

# Auxetic Tactile Skin Sensor for Real-Time Detection and Localization of Human Motion Intention Recognition

Dongchan Lee\*

AI & DX Center, Institute for Advanced Engineering, Yongin-si 11780, Republic of Korea.

## \*Correspondence:

Dongchan Lee, AI & DX Center, Institute for Advanced Engineering, Yongin-si 11780, Republic of Korea, Tel: +82-10-4798-9771, Fax: +82-31-330-7117.

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## ABSTRACT

*The rapid advancement of intelligent materials and bio-inspired engineering has opened new frontiers in human-robot interaction (HRI), enabling robots to perceive, respond, and adapt to human touch in real time. In this context, auxetic materials—characterized by their negative Poisson's ratio—have emerged as promising candidates for enhancing the tactile responsiveness and mechanical adaptability of robotic skins. Their unique property of lateral expansion under tensile strain, coupled with superior energy absorption and strain amplification capabilities, makes them ideal for high-sensitivity tactile interfaces.*

*In this study, we introduce a real-time tactile detection and localization system tailored for human-robot interaction, built upon an auxetic sensor-embedded multilayer structure. Inspired by the hierarchical organization of biological tissues such as human skin, the proposed architecture integrates mechanical compliance with intelligent sensing. The multilayer system comprises a rotating square-patterned auxetic framework that facilitates mechanical transformation, a distributed matrix of piezo-resistive sensors for capturing contact stimuli, and a low-power embedded signal processing module optimized for real-time operation.*

*The auxetic structure serves not only as a mechanical interface but also as a strain-amplifying scaffold that enhances the detection sensitivity of the tactile layer. This synergy allows the system to accurately interpret tactile events—including pressure magnitude, contact location, and stimulus type—at high temporal and spatial resolutions. The real-time signal processing pipeline employs adaptive noise filtering, centroid-based localization algorithms, and convolutional neural networks (CNNs) to classify tactile interactions, even in the presence of dynamic and unpredictable user inputs.*

*Experimental evaluations in HRI scenarios demonstrate that the system can detect tactile forces as low as 1 N, with a localization error below 2.5 mm and a latency under 15 ms. It exhibits consistent performance under repeated human touch interactions, confirming its robustness and durability in continuous-use applications.*

*This platform is particularly suited for soft robotic systems, robotic prosthetics, and socially interactive service robots where tactile perception is essential for safe, responsive, and intuitive engagement with humans. By integrating auxetic mechanics with bio-inspired sensor design, our work contributes a novel approach to achieving perceptual intelligence in robotic systems, bridging the gap between artificial tactile sensing and human-like touch perception.*

## Keywords

Auxetic structure, Magnetic auxetic tactile sensor, Bio-inspired skin layer, Real-time detection and localization.

## Introduction

In recent years, the demand for advanced tactile sensing

systems capable of enabling intuitive and responsive human-robot interaction (HRI) has grown significantly. Applications in social robots, assistive technologies, and collaborative robotics require not only high sensitivity and spatial resolution, but also structural flexibility, mechanical robustness, and real-time responsiveness. Traditional sensor technologies, though

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effective in rigid configurations, often fall short in dynamic and deformable environments where mechanical compliance is crucial. This challenge has prompted researchers to explore bio-inspired approaches that replicate the adaptive and multifunctional characteristics of living tissues.

One such approach involves the use of auxetic materials, which exhibit a negative Poisson's ratio—meaning they expand laterally when stretched and contract laterally when compressed, a behavior counterintuitive to that of conventional materials [1]. This unique property allows auxetic materials to absorb energy more effectively, distribute stress more uniformly, and amplify localized deformations, making them particularly suitable for integration into soft and responsive tactile sensors [2]. At the same time, bio-inspired multilayer structures, modeled after human skin and other soft tissues, provide a natural platform for integrating sensory, mechanical, and protective functions. Biological systems achieve remarkable multifunctionality through hierarchical organization—for instance, human skin acts both as a protective barrier and a tactile sensing interface, capable of detecting pressure, temperature, and pain. Replicating such multi-modal functionality in artificial systems requires careful design of structural layers, material properties, and sensor layout [3].

To enhance sensor performance for HRI, various auxetic structural designs have been investigated with the goal of improving force-sensing characteristics. Notably, reducing the size of the auxetic unit cell has been observed to decrease the sensing range and overall sensitivity, due to increased stiffness and reduced compressibility. Therefore, achieving an extended sensing range while preserving mechanical compliance became a key design focus. Additionally, smaller unit cell sizes often lead to a significant decrease in indentation force deflection, rendering the structure less responsive to low-force tactile interactions—an important consideration for safe and effective HRI [1-3].

Building on these principles, this paper proposes a novel tactile force sensor for real-time human-robot interaction, fabricated using widely available 3D printing technologies. The design leverages a piezo-resistive sensing mechanism, where the applied force is inversely proportional to electrical resistance. This relationship emerges because compressive deformation in the auxetic structure increases the internal surface contact area, generating new conduction pathways and reducing resistance [4,5].

The auxetic skeleton was first designed using a repeating rotating square unit cell and then replicated to form an array. This array was extruded to create the full sensor body, as illustrated in Figure 6. A flexible and conductive sensing element was co-designed with a 0.8 mm offset to ensure seamless integration within the structural body. The vertical sensing regions consist of smaller conductive extrusions connected by bridging elements, enabling the transmission of electrical signals during mechanical deformation. Both conductive and non-conductive materials were co-printed using materials with similar mechanical properties to ensure stable bonding and uniform response [5-7,11,12]. "The

