# Design Report

## EN2160 - Electronic Design Realization

Department of Electronic and Telecommunication Engineering
University of Moratuwa

## Capacitive Torque Sensor

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# 1 Introduction

Torque measurement is a critical aspect in various mechanical and electromechanical systems, playing a vital role in applications ranging from industrial automation and automotive systems to robotics and biomedical devices. Accurate and reliable torque sensing is essential for performance monitoring, control, and safety in rotating machinery.

Conventional torque sensors such as strain gauge-based sensors and magnetoelastic sensors, while widely used, often suffer from limitations including sensitivity to environmental disturbances, mechanical wear, and complex signal conditioning requirements. In contrast, capacitive sensing offers a promising alternative due to its high sensitivity, low power consumption, compact form factor, and compatibility with modern digital signal processing techniques.

This project focuses on the design and development of a **Capacitive Torque Sensor**, which operates based on the principle that the application of torque to a shaft induces a mechanical twist, resulting in a change in capacitance between specially arranged conductive plates. By accurately detecting and processing these capacitance variations, the system can quantify the applied torque.

The primary objective of this project is to develop a compact, sensitive, and cost-effective capacitive torque sensor that can be integrated into rotating machinery. The proposed system includes a high-resolution capacitance-to-digital converter (PCAP04), innovative plate designs to enhance sensitivity, and a digital telemetry system to wirelessly transmit data from the rotating shaft to a stationary receiver.

This report outlines the background theory, concept development, system design, component selection, and the overall implementation strategy of the capacitive torque sensing solution. The project aims to bridge the gap between theoretical torque measurement principles and practical, deployable sensor systems suitable for real-world engineering applications.

## 2 Stakeholder Analysis

Stakeholders are individuals, groups or organizations that have an interest in or are affected by a product, project or a business. In this case the stakeholders can be categorized into three main groups.

### 2.1 Primary Stakeholders (Direct users of the torque sensor)

- **Users (Engineers)** – Require easy to use, lightweight accurate sensor. Require ease of integration
- **Business Owners** – Need cost effective options and reliability.

### 2.2 Secondary Stakeholders (Indirectly involved but affected by sensor performance)

- Production & Quality Control Teams – Ensure sensor reliability in manufacturing.
- Maintenance Technicians – Responsible for calibration and upkeep.
- Software Developers – Develop data acquisition and analysis tools for sensor readings.
- Procurement & Supply Chain Managers – Manage purchasing and availability.

### 2.3 Tertiary Stakeholders (Broader influence on the torque sensor's market and compliance)

- Regulatory Bodies – Ensure compliance with ISO, ASTM, and NIST standards.
- Marketing & Sales Teams – Position the product in the market.
- Competitors – Influence industry trends and innovation. (Robotuous, Wacoh-Tech, Futek, Honeywell)

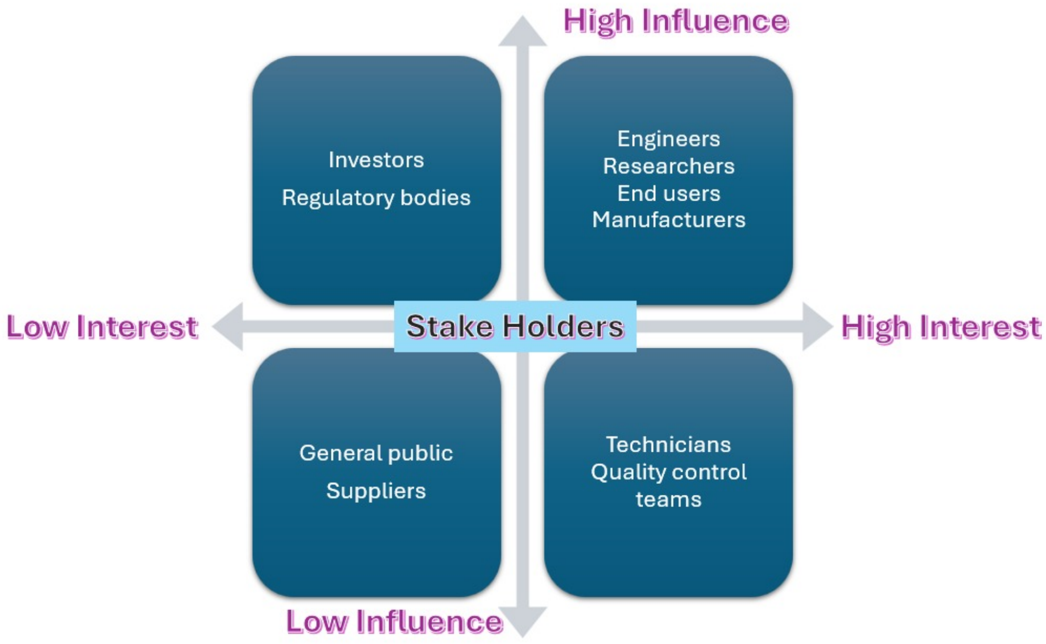



Figure 1: Stake Holder Map

# 3 User Journey for a Torque Sensor

- **Product Selection & Procurement** – The user selects a torque sensor based on accuracy, compatibility, and budget, then places an order.
- **Installation & Setup** – The sensor is mounted on the machine, connected to a data system, and tested for proper functionality.
- **Calibration & Configuration** – The user calibrates the sensor, sets sensitivity, verifies accuracy against a known torque standard
- **Operation & Data Collection** – The sensor continuously measures torque, logs data, and alerts the user to anomalies.
- **Maintenance & Troubleshooting** – Routine checks, recalibration, and cleaning ensure long-term performance, with troubleshooting as needed.
- **End of Life: Removal or Replacement** – The sensor is removed, recycled, or replaced with a new unit, repeating the setup process.

# 4 User Need Analysis

After observing videos of torque sensors used by individuals, we can get a sense of what they expect from a product and how they interact with existing products. It is also possible to see where current solutions cause inconveniences and frustrations to users and give us an idea about how to improve what is already available.

- **Light Weight**: First thing that was observed was the fact that individuals in videos handled the sensors often with one hand. This shows that the designed sensor has to be lightweight enough for users to handle comfortably. Also there were footages of torque sensors being attached to robot joints. Making the sensors heavy would put additional strain on limbs of the robot.
- **Accuracy and Precision**: There were videos of torque sensors being used in robots which did pick and placing of objects as well as medical robots which performed surgeries. Accuracy and precision of the measurements are critical in these scenarios since that data is fed into the control system for the robot.
- **Structural Rigidity**: Since there are deforming parts inside the sensor, it must be made sure that no part will be permanently deformed. Otherwise, it will require frequent sensor replacement. Proper material analysis and finite element analysis is required for this.
- **Easy to set up**: The sensors we observed had one cable attaching it to computers. The data from the sensor and the power to sensor is supplied through that. If users were able to use the sensor with no(minimal) calibration and set-up procedure, it would improve their experience of using the product.
- **Stability over time and Environmental Condition**: The sensor readings can change over time due to internal components being worn out(Sensor Drift). Environmental factors such as humidity and temperature can also affect capacitance. Users will require sensors that compensate for these issues.

# 5 Existing Products

In industry, there are two main types of Capacitive torque sensors:

### 5.0.1 Rotary (dynamic) torque sensors

These measure torque in rotating systems, such as motors or drivetrains, using strain gauges and slip rings or wireless telemetry to transmit data.

### 5.0.2 Reaction (Static) Torque Sensors

These measure torque without rotation by detecting the reaction force exerted on a stationary component. They are used in test benches, bolted joints, brake testing, and robot joints where rotation isn't required.

