Honours Project Report

Course Code: CP302

Implementation of Flexible Mechanical Metamaterials Enabling Soft Tactile Sensors with Multiple Sensitivities at Multiple Force Sensing Ranges

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Contents

1 Abstract

This project focuses on the development of a novel Multi-sensitivity Soft Tactile (MST) sensor based on flexible mechanical metamaterials. The primary objective is to design, model, and simulate a sensor that provides multiple sensitivities across different force sensing ranges, overcoming the traditional limitation of single-sensitivity tactile sensors. The proposed design utilizes a heterogeneous multi-layered structure with tunable stiffness properties, integrated with magnetic-based transduction method for force measurement.

The mechanical metamaterial structure consists of collapsible layers that exhibit step-by-step locking behavior, enabling different sensitivity regimes at various force magnitudes. This project involves CAD design, mathematical modeling, and COMSOL Multiphysics simulation of the metamaterial structure, aiming to demonstrate the feasibility of creating tactile sensors with programmable sensitivity characteristics for applications in robotics, prosthetics, and human-machine interaction.

2 Introduction

Tactile sensing is a fundamental requirement for advanced robotic systems, prosthetic devices, and human-machine interfaces. Traditional tactile sensors are typically designed with fixed sensitivity and operate within a predetermined force range, limiting their versatility in real-world applications. The need for adaptive tactile sensing capabilities has grown significantly with the advancement of soft robotics and the demand for more sophisticated human-robot interactions.

Modern applications such as robotic manipulation, texture identification, slip detection, and in-hand manipulation require tactile sensors capable of operating with different sensitivities across multiple force ranges. Current soft tactile sensors face inherent trade-offs between sensitivity and sensing range, where high sensitivity is achieved at narrow force ranges or low sensitivity across wide force ranges.

This project addresses these limitations by developing a novel approach based on flexible mechanical metamaterials that can provide multiple predetermined sensitivities at different force sensing ranges. The approach is inspired by human tactile sensing capabilities, where the skin's multi-layered structure with varying stiffness properties enables sophisticated touch perception.

The current phase of development involves designing, modeling, and simulating a Multi-sensitivity Soft Tactile (MST) sensor that utilizes mechanical metamaterials as the force transfer medium, integrated with magnetic-based transduction for displacement measurement and force calculation.

3 Mathematical Theory and Formulations

3.1 Fundamental Sensitivity Definition

Based on the original research by Mohammadi et al. (2021), the core mathematical foundation of the MST sensor begins with the definition of sensitivity in terms of magnetic field variation with respect to applied force. The sensitivity S is mathematically defined as:

$$S = \frac{(\Delta B/B_0)}{\Delta F} \quad [N^{-1}] \tag{1}$$

where:

- S = Sensitivity of the sensor (inverse Newtons)
- ΔB = Change in magnetic field magnitude (Tesla)
- B_0 = Initial magnetic field without applied force (Tesla)
- ΔF = Change in applied force (Newtons)

This fundamental equation establishes the relationship between the measurable magnetic field changes and the applied forces, forming the basis for all subsequent calculations.

3.2 Multi-Layer Mechanical Model

3.2.1 Spring Model Analogy

The metamaterial structure can be mathematically modeled as a system of springs in series, where each unit cell i in block j acts as a spring with stiffness k_{ji}. For a single block with i layers, the force-displacement relationship for each unit cell follows Hooke's law:

$$F_i = k_i \cdot d_i \tag{2}$$

where:

- F_i = Force acting on the i^{th} unit cell (N)
- k_i = Stiffness of the i^{th} unit cell (N/mm)
- d_i = Displacement of the i^{th} unit cell (mm)

3.2.2 Stiffness Hierarchy Condition

For proper step-by-step locking behavior, the unit cells must be arranged in ascending order of stiffness:

$$k_{j1} \ll k_{j2} \ll \cdots \ll k_{ji} \tag{3}$$

This condition ensures that the softest layer deforms first, followed by progressively stiffer layers as the applied force increases.