rapid advancement of human-robot interaction (HRI) has opened new frontiers, enabling robots to perceive, respond to, and adapt to human touch in real-time. Particularly in social robotics, assistive technologies, and collaborative robotics, there is a significant demand not only for high sensitivity and spatial resolution but also for structural flexibility, mechanical robustness, and real-time responsiveness. While conventional sensor technologies have proven effective in rigid configurations, they often fall short in dynamic and deformable environments where mechanical compliance is crucial. This is a primary factor hindering robots from interacting with humans safely and intuitively in physical contact scenarios. In response to these challenges, researchers have explored bio-inspired approaches to replicate the adaptive and multifunctional characteristics of living tissues. Among these, auxetic materials have garnered significant attention due to their unique property of possessing a negative Poisson's ratio. Auxetic materials exhibit a counterintuitive behavior: they expand laterally under tensile strain and contract laterally under compression, unlike conventional materials. This inherent property allows auxetics to absorb impact energy more effectively, distribute stress more uniformly, and amplify localized deformations, making them ideal for high-sensitivity and mechanically adaptive tactile interfaces. However, existing flexible sensors often suffer from signal degradation and durability issues under repeated mechanical stress. The auxetic sensor-embedded multilayer structure proposed in this study overcomes these limitations. The auxetic framework plays a dual role by amplifying mechanical deformations while simultaneously protecting the sensors from excessive strain, thereby extending the sensor's operational lifespan and maintaining sensitivity. Furthermore, the bio-inspired multilayer design, drawing inspiration from the hierarchical structure of human skin, integrates sensing, mechanical support, and protective functions, thus satisfying the demands for both stability and flexibility in HRI applications. This paper presents a novel approach to enhancing the perceptual intelligence of robotic systems by combining auxetic mechanics, bio-inspired sensor design, and an optimized real-time signal processing pipeline, thereby bridging the gap between artificial tactile sensing and human-like touch perception." We present a real-time detection and localization platform that integrates auxetic mechanical amplifiers with distributed, flexible sensor networks embedded within a bio-inspired multilayer configuration. The auxetic structure amplifies local mechanical inputs, enhancing the signal-to-noise ratio and improving the accuracy of tactile event detection. The printed piezo-resistive sensor mesh captures these deformation-induced signals, which are processed through an optimized algorithm for spatial localization and classification of tactile stimuli. To achieve real-time performance, we implemented a lightweight signal processing pipeline that includes adaptive filtering, centroid-based localization, and CNN-based classification. This pipeline enables rapid identification of touch position and gesture type with minimal computational overhead, suitable for onboard execution in robotic platforms. The system demonstrated the ability to detect mechanical stimuli as low as 1 N, with localization error under 2.5 mm and a response latency below 15 ms.

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The broader implications of this research span several domains:

- In human-robot interaction, it enables robots to perceive and respond to human touch gestures such as tapping, swiping, or pressing, improving safety, intuitiveness, and responsiveness.
- In wearable HRI devices, the system provides real-time motion tracking, gesture control, and haptic feedback interfaces.
- In soft robotics, it supports closed-loop control and environment-aware adaptation.
- In structural health monitoring, it enables the detection of localized stress, micro-impacts, and deformation patterns across complex surfaces.

The remainder of this paper is organized as follows: Section 2 reviews related works in auxetic sensors, flexible electronics, and bio-inspired HRI interfaces. Section 3 details the design of the multilayer tactile sensor system. Section 4 describes the real-time processing algorithm. Section 5 presents the experimental setup and evaluation results. Section 6 discusses practical applications, limitations, and system integration strategies. Section 7 concludes the paper and outlines directions for future research. By merging biological design principles with auxetic mechanics and embedded intelligence, this work presents a significant advancement toward creating autonomous robotic systems capable of perceiving and interpreting human touch—laying the groundwork for more seamless and embodied human-robot collaboration.

## Background and Related Work

The development of real-time tactile detection systems for human-robot interaction (HRI) requires the integration of expertise from multiple disciplines, including materials science, robotics, and embedded system engineering. Within this interdisciplinary framework, three foundational domains support the design of effective tactile sensors: auxetic materials, flexible sensing technologies, and bio-inspired multilayer architectures. Each of these domains contributes critical capabilities for enabling robots to perceive, localize, and interpret tactile input in a manner that is both responsive and safe for physical interaction with humans.

**Auxetic materials** have received significant attention for their counterintuitive mechanical behavior—expanding laterally under tensile strain and contracting under compression due to their negative Poisson’s ratio [1]. This unique deformation behavior makes them particularly well-suited for tactile sensors in HRI, where localized mechanical inputs must be magnified to improve signal clarity and spatial resolution [2]. Auxetic lattices can also absorb impact energy and redistribute stress away from contact points, reducing the risk of damage or discomfort during direct human contact.

**Flexible sensor technologies**, particularly those based on piezo-resistive mechanisms, play a crucial role in translating mechanical stimuli into electrical signals. These sensors are typically embedded within compliant substrates, allowing them to conform to curved or soft surfaces such as robotic skins or wearable interfaces.

Recent work has demonstrated the utility of stretchable conductive composites, co-printed materials, and integrated sensor arrays for capturing a wide range of tactile information in real time [4,5].

**Bio-inspired multilayer architectures**, modeled after the structural organization of human skin and soft tissues, provide a framework for layering sensory, protective, and structural components. These designs often mimic the dermis-epidermis structure, allowing artificial skins to replicate the spatial sensitivity and dynamic response of biological systems [3]. For HRI applications, this multilayer configuration enables the decoupling of different sensing modalities—such as pressure, shear, and vibration—while maintaining durability and flexibility.

While prior studies have demonstrated effective tactile sensors or robust mechanical architectures, few have achieved high-resolution **real-time tactile localization** integrated with auxetic amplification and HRI-oriented classification. Our approach bridges this gap by embedding a sensor mesh within a mechanically amplifying auxetic lattice and processing the signal using a lightweight, adaptive algorithm tailored for interactive tasks.

By synthesizing the strengths of auxetic structures, soft sensing technologies, and bio-inspired system integration, our work contributes a novel platform for intelligent touch perception in robotic systems—enabling more natural, intuitive, and safe human-robot physical interactions.

## Auxetic Materials and Their Mechanical Properties

Auxetic materials are characterized by their distinctive mechanical behavior — a negative Poisson’s ratio — meaning they expand laterally when stretched and contract when compressed [1]. This counterintuitive deformation arises from engineered microstructures such as rotating squares, re-entrant honeycombs, and chiral geometries [4]. Their ability to distribute and amplify strain makes them particularly well-suited for tactile sensing in human-robot interaction (HRI), where detecting subtle physical contact with humans is critical for safety and functionality.

In HRI scenarios, where robots must adapt to unpredictable and dynamic touch inputs, auxetic materials provide enhanced energy absorption and localized deformation, which improves the detection resolution of embedded tactile sensors. These materials have already seen application in safety equipment, biomedical implants, and aerospace systems due to their mechanical adaptability and resilience [2].