## I-PEX USA Company

**ESTORQ sensor**:

- Up to 10 Nm capacity
- IP65 Dust water resistance
- Built in 32-bit microprocessor

Figure 2: Eg:- Rotating type

## Robotous – Korean Company

**RFT sensor lineup**:

- Up to 20Nm capacity
- Dust protection in some models
- Communication Protocols – CAN/RS-232/RS-422/USB/EtherCAT

Figure 3: Eg:- Reaction type

# 6 Industries that generally use torque sensors

### Automotive Industry

- Used in engine testing, transmission testing, and drivetrain analysis.
- Helps improve fuel efficiency, durability, and performance of vehicles.
- Applications in electric vehicle (EV) motor efficiency testing.

### Aerospace & Aviation

- Ensures precise torque measurement for aircraft components like landing gear, turbines, and actuators.
- Used in flight simulators and wind tunnel testing.

### Robotics & Automation

- Enables force feedback control for robotic arms in manufacturing and medical robotics.
- Used in collaborative robots (cobots) to prevent damage by sensing force changes.

### Industrial Manufacturing

- Used in assembly line torque verification for bolts, screws, and fasteners.
- Ensures quality control in gearboxes, motors, and machine tools.

# 7 Stimulate Ideas

To explore innovative approaches for measuring torque using capacitive sensing, we engaged in brainstorming sessions and concept generation techniques. Our goal was to identify methods that not only leverage the capacitive principle but also overcome practical limitations in real-world applications.

## Basic Principle

The core idea behind capacitive torque sensing is based on the measurement of changes in capacitance caused by the deformation of a structure under torque. When a torque is applied to a shaft, it induces a slight twist or displacement. If capacitive plates are positioned in a way that their relative alignment changes with this twist, the resulting change in capacitance can be correlated directly to the applied torque.

## Initial Concept: Variable Overlap Capacitive Plates

Our starting concept used interdigitated electrodes—alternating conductive fingers mounted on both rotating and stationary parts of the shaft. As the shaft twists under torque, the overlap area between these electrodes changes, altering the capacitance. This variation can be measured and processed to derive the torque.

To increase sensitivity and resolution, we explored the use of **high-permittivity dielectric materials** placed between the electrode pairs. This enhancement significantly amplifies the measurable capacitance change, making the sensor more responsive to even small torque variations.

## Advanced Concept: Parallel-Plate Design with Radial Displacement

We developed an alternative design where capacitive plates are arranged radially around the shaft. Under torque, one plate set rotates slightly with the shaft, causing radial displacement relative to the stationary plates. This geometry maximizes the effect of twist on capacitance and allows for compact sensor integration.

## Signal Acquisition and Processing

A major challenge with capacitive torque sensors is accurately capturing the small capacitance changes, especially in noisy environments. We selected the **PCAP04 capacitance-to-digital converter (CDC)** for its precision and low noise characteristics. This IC allows real-time digital readout of capacitance variations with high resolution.

To improve performance further, we considered **differential measurement techniques**, using a reference capacitor to eliminate common-mode noise and temperature effects.

# 8 Our Approach

In the initial phase of our project, we conducted extensive background research to explore existing technologies related to capacitive torque sensing. During this process, **we identified a key patent titled** Differential Capacitive Torque Sensor This patent provided valuable insights into a feasible configuration for capacitive torque measurement using interleaved rotors and stationary stator plates.

Leveraging the design disclosed in the patent, we formulated our own mechanical structure using a similar multi-disk arrangement. Our configuration, as illustrated in Figure 4, features three primary rotor disks—Rotor 1A, Rotor 2, and Rotor 1B—interleaved with stationary plates connected to the sensing electronics. These rotors are mounted on a shaft that transmits torque, causing differential displacement and corresponding changes in capacitance between the plates.

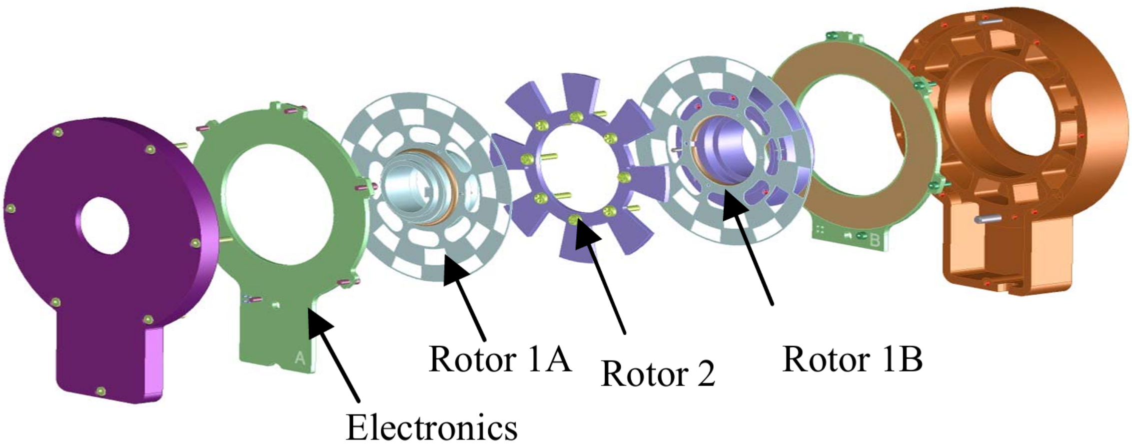



Figure 4: Exploded view of the differential capacitive torque sensor mechanical assembly.

Figure 5 shows the top-down views of the individual rotor disks, which are designed to maximize the change in overlapping area and hence the capacitance as torque is applied.

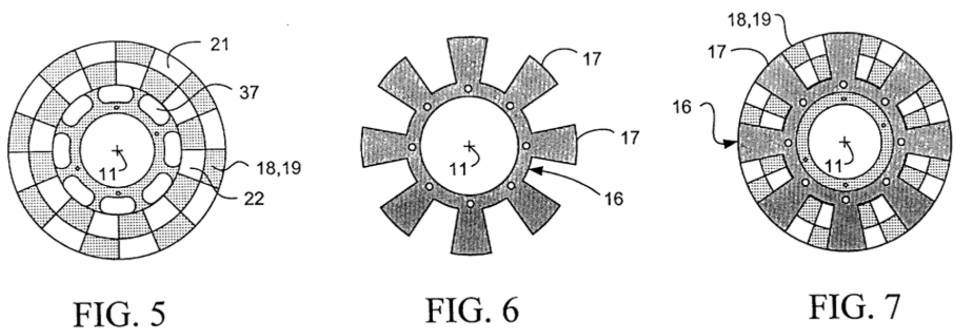



Figure 5: Rotor disk geometries inspired by the referenced patent: Rotor 1A and 1B (left and right), and central Rotor 2 (middle).

Additionally, we studied the internal working principles and mechanical coupling mechanisms using the cross-sectional schematic provided in the patent, shown in Figure 6. This schematic helped us understand how torque is transferred and differentially sensed across the rotors, informing our own shaft and disk mounting strategy.