3.3 Layer-Specific Sensitivity Calculation

For each individual layer i in the multi-layered structure, the sensitivity can be expressed as:

$$S_i = \frac{(\Delta B/B_0)/\Delta d_i}{k_i} \quad [N^{-1}] \tag{4}$$

This equation demonstrates that the sensitivity of each layer depends on:

- The magnetic field gradient with respect to displacement $(\Delta B/B_0)/\Delta d_i$
- The mechanical stiffness of the unit cell k_i

3.4 Force Sensing Range Determination

The force sensing range for each layer i is mathematically defined as:

$$R_i = d_{max_i} \times k_i \quad [N] \tag{5}$$

where:

- R_i = Force sensing range of the i^{th} layer (N)
- d_{max_i} = Maximum displacement of the i^{th} unit cell before locking (mm)
- k_i = Stiffness of the i^{th} unit cell (N/mm)

3.5 Magnetic Field-Displacement Relationship

3.5.1 General Functional Form

The relationship between magnetic field magnitude and permanent magnet displacement can be represented by a function:

$$B = f(d) \tag{6}$$

where:

- B = Magnetic field magnitude (Tesla)
- d = Displacement of permanent magnet (mm)

The specific functional form depends on the magnetic system configuration and can be determined through simulation or experimental measurement.

3.5.2 Normalized Magnetic Field Variation

The normalized change in magnetic field is calculated as:

$$\frac{\Delta B}{B_0} = \frac{B(d) - B_0}{B_0} \tag{7}$$

The gradient of this relationship provides the displacement sensitivity:

$$\frac{\partial}{\partial d}\left(\frac{\Delta B}{B_0}\right) \tag{8}$$

3.6 Complete Sensitivity Calculation Process

3.6.1 Step-by-Step Calculation Method

The complete process for calculating multi-layer sensitivity involves the following steps:

Step 1: Determine Individual Layer Stiffnesses

Using finite element analysis or experimental testing, determine the stiffness values:

$$k_1 = f(\theta_1, t_1, h_1, D_1, H_1, W_1) \tag{9}$$

$$k_2 = f(\theta_2, t_2, h_2, D_2, H_2, W_2) \tag{10}$$

$$k_3 = f(\theta_3, t_3, h_3, D_3, H_3, W_3) \tag{11}$$

where θ, t, and h are the tuning parameters, and D, H, W are the overall dimensions.

Step 2: Calculate Maximum Displacements

For each layer, determine the maximum displacement before locking occurs:

$$d_{max_i} = f(\text{unit cell geometry}) \tag{12}$$

Step 3: Determine Force Ranges

Calculate the force range for each layer using Equation (5):

$$R_1 = d_{max_1} \times k_1 \tag{13}$$

$$R_2 = d_{max_2} \times k_2 \tag{14}$$

$$R_3 = d_{max_3} \times k_3 \tag{15}$$

Step 4: Calculate Magnetic Field Gradients

For each displacement range, calculate the magnetic field gradient through simulation or measurement:

$$\left(\frac{\Delta B}{B_0}\right)_i = f(\text{magnetic system configuration}) \tag{16}$$

Step 5: Compute Final Sensitivities

Apply Equation (4) to obtain the sensitivity for each layer:

$$S_i = \frac{(\Delta B/B_0)_i/\Delta d_i}{k_i} \tag{17}$$

3.7 Design Parameters from Literature

Based on the example provided in Mohammadi et al. (2021), the following design parameters were used:

Optimized Design Parameters:

$$\theta = (25, 33, 37) \tag{18}$$

$$t = (0.6, 1.0, 1.4) \text{ mm} \tag{19}$$

$$h = (2.0, 2.8, 3.5) \text{ mm} \tag{20}$$

Resulting Performance:

$$\text{Sensitivities: } S = (0.26, 0.08, 0.03) \text{ N}^{-1} \tag{21}$$

$$\text{Force ranges: } R = (0.9, 4.8, 16.2) \text{ N} \tag{22}$$

4 Background / Literature Review

4.1 Tactile Sensing Technologies

Tactile sensing has been extensively researched with various transduction mechanisms, each presenting unique advantages and limitations for multi-range sensing applications.

4.1.1 Resistive and Piezoresistive Sensors

Piezoresistive materials change their electrical resistance under mechanical deformation. While offering good sensitivity, they often suffer from hysteresis and drift issues [1, 2].

4.1.2 Capacitive Tactile Sensors

Capacitive sensors measure changes in capacitance due to deformation. They provide good linearity but are sensitive to environmental factors and require complex readout circuits [3].

4.1.3 Optical Tactile Sensors

Optical sensors utilize light intensity or wavelength changes to measure deformation. They offer high resolution but are typically bulky and expensive [4].

4.1.4 Magnetic-Based Tactile Sensors

Magnetic sensors employ permanent magnets and magnetometers to measure displacement. They provide contactless operation and good linearity with minimal drift [5, 6].

