Technical Analysis for Electro-Sensory 3D Foot Scanning in a Shoe

Denys J.C. Matthies
Technical University of Applied Sciences Lübeck, Fraunhofer IMTE
Lübeck, Germany

Maximilian Kasbohm
Ilmenau University of Technology, Fraunhofer IGD
Ilmenau, Germany

Gerald Bieber
Fraunhofer IGD Rostock
Rostock, Germany

Figure 1: The process of building a 3D foot scanning shoe begins with preparing materials and design templates (a) and progresses to creating a transparent mold (b) for precise shaping. The inner lining (c) is integrated with conductive elements, ensuring both comfort and functionality. Conductive ink electrodes are then embedded onto the shoe's surface in specific patterns (d) to enable advanced sensing capabilities. Finally, the fully assembled shoe (e) combines ergonomic design with innovative sensing technology, resulting in a wearable prototype.

Abstract

This paper teases our exploration – the application of electro-sensory technologies for three-dimensional foot scanning within a shoe. This research investigates resistive and capacitive sensor technologies, assessing their suitability for identifying foot pressure points, ensuring ergonomic fit, and indicating shoe wear status. Experimental findings support the potential for integrating advanced sensory systems into footwear, providing significant benefits in preventing foot injuries and improving patient outcomes, particularly for individuals with conditions like diabetes mellitus and peripheral arterial disease.

CCS Concepts

• **Applied computing** → **Life and medical sciences**; *Electronics*;
• **Hardware** → *Hardware validation.*

Keywords

Electro-sensory technology, 3D foot scanning, ergonomic footwear, pressure sensors, diabetic foot syndrome

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1 Introduction

Foot health is vital for overall well-being, but the feet constantly endure stress, which can lead to a variety of issues such as deformities, injuries, and complications linked to conditions like diabetes mellitus and peripheral arterial disease. Worldwide, approximately 540 million people are diagnosed with diabetes [8], including 7 million in Germany alone [11]. This marks a twofold increase in cases compared to 1980, and the number of affected individuals continues to rise, especially in industrialized countries. Diabetes is a metabolic disorder in which the pancreas either fails to produce enough insulin or the body cannot effectively use it, disrupting the regulation of blood sugar levels [16]. This dysfunction often leads to nerve damage (neuropathy) and arterial issues (peripheral arterial occlusive disease, PAD), resulting in a reduced sense of touch in the feet. This condition, known as Diabetic Foot Syndrome (DFS), involves foot complications such as infections and ulcers, which can lead to tissue death [3]. As such, monitoring areas where the foot might rub excessively against the shoe becomes crucial. Addressing these concerns calls for the creation of personalized ergonomic footwear, but current technologies—such as foam impressions and external 3D models—fall short in providing real-time, in-shoe pressure analysis.

The role of foot interfaces in technology dates back to the creation of the world's first wearable computer—an instrumented shoe with a toe-operated switch used to transmit casino roulette results [22]. Since then, foot interfaces have evolved substantially, progressing from simple devices like Engelbart's "Mole," a mouse alternative [7], to more advanced systems that leverage ubiquitous computing and miniaturized electronics [17].

Today, commercial innovations like smart shoes and insoles have entered the market, with applications such as gait analysis, step counting [19], fall detection [1], and ulcer prevention [20]. In addition, research has expanded the capabilities of foot interfaces, enabling the detection of gait patterns [10, 12], body posture [5, 18], terrain types [14], stress levels [6], and leg length discrepancies [13]. Moreover, actuation technologies such as vibrotactile feedback and electrical muscle stimulation (EMS) [23] have further broadened

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Table 1: Summary of the advantages and limitations of the material selected.

	Advantages	Limitations
Copper Tape	Great conductivity, Electrode shape can be cut to size, Lots of experience (smart soles)	Flexible in one direction only
Zebra Fabric	Great conductivity, Highly flexible, Can be incorporated directly into the shoe	Electrode shape determined, High Costs
Conductive Paint	Great conductivity, Electrode shape and size can be individually adjusted	Limited flexibility for thick layers

their application scope to include tactile augmented reality [24], navigation [15], rehabilitation [25], and virtual reality [21].