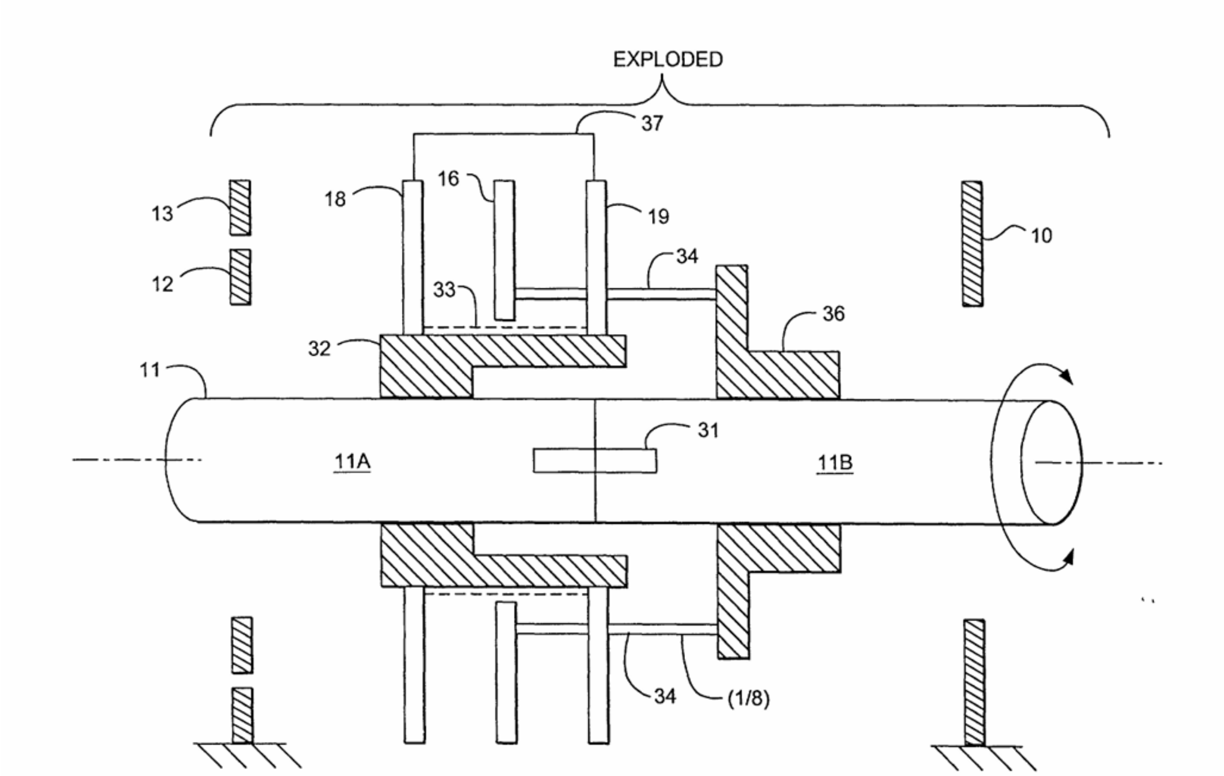
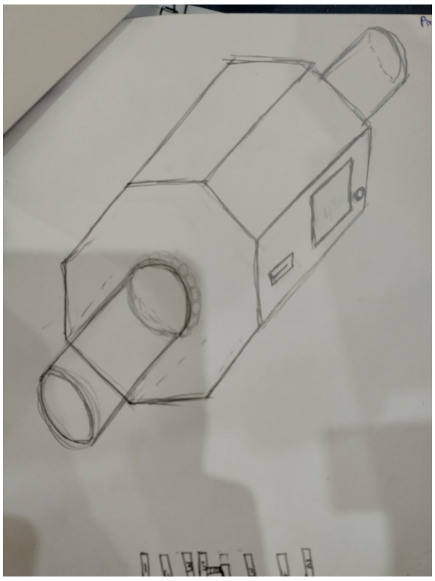



Figure 6: Cross-sectional diagram from the referenced patent showing torque transmission through differentially rotating shafts and rotors.

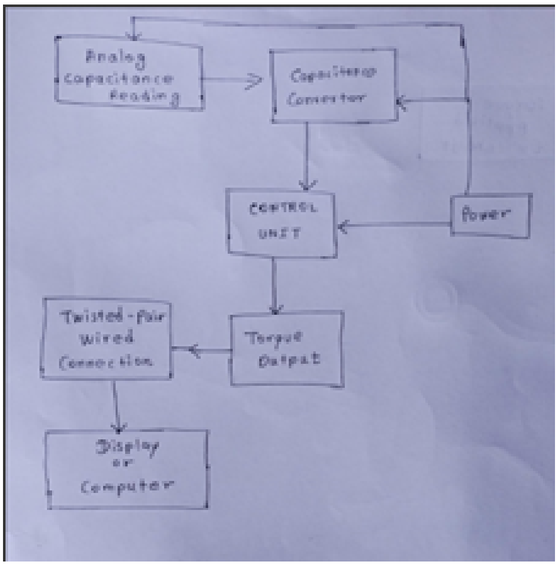
By basing our design on proven concepts from this patent while adapting it to our specific use-case, we ensured both innovation and functional reliability in our differential capacitive torque sensor design.

# 9 Conceptual Designs

## 9.1 Conceptual Design 1



(a) Enclosure and Shaft Design




(b) Block Diagram

**Enclosure Design**

The hexagonal enclosure with cylindrical shafts is compact and stable for housing capacitive electrodes. A non-conductive material is recommended to avoid interference.

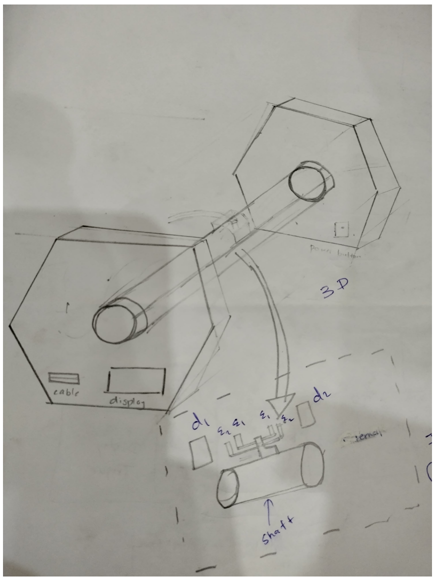
**Shaft Design**

The cylindrical shafts enable torque transmission and deformation for capacitance measurement. Adding a high-permittivity dielectric, as suggested in prior methodologies, could enhance sensitivity.

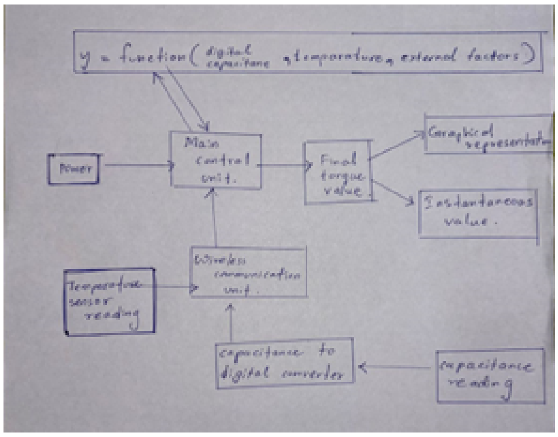
**Block Diagram**

The system converts analog capacitance readings into torque output via a control unit, using a twisted-pair wired connection for reliable data transfer. Wireless telemetry could improve flexibility.

## 9.2 Conceptual Design 2




(a) Enclosure and Shaft Design




(b) Block Diagram

Figure 8: Conceptual Design 2

### Enclosure Design

The dual hexagonal enclosures with cylindrical shafts provide structural stability for housing capacitive electrodes. The compact design suits space-limited applications, but a non-conductive material is essential to prevent interference.

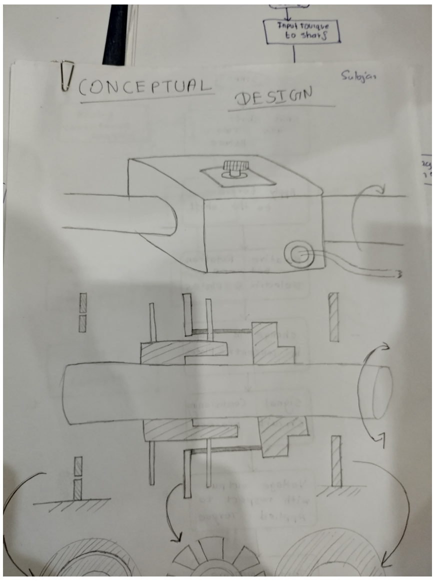
### Shaft Design

The cylindrical shaft connecting the enclosures transmits torque, enabling deformation for capacitance measurement. Dimensions (d1, d2, 3D) suggest a focus on precision, but a high-permittivity dielectric could enhance sensitivity.