4.2 Mechanical Metamaterials

Mechanical metamaterials are artificially structured materials whose mechanical properties are determined by their geometric structure rather than their constituent materials [7]. These materials offer unprecedented control over mechanical properties through structural design.

Key characteristics of mechanical metamaterials include:

- Programmable stiffness and deformation patterns
- Ability to achieve properties not found in natural materials
- Scalable manufacturing through additive manufacturing
- Tunable mechanical responses through geometric parameters

4.3 Multi-Range Sensing Approaches

Several approaches have been developed to extend the sensing range while maintaining sensitivity:

Hierarchical Structures: Multi-level microstructures that provide different mechanical responses at various force levels [9, 10].

Intrafillable Architectures: Structures with graded stiffness properties that compress progressively under increasing loads [11].

Pressure-Peak Effects: Utilization of structural instabilities to create non-linear force-displacement relationships [12].

However, these approaches typically provide limited control over sensitivity characteristics and cannot achieve arbitrary predetermined sensitivity profiles.

4.4 Research Gap

Despite advances in tactile sensing technology, there remains a significant gap in developing sensors that can provide:

- Multiple arbitrary predetermined sensitivities

- Programmable force sensing ranges
- Simple manufacturing processes
- Integration flexibility for various applications

This project addresses these gaps by developing the MST sensor concept based on flexible mechanical metamaterials.

5 Problem Statement/Aim

5.1 Problem Statement

Existing soft tactile sensors are limited to single predetermined sensitivity and force sensing range, which restricts their applicability in complex real-world scenarios. Applications such as robotic manipulation, prosthetic control, and health monitoring require tactile sensors that can adapt their sensitivity based on the interaction context and force magnitude.

The main challenges include:

1. **Limited Sensitivity Range:** Traditional sensors cannot provide high sensitivity across wide force ranges
2. **Fixed Characteristics:** Sensor sensitivity and range are predetermined during design and cannot be modified
3. **Trade-off Constraints:** Existing designs face inherent trade-offs between sensitivity and sensing range
4. **Manufacturing Complexity:** Multi-sensitivity sensors often require complex fabrication processes

5.2 Aim and Objectives

Primary Aim: To develop and simulate a Multi-sensitivity Soft Tactile (MST) sensor based on flexible mechanical metamaterials that can provide multiple predetermined sensitivities at different force sensing ranges.

Specific Objectives:

1. Develop the mathematical framework and design equations for the metamaterial structure
2. Implement systematic calculation procedures for sensitivity and range determination

3. Design and optimize CAD models using the derived mathematical relationships
4. Develop multi-physics simulation models in COMSOL for validating the theoretical calculations
5. Simulate and analyze the force-displacement characteristics and sensitivity profiles
6. Create and validate the step-by-step locking mechanism through mathematical modeling and FEA
7. Develop the integration approach for the magnetic-based transduction system
8. Create a comprehensive design methodology based on mathematical foundations
9. Prepare for subsequent experimental validation and performance evaluation

6 Methodology

6.1 Integrated Design and Simulation Methodology

This project employs a comprehensive methodology that integrates theoretical design, computational simulation, and systematic validation to develop the MST sensor system. The approach is structured to ensure seamless transition from mathematical concepts to practical implementation.

6.2 Phase 1: Design Requirements and Specifications

6.2.1 Target Performance Based on Literature

Based on the research by Mohammadi et al. (2021), the target specifications are:

Target Sensitivities and Ranges:

- Layer 1: Sensitivity $S_1 = 0.26\ \text{N}^{-1}$, Range $R_1 = 0.9$ N
- Layer 2: Sensitivity $S_2 = 0.08\ \text{N}^{-1}$, Range $R_2 = 4.8$ N
- Layer 3: Sensitivity $S_3 = 0.03\ \text{N}^{-1}$, Range $R_3 = 16.2$ N

6.2.2 Material and Manufacturing Specifications

Based on the original research:

- Material: Thermoplastic Polyurethane (TPU) with Shore hardness A85
- Manufacturing: 3D printing using standard benchtop printers

- Magnet specifications: Disc-shape Neodymium gold coated magnet, diameter 6 mm, thickness 2 mm, remanent magnetization 1.3 T
- Magnetometer: Tri-axis magnetometer (MLX90393, Melexis Inc.) with sensitivity 6211 mT^{-1} and resolution 0.161 T

6.3 Phase 2: Multi-Physics Simulation Framework

6.3.1 COMSOL Multiphysics Implementation Strategy

The simulation framework employs coupled physics modules to capture the complete sensor behavior:

