PhD School: Navigating Interdisciplinary Challenges: Taking A Low-power Wireless Plantar Pressure Monitoring System with 3D-Printed Sensors as An Example

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Abstract

Interdisciplinary research plays a vital role in addressing complex, real-world challenges by integrating diverse expertise and perspectives. Our research focuses on the development of a low-power, wireless wearable insole device equipped with three-dimensional (3D) printed pressure sensors, designed to monitor plantar pressure in diabetic patients. This project encompasses a wide range of disciplines, including ink synthesis, pressure sensor fabrication, embedded system design, and clinical testing with patients. It is part of a broader initiative that brings together researchers from rehabilitation science, materials science, and computer science.

While significant progress has been made, the integration of these diverse elements and the management of interdisciplinary collaboration present ongoing challenges. This paper discusses both the technical and organizational hurdles encountered throughout the project, offering strategies to overcome these obstacles. By sharing our experiences, we aim to provide valuable insights into effectively managing interdisciplinary research and fostering productive collaboration across multiple fields.

CCS Concepts

• **Computer systems organization** → *Sensors and actuators*; • **Hardware** → *PCB design and layout*; **Sensor devices and platforms**.

Keywords

Interdisciplinary project, Low-power embedded system, Wireless system, Smart sensors, Wearable devices

Figure 1: An overview of the key components of the project, including ink synthesis, circuit design, application development, and 3D-printed sensor fabrication.

1 Outline of Planned Research Activities

1.1 Background

Diabetic foot ulcers (DFUs) represent a significant health concern, affecting up to 34% of individuals with diabetes over their lifetime [1]. These ulcers contribute to more than 85% of foot amputations among diabetic patients [2], highlighting the critical need to shift the focus from treatment to prevention. One promising preventive approach involves the development of footwear systems equipped with pressure sensors, which can monitor foot pressure daily, thereby helping reduce the incidence of DFUs.

Although several commercial products, such as the FScan insole system [4] and the Sensoria smart sock system [5], are available on the market, but they tend to be expensive and lack durability. Additionally, their standard sizing and lack of customization often fail to meet the specific needs of populations like diabetic and Parkinson's patients. In contrast, much of the current academic research has focused on enhancing sensor sensitivity within low-pressure ranges, such as those used for detecting heart rate or pulse signals.

Wearable systems like these also face significant power constraints, requiring continuous operation over extended periods without frequent recharging. Developing a low-power solution is essential to ensure the usability and practicality of such devices, particularly for long-term monitoring. Our project seeks to address these challenges by employing 3D printing to develop customized, cost-effective piezoresistive sensors. These sensors not only improve material efficiency but also integrate with an ultra-low-power wireless system, enabling continuous monitoring while optimizing battery life, thus enhancing the feasibility of daily use in real-world settings.

1.2 Objectives

The first objective of this research is to develop high-sensitivity pressure sensors using a specialized ink synthesized for this purpose. This ink will be applied through the Direct Ink Writing (DIW) printing method, which is well-suited for fabricating sensors with high precision and sensitivity[3]. The goal is to create sensors that are both durable and responsive, meeting the specific requirements for monitoring diabetic foot pressure.

The second objective is to design an ultra-low power data acquisition system that will efficiently collect and process pressure data from wearable sensors. This system will be engineered to minimize power consumption while ensuring accurate and reliable data collection. Integrating this system with the pressure sensors and the wearable insole is crucial for the system's overall functionality and effectiveness.

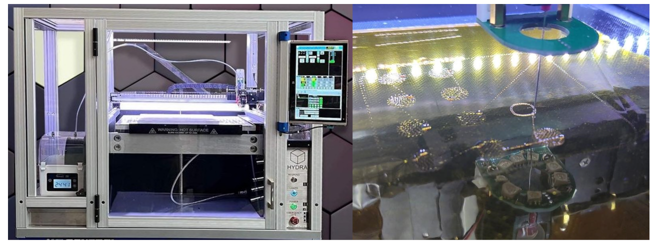
The third objective involves collaboration with team members across different disciplines, including rehabilitation, materials science, and computer science, to implement the developed system in human trials. These trials will test the wearable device's performance in real-world conditions, evaluating its effectiveness in preventing DFUs and gathering feedback to refine the system further. Effective teamwork and coordination will be essential to address the interdisciplinary challenges and ensure the project's success.

2 Research Approach and Methodology

The research approach is designed to address the development and integration of a wearable insole with advanced pressure-sensing capabilities, focusing on both the technical and practical aspects of the project. The approach encompasses three main components: sensor development, system design, and implementation in human trials.

To begin with, the research will focus on the development of high-sensitivity pressure sensors. This involves synthesizing a specialized conductive ink that will be used in the DIW printing method (Fig. 2). The ink will be optimized for high-pressure ranges to ensure that the sensors exhibit both high sensitivity and durability. The DIW method will allow for precise control over the sensor's dimensions and performance characteristics, which is essential for creating a reliable and effective pressure monitoring system. Next, an ultra-low power data acquisition system will be designed to interface with the pressure sensors. This system will be tailored to efficiently collect and process data while minimizing power consumption. Key design considerations will include the integration of the sensors with the embedded system, real-time data processing, and user feedback mechanisms. The goal is to create a system that not only meets technical specifications but also is practical and comfortable for everyday use.

Finally, the developed system will undergo human trials to assess its performance and usability. These trials will be conducted in collaboration with experts in rehabilitation, materials science, and computer science. The trials will evaluate the device's effectiveness in preventing DFUs and will provide critical insights into user experience and device functionality. Feedback from these trials will be used to make necessary refinements to both the sensor technology and the data acquisition system.



(a) (b)

Figure 2: 3D printer system for sensor fabrication. (a) A commercial 3D printer from Hyrel 3D. (b) An image of the printer in operation.