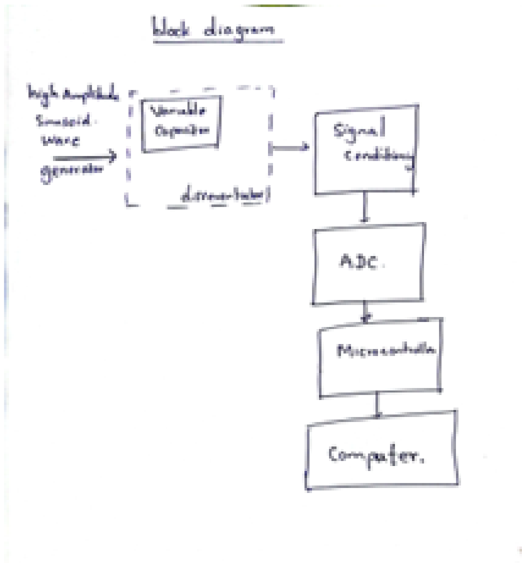
### Block Diagram

The system uses a capacitance-to-digital converter to process readings, feeding into a main control unit. Wireless communication transmits the final torque value to a graphical representation on a display or PC. Temperature sensor readings account for external factors, improving accuracy.

## 9.3 Conceptual Design 3




(a) Enclosure and Shaft Design




(b) Block Diagram

Figure 9: Conceptual Design 3

### Enclosure Design

The rectangular enclosure with cylindrical shafts provides a stable housing for the capacitive sensor. Its design supports integration into a rotary system, but using a non-conductive material is critical to avoid interference.

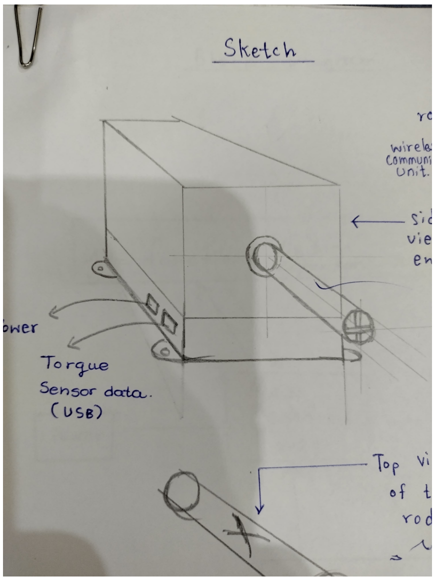
### Shaft Design

The cylindrical shaft, with a gear-like component, transmits torque, causing deformation for capacitance measurement. The gear may aid in precise torque application, but a high-permittivity dielectric could improve sensitivity.

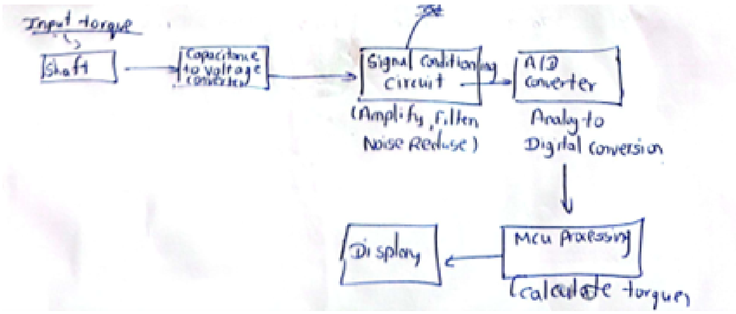
### Block Diagram

A high-amplitude sinusoidal wave generator powers a variable capacitor (distometer), feeding into signal conditioning, an ADC, and a microcontroller, with final output to a computer. This setup converts capacitance changes into digital torque data effectively.

## 9.4 Conceptual Design 4




(a) Enclosure and Shaft Design




(b) Block Diagram

Figure 10: Conceptual Design 4

### Enclosure Design

The rectangular enclosure with a cylindrical shaft is sturdy for housing the sensor. Feet on the base suggest stable mounting, but a non-conductive material is necessary to avoid interference.

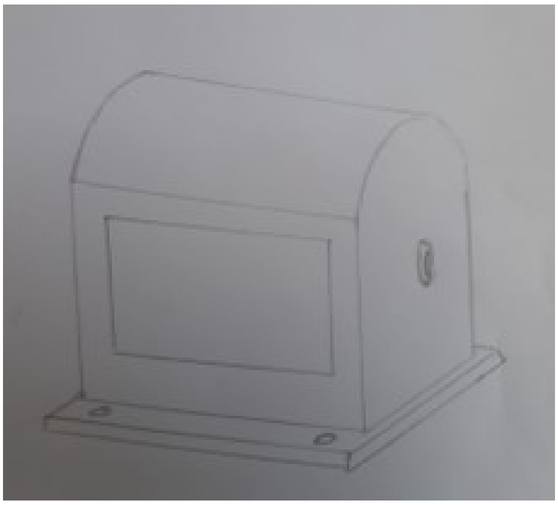
### Shaft Design

The cylindrical shaft transmits torque, enabling deformation for capacitance measurement. The top view shows a rod for torque input, but a high-permittivity dielectric could improve sensitivity.

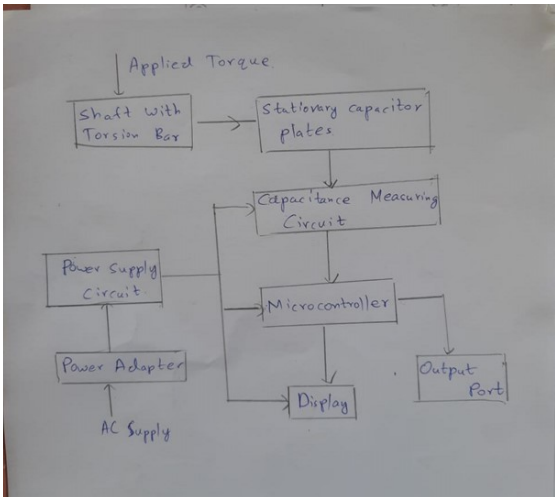
### Block Diagram

The system converts capacitance to voltage, processes it through a signal conditioning circuit (amplify, filter, noise reduction), and uses an A/D converter and MCU for torque calculation, displayed on a screen. USB torque data output and wireless communication enhance flexibility.

## 9.5 Final Selected Design



(a) Enclosure and Shaft Design




(b) Block Diagram

Figure 11: Final Selected Design

**Enclosure Design**

The semi-cylindrical enclosure with a flat base and mounting feet ensures stability and easy integration. The compact design is practical, but a non-conductive material is essential to prevent interference with capacitance measurement.

**Shaft Design**

The shaft with a torsion bar, as shown in the block diagram, transmits torque, causing deformation between stationary capacitor plates. Incorporating a high-permittivity dielectric could enhance sensitivity.

**Block Diagram**

Torque applied to the shaft alters capacitance, measured by a circuit, processed by a microcontroller, and displayed. A power supply circuit with an adapter ensures reliable operation, and an output port allows data transfer. The setup is straightforward and effective.