1. **Solid Mechanics Module**

- **Purpose:** Analyze mechanical deformation of metamaterial unit cells under applied forces
- **Material Model:** Hyperelastic model appropriate for TPU material
- **Boundary Conditions:** Fixed constraint at base, prescribed displacement or force at top surface

2. **Magnetic Fields Module**

- **Purpose:** Calculate magnetic field distribution and variations due to magnet displacement
- **Magnet Model:** Permanent magnet with specifications matching experimental setup
- **Boundary Conditions:** Magnetic insulation on outer boundaries

3. **Deformed Geometry Module**

- **Purpose:** Couple mechanical deformation with magnetic field changes
- **Implementation:** Automatic re-meshing based on structural displacement

6.3.2 Simulation Workflow

Step 1: Individual Unit Cell Characterization

1. Create parametric 3D models of unit cells with tuning parameters (θ, t, h)
2. Perform compression simulations under various loading conditions
3. Extract force-displacement data and calculate stiffness values

4. Develop relationships between geometric parameters and stiffness

Step 2: Multi-Layer Assembly Simulation

1. Assemble three-layer system using literature-based parameters
2. Apply progressive loading to demonstrate locking behavior
3. Validate step-by-step compression mechanism
4. Measure individual layer deformation contributions

Step 3: Magnetic System Integration

1. Position permanent magnet within deformable structure
2. Simulate magnetic field distribution for undeformed state
3. Calculate field variations during mechanical deformation
4. Map magnetic field magnitude vs. displacement relationships

Step 4: Coupled Multi-Physics Analysis

1. Execute fully coupled mechanical-magnetic simulation
2. Apply force loads across the expected operating range
3. Extract displacement and magnetic field data simultaneously
4. Calculate sensitivity values using the fundamental equation

6.4 Phase 3: Design Validation and Analysis

6.4.1 Parameter Validation

Validate the simulation framework using the known design parameters:

$$\theta = (25, 33, 37) \tag{23}$$
$$t = (0.6, 1.0, 1.4)\ \text{mm} \tag{24}$$
$$h = (2.0, 2.8, 3.5)\ \text{mm} \tag{25}$$

6.4.2 Performance Verification

Compare simulation results with the expected performance:

$$\text{Target Sensitivities: } S = (0.26, 0.08, 0.03)\ \text{N}^{-1} \tag{26}$$
$$\text{Target Force ranges: } R = (0.9, 4.8, 16.2)\ \text{N} \tag{27}$$

7 CAD Design and Modeling

7.1 Unit Cell Design

The unit cell design is based on the mathematical relationships and parameters from the literature. Each unit cell is designed with specific geometric parameters to achieve target stiffness values.

Design Parameters from Literature:

- Depth (D): 20 mm
- Height (H): 5 mm
- Width (W): 30 mm
- Tuning parameters: θ, t, h as specified above

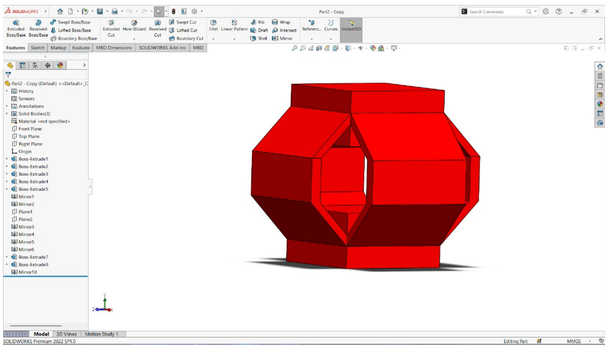

Figure 1: Single unit cell design showing the internal collapsible structure and geometric parameters. The strut architecture enables controlled deformation characteristics under applied loads.

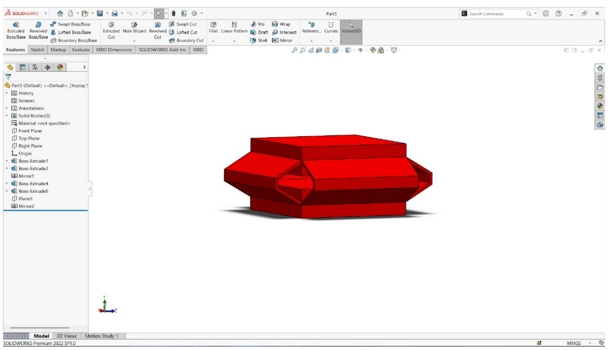

Figure 2: Unit cell in compressed state demonstrating deformation behavior and locking mechanism. The flattened configuration shows how the structure locks to prevent further compression.