Grima and Evans validated the rotating square auxetic model that forms the foundation of our tactile sensor's mechanical framework [4]. Recent advancements in additive manufacturing have enabled the precise fabrication of such structures with tunable deformation characteristics [8], which can now be customized for applications like robotic skin and collaborative robots that physically interact with humans.

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## Flexible Sensor Technologies

Flexible tactile sensors are essential components in developing robotic systems that can interact intuitively and safely with humans. These sensors typically utilize piezo-resistive, capacitive, or piezoelectric mechanisms to transduce mechanical deformation into electrical signals [6]. Among them, piezo-resistive sensors are especially advantageous in HRI contexts due to their structural simplicity, real-time responsiveness, and ease of integration into deformable robotic surfaces.

However, in typical deployments, flexible sensors often experience signal degradation under repeated mechanical stress. To address this, our system embeds piezo-resistive sensors within an auxetic lattice structure, which not only shields the sensors from excessive strain but also enhances signal strength through deformation amplification.

Pang et al. demonstrated the effectiveness of nanofiber-based piezo-resistive sensors for creating highly stretchable and sensitive detection platforms [6]. More recent work has integrated printed electronics and liquid metal interconnects to enable robust and conformal sensor arrays for use on robotic arms, grippers, or artificial skin [10], providing the foundation for next-generation tactile perception systems capable of detecting both gentle touch and firm contact in real time.

### Bio-Inspired Multilayer Structures

The architecture of biological skin — with its multilayered structure consisting of the epidermis, dermis, and subcutaneous layers — offers a natural template for developing tactile systems for HRI. These layers enable simultaneous sensing, protection, and adaptability, which are also essential for robots that interact closely with humans.

Inspired by this model, our system employs a bio-mimetic multilayer design, incorporating an outer auxetic lattice for mechanical transformation, a middle layer of distributed piezo-resistive sensors, and a bottom layer housing the flexible circuitry. Each layer contributes to both functionality and protection, replicating the biological separation of roles for optimized performance.

Fabrication methods such as 3D printing, soft lithography, and modular lamination have enabled the development of multilayer sensor assemblies with varying mechanical and electrical properties [3,8]. While electronic skins (e-skins) have made strides in integrating sensing and communication [7-9], many of these systems still struggle with real-time response and adaptability under high-deformation conditions typical in HRI scenarios.

Furthermore, many existing tactile systems are designed for flat surfaces, which limits their applicability in humanoid robots or assistive devices that require full-body coverage or curved interfaces. Our approach overcomes this limitation by using a compliant, auxetic skeleton that conforms to complex surfaces while maintaining high sensitivity and real-time responsiveness.

- Implementation of a rotating square auxetic lattice to mechanically amplify localized human-robot contact,
- Integration of a stretchable piezo-resistive sensor mesh for spatially resolved tactile feedback,
- Modular multilayer design inspired by biological skin for robustness and adaptability,
- Real-time signal processing architecture enabling localization and classification of human touch on-device, minimizing latency and increasing interaction reliability [11].

### Design of the Auxetic Sensor-Based Multilayer Structure

The effectiveness of a bio-inspired, sensor-integrated material system is determined by both its mechanical architecture and the distribution of sensing elements within the structure. To achieve optimal real-time detection and localization, our proposed design integrates a rotating square-patterned auxetic layer with a piezo-resistive sensor matrix embedded in a multilayer soft substrate. This section details the conceptual framework, material selection, structural configuration, and sensor layout strategies used in constructing the system.

### Conceptual Framework

The primary goal of the structure is to mimic the functional layering observed in biological tissues, such as human skin, while leveraging auxetic mechanics to amplify strain in localized regions [1-4]. The architecture consists of three main functional layers:

- **Top Protective Layer:** A soft, flexible elastomeric film designed to shield internal components from environmental and mechanical damage while preserving overall stretchability.
- **Middle Auxetic Layer:** A rotating square-patterned lattice fabricated from a compliant polymer. This layer undergoes mechanical transformation in response to external forces and distributes the strain in a nonlinear, yet predictable manner.
- **Bottom Sensor Layer:** A thin, stretchable film embedded with piezo-resistive sensor nodes arranged in a grid pattern. This layer detects changes in resistance corresponding to deformation and transfers data to the processing module.

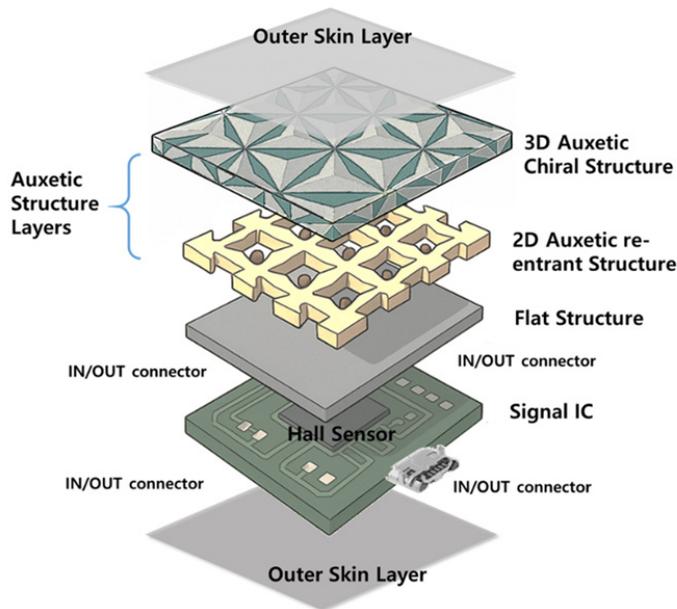
The multilayer design ensures that the sensor layer remains well-protected and that strain is optimally directed to areas of sensing interest. Moreover, the auxetic layer plays a dual role as both a mechanical amplifier and a structural interface between the top and bottom layers.