# 10 Evaluation of the Designs

| Design | User Need | Design 01 | Design 02 | Design 03 | Design 04 |
|---|---|---|---|---|---|
| Enclosure | Ergonomics | 6 | 8 | 8 | 6 |
| | Durability | 6 | 6 | 6 | 9 |
| | Size & Weight | 7 | 8 | 5 | 7 |
| | Manufacturability | 8 | 7 | 8 | 6 |
| | Robustness | 6 | 6 | 7 | 6 |
| | Cost Effectiveness | 8 | 9 | 6 | 8 |
| Block Diagram | Accuracy | 7 | 7 | 7 | 8 |
| | Signal Integrity | 6 | 7 | 8 | 5 |
| | Cost Effectiveness | 7 | 8 | 5 | 7 |
| | Ease of Use | 8 | 7 | 7 | 8 |
| | Power Efficiency | 9 | 7 | 6 | 7 |
| | Scalability | 7 | 7 | 8 | 6 |
| **Overall** | | 85 | 87 | 81 | 83 |

Table 1: Evaluation Table for Design Aspects

# 11 Capacitance and CDC Requirements Evaluations

## 11.1 Capacitance Calculation

**At 0 Nm Area,**

$$\begin{aligned}\text{Area of Dielectric \& Air} &= \pi\left(\frac{5^2-2^2}{100^2}\right)\times\frac{1}{2}\times\frac{1}{2}\\ &= \frac{21\pi}{4\times 10^4}\\ &= 16.5\times 10^{-4}\ \text{m}^2\end{aligned}$$

**At 0 Nm Capacitance,**

$$\begin{aligned}\text{Capacitance} &= \frac{A\varepsilon_0}{d}+\frac{A\varepsilon_r\varepsilon_0}{d}\\ &= \frac{A\varepsilon_0}{d}(\varepsilon_r+1)\\ \varepsilon_r &= 4.3\end{aligned}$$

$$\begin{aligned}C &= \frac{16.5\times 10^{-4}}{8\times 10^{-3}}\times 8.854\times 10^{-12}\times 5.3\\ &= 9.67\ \text{pF}\end{aligned}$$

**Rotation for 1 Nm = 0.268**
**Change of Area**

$$\begin{aligned}\Delta A &= \pi\left(\frac{5^2-2^2}{100^2}\right)\times\frac{0.268}{360}\times 20\\ &= 9.82\times 10^{-5}\ \text{m}^2\end{aligned}$$

## 11.2 Change of Capacitance

### 1) Clockwise Rotation

$$\Delta C = \frac{9.82 \times 10^{-5} \times 8.854 \times 10^{-12}}{8 \times 10^{-3}}$$
$$= 0.1087 \text{ pF}$$

### 2) Anti-clockwise Rotation

$$\Delta C = \frac{9.82 \times 10^{-5} \times 8.854 \times 10^{-12} \times 4.3}{8 \times 10^{-3}}$$
$$= 0.4673 \text{ pF}$$

## 11.3 CDC Calculations

**FDC2214** - Datasheet

$$\Rightarrow \text{Conversion time} = \frac{1\text{s}}{1000} = 1 \text{ ms}$$

**By Datasheet (Page 16):**

$$t_{C_x} = \frac{(\text{CH}x\text{Rcount} \times 16) + 14}{f_{\text{ref}}}$$

$$1 \times 10^{-3} = \frac{(\text{CH}x\text{Rcount} \times 16) + 14}{40 \text{ MHz}}$$

$$\text{CH}x\text{Rcount} = 2500$$

**From Datasheet (Page 01):**

$$* 0.3 \, \text{fF noise at 100 samples/s}$$

$$100 \, \text{samples/s} \Rightarrow t_{C_x} = 10 \, \text{ms}$$

$$\text{CH}x\text{Rcount} = \frac{40 \times 10^{6} \times 10^{-2}}{10} = 25000$$

By Oversampling theory:

$$\text{Noise} \propto \frac{1}{\sqrt{C_H \cdot R_{\text{count}}}} \tag{1}$$

$$0.3 \propto \frac{1}{\sqrt{25000}}$$

$$n' \propto \frac{1}{\sqrt{2500}}$$

$$n' = 950 \text{ aF}$$

For **PCAP04 - Page 13** - Datasheet,

$$\text{Noise} = 156 \text{ aF at 1 kHz(1000samples/s)}$$

**PCAP04 Performs better than FDC2214**

# 12 CDC Evaluation

The requirements for choosing a capacitance-to-digital converter (CDC) were:

- Resolution – Able to measure few femto Farads of capacitance change.
- Sampling frequency – 1000 samples/second
- Range – ±360 fF

| | AD7746 | AD7150 | FDC1004 | PCAP04 | FDC2114 |
|---|---|---|---|---|---|
| Frequency | 2 | 4 | 6 | 10 | 10 |
| Resolution | 9 | 6 | 7 | 8 | 6 |
| Range | 7 | 8 | 9 | 9 | 9 |
| Environmental Compensation | 9 | 6 | 7 | 8 | 8 |
| Price | 6 | 8 | 9 | 7 | 7 |
| Availability | 10 | 7 | 9 | 8 | 8 |
| Total | 43 | 39 | 47 | 50 | 48 |

Figure 12: CDC Evaluation table

AD7746, AD7150, and FDC1004 could not support the 1000 Samples/second requirement and were therefore eliminated. Although the AD7746 had 4aF resolution, its sampling frequency was only 10Hz, which was well below the requirements. The final selection was between PCAP04 and FDC2114. Both satisfied the required sampling rate and capacitance range, but PCAP04 had better resolution at 1kHz.

## PCAP Qualities

- 156aF resolution at 1kHz
- ±50pF range
- Temperature compensation


Figure 13: PACP04 CDC

# 13 MCU Evaluation

## Comparison Table

| **MCU** | ATmega32U4 | ATmega32U2 | ATmega64M1 | PIC18F46J50 | EFM8UB20 |
|---|---|---|---|---|---|
| Performance | 8 | 7 | 10 | 10 | 9 |
| Size (Compactness) | 8 | 9 | 9 | 8 | 9 |
| USB Capability | 10 | 10 | 10 | 10 | 10 |
| EMC/EMI Robustness | 7 | 7 | 8 | 7 | 9 |
| Ease of Development | 10 | 9 | 8 | 7 | 7 |
| Documentation | 9 | 8 | 7 | 8 | 7 |
| Availability | 10 | 10 | 8 | 9 | 7 |
| Cost | 7 | 8 | 6 | 7 | 9 |
| **Total** | 69 | 68 | 66 | 66 | 67 |

## Selection Criteria

- Native USB support
- Enough performance for 1kHz sample processing
- Ease of development
- EMC/EMI resilience

## Chosen MCU – ATmega32U4

**Specifications:**

- 16MHz / 32KB Flash / 2.5KB SRAM
- Compact – 44 pins
- Microchip Studio free IDE / beginner friendly
- Internal crystal oscillator / brownout protection

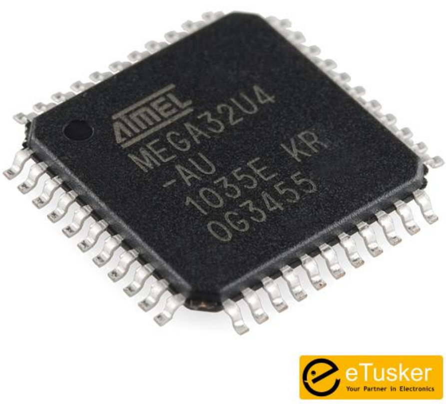



Figure 14: ATMega32U4

# 14 Dielectric Material Evaluation

## Desired Specifications

- Higher dielectric constant
- Good strength
- Ease of machining
- Lower cost

| | PTEF (Teflon) | Polyimide (Kapton) | Alumina Ceramic (Al2O3) | FR4 (Glass Epoxy) | Polycarbonate |
|---|---|---|---|---|---|
| Dielectric Constant | 7 | 9 | 10 | 8 | 6 |
| Flexural Strength | 4 | 7 | 9 | 10 | 5 |
| Ease of Machining | 8 | 6 | 3 | 7 | 9 |
| Stability | 9 | 8 | 10 | 8 | 7 |
| Cost | 6 | 4 | 3 | 9 | 10 |
| Total | 34 | 34 | 35 | 42 | 37 |

Figure 15: Evaluation Table

$Al_2O_3$ was initially considered due to its high dielectric constant and excellent stability. However, it is brittle and requires diamond cutting/laser sintering, making it unsuitable for the project.

## Chosen Material – FR4 (Glass Epoxy)

**Properties:**

- Dielectric constant – Around 4.5
- Shear Strength – Approx. 25,000 psi
- Flexural Strength – Approx. 60,000 psi
- Machinability – CNC milling, laser cutting, water jet cutting
- Stability – 140°C / Water Absorption 0.1%

Figure 16: FR4 - Epoxy Glass

# 15 Shaft Design

The shaft for mounting metal/dielectric disks was designed and simulated in SolidWorks. Several shaft designs were explored with different geometries and materials.

