Department of Electrical Engineering

EE6680D/EE6680 Dissertation

Project Title:

High sensitivity e-skin for teaching nerve procedures

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Abstract

Nerve blocks are critical diagnostic and therapeutic procedures in equine veterinary medicine, requiring precise administration of local anesthetics to desensitize specific nerves temporarily. Traditional training methods rely on live horses or cadaveric limbs, posing ethical, logistical, and sustainability challenges. To address these issues, this study introduces a novel training tool that integrates advanced material science and electronics. A new high-sensitivity material was developed and applied to create electronic skin. Designed and developed based on FPGA technology, the electronic skin offers exceptional sensitivity, enabling precise detection of needle positioning. Extensive trials were conducted to evaluate the model's performance, demonstrating its effectiveness in simulating realistic nerve block procedures. This innovative system provides real-time feedback during training, offering a reusable, interactive, and ethical solution to enhance skill acquisition, reduce animal use, and standardize veterinary education.

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Chapter 1: Introduction

Skin is one of the most remarkable human organs as it covers the whole body and contains a large number of neural sensors that can sense different stimuli. Roland S. Johansson and J. Randall Flanagan provide an in-depth exploration of how tactile sensory information is encoded, processed, and utilized by the brain during complex object manipulation [1]. Roland S. Johansson and J also point out that along with its excellent sensing capability, human skin has other remarkable properties including flexibility, stretchability, and self-healing [2]. Andrew Pruszynski and Roland S. Johansson, investigates the early-stage processing capabilities of first-order tactile neurons in the human somatosensory system. Contrary to the traditional understanding that feature extraction primarily occurs in the cerebral cortex, the study reveals that geometric feature processing, such as edge orientation detection, begins at the peripheral level within the tactile neurons themselves. This paper has significant implications for the development of prosthetics, haptic technologies, and robotics [3].

Research on tactile sensors for prosthetics and robotic arms dates back to the 1970s and 1980s, demonstrating the integration of tactile feedback with computers via touch screens to enhance the functionality of prosthetic hands. Since then, tactile sensors and electronic skins have been applied in a wide range of fields, including robotics, artificial intelligence, prosthetics, health monitoring, and human-machine interfaces [4]. Electronic skins (e-skins) have emerged as a leading research focus, driven by their potential to revolutionize multiple fields with advanced sensing capabilities. For instance, e-skins equipped with tactile sensors can provide critical action-related information, such as detecting sticking, slipping, or grasping during object manipulation. These systems can further estimate control parameters like contact force by analyzing the softness, hardness, or texture of objects, enabling more precise and adaptive interactions.

E-skins embedded with pressure sensors offer significant benefits in robotics by allowing robots to detect and localize external pressures exerted by surrounding objects, thus enhancing their ability to navigate and interact with dynamic environments. For amputees, these technologies can simulate sensory feedback, restoring a sense of touch and improving the usability of prosthetic limbs. Furthermore, when integrated with multifunctional sensors, e-skins can expand their applications into health monitoring. These advanced systems can accurately track vital biometrics, such as blood pressure, oxygen saturation, body temperature, blood sugar levels, and hydration status, offering real-time data for healthcare diagnostics and personal health management. This multifunctionality positions e-skins as transformative tools not only in robotics and prosthetics but also in healthcare, paving the way for innovative solutions in human-machine interfaces, wearable technology, and biomedical applications.

Óscar Oballe-Peinado et al. addresses a critical challenge in assistive robotics and prosthetics: enabling efficient and real-time tactile sensing for artificial hands [5]. The proposed architecture integrates tactile arrays with FPGA-based systems to perform high-speed data acquisition and preprocessing, ensuring that tactile feedback can meet the demands of dexterous manipulation.

By employing a direct interface between tactile sensors and FPGAs, the system eliminates the need for traditional analog-to-digital converters, simplifying the hardware design while maintaining precision. The architecture allows for robust serial communication among sensors distributed across fingertips, mid-digits, and palms. It supports a data rate of 200 frames per second, sufficient to detect complex tactile events like slippage, critical for enhancing manipulation and interaction in robotic hands.

