

InkFusion3D: 3D Printing Flexible Sensors with Silicone Rubber and Conductive Ink Materials

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Abstract: With the continuous advancement in current sensor design research, most design schemes still rely on rigid or semi-flexible materials for sensor usage. These interactive devices are increasingly unable to meet the demands of users for adaptability, durability, and biocompatibility, limiting their use in dynamic environments. This paper introduces a novel flexible sensor, InkFusion3D, which is fabricated using a combination of low-cost conductive ink and silicone rubber through 3D printing technology. Due to the significant advantages of InkFusion3D material, such as low cost, durability, good biocompatibility, and wide applicability, it can be customized for various applications to address challenges. The paper elaborates on the manufacturing method of InkFusion3D and its sensing principle upon force application. It also proposes applications in medical and gaming scenarios, such as joysticks, buttons, tangible interaction models, and smart filler materials.

Keywords: Flexible sensor, Conductive ink, Silicone rubber, 3D printing, Human-computer interaction; Interaction devices.

1. Introduction

As research on sensor types and design methods gradually develops, attention begins to shift towards enhancing user and interaction experience during the design process. This place demands on the shape and material properties of sensors, requiring them to adapt to various surfaces and offer rich adaptability. Hence, researchers have started to explore high customization possibilities through 2D and 3D, but are still constrained by the lack of suitable materials that can cater to diverse application needs[1, 2]. Seeking multifunctional, durable, and biocompatible solutions has become one of the current research focal points.

Existing sensors and conductive technologies typically rely on rigid or semi-flexible materials, limiting their applications in dynamic and complex environments[3, 4]. Some of these materials lack durability, leading to wear and aging, thereby shortening the lifespan of the devices[4, 5]. Moreover, only a few flexible conductive materials and sensors are biocompatible, restricting their use in medical applications or other wearable device domains[6, 7]. For a better user experience and design outcome, researchers have started to focus on using flexible materials as input interfaces, especially in applications related to interaction design, medical devices, and gaming interfaces[1, 7, 8].

In this paper, we propose a new flexible material as a potential sensor. The sensor can be easily fabricated through 3D printing. By redesigning the 3D printer, users can print silicone rubber with a porous structure using preset programs, while the machine injects conductive ink inside. We named the sensor InkFusion3D. Connecting the sensor to external output wiring can create various interactive designs, such as various force sensors and touch sensors. This paper will discuss and showcase the potential of InkFusion3D as various sensors in the future, providing feasible and meaningful solutions to existing challenges.

Compared to existing solutions, the proposed material has several distinct advantages: Firstly, its low cost and durability, as the sensor is made from a combination of low-cost conductive ink and silicone rubber, ensuring the material's

durability against wear. Next, its biocompatibility with biological systems provides a direction for research in medical applications, including implants and wearable devices. Furthermore, InkFusion3D is multifunctional: the 3D printing process can achieve intricate custom designs, helping users customize suitable interaction methods. Lastly, its potential applications are vast, from medical devices to gaming interfaces, showcasing its adaptability and relevance across various domains.

In summary, the contributions of this paper include:

Introducing a novel flexible sensor capable of adapting to various soft object device interactions.

Presenting the manufacturing method and design principles of InkFusion3D for research and further exploration.

Proposing two application scenarios (pertaining to medical and gaming domains) to support the needs of different user groups.

2. Related Works

This section will discuss and analyze some existing research related to the article from three perspectives.

2.1. Designs of 2D and 3D Sensors

To achieve rapid fabrication of various sensors while ensuring their flexibility, HCI researchers have developed various design and manufacturing methods, broadly categorized into 2D and 3D. Under 2D fabrication, users can sketch circuits and sensor designs on commonly seen material surfaces using handheld printers[2], or create interactive interfaces on human skin using electric pens[1]. In 3D fabrication, some researchers quickly design pneumatic soft robots using programming software[9], while others use organosilicon-treated paper to make wearable devices[10]. Although these methods meet user needs to some extent, proficient use still requires time investment for learning. We aim to explore a method where users can directly 3D print the required sensors through preset programs and quickly put them into use.

2.2. Semi-Flexible and Flexible Sensors

In the design domain, the advantages of traditional breadboards, printed circuit boards, and soldered circuit boards previously used by tech enthusiasts have gradually diminished[11]. With the democratization of various materials and the development of personal manufacturing technologies, researchers have started using semi-flexible materials and liquid conductive materials to make sensors. Examples include designing resistive soft sensors using flexible conductive materials for 3D printing[12], and universal circuit boards for quick design on curved and deformable surfaces[3]. Moreover, researchers have explored methods like smearing emulsions on the skin as a medium to drive screen interactions[7], and making sensors by soaking porous soft objects in conductive ink[8]. While these new sensors are more flexible, they often suffer from severe wear and aging due to material limitations, becoming less durable. Thus, we follow the direction of designing flexible sensors, exploring a more accessible and highly durable sustainable material.