## Design Requirements

- High deformation at 1Nm – measurable capacitance difference
- Must not exceed the shear stress of material at 5Nm

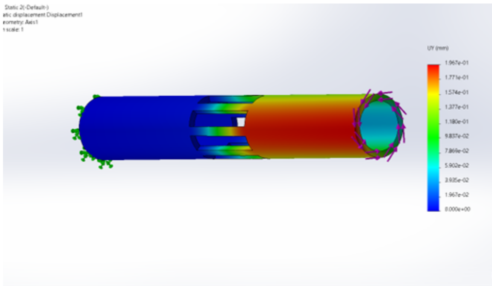


Figure 17: Short shaft – similar to the reference design

## Design Iterations

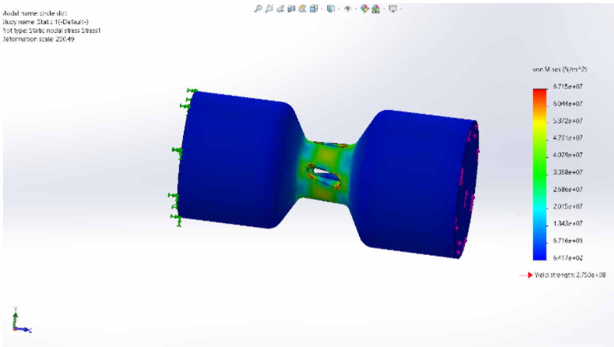


Figure 18: Shaft with pill-shaped cutouts

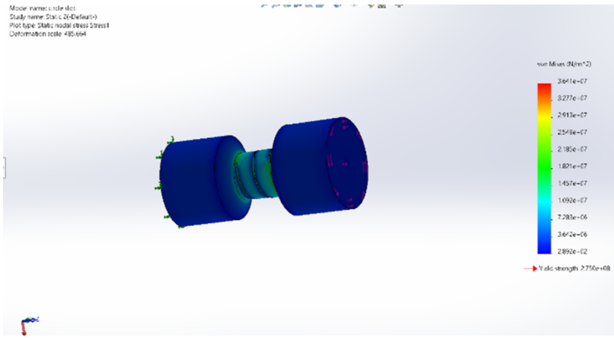


Figure 19: Shaft with helical groove

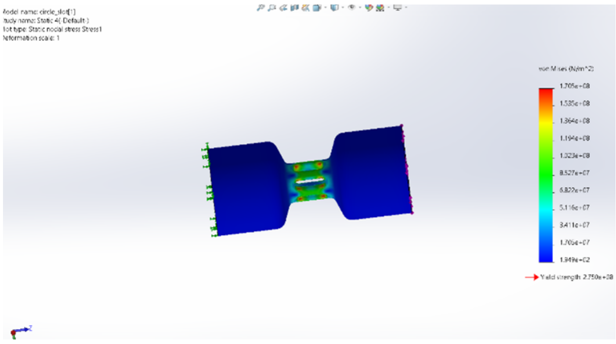


Figure 20: Pill-shaped cutouts + fillets

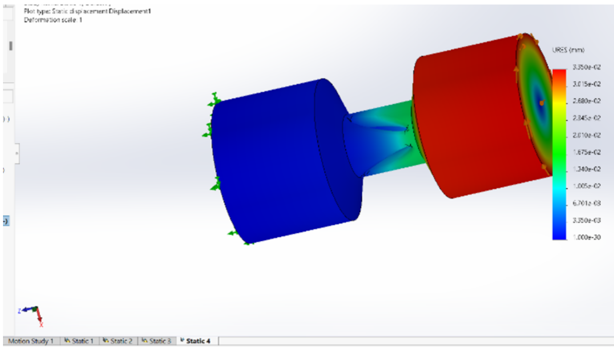


Figure 21: Angled pill-shaped cutouts + fillets

All versions with cutouts exceeded the shear stress limit at 5Nm. The final design was a shaft with no cutouts and a reduced diameter.

## Final Shaft Design

- Diameter at ends – 1.7 cm
- Diameter at middle – 0.6 cm
- Thickness – 2 mm
- Deformable region length – 1.4 cm
- Material – Aluminum alloy 6061-T6

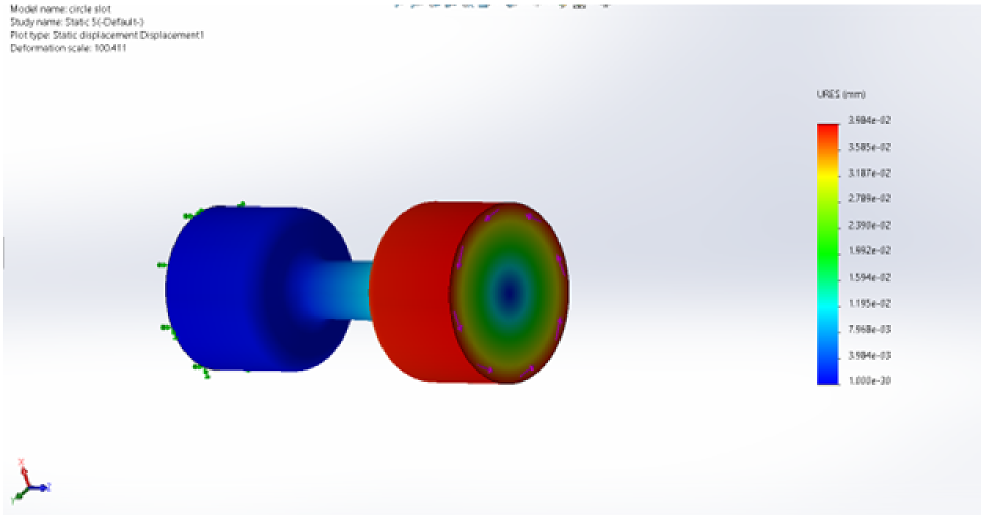



Figure 22: Final Shaft

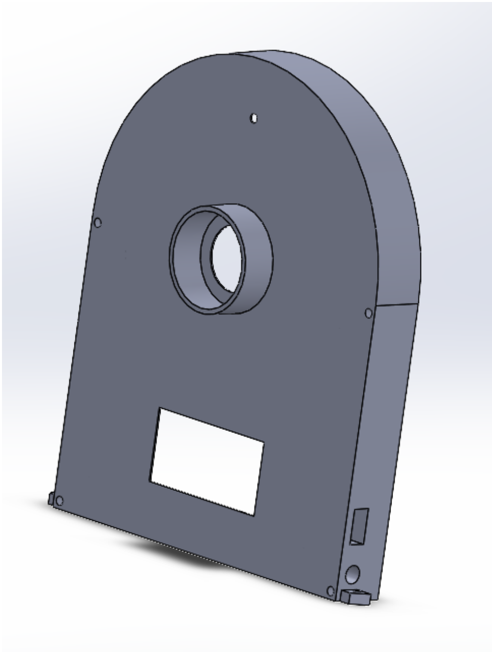
**Performance:**

- Deformation at 1Nm – $3.984 \times 10^{-4}$ mm
- Angle of rotation – 0.2680 degrees
- Change in capacitance – 357.4 fF (measurable with 156aF resolution of PCAP04)