This innovative design demonstrates the potential of FPGAs for distributed sensor networks, achieving high-speed tactile data processing locally, which minimizes communication bottlenecks. The study provides a foundational framework for improving tactile sensor integration in robotics, paving the way for smarter and more responsive artificial hands.

Chapter 2: Literature Survey

Piezo-resistive sensors are widely utilized due to their straightforward device design, fabrication process, and easy-to-implement readout mechanisms. These sensors operate by converting force variations into measurable changes in electrical resistance, making them highly suitable for integration into various electronic systems [6]. Their simplicity and adaptability have made them a staple in applications ranging from robotics and healthcare to wearable technologies and industrial automation.

The functionality of piezo-resistive sensors is based on detecting changes in resistance that occur in response to applied pressure. Two primary mechanisms are commonly employed to achieve this:

Contact Resistance Changes:

This approach relies on variations in the resistance at the interface between two conductive materials under pressure. When force is applied, the contact area between the materials increases, reducing the resistance. This principle is particularly effective in sensors with structured or granular conductive interfaces, as it allows for precise detection of small force variations.

Changes in the Conductive Path:

In this method, pressure alters the internal structure of a conductive elastic composite, such as a polymer matrix embedded with conductive particles (e.g., carbon nanotubes, graphene, or metallic nanowires). The applied force deforms the composite, modifying the conductive pathways and causing a corresponding change in resistance. This approach is advantageous for creating flexible, stretchable, and highly sensitive sensors suitable for dynamic environments.

These mechanisms enable piezo-resistive sensors to achieve high sensitivity, wide dynamic range, and compatibility with various substrates, including rigid, flexible, and stretchable materials [7]. Furthermore, advancements in materials science have enhanced their performance by introducing nanostructured materials, improving signal resolution, and expanding their applicability to areas requiring ultra-thin or wearable configurations.

The combination of simplicity, versatility, and effectiveness ensures that piezo-resistive sensors continue to play a pivotal role in the development of next-generation tactile sensing technologies and intelligent systems [8].

The paper [9] presents a novel wearable pressure sensor utilizing MXene-coated cotton fabric. The study addresses key challenges in wearable electronics, such as achieving both high sensitivity and broad sensing ranges while maintaining stability, durability, and comfort. The proposed sensor is fabricated through a cost-effective dip-coating method, resulting in a lightweight and flexible device with a unique three-dimensional porous structure.

By combining MXene nanosheets with the natural hydroxyl groups of cotton fabric, the sensor forms effective conductive networks, enabling precise pressure detection. The sensor exhibits impressive performance metrics, including high sensitivity (5.30 kPa^{-1} for pressures between 0–1.30 kPa), a wide sensing range (0–160 kPa), and rapid response and recovery times (50 ms and 20 ms, respectively). It is capable of detecting diverse human motions, such as finger movements, wrist pulses, and breathing, and it can also monitor early-stage Parkinson’s disease tremors.

Chapter 3: Problem Statement

Nerve blocks are essential veterinary procedures used in equine medicine to diagnose and manage conditions affecting a horse’s limbs. These procedures involve inserting a needle into specific areas of the horse’s leg to inject a local analgesic, temporarily blocking sensation near targeted nerves. This enables veterinarians to identify the source of pain or discomfort and treat it effectively. Despite their clinical importance, training for these procedures is currently limited by reliance on live horses or cadaveric limbs, raising concerns regarding ethical considerations, sustainability, and accessibility for repeated practice.

To address these challenges, this project proposes the development of an innovative 3D-printed anatomical model of a horse’s leg. The model will replicate the detailed anatomy of the equine limb and incorporate advanced electronic pressure sensors designed to mimic the tactile feedback experienced during an actual nerve block procedure. These sensors will provide immediate, real-time feedback when the needle is correctly positioned near the targeted nerve, ensuring that trainees can accurately practice and refine their technique.

In the conclusion, the Limitations of current approach to the problem statement is that using live animals or cadaveric limbs for training in veterinary procedures poses significant limitations, particularly when it comes to sustainability and ethical considerations. Repeated practice on live animals raises welfare concerns, while the availability of cadaveric parts is both inconsistent and resource-intensive. Furthermore, these methods are impractical for scaling up training programs, making them less accessible for widespread educational use.