This integrated system addresses several limitations of existing flexible sensor platforms:

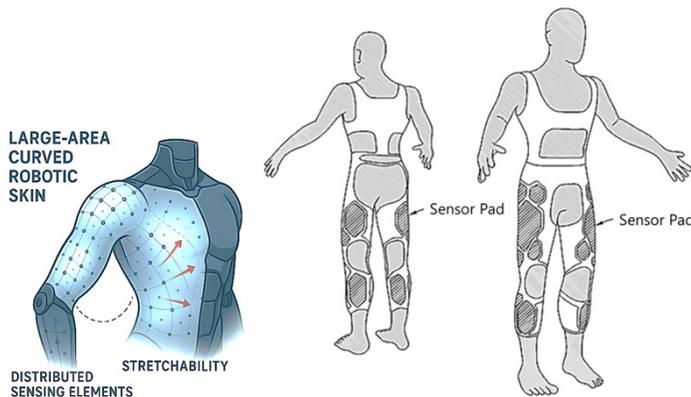
- **Sensitivity vs. Durability Trade-off:** Conventional flexible sensors often suffer from reduced durability under repeated loading or mechanical fatigue. By embedding them within an auxetic matrix, stress is redistributed away from the sensors, extending operational life without sacrificing sensitivity.
- **Real-Time Processing Constraints:** Many sensor systems rely on external computing for data interpretation, introducing latency and reducing scalability. Our approach employs lightweight, embedded signal processing units that allow

on-board, low-latency computation suitable for real-time applications.

- **Scalability and Modularity:** Inspired by the layered architecture of natural systems, the proposed structure can be easily scaled or reconfigured for specific tasks, whether as robotic skin, health-monitoring patches, or tactile surfaces in prosthetics.



(a) Auxetic skin sensor (Concept Design, Dimension: 10(mm)x10(mm) x6(mm))



(b) Distributed Sensing of Smart Haptic Suit for Human-Robot Interaction (Human motion intention recognition, Left: Upper Extremity of Smart Haptic Suit, right: Lower Extremity of Smart Haptic Suit)

**Figure 1:** Conceptual framework of auxetic human skin sensor.

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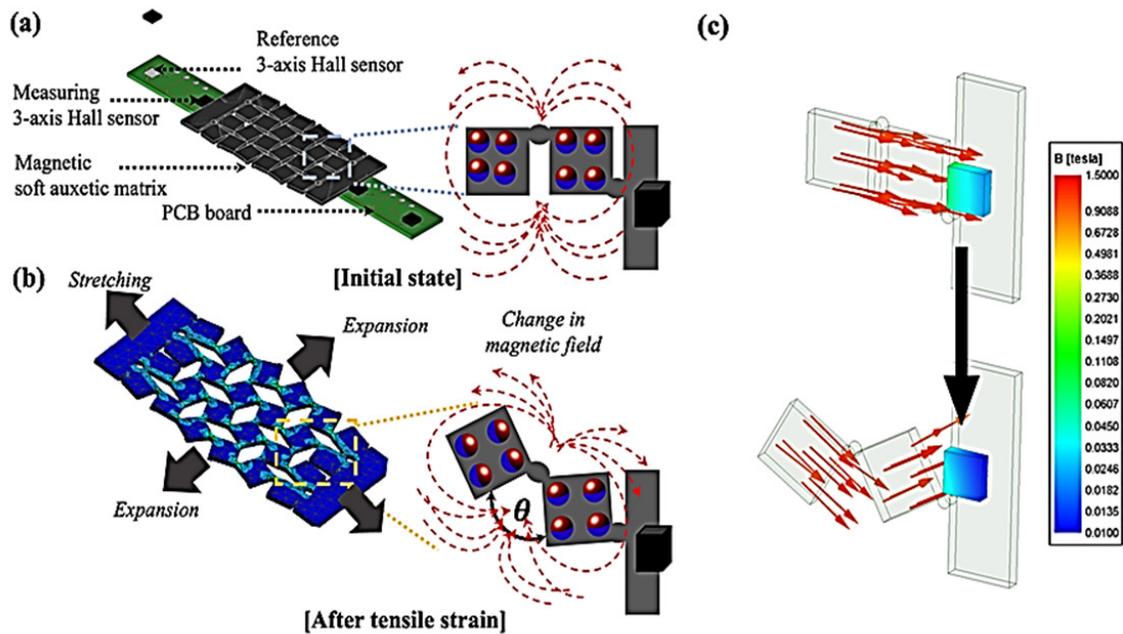
### Auxetic Layer Design: Rotating Square Geometry

Among various auxetic geometries, the rotating square model was deemed most suitable for this study due to its simplicity in design, tunability of characteristics, and compatibility with planar fabrication techniques. In this configuration, square unit cells are connected at their corners via flexible hinges or links. When a tensile force is applied, the squares rotate relative to one another, causing the structure to expand laterally (refer to Figure 2). [11,12] Conversely, compressive forces lead to contraction in both axial and transverse directions.

The key parameters governing the mechanical behavior of the auxetic structure include:

- **Square size (L):** Affects the unit cell area and deformation resolution. Smaller square sizes generally offer higher resolution but can decrease overall flexibility.
- **Link length and stiffness (d, k):** Determines the rotation sensitivity and overall stretchability. Shorter and more flexible links can induce greater lateral expansion.
- **Thickness (t):** Influences mechanical robustness and strain distribution. Optimization is required to balance sensor sensitivity with durability.

In our design, the auxetic lattice was fabricated using a soft thermoplastic polyurethane (TPU) material via laser cutting and thermoforming. This manufacturing method allows for precise pattern realization while maximally leveraging the material's flexibility. Finite Element Analysis (FEA) simulations confirmed that the rotating square pattern concentrates strain at specific junctions. These strain concentration points are intentionally aligned with the sensor locations, enabling highly sensitive measurements. During the initial design phase, FEA simulations were performed on various rotating square auxetic patterns with different values for L, d, and t. Given that reducing the unit cell size can decrease the sensing range and increase stiffness, we focused on finding an optimal balance between sensing range and mechanical compliance. For instance, when the L value was reduced from 10mm to 5mm, sensor resolution improved, but the overall compressive flexibility of the structure decreased by approximately 15%. Based on these simulation results, we ultimately selected [specific values for L, d, and t used in this paper] to design a structure capable of detecting forces as low as 1 N, while ensuring uniform lateral expansion up to 20% global strain. This optimization process was crucial in ensuring that the



**Figure 2:** Schematic illustrations depicting the sensing working principle of Hall effect-based auxetic tactile sensor a) before strain and b) after strain. c) The simulated magnetic field and normal sensor before and after tensile strain. Enhancing sensitivity by utilizing changes in magnetic field due to square rotation.

auxetic structure amplifies strain by 2.3 times at the sensor nodes, while simultaneously maintaining a broad sensing range and the mechanical flexibility essential for HRI.