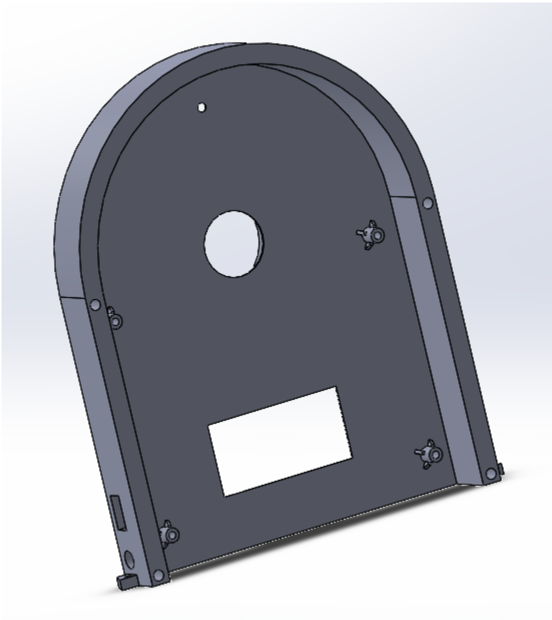
# 16 Solidworks Design

## 16.1 Outer Enclosure

### Frontside half with Draft Analysis



(a) Outer view



(b) Inner view

Figure 23: Front Half

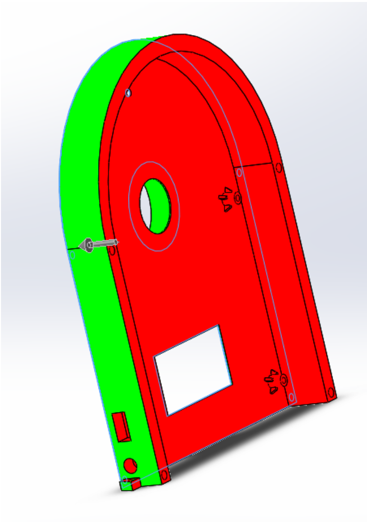
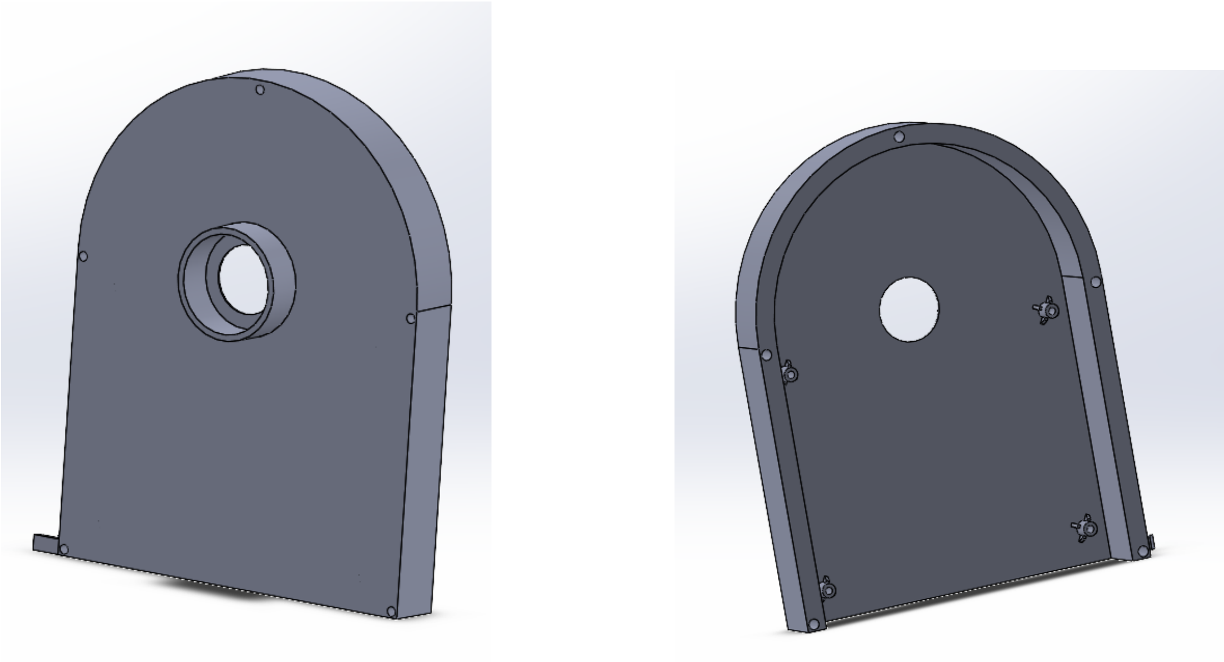


Figure 24: Draft Analysis

**Backside view with Draft Analysis**



(a) Outer view

(b) Inner view

Figure 25: Backside Half

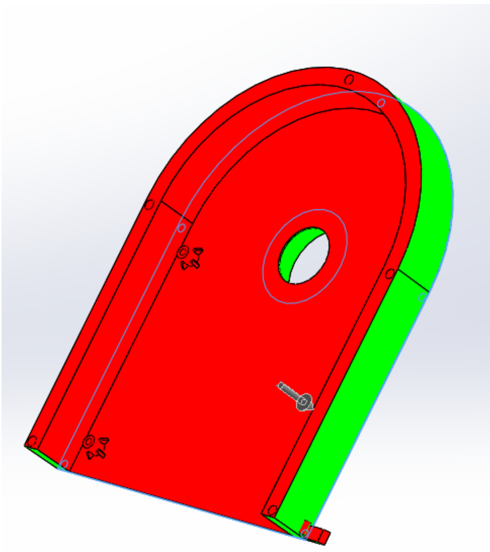
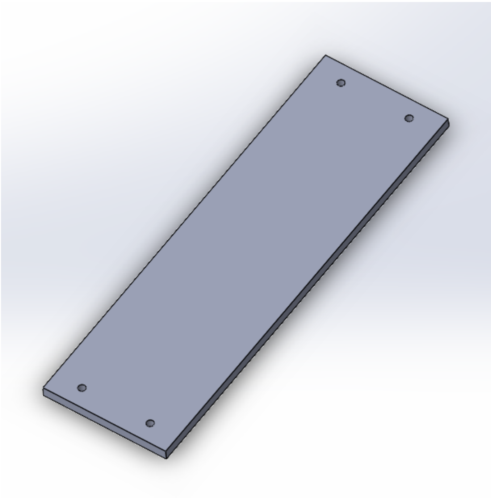
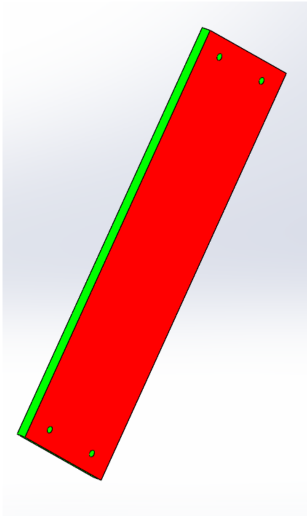