In addition to these challenges, replicating the precise tactile feedback required for such procedures introduces significant technical hurdles. Detecting subtle pressure variations caused by a needle prick is a complex task for current electronic skin technologies. These systems must not only demonstrate high sensitivity but also accurately mimic the intricate tactile sensations experienced during real procedures. This level of precision is essential for providing realistic feedback that can guide trainees in developing the necessary skills for successful nerve block techniques.

Chapter 4: Solution

A. Sensor design

To address the problem, I used a flexible 8 × 8 resistive sensor array utilizing a combination of conductive and piezoresistive fabrics. The core sensing component was a piezoresistive fabric layer that served as the force transducer, strategically placed between two layers of conductive fabric. These conductive layers were arranged in a grid-like pattern consisting of rows and columns, with each intersection forming a discrete sensing element. This configuration allowed the sensor to detect force variations at each intersection point by measuring the changes in resistance.

To ensure structural integrity and prevent electrical interference, the entire assembly was secured using a nonconductive fusible interfacing fabric. This layer not only provided mechanical stability but also acted as an insulating barrier between the conductive strips. The final sensor array had an active sensing area measuring 97.5 × 97.5 mm, offering a well-balanced compromise between coverage and resolution. The spacing between adjacent sensing elements was maintained at an average of 2.5 mm, enabling precise detection of localized force distributions.

This innovative design leverages the unique properties of piezoresistive fabrics for high sensitivity while maintaining flexibility and durability, making it suitable for applications requiring accurate and real-time pressure mapping.

B. Cross-talk cancellation

Row-column multiplexing is a widely used method for reducing the number of wires required in tactile sensor arrays. While this technique simplifies wiring, it introduces the issue of cross-talk due to parasitic currents. These unwanted currents can flow through multiple elements along shared rows and columns, leading to inaccurate sensor readouts. The problem becomes particularly pronounced in large sensor arrays, where the number of potential parasitic current pathways increases exponentially with the size of the array, significantly degrading the accuracy and reliability of the sensor readings.

To address the challenges posed by parasitic currents, we implemented a grounding approach to eliminate cross-talk effectively. In this method, all row conductors were maintained at a reference voltage ($Vref$) through the use of transimpedance amplifiers, ensuring that no unwanted voltage differentials arose across the rows. Similarly, column conductors were also held at $Vref$, with the exception of the active readout column, which was grounded during the sensing operation.

This configuration ensured that current could only flow directly from the rows to the grounded readout column, as all other pathways were virtually shorted and, therefore, incapable of supporting current flow. By restricting the flow of current to a single column at a time, the system effectively isolated the sensor elements along the selected column, eliminating cross-talk and preserving the integrity of the measurements.

Additionally, this approach allowed for simultaneous readout of all sensing elements within the active column, significantly enhancing the throughput of the system. The ability to process multiple elements at once makes this method particularly advantageous for large arrays, where high-speed data acquisition is essential. This grounding technique thus ensures accurate, reliable, and efficient readout performance, enabling scalable sensor designs suitable for advanced tactile sensing applications.

C. Readout circuitry

To efficiently perform analog-to-digital (A/D) conversion while minimizing resource requirements, we designed a streamlined circuitry system centered around an array of comparators. These comparators were employed to reduce the number of input pins needed, enabling a simpler and more compact design. The circuitry was further supported by the microcontroller ESP32, a versatile and cost-effective device well-suited for this application. Leveraging the ADC pins of the ESP32 significantly reduced the complexity of the circuit and the amount of wiring, as the ESP32 also served as a controller to generate the necessary switching signals. This integration not only simplified the hardware design but also enhanced its reliability and efficiency.

To ensure precise switching with minimal error, we incorporated digital switches featuring low on-resistance. This choice reduced power loss and improved signal integrity, particularly in scenarios requiring high-speed data acquisition. The ESP32's capability to control these switches made it an ideal choice for managing the switching operations seamlessly within the circuit.

