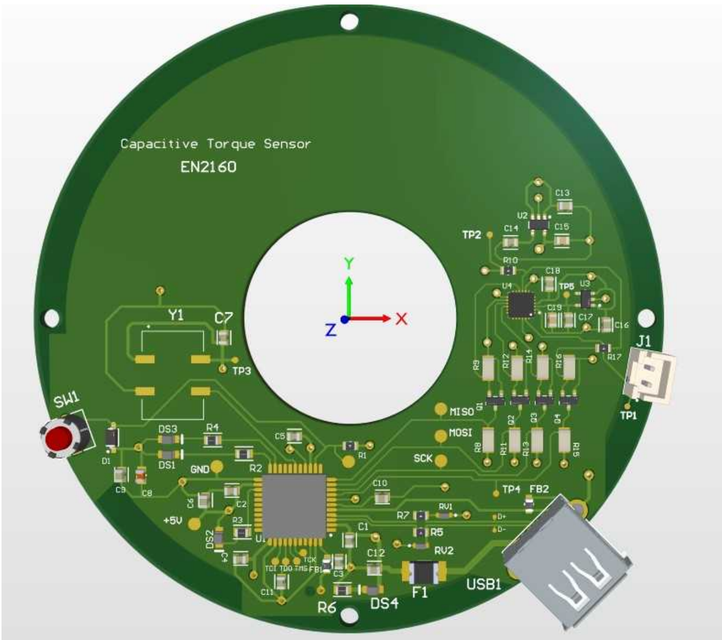

Figure 16: PCB with components.

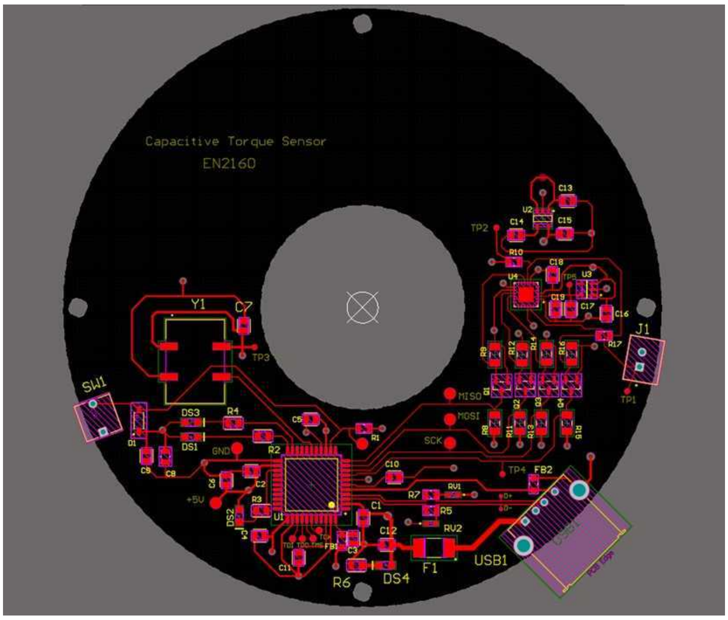

Figure 17: Top Layer of the PCB

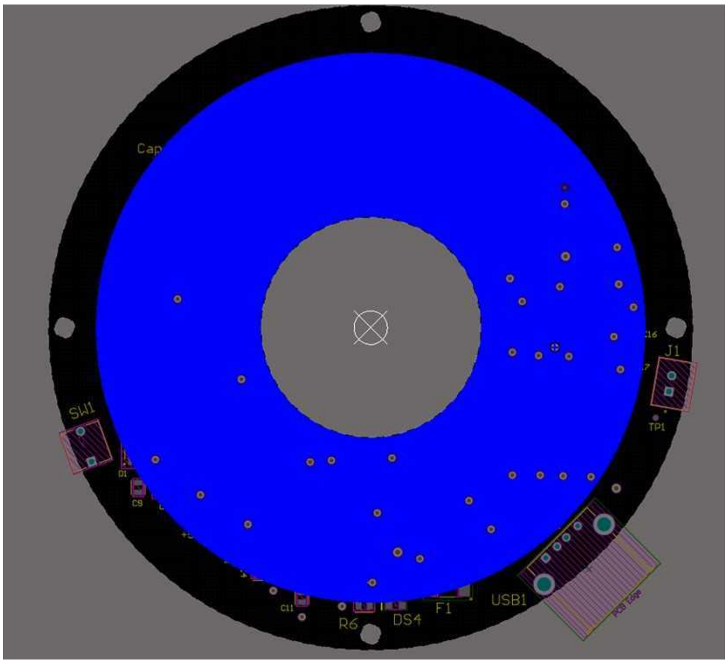

Figure 18: Bottom Layer of the PCB

5.2 Layer Stack-Up

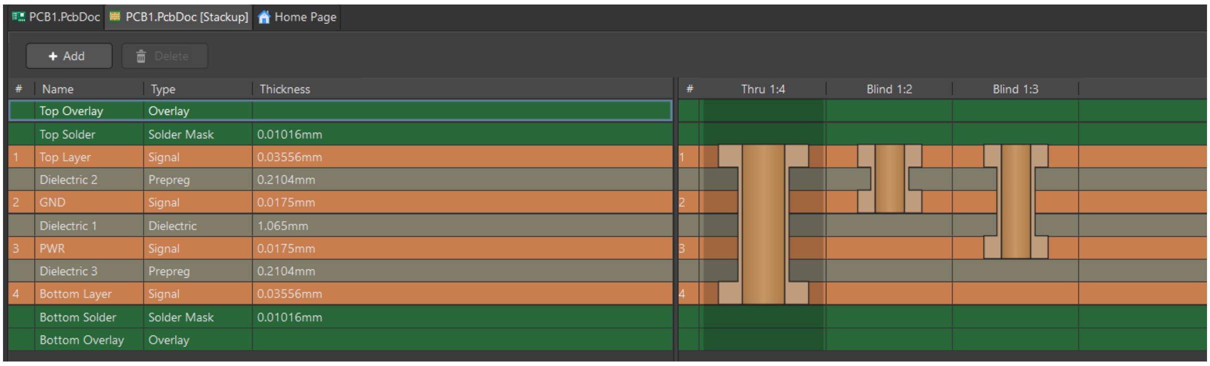

Figure 19: Layer Stack-Up of the PCB

As illustrated in Figure 19,The Printed Circuit Board (PCB) comprises a four-layer stack-up: the top and bottom layers are allocated for signal routing, while the inner layers are designated as follows: Inner Layer 1 serves as the ground plane, and Inner Layer 2 is dedicated to the power distribution network (3.3V and 5V).