The combination of biomechanical, sensory, and advanced feedback technologies has enabled the development of foot augmentations, which have the potential to enhance human abilities [4]. The feet's unique characteristics—such as their stable contact with surfaces and available space for embedding sensors—make them an ideal platform for influencing posture, balance, and movement in ways distinct from augmenting other body parts.

Despite significant advances in both research and commercial innovations, most foot interfaces remain restricted to specific applications, leaving vast potential for broader human augmentation largely untapped [4]. This paper aims to fill these gaps by introducing a novel approach to 3D foot scanning within shoes, utilizing electro-sensory technologies to dynamically track foot position. By integrating resistive and capacitive sensor systems, this research provides a foundation for the future development of advanced ergonomic footwear and broader applications in human augmentation.

2 Implementation

2.1 Materials Selection

Sensor materials and electrode designs were chosen based on accuracy, compactness, durability, and ease of shoe integration, considering past performance and experimental adaptability.

2.1.1 Copper Tape. Copper, valued for its conductivity and flexibility, was shaped into thin (<1 mm) foot-contour-specific electrodes for resistive and capacitive sensing (*see figure 2a*).

2.1.2 Conductive Textiles. Zebra Fabric (HITEK) and EeonTex fabric were selected for their flexibility, durability, and low resistance (20 k/cm²) (*see figure 2b*). While easily embedded, their predefined conductive pathways required precise alignment.

2.1.3 Conductive Paint. Conductive paint offers versatility for creating custom electrodes on curved shoe surfaces (*see figure 2c*). We tested 11 mixtures, finding that thin, even layers prevented cracking. Conductive ink, made with graphite or copper powder, is affordable and popular for simple circuits but lacked adhesion and durability on fabrics. Adding adhesive improved wear resistance, ensuring flexibility for footwear use. Finally, Bare Conductive Electric Paint was chosen for its superior conductivity.

2.2 Technology Selection

2.2.1 Arduino CapSense Library. We utilized the CapSense library by Paul Badger [2] as it is the most simple and modular design. We simply require a microcontroller board, such as the Arduino micro, bluetooth modem and a battery (*see Figure 2*). In order to ultimately determine which pull-up resistor is most suitable for this measurement, each of the three sensitivity levels was tested with the three previously mentioned scenarios of rest, touch and pressure and the respective values were recorded. This was done separately for each electrode material.

2.2.2 OpenCapSense: Another rapid prototyping tool that provides stable measurements without requiring external resistors is the OpenCapSense toolkit [9]. The toolkit deploys a loading mode electrodes, which charges and discharges the electrode, determining the time constant, then sends the data to an Arduino, which transmits it via Bluetooth for storage. OpenCapSense offers a compact design with fewer cables and built-in resistors. Sensitivity level division is unnecessary. Each electrode type was tested under rest, touch, and pressure, with values recorded

2.2.3 Resistive Sensing. Unlike resistive sensors, capacitive sensing requires two electrodes separated by a dielectric (*see Figure 2*). Pressure alters electrical resistance by compressing the dielectric. EeonTex fabric from the HITEK Kit was used for its flexibility and 20kΩ/cm² resistance. Electrodes (1×1 cm) were arranged in overlapping 1 cm strips, with one acting as a transmit pin and the other as a receive pin on the Arduino. Applying pressure compresses the dielectric, reducing the electrode distance *d*.

3 Final Prototype Assembly

From our evaluation, we decided to use conductive ink with a combination of capacitive and resistive sensing. This series of images in figure 1 demonstrates the systematic approach to combining traditional shoemaking techniques with advanced sensing technology, resulting in a functional prototype of a 3D-sensing shoe.