Additionally, we implemented operational amplifiers (LM386) with feedback resistors (Rf) dedicated to individual rows in the sensor array. These amplifiers were critical for maintaining signal amplification and stability across the system, especially in managing variations in the input signals. The use of feedback resistors allowed precise control of the amplification factor, ensuring consistent performance across all rows of the array.

This design approach, combining an efficient A/D conversion mechanism with optimized circuit elements, achieved a balance between simplicity, performance, and scalability. The integration of ESP32 as a central controller, paired with carefully chosen components such as low-resistance switches and operational amplifiers, ensures that the system operates with high accuracy and low error rates. This makes it a robust solution for applications requiring reliable analog-to-digital conversion and efficient signal processing.

Chapter 5: Experiment design

A. Sensor material

We selected the M0808MS pressure sensor array, manufactured by Changzhou Electronic Technology Co., Ltd., for its excellent performance and suitability for our application. This sensor material exhibits an almost linear relationship between applied force and the inverse of resistance (1/R), making it ideal for developing a precise and reliable sensing mechanism.

This linear behavior simplifies the process of calibrating the sensor and interpreting its output, enabling the design of a robust sensor array system capable of accurately reflecting real-world force measurements. The M0808MS sensor array's characteristics also support high sensitivity and consistency across a range of force levels, ensuring reliable performance even in applications requiring fine-grained force detection.

By leveraging these properties, we can create a pressure sensing mechanism tailored to provide accurate feedback for tasks such as tactile mapping, pressure distribution analysis, or dynamic load detection, thereby enhancing the overall functionality and applicability of our system.

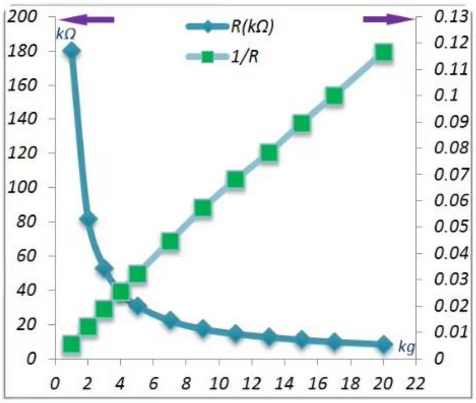

Fig. 1: The function graph between 1/R and force (f) of M0808MS

$$\frac{1}{R_1} = 0.0075 \times f \qquad (1)$$

Resources: Fig. 1 come from the website of Changzhou Electronic Technology Co., Ltd

B. Circuit design

To facilitate precise analysis, when the switching signals activate the corresponding column, a single row is isolated for measurement.

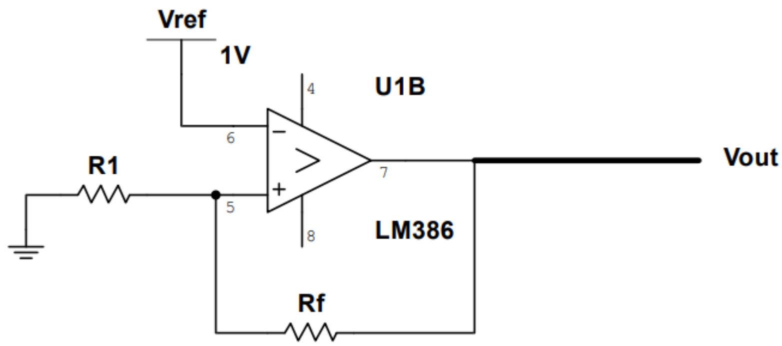

Fig. 2 Single unit read-out circuit

The relationship between the circuit's components is expressed by the following equations

$$\frac{0-v_{ref}}{R_1} = \frac{v_{ref}-v_{out}}{R_f} \tag{2}$$

Combined (1) and (2), and given v_{ref} = 1v and R_f = 68k.

we derive the following expression:

$$v_{out} = 0.5 \cdot f + 1 \tag{3}$$

Further analysis yields the force-to-voltage relationship:

$$f = 1.96 \cdot (v_{out} - 1) \tag{4}$$

Ultimately, this establishes a clear mathematical relationship between the applied force and the voltage output, enabling accurate interpretation of the sensor's response.