2.3. Special applications of sensors into various materials

In the HCI domain, flexible and semi-flexible sensors are typically combined with rigid and semi-flexible materials for product manufacturing and deployment. This combined fabrication technique enriches the product. Examples include ceramic dishes surface-printed with circuits made of conductive ink[4], sewable microcontrollers for electronic textiles[5], and resistance controllers made by 3D printing and inkjet printing conductive materials[13]. Researchers have also explored using sustainable materials as raw materials for designing and manufacturing transient electronic devices[6]. These diverse material applications have expanded the presentation of sensors and enriched interaction modes. Therefore, our work will also focus on designing sensors combined with flexible materials.

3. InkFusion3D Method

As described above, many sensors have been proposed, including flexible and semi-flexible sensors, which are combined with different types of materials for design. However, these designs still have some limitations, such as the need for manual participation in the production process and the overall design containing hard components. To address this, we propose a flexible sensor design method composed entirely of soft components and have named the designed device InkFusion3D.

InkFusion3D is a flexible sensing device that achieves conductivity by injecting conductive ink into the porous silicone rubber material during the 3D printing process, and then connecting it to external electrodes. After prolonged use or drying, the conductive ink inside will transition from a liquid to a solid state. Both states allow the conductive material to be evenly dispersed inside the silicone rubber material. When external forces are applied to the material in different directions, the conductivity and circuit direction change. This method allows us to design this material as a deformable flexible sensor. We will interact with the material through pressing, twisting, and shearing, designing its practical applications.

3.1. InkFusion3D Production

The design concept of InkFusion3D is to inject conductive ink into the internal porous silicone rubber material, transforming it into a sensor. The entire process starts with a user-friendly software interface where users can quickly design models. The software not only renders the model with an internal porous structure but also calculates the optimal path for injecting conductive ink. Once the design is complete, the 3D printer will print based on the calculated results. Printing starts from the bottom layer, followed by the main body with a porous structure. Simultaneously, conductive ink is injected into the designated channels. The final stage is printing the top layer, which is designed with a reserved opening to facilitate users to replenish conductive ink when the sensor's conductivity decreases. This innovative design not only simplifies the production process of interactive sensors, ensuring sustainability, but also provides a customizable method for HCI development.

3.2. InkFusion3D Material

The material combination of InkFusion3D utilizes the inherent flexibility and permeability of porous silicone rubber and the conductivity of conductive ink, making it a highly adaptive and efficient sensor. The porosity of silicone rubber allows for precise injection of conductive ink, ensuring uniform conductivity throughout the sensor structure. This not only aids in manufacturing customizable flexible sensors but also enhances the sensor's sensitivity and response speed. Moreover, the combination of the durability of silicone rubber with low-cost conductive ink ensures the sensor can withstand wear, making it an ideal choice for designing interactive devices in the HCI domain.

3.2.1. Silicone Rubber

Silicone rubber is characterized by its flexibility, durability, and biocompatibility, and is used in numerous industries ranging from medical devices to consumer electronics. If designed to have internal porosity, its utility can be further enhanced. Porous silicone rubber is directly produced by a 3D printer, with its material interior filled with interconnected micropores. These micropores not only lighten the material, increase its compressibility, but also give it gas and liquid permeability. This unique characteristic makes porous silicone rubber an ideal base material for applications requiring controlled substance injection, such as injecting conductive ink. Additionally, its inherent elasticity ensures the material maintains its shape and function under mechanical stress, making it the preferred choice for wearable and flexible electronics.

3.2.2. Conductive Ink

Conductive ink is a material that combines conductivity and adaptability, promoting the development of printed electronics. These inks typically consist of conductive nanoparticles (such as silver, copper, or carbon) suspended in a liquid medium. When applied to a substrate and dried, the nanoparticles form a continuous conductive path, allowing current to flow. The real advantage of conductive ink lies in its applicability to various surfaces, from rigid circuit boards to flexible materials like paper or fabric. For porous silicone rubber, the fluidity of the ink allows it to be precisely injected into the porous structure of the silicone rubber, ensuring uniform conductivity throughout the sensor. Moreover, advancements in conductive ink formulations have made the

ink stretchable and elastic, adapting well to the flexibility of silicone rubber, ensuring the interactive sensor's lifespan.

3.3. Sensing Mechanics

InkFusion3D, a combination of conductive ink and a three-dimensional porous silicone structure, is ideally suited to detect and respond to various mechanical interactions. Its unique structure provides a plethora of sensing functionalities.