3 Preliminary Results

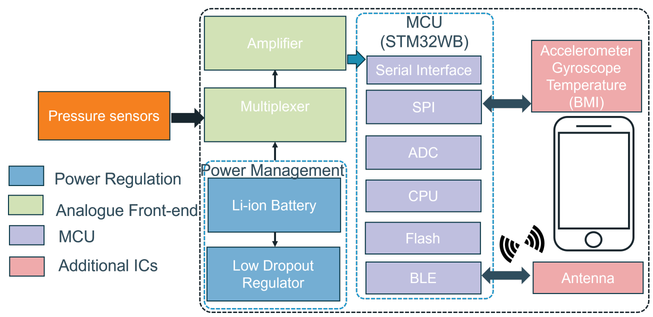


Figure 3: Block diagram of the data acquisition system.

For the sensor fabrication, graphene has been selected as the primary material for ink synthesis, serving as the conductive layer in the piezoresistive pressure sensors. Current research is focused on refining the material composition, with an emphasis on optimizing the sensor's performance by adjusting the material ratios.

For the wireless monitoring system, we have successfully designed the initial version of the printed circuit board (PCB), incorporating low-power components and a Bluetooth Low Energy (BLE) module (Fig. 3). The system is capable of supporting eight channels, facilitating the simultaneous collection of data from eight sensors. This data is displayed in real-time via a custom-developed Android application (Fig. 4), enabling continuous monitoring of pressure changes.

Preliminary results have confirmed the viability of utilizing 3D printing for fabricating pressure sensors and developing the core components of the embedded system. Nevertheless, challenges persist in achieving seamless system integration and optimizing sensor performance in practical applications.

4 Technical and Non-Technical Challenges

4.1 Technical Challenges

One of the primary technical challenges is the formulation and synthesis of the conductive ink used for 3D-printed pressure sensors.

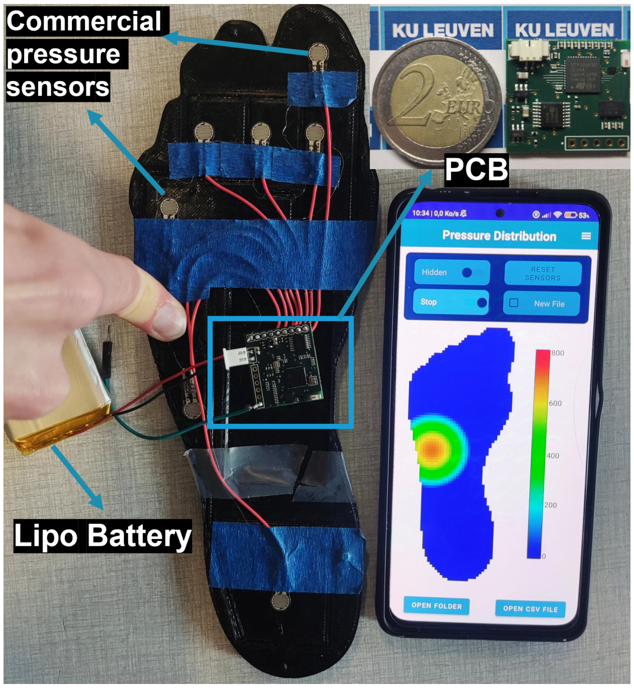


Figure 4: Prototype of the insole system featuring commercial pressure sensors integrated with an Android application.

Achieving the optimal balance in the ink's composition is crucial to ensure that it delivers both the required sensitivity and durability for high-pressure range applications. Additionally, the DIW printing method must be finely tuned to consistently produce sensors with precise dimensions and performance characteristics, which can be complex due to the need for high precision and reproducibility.

Another significant challenge lies in integrating the 3D printed sensors with the ultra-low power data acquisition system. Ensuring that the sensors remain reliable and functional over extended periods and under various conditions is critical. Effective system integration is essential to maintain performance and reliability, which requires careful attention to how the sensors and data acquisition components interact.

Power management is also a key technical hurdle. Developing a data acquisition system that minimizes power consumption while ensuring accurate and reliable data collection poses a substantial challenge. The system must be designed to extend battery life without compromising the device's functionality, requiring innovative approaches to power efficiency.

Finally, ensuring data accuracy and reliability is crucial. The pressure sensors must provide precise measurements across the expected pressure range, and real-time data processing must be handled efficiently. This involves creating a system that processes and transmits data without impacting the device's performance or user comfort.

4.2 Non-Technical Challenges

Interdisciplinary collaboration presents a significant non-technical challenge in our project. Effective communication and coordination among team members from diverse fields are essential but often difficult due to differences in terminology, methodologies, and expectations. Aligning everyone on shared goals and timelines is crucial for maintaining progress and achieving objectives, yet this can be particularly challenging in a multidisciplinary environment.

One of the most pressing difficulties we face is determining where to focus our time and energy. The project's interdisciplinary nature—spanning 3D printing, low-power circuit design, and software development—often leaves researchers torn between competing demands. Each area presents its own complexities, and balancing them can be overwhelming. This dilemma is compounded by uncertainty about which aspect will be most critical for future career competitiveness, especially as we near the completion of our PhDs. While interdisciplinary work offers the advantage of gaining knowledge across multiple domains, it can also create concerns about not achieving deep expertise in any one area. This ambiguity complicates decision-making, making it harder to chart the best course forward, both for the project and our long-term careers.

Managing the project's progress amidst these uncertainties adds further complexity. Coordinating various technical phases and ensuring the integration of components, all while maintaining momentum requires constant balance. The challenge is heightened by the difficulty of setting clear priorities when our focus remains divided across multiple, equally important areas.

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