C. Mathematics statement

Since we use the parallel reading circuit, we can further summarize the whole matrix transformation.

$$force = \begin{pmatrix} V_{ref1}R_{f1}/R_{11} & 0 & 0 & 0 \\ 0 & V_{ref2}R_{f2}/R_{12} & 0 & 0 \\ 0 & 0 & V_{ref3}R_{f3}/R_{13} & 0 \\ 0 & 0 & 0 & V_{ref4}R_{f4}/R_{14} \end{pmatrix}^{-1} voltage + \begin{pmatrix} 1/V_{ref1} \\ 1/V_{ref2} \\ 1/V_{ref3} \\ 1/V_{ref4} \end{pmatrix} \tag{5}$$

$$where, force \in \mathbb{R}^4, voltage \in \mathbb{R}^4$$

By processing the parallel input voltages and applying Equation (5), we can convert them into a force matrix.

Chapter 6: Equipment

Microcomputer: ESP32-C6-DevKitM-1 *1
Amplifier unit: LM358 * 2
PC: LEGION*1
FPGA IDE: Arduino IDE
Multi-resistance and multi-line

Chapter 7: Analysis and operation method

Our personal computer sends switching signals to the ESP32 microcontroller, initiating the process. Upon receiving these signals, the ESP32 activates the designated columns in the sensor array. Simultaneously, the corresponding ADC (Analog-to-Digital Converter) pins on the ESP32 read the voltage values from the active rows and columns, which are then transmitted back to the PC for further processing.

Once the voltage data is received, the PC applies Equation (5) to convert these readings into corresponding force values in the parallel direction. This conversion enables the accurate mapping of the forces being applied to the sensor array. The entire process operates in a continuous loop controlled by the switching signal program, allowing the system to dynamically update and generate a complete real-time force matrix. This iterative approach ensures precise and efficient force data acquisition for real-time applications.

Chapter 8: Result

Experiment Overview:

Measuring Detection Results Under Varying Needle Sizes with Minimal Force

Needle Size (Gauge)	Diameter (mm)	Detection Result
25	0.5	YES
23	0.6	YES
21	0.8	YES
19	1.1	YES
17	1.4	YES

Chart.1 Measuring Detection Results

In this experiment, we apply a very small force and record the detection results for various needle sizes. Forces are computed in with the scanning of the first row of the next frame (this takes 100 us).

Chapter 9: Conclusions and future direction

This study achieved outcomes in developing an innovative 3D-printed anatomical model with integrated electronic pressure sensors. The following outcomes were identified:

1. The system successfully captures and reflects location parameters with high accuracy.
2. It exhibits exceptional sensitivity, enabling precise and reliable measurements.
3. It accurately detects and processes real forces within the PC environment, ensuring effective feedback.
4. The proposed solution is cost-effective, making it an excellent choice for practical and economical applications.

The primary objective of this project was to design a hands-on, interactive learning tool for procedural training. Experimental results demonstrate that the system fulfills the requirements of a 3D-printed anatomical model, confirming its suitability for use in educational and training contexts. The model effectively bridges the gap between theoretical knowledge and practical application, providing an ethical and sustainable alternative to traditional training methods.

To further enhance the system's capabilities and broaden its applications, the following directions are proposed for future work:

1. Enhanced Sensor Integration: Incorporate more advanced sensor technologies, such as multi-functional sensors capable of detecting additional parameters like temperature or texture.
2. Feedback Optimization: Develop more sophisticated feedback mechanisms, such as haptic feedback or visual cues, to enrich the training experience.
3. Wireless Communication: Integrate wireless data transmission to improve system flexibility and reduce dependency on physical connections.
4. Scalability and Versatility: Expand the design to support other anatomical models or simulate more complex procedures for broader educational use.
5. Software Enhancement: Implement advanced algorithms for real-time data visualization and analysis to improve usability and interactivity.
6. User Testing and Validation: Conduct extensive user studies with trainees and professionals to gather feedback and iteratively refine the model.

These advancements will contribute to a more robust, versatile, and impactful training tool, paving the way for wider adoption in veterinary and medical education.

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