Figure 26: Draft Analysis

**Bottom Part with Draft Analysis**



(a) Bottom Plate



(b) Draft

Figure 27: Bottom plate and Draft analysis

## 16.2 Inner Parts

**Disks**

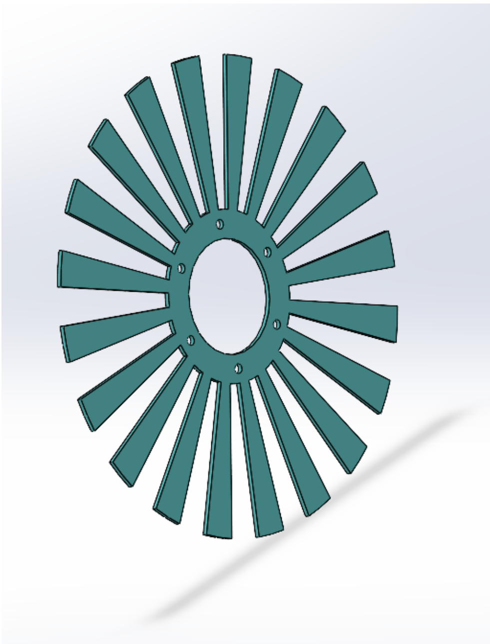


Figure 28: Dielectric Disk

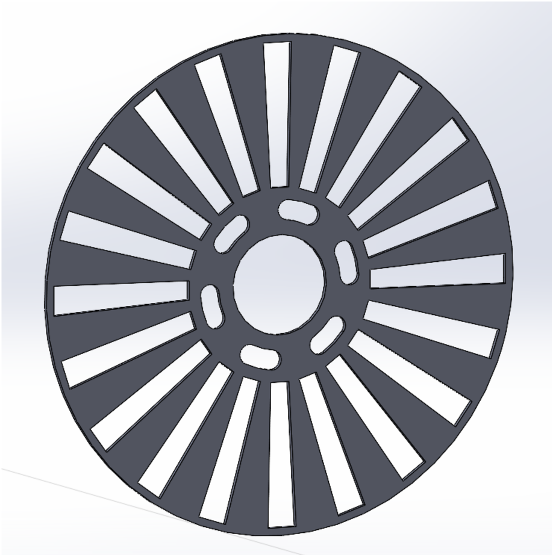
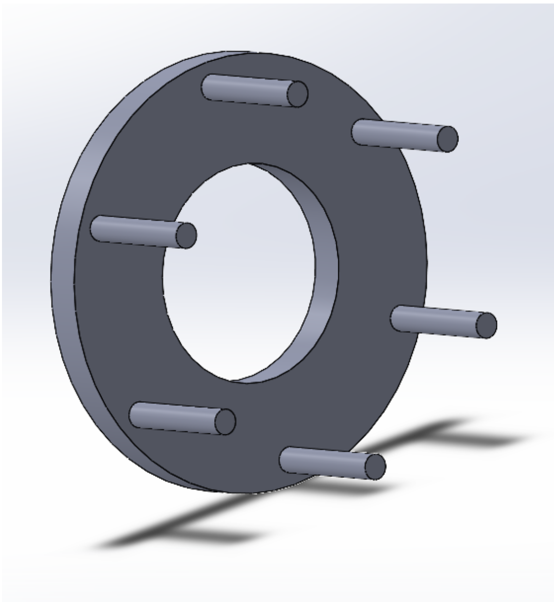
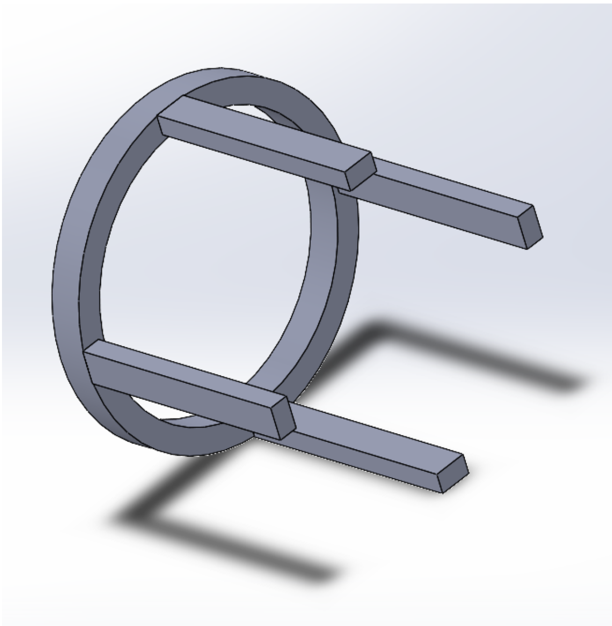


Figure 29: Metal Disk

**Connecting Parts**



(a) Dielectric Holder



(b) Metal Plate Holder

Figure 30: Connecting Holders

### Shaft

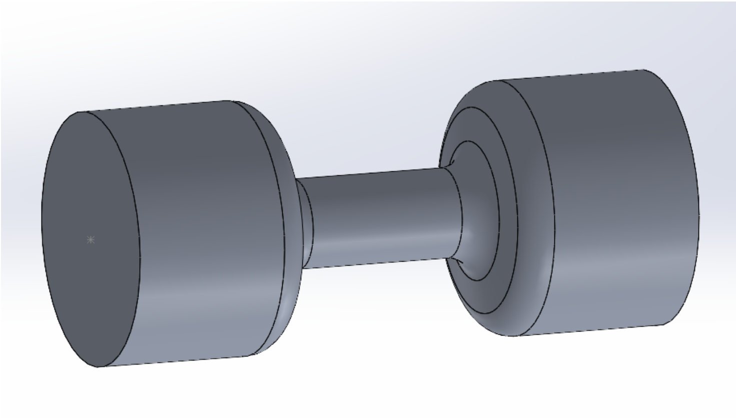


Figure 31: Shaft

### PCB Plate

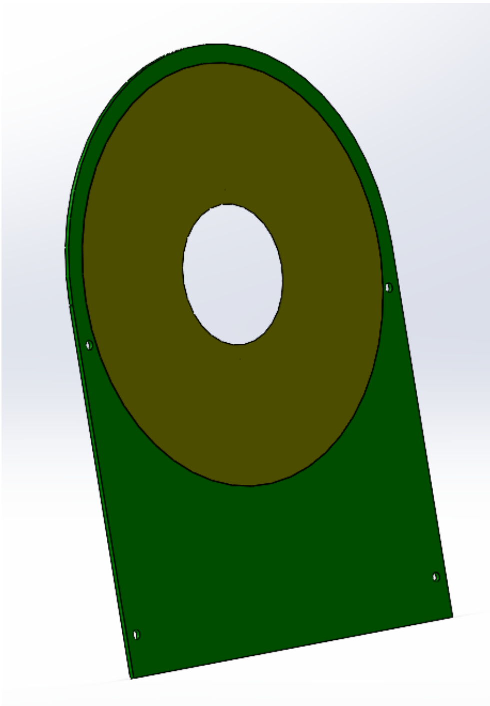


Figure 32: PCB Plate with Capacitance sensing Part

## 16.3 Final Assembly

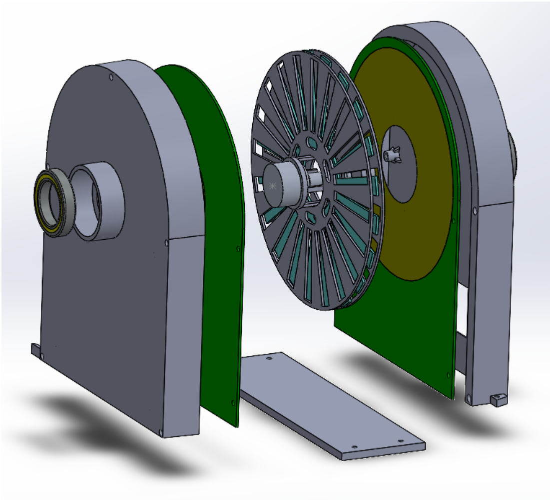


Figure 33: Backside View

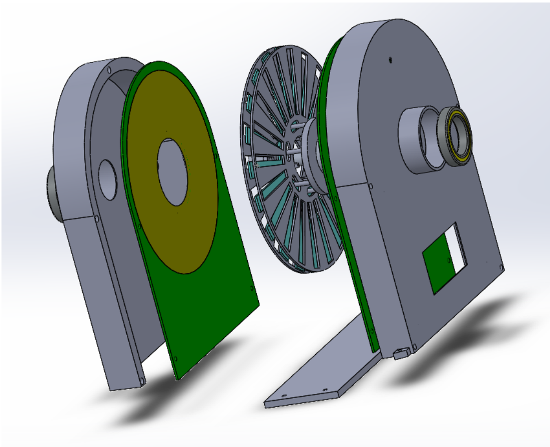


Figure 34: Frontside View

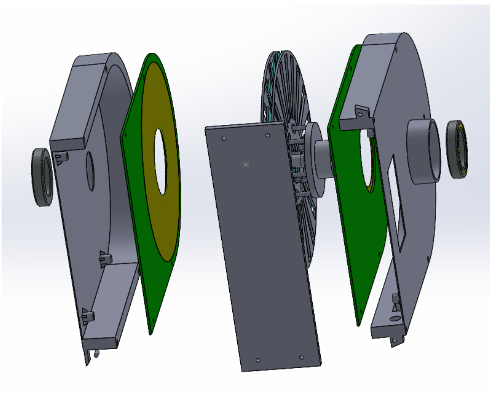


Figure 35: Bottom view