7.2 Multi-Layer Assembly

The multi-layer assembly follows the design approach from Mohammadi et al. (2021):

Assembly Configuration:

- Three-layer structure with ascending stiffness values
- Integrated permanent magnet housing in top layer
- Magnetometer housing in base structure
- Proper spacing for mechanical coupling and magnetic field measurement

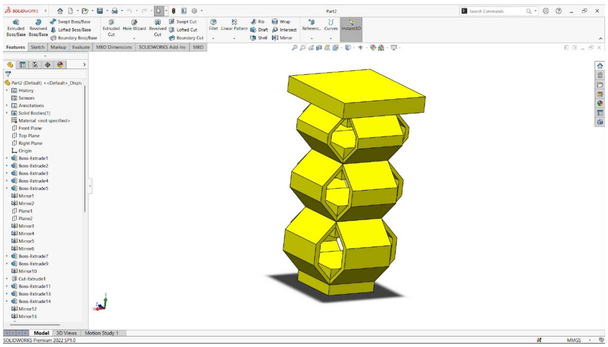

Figure 3: Complete three-layer metamaterial structure showing stacked unit cells with different stiffness properties. The assembly demonstrates the hierarchical arrangement with progressively increasing stiffness from bottom to top layer.

8 Expected Results and Analysis

8.1 Simulation Validation

The COMSOL simulations are expected to validate the theoretical framework and reproduce the performance characteristics reported in the literature:

Force-Displacement Analysis: The simulations should demonstrate distinct linear regions corresponding to the three-layer structure, with step-by-step locking behavior as force increases.

Sensitivity Validation: The calculated sensitivity values should match the literature values within acceptable simulation tolerances:

$$S_1 \approx 0.26 \text{ N}^{-1} \tag{28}$$

$$S_2 \approx 0.08 \text{ N}^{-1} \tag{29}$$

$$S_3 \approx 0.03 \text{ N}^{-1} \tag{30}$$

8.2 Performance Analysis

Dynamic Range Assessment: The MST sensor design should demonstrate significant improvement in dynamic range compared to traditional single-sensitivity sensors, with continuous operation across multiple force ranges.

Locking Mechanism Validation: The simulation should confirm proper sequential locking behavior, where each layer progressively locks as the applied force reaches the transition thresholds.

8.3 Current Progress and Plan of Action

Current Progress: At present, the problem statement has been clearly defined and the simulation framework has been initiated in COMSOL Multiphysics. The following modules are being integrated:

- **Solid Mechanics Module** – to model the mechanical deformation and structural response of the unit cells under applied force.
- **Magnetic Fields, No Currents Module** – to evaluate the magnetic field distribution generated by the embedded permanent magnets.
- **Deformed Geometry Module** – to couple structural deformation with magnetic field variation, enabling the calculation of magnetic distance as a function of compression.

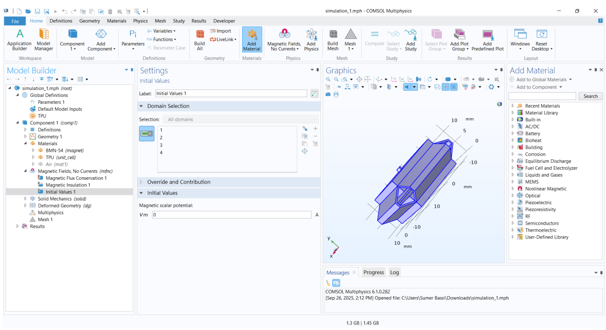

Figure 4: Simulation setup in COMSOL showing assigned materials for the unit cell and magnet.

Currently, the simulations are in the initial stages, and efforts are focused on ensuring that all three modules operate simultaneously in a multiphysics environment. The immediate goal is to obtain a plot of magnetic distance versus compressed distance, which will serve as the primary validation metric for sensor functionality.

Plan of Action:

- Complete multiphysics coupling of solid mechanics, magnetic field, and deformed geometry modules.

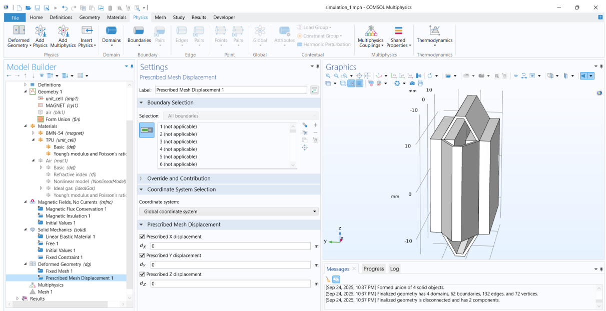

Figure 5: Simulation setup in COMSOL with constraints applied to the bottom face and the top face of the unit cell.