Initial Design and Materials Preparation: Figure 1–a showcases the preparatory stage where various materials and design patterns are laid out on a workbench. You can see different cutouts of fabric or leather, likely intended to form the upper and inner components of the shoe. Additionally, there are templates for shaping the shoe and other tools to assist with precise assembly. The workspace suggests careful planning and prototyping before integrating the sensing technologies.

Creation of the Transparent Mold: Figure 1–b showcases the creation of a transparent mold, which appears to be made of flexible or rigid polymer material. This mold is likely used as a structural framework to shape and align the shoe components accurately. The transparency ensures visual inspection during assembly, ensuring precision in the application of conductive ink or placement of other internal features.

Integration of the Inner Lining: In figure 1–c the inner lining of the shoe is being assembled. The lining is crafted to incorporate sensing elements while maintaining comfort and durability. The close-up provides a view of the stitching or adhesive techniques used, ensuring the integration of conductive ink electrodes within the shoe's structure without compromising the user's comfort or the sensing accuracy.

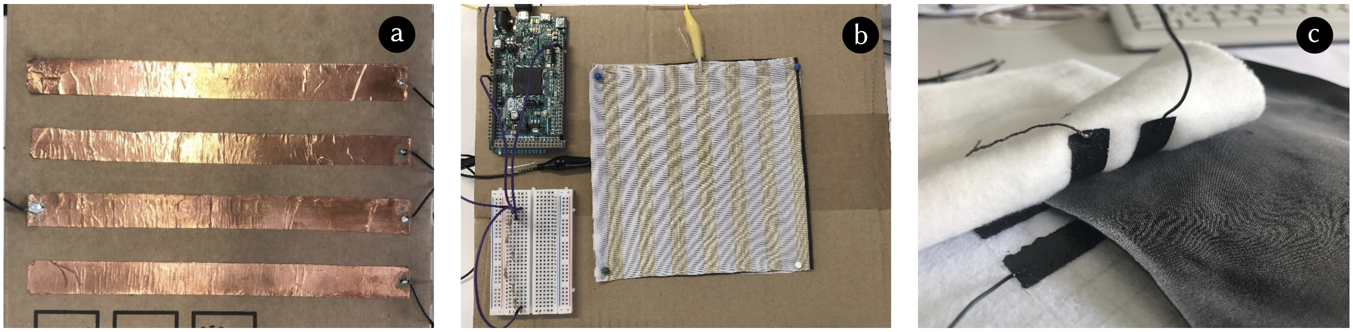

Figure 2: Showing all three types of electrodes we evaluated: a) Copper tape, b) Zebra Fabric (HITEK) and EeonTex fabric, and c) Conductive paint, which we mixed by ourselfes (see Table 1).

Embedding the Conductive Electrodes: This figure 1–d illustrates the crucial step of embedding conductive ink electrodes onto the shoe's surface. The electrodes are applied in precise patterns, possibly using screen printing or similar techniques, to create a 3D-sensing wall. The foam or padding visible in this stage suggests efforts to combine functional sensing elements with cushioning to maintain the ergonomic quality of the footwear.

Final Shoe Assembly: The last image, figure 1–e, presents the fully assembled shoe, featuring a polished and wearable design. The shoe integrates all the previously assembled components, including the conductive ink electrodes and 3D-sensing wall, seamlessly into a professional and ergonomic product. A foam last (a model of a foot) is visible in the background, indicating its use during the shoe's shaping process.

4 Conclusion

This paper teased an approach how to integrate 3D foot-scanning into footwear using conductive ink electrodes for a functional sensing wall. We deployed copper electrodes, conductive textiles, and capacitive-resistive sensor synergy, highlighting both opportunities and limitations. Embedding sensors into shoe walls enables applications in medical diagnostics, sports, and human augmentation. Despite material challenges, this research lays the foundation for future electro-sensory footwear innovations. Smart soles and shoes could soon support elderly care by monitoring daily activities as health indicators.

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