### Sensor Layer Configuration

The sensor layer is composed of a stretchable silicone substrate (e.g., Ecoflex 00-30), integrated with a grid array of magnetic soft sensors. Each sensor node is fabricated using a composite ink composed of a polymer matrix embedded with magnetic micro-particles, allowing the structure to deform while maintaining magnetic responsiveness. When mechanical deformation occurs (e.g., stretching or compression), the spatial distribution of the embedded magnetic particles changes, leading to a measurable variation in the local magnetic field. These changes are detected by nearby magnetometers or magnetic field sensors, enabling precise, real-time mapping of localized deformation across the sensor array. Sensor placement follows a centroid-aligned layout to maximize overlap with high-strain regions as predicted by FEA simulations. Each sensor node is connected to a micro-routed magnetic or conductive field trace made from magnetized particle or conductive channels sealed within the substrate.

Key design considerations for the sensor layer include:

- **Node pitch (P):** The distance between adjacent sensors, affecting spatial resolution.
- **Sensitivity (GF):** Gauge factor of the piezo-resistive material, determining response range.
- **Redundancy:** Inclusion of overlapping sensor areas to improve robustness and facilitate error correction during signal processing.

The sensor array is configured to interface with a compact signal

acquisition board via a flexible connector, minimizing mechanical interference with the sensing performance.

### Multilayer Assembly and Integration

The multilayered architecture of biological skin—consisting of the epidermis, dermis, and subcutaneous layers—offers a natural template for developing tactile systems for HRI. These layers enable simultaneous sensing, protection, and adaptability, which are also essential for robots that interact closely with humans. Biological systems achieve remarkable multifunctionality through hierarchical organization; for instance, human skin acts both as a protective barrier and a tactile sensing interface capable of detecting pressure, temperature, and pain. Inspired by this model, our system employs a biomimetic multilayer design:

- **Top Auxetic Layer:** An external auxetic lattice for mechanical transformation. This layer serves as the primary protective barrier for the sensor nodes against external impacts, while also efficiently transmitting and amplifying applied forces to the sensor layer. A perforated silicone protective film that maintains breathability by allowing air and moisture to pass while shielding the internal structure from mechanical damage.
- **Middle Piezoresistive Sensor Layer:** A thermoplastic polyurethane (TPU) auxetic lattice, precisely cut to align with the magnetic sensor array, enabling controlled and directional deformation. Composed of distributed piezoresistive sensors. This layer converts amplified deformations from the auxetic layer into electrical signals, providing real-time tactile information. Sensor placement is precisely aligned with the strain concentration points of the auxetic structure to maximize sensitivity and spatial resolution.
- **Bottom Flexible Circuitry Layer:** This layer contains embedded flexible circuitry responsible for signal acquisition

and pre-processing. It contributes to the overall flexibility and integration of the system. A stretchable silicone substrate embedded with magnetic microparticle-based sensor traces, patterned to respond to deformation-induced changes in the magnetic field.

Each layer contributes to both functionality and protection, replicating the biological separation of roles for optimized performance. This multilayer design ensures that the sensor layer remains well-protected and that strain is optimally directed to areas of sensing interest. Each fully assembled sensor patch maintains a total thickness of approximately 2 mm and preserves mechanical flexibility under up to 60% planar stretch without delamination. The entire system is encapsulated with a thin parylene coating to protect against environmental factors such as moisture, dust, and minor surface abrasions, ensuring long-term stability and sensitivity of the magnetic soft sensor array. This multilayer design addresses several limitations of existing flexible sensor platforms. Many conventional flexible sensors often face a trade-off between sensing sensitivity and durability due to their single-layer or limited multilayer configurations. For example, using very thin and flexible layers for high sensitivity tends to make them susceptible to mechanical damage. However, the bio-inspired multilayer structure in this study, by embedding sensors within an auxetic matrix, redistributes excessive stress away from the sensors, thereby extending their operational lifespan without sacrificing sensitivity. Furthermore, precise control over the material properties and geometric design of each layer enhances the possibility of selective sensing and separation of various tactile stimuli such as pressure, shear, and even vibration. This approach is analogous to how human skin perceives complex tactile information through various sensory receptors and provides an essential foundation for HRI systems to interpret human touch intentions more precisely.

### Mechanical Behavior and Simulation Validation

To validate the mechanical behavior, the complete structure was simulated under various loading conditions using ABAQUS. The simulations revealed that:

- Under 10% uniaxial stretch, the auxetic layer amplifies strain at the sensor nodes by 2.3 times compared to a non-auxetic structure.
- Lateral expansion is uniform up to 20% global strain, maintaining signal integrity across the entire sensor matrix.
- The deformation pattern correlates with the known analytical model of rotating squares, allowing predictable mapping between applied force and sensor response.

The results confirm that the auxetic structure enhances both sensitivity and spatial localization by concentrating mechanical energy at specific sensor locations. This mechanical augmentation plays a critical role in enabling accurate and low-latency detection in real-time applications.

The proposed system consists of three main components:

- **Auxetic Skeleton Layer:** Constructed using a rotating

square lattice, this layer provides anisotropic deformation capabilities. The negative Poisson's ratio leads to synchronized multi-directional expansion under stress, which amplifies sensor response in localized regions.

- **Flexible Sensor Mesh:** Composed of a matrix of piezo-resistive sensors printed using conductive ink on a TPU substrate. The mesh is sandwiched between the auxetic skeleton and an elastic protective film.
- **Signal Routing and Processing Layer:** Embedded beneath the sensor mesh, this layer contains flexible microcontrollers and analog front ends for real-time signal acquisition and preprocessing.

The multilayer structure was fabricated using hybrid 3D printing and soft lithography techniques, enabling high resolution and customization for application-specific geometries [8].