- Generate preliminary plots of magnetic displacement against structural compression.
- Validate the simulation outputs against theoretical predictions from literature.
- Refine boundary conditions, meshing strategies, and material properties for accuracy.
- Progress toward parameter optimization for improving sensitivity and dynamic range.
- **Develop a physical prototype of the Multi-Sensitivity Tactile (MST) sensor**, enabling experimental testing and real-world validation.

9 Applications and Future Development

9.1 Application Potential

The MST sensor technology demonstrates potential across diverse fields where multi-sensitivity tactile sensing can significantly enhance performance:

9.1.1 Robotics Applications

- **Enhanced Robotic Manipulation:** Robots can perform delicate operations (e.g., handling fragile objects, medical tools, or electronic components) by dynamically adjusting grip strength across force ranges.
- **Graduated Force Feedback:** Multi-range force sensing enables robots to transition smoothly between precision grip and high-force tasks, reducing the risk of slippage or breakage.
- **Advanced Tactile Exploration:** Integration into robotic end-effectors allows surface texture recognition and shape estimation, improving adaptability in unstructured environments.

9.1.2 Prosthetic Applications

- **Multi-Level Tactile Feedback:** Provides users with a more natural sense of touch, distinguishing between light contact (e.g., touching fabric) and strong grip (e.g., holding a bottle).
- **Improved Control:** Graduated feedback enhances closed-loop prosthetic control, enabling more precise manipulation of objects in daily life.
- **User-Centric Experience:** By mimicking natural human tactile perception, prosthetics can reduce cognitive load and improve user comfort.

9.1.3 Human-Machine Interface Applications

- **Touch-Sensitive Interfaces:** Devices can respond differently depending on the applied force (light touch for navigation, stronger press for activation).
- **Adaptive Control Systems:** Force-dependent inputs enable more intuitive interaction with industrial machines, medical devices, and consumer electronics.
- **Safety-Critical Systems:** Multi-sensitivity sensing can prevent overload or hazardous conditions by triggering alarms or control actions at specific force thresholds.

9.1.4 Impact Monitoring Applications

- **Helmet Integration:** Embedding the MST sensor into protective helmets (for sports, military, or industrial use) can provide real-time measurement of impact forces during collisions or accidents.
- **Force Threshold Detection:** The graduated sensitivity allows the system to distinguish between minor bumps and potentially dangerous impacts, improving user safety.
- **Data-Driven Safety Insights:** Logged impact data can be analyzed to design better protective equipment and assess cumulative exposure to harmful forces.

9.2 Future Development Directions

Experimental Validation:

- Physical prototype fabrication using 3D printing
- Experimental testing and performance characterization
- Comparison with simulation predictions

- Optimization based on experimental results

Advanced Design Optimization:

- Parameter optimization for specific applications
- Multi-objective design optimization
- Integration with different transduction methods
- Scaling for various sensor sizes and configurations

10 Conclusion

This project presents a comprehensive approach to developing Multi-sensitivity Soft Tactile sensors based on flexible mechanical metamaterials. The mathematical framework established from the literature provides a solid foundation for systematic design and optimization of sensors with programmable sensitivity characteristics.

The current phase focuses on validating the theoretical approach through detailed COMSOL Multiphysics simulations, incorporating the design parameters and performance specifications from the original research by Mohammadi et al. (2021). This simulation-based validation is crucial for understanding the underlying physics and optimizing the design parameters for specific applications.

The systematic methodology integrating mathematical modeling, CAD design, and multi-physics simulation provides a robust framework for developing application-specific tactile sensors. The approach demonstrates the potential for significant improvements in sensor dynamic range and programmable sensitivity characteristics.

The mathematical foundation and simulation framework developed in this project provide a solid basis for future experimental validation and application-specific optimization. The demonstrated multi-sensitivity capability represents a significant advancement in tactile sensing technology with broad applicability across robotics, prosthetics, and human-machine interaction fields.

Future work will focus on experimental validation of the simulation results, comprehensive performance characterization, and development of application-specific sensor configurations. The established theoretical and computational framework provides the necessary foundation for these future developments and demonstrates the potential for creating truly adaptive and intelligent tactile sensing systems.

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