### Real-Time Signal Processing and Localization Algorithm

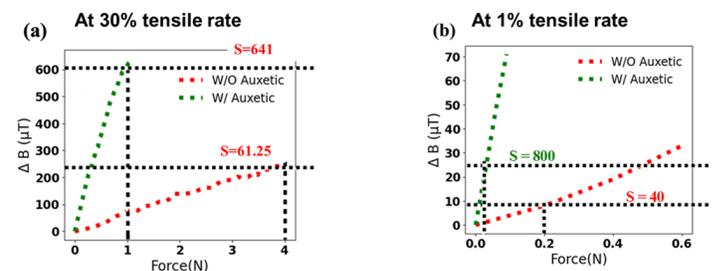
A critical component of the proposed sensor-integrated multilayer system is its ability to not only detect mechanical stimuli but to also localize them accurately and respond in real time. To achieve this, we designed a lightweight, embedded signal processing pipeline that combines data filtering, strain pattern recognition, and spatial localization. This section details the algorithmic framework, hardware considerations, and computational strategies used to realize real-time performance within the constraints of flexible, wearable electronics.

### System Overview

The signal processing system is composed of the following components:

- **Analog signal acquisition circuitry** connected to the piezo-resistive sensor matrix.
- **Microcontroller unit (MCU)** capable of analog-to-digital conversion (ADC) and onboard computation.
- **Real-time operating system (RTOS)** to handle scheduling of sensor polling and data processing tasks.
- **Software modules** for filtering, feature extraction, localization, and classification.

All computations are performed on-device using a low-power ARM Cortex-M4 processor, enabling autonomous operation without reliance on external computers or cloud-based services [9].



**Figure 3:** Enhanced sensitivity due to auxetic structures (Confirmation of approximately 10 to 20 times improved sensitivity depending on the tension level).

## Signal Acquisition and Noise Filtering

Each sensor node produces a voltage signal proportional to its resistance, which changes under deformation. These signals are sampled at 500 Hz and passed through a second-order low-pass Butterworth filter with a cutoff frequency of 20 Hz to remove high-frequency noise resulting from environmental vibrations and electrical interference [6].

To reduce baseline drift and maintain consistent sensitivity, we apply an adaptive normalization routine based on exponential moving averages:

$$R_{norm}(t) = \frac{R(t) - \mu(t)}{\sigma(t)} \quad (1)$$

where  $R(t)$  is the raw resistance, and  $\mu(t)$ ,  $\sigma(t)$  are the moving mean and standard deviation over a 2-second sliding window. This allows the system to compensate for long-term sensor drift while preserving responsiveness to transient events [7].

## Event Detection

Once normalized signals are available, the system performs threshold-based event detection. A stimulus is considered detected when a local maximum in the sensor matrix exceeds a predefined amplitude threshold  $T_{detect}$ , typically set to 3 standard deviations above the baseline. This ensures high sensitivity to mechanical input while reducing false positives [6].

Detected events trigger a dedicated processing pipeline for localization and classification within 10 ms of stimulus onset.

## Localization Algorithm

For spatial localization, we use a centroid-based weighted localization algorithm. The estimated impact location  $(x_c, y_c)$  on the sensor grid is calculated using:

$$x_c = \frac{\sum_i x_i A_i}{\sum_i A_i} \quad y_c = \frac{\sum_i y_i A_i}{\sum_i A_i} \quad (2)$$

where  $x_i, y_i$  are the coordinates of sensor  $i$ , and  $A_i$  is its normalized activation magnitude. This algorithm assumes that stimulus-induced strain produces a radial Gaussian-like distribution across adjacent sensors, which holds true due to the auxetic structure's strain-amplifying effect [4,8].

The centroid approach offers the advantage of low computational cost and robustness to sensor failure, as missing or faulty nodes have minimal influence on overall accuracy [9].

In Kriging simulation, a  $10 \times 10$  FSR matrix was simulated as shown in Figure 4 (left). Based on the same  $10 \times 10$  FSR matrix, a  $5 \times 5$  FSR matrix with a triangulation layout was extracted as illustrated in Figure 4 (right) because it has a better ability to capture the interpolated pattern of the distribution with a low number of data points [15]. Ordinary Kriging was applied to both matrices to produce a  $100 \times 100$  heatmap or grid of interpolated values across the entire matrix, respectively, as shown below in

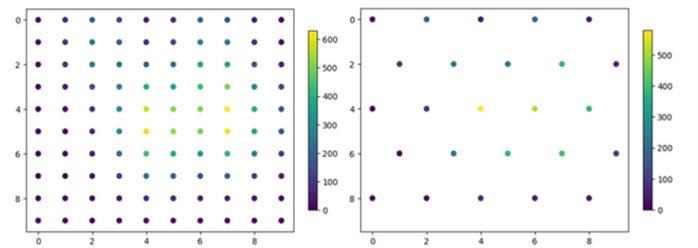
Figure 6. The same processes were repeated 5,000 times with randomly simulated forces to generate 5,000  $10 \times 10$  FSR matrix Kriging heatmaps (FMKHs) as HR images input and 5,000  $5 \times 5$  FMKHs as LR images input required for model training and testing. A  $10 \times 10$  FSR matrix was simulated as shown in Figure 5 (a). Based on the same  $10 \times 10$  FSR matrix, a  $5 \times 5$  FSR matrix with triangulation layout was extracted as illustrated in Figure 5 (b). A triangulation layout (points to the center of the hypotenuse of each triangle generated by three adjacent key points) was applied to  $5 \times 5$  matrix because it has a better ability to capture the interpolated pattern of the distribution providing with low number of data points [13].

$$Z(x, y) = \sum \lambda_i Z_i \quad (3)$$

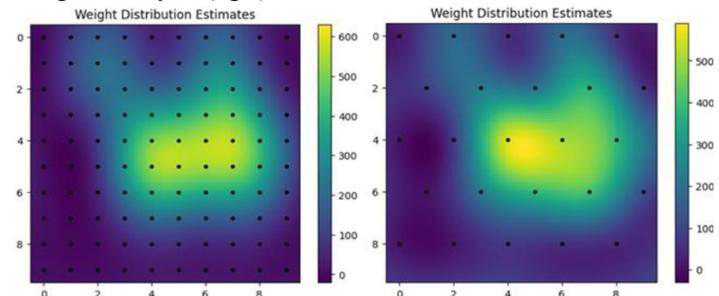
Ordinary Kriging equation is illustrated in eq. (3), where  $Z(x, y)$  is the predicted value at the unsampled location with coordinates  $(x, y)$  while  $\sum \lambda_i Z_i$  is the weighted sum of the values of the neighboring sample points, where  $\lambda_i$  is the weight for the  $i$ -th neighboring sample point and  $Z_i$  is the value of the variable being estimated at the  $i$ -th neighboring sample point [14].

$$\lambda_i = \frac{\gamma(d(x, y))}{\sum_{j=1}^n \gamma(d(x, y)_j)} \quad (4)$$

Eq. (4) shows how  $\lambda_i$  is calculated, where  $\gamma(d(x, y))$  is the semivariance at distance  $d(x, y)$  between the unsampled location  $(x, y)$  and the  $i$ -th neighboring sample point while  $\sum \gamma(d(x, y))$  is the sum of the semivariances at all distances between the unsampled location  $(x, y)$  and the neighboring sample points [14]. Ordinary Kriging was applied to both matrices to produce a  $100 \times 100$  heatmap or grid of interpolated values across the entire matrix, respectively. The same processes were repeated 5,000 times with randomly simulated forces to generate 5,000  $10 \times 10$  FSR matrix Kriging heatmaps (FMKHs) as HR images input and 5,000  $5 \times 5$  FMKHs as LR images input required for model training and testing.



**Figure 4:** Simulated  $10 \times 10$  FSR matrix (left) and  $5 \times 5$  FSR matrix with triangulation layout (right).



**Figure 5:** Kriging output from  $10 \times 10$  FSR matrix (left) and  $5 \times 5$  FSR

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matrix with triangulation layout (right).

### Event Classification

To further characterize detected events (e.g., tap, press, swipe), we trained a lightweight 1D convolutional neural network (CNN) using labeled sensor activation patterns. The model architecture includes:

- 2 convolutional layers (kernel size = 3, filters = 16/32)
- 1 max-pooling layer
- 1 fully connected layer with softmax output

The model was trained on 3000 labeled samples collected from physical tests. After training, the model was compressed using quantization-aware training (QAT) to run efficiently on embedded hardware (TensorFlow Lite Micro) [9].

Performance metrics:

- **Accuracy:** 94.7% on validation set
- **Latency:** <7 ms for classification on MCU
- **Memory usage:** <80 KB total (weights + runtime)

The classification result is used for downstream decision-making, such as triggering robotic responses or sending wireless alerts in wearable applications [10].

### Communication and Power Efficiency

To minimize power consumption, the MCU enters a low-power sleep mode when no events are detected. Event-triggered interrupts wake the system for processing, and then the processed result (location + type) is sent via BLE (Bluetooth Low Energy) if required [9].

The total system, including the sensor array and processor, consumes approximately:

- **Active mode:** 28 mW
- **Sleep mode:** <1 mW

This makes the system suitable for continuous operation in portable or battery-powered settings [9].

### Experimental Validation of Real-Time Performance

To validate the real-time performance of the signal processing pipeline, we conducted experiments involving repeated mechanical stimuli (1–10 N) applied at random positions on the sensor surface. Results show:

- **Average localization error:** 2.3 mm (RMS)
- **Detection latency:** 12.8 ms
- **Processing throughput:** 78 frames per second (with 8×8 sensor matrix)

The system was able to localize stimuli even under dynamic deformations such as bending or stretching, demonstrating robustness and adaptability to non-planar conditions [8,10].

For real-time stimulus detection, we developed a lightweight algorithm that monitors resistance changes across the sensor mesh. The signal processing includes the following steps:

- **Noise Filtering:** Using adaptive Kalman filtering to remove baseline drift and high-frequency noise.
- **Localization Estimation:** Implementing a weighted centroid localization method that computes the force centroid based on signal intensity across sensor nodes.
- **Event Classification:** Using a convolutional neural network (CNN) trained on deformation profiles to categorize events such as tapping, stretching, or pressure.

This algorithm runs on a low-power ARM Cortex-M microcontroller with a processing latency of under 10 ms, making it suitable for real-time applications [9].

### Experimental Setup

To validate the proposed auxetic sensor-based tactile system for **real-time human-robot interaction (HRI)**, a comprehensive series of experiments was conducted. The goals were to assess the system's ability to detect and localize tactile interactions accurately and rapidly in scenarios mimicking physical contact between a human and a robot. This section outlines the hardware setup, interaction conditions, and quantitative results from HRI-relevant test cases.

The tactile system comprised a flexible 8×8 piezo-resistive sensor array (64 channels), embedded within a rotating-square auxetic substrate. This configuration was designed to amplify localized deformations—common in human touch—and improve spatial resolution of tactile feedback. The sensor array was connected to a real-time embedded processing unit based on the ARM Cortex-M4 microcontroller, optimized for fast, low-latency response.

### Key components included:

- **Robotic Interaction Emulator:** A robotic manipulator equipped with a soft end-effector was used to simulate human touches, including gentle taps, sustained presses, and sliding gestures. Controlled force profiles (1 N to 10 N) were applied across the sensor area at varied contact speeds and angles to reflect real-world HRI conditions.
- **Signal Acquisition and Processing:** The sensor data was sampled at **500 Hz** through an SPI interface, processed on-board using the system's lightweight localization algorithm, and logged in real time for performance evaluation.
- **Environmental and Geometric Variability:** The sensor system was evaluated under various surface curvatures (to simulate mounting on curved robotic arms or torsos), as well as ambient variations in **temperature (-10°C to 40°C)** and **humidity (30% to 80%)**, representing real-world deployment scenarios.

### Test Procedures

To simulate realistic physical contact in HRI, the following test scenarios were implemented:

- **Contact Localization Tests:** The robot end-effector performed tapping actions at random locations. The system's ability to detect and spatially localize the contact event was recorded, and the

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position error was calculated.

- **Press-and-Hold Interaction:** Force was steadily applied across a region to simulate human gripping or resting contact. The system was tested for its capacity to detect steady pressure and resolve the contact zone with minimal drift.
- **Gesture Recognition under Deformation:** The sensor array was mounted onto a flexible robotic surface and subjected to stretching and bending while continuous tactile gestures (e.g., swipes, multi-point contact) were applied. This tested the robustness of localization algorithms under non-planar deformation. Each test was repeated across multiple trials and interaction locations to ensure statistical significance.

## Results

The experimental findings confirmed the system's high performance in key metrics relevant to real-time tactile sensing in HRI environments:

- **Localization Accuracy:**
  - **Average Error:** 2.3 mm RMS across all scenarios.
  - **Tapping (Impact) Events:** 1.8 mm error with <12 ms latency.
  - **Press-and-Hold:** Slightly higher error (2.5 mm) due to force distribution, but sufficient for HRI intent detection.
  - **Under Deformation:** Maintained <2.8 mm accuracy even on curved, moving robotic surfaces.
- **Detection Latency:** Events were consistently processed in **under 13 ms**, ensuring seamless response times for real-time HRI. Even under high-frequency interactions, the system exhibited stable temporal behavior, with jitter under 2 ms.
- **Throughput:** Achieved a frame rate of **78 fps**, sufficient for real-time multi-contact gesture recognition or active feedback control in robots.
- **Power Efficiency:** Consumed **28 mW** during operation and under **1 mW** in idle mode, suitable for **battery-powered mobile robotics** and wearable HRI devices.

## Conclusion and Future Directions

This research introduced a novel **real-time tactile sensing platform for human-robot interaction (HRI)** that leverages the unique mechanical behavior of auxetic structures and a flexible piezoresistive sensor array. The system integrates an efficient real-time signal processing pipeline to accurately detect and localize touch-based interactions, even under dynamic deformation or non-planar mounting. Through a series of targeted experiments simulating physical contact between humans and robotic surfaces, the proposed system was proven to be responsive, accurate, and robust for next-generation collaborative robotic platforms.

### Summary of Key Findings

Key outcomes of this study include:

- **High Localization Accuracy**

The proposed system achieved an average localization error of **2.3 mm (RMS)**, maintaining performance across planar and curved geometries. This level of precision supports responsive and safe HRI, where accurate touch detection is critical for gesture

recognition, intent inference, and safety-aware behavior.

- **Low Latency and High Throughput**

With consistent detection latency below **13 ms** and throughput of **78 frames per second**, the system enables **real-time responsiveness** required in dynamic interaction environments, such as collaborative manufacturing, assistive robotics, or haptic-enabled telepresence.

- **Power Efficiency for Embedded Use**

The system consumed only **28 mW** during operation and **<1 mW** in sleep mode, making it well-suited for **battery-powered robotic skins or wearable robotic interfaces**, supporting continuous monitoring with minimal energy overhead.

- **Environmental Robustness**

Performance remained stable under a wide range of **temperature and humidity conditions**, highlighting the system's readiness for real-world deployment on mobile robots or service robots operating in diverse environments.

## Implications and Applications

The ability to detect tactile stimuli in real-time with high spatial resolution and temporal fidelity opens a wide range of opportunities in HRI:

- **Collaborative Robots (Cobots)**

The tactile system enables robots to perceive physical contact from humans and react accordingly, supporting intuitive, touch-based interaction in shared workspaces—enhancing both safety and usability.

- **Wearable Robotic Systems**

The flexible and lightweight sensor platform can be integrated into **wearable assistive devices or exosuits**, providing high-resolution tactile feedback and gesture detection to assist user motion or enhance sensory awareness.

- **Haptic Feedback for Teleoperation**

Accurate and real-time tactile sensing can be utilized in **remote operation scenarios**, such as robotic surgery or hazardous environment exploration, enabling operators to receive tactile feedback via robotic avatars.

- **Soft Robotic Skins**

For robots using compliant surfaces, this sensor architecture provides a viable method for **continuous surface monitoring**, aiding in tasks such as adaptive manipulation, proximity detection, and user-responsive behaviors.

## Future Directions

While the current implementation demonstrates promising results for HRI, several areas offer potential for advancement:

- **High-Resolution Scaling and Coverage Expansion:** Future iterations can scale the sensor array to cover larger surfaces, such as full robotic limbs or torsos, while optimizing spatial resolution based on task-specific needs.
- **Advanced Learning-Based Interaction Recognition:** Integration with **deep learning algorithms**, including spatiotemporal models or transformer-based encoders, could enhance the system's ability to recognize complex gestures, multi-touch patterns, or interaction intent.
- **Flexible Integration into Robotic Structures:** Future work

should focus on seamless embedding into **soft or articulated robotic surfaces**, improving conformability and minimizing mechanical mismatch during movement.

- **Wireless Communication and Distributed Sensor Networks:** Implementing **wireless modules (e.g., BLE, Zigbee, UWB)** would allow scalable deployment across multi-part robotic systems, enabling fully networked tactile-aware platforms for social or assistive robotics.
- **Self-Calibration and Long-Term Stability:** Long-term deployment in robotic systems will require **automated calibration algorithms** that adjust for material fatigue, environmental drift, or sensor degradation over time.
- **Bidirectional Feedback and Haptics:** A future goal is to integrate **actuation elements** (e.g., vibrotactile motors or electroactive polymers) with the sensor system to create **bidirectional interfaces**, enabling the robot to both sense and express touch.

### Final Remarks

This study demonstrated a **bioinspired, auxetic sensor-based multilayer structure** capable of real-time tactile detection and localization, specifically optimized for **safe and effective human-robot interaction**. The combination of auxetic mechanics, flexible electronics, and low-latency signal processing presents a viable solution for tactile perception in collaborative and assistive robotics.

With continued research focused on **scalability, intelligence, and integration**, this platform is positioned to become a foundational technology in the evolution of socially intelligent robots. Potential future applications span from **collaborative manufacturing lines** to **rehabilitative wearables**, offering rich, intuitive, and responsive interaction between humans and intelligent machines.

### Key application domains include

- **HRI in Smart Manufacturing:** Real-time surface monitoring for safety in collaborative robot arms.
- **Assistive Robotics:** Interactive sensing in robotic caregivers or prosthetics.
- **Wearable Haptics:** Tactile interfaces for immersive VR/AR or motion augmentation systems.
- **Tactile AI Systems:** Combining sensing with machine learning for context-aware robot decision-making.
- Ultimately, this work lays the groundwork for **next-generation robotic platforms** that can physically understand and respond to the world in human-like ways—safely, intuitively, and intelligently.

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