3.3.1. Twisting

When the InkFusion3D sensor is twisted, the porous silicone structure undergoes torsional deformation. This action causes the injected conductive pathways to reorient, changing the circuit direction and, consequently, its conductivity. By monitoring these conductivity changes, the degree of twisting can be accurately measured, enabling precise gesture recognition.

3.3.2. Pressing

Applying pressure to the sensor compresses the porous silicone rubber, bringing the conductive ink pathways closer together. This compression results in a decrease in circuit resistance, which can be calibrated to determine the force applied to the sensor. The inherent elasticity of silicone rubber ensures the sensor returns to its original state after pressure is released, making it highly suitable for touch interactions.

3.3.3. Shearing

Lateral forces or shearing actions cause misalignment of the conductive pathways inside the sensor. This misalignment disrupts the continuity of the circuit, resulting in conductivity changes. By monitoring these changes, the sensor can detect and measure lateral movements or sliding, adding another dimension to its interactive capabilities.

3.3.4. Stretching

Extending the InkFusion3D sensor causes the conductive ink pathways to elongate, increasing circuit resistance. This characteristic can be crucial for monitoring stretching or pulling, especially in wearable devices that need to adapt to user movements.

3.3.5. 3.3.5 Bending

When the sensor is bent, the conductive pathways on the convex side of the bend stretch, while those on the concave side compress. This dual action results in different conductivity changes, allowing the sensor to determine the direction and degree of bending.

4. Applications

In this section, we will discuss the applications of InkFusion3D in two practical scenarios: gaming and medical and explain its advantages.

4.1. Gaming

Applications in the gaming scenario can be broadly divided into three types.

4.1.1. Joycon Sensing

InkFusion3D integrated sensors into the controller design to enhance the player's control and responsiveness. The sensor's ability to detect twisting, pressing, and shearing can be mapped to various in-game actions. For instance, in racing games, a slight twist of the joystick can result in a gentle turn, while a more forceful twist might lead to a sharp curve. Similarly, pressing down on the joystick in action games can trigger special abilities or weapons. This enhanced sensitivity

offers players a more immersive and nuanced gaming experience.

4.1.2. Keystrokes

Installing InkFusion3D sensors under each key can enhance the performance of traditional gaming keyboards. The sensor's sensitivity to pressure can determine the force of a keypress, allowing different in-game actions based on the strength of the press. This introduces a new dimension to gaming, where player actions are directly proportional to keypress strength.

4.1.3. VR Wearable Devices

VR gloves or suits embedded with InkFusion3D sensors can provide tactile feedback and capture user movements in real-time. The sensor's ability to detect stretching and bending can be used to simulate player actions in the virtual world, from bending fingers to full-body gestures, enhancing the overall VR experience.

4.2. Medical

Applications in the medical scenario can also be divided into three types.

4.2.1. Human Body Model

InkFusion3D can be used to create realistic models of the human vascular and musculoskeletal system. The sensor's response to pressure and shearing can simulate the pulsation of vessels or the tension in muscles, providing hands-on tools for medical students and professionals to learn and practice.

4.2.2. Filler Materials

In cosmetic surgeries or beauty procedures, InkFusion3D sensors can be used as filler materials to monitor the pressure or tension in the implanted area. This provides real-time feedback to medical professionals about the success of the implant and any potential issues that might arise.

4.2.3. Wearable Devices

Medical wearable devices equipped with InkFusion3D can monitor a patient's vital signs or physical activity. For example, a wearable band on the chest can detect breathing patterns, while gloves can monitor the hand movements of patients undergoing physical therapy. The adaptability of the sensors ensures these devices remain comfortable during prolonged wear and provide accurate data for medical analysis.

5. Conclusions and Limitations

In this section, we will summarize the paper and discuss the limitations of InkFusion3D.

5.1. Conclusions

InkFusion3D, combining the adaptability of porous silicone rubber with the conductivity of conductive ink, represents an innovation in soft sensor materials. With sensing mechanisms ranging from twisting to shearing, it serves as a versatile tool with applications in both gaming and medical fields. In gaming, it promises to redefine user interactions, especially in joystick controls, offering a more nuanced and immersive experience. Meanwhile, in the medical sector, its potential to simulate human systems and integrate into wearable devices can revolutionize patient monitoring and medical training. With continued exploration and technological advancements, InkFusion3D may address challenges in the human-computer interaction domain with richer interactive methods.

5.2. Limitations

However, there are still some limitations associated with InkFusion3D:

Calibration Challenges: The sensor's sensitivity to various interactions means that it requires meticulous calibration to ensure accurate readings. This becomes especially challenging in dynamic environments where multiple interactions occur simultaneously.

Complex Production Process: The intricate design of InkFusion3D, involving 3D printing and precise ink injection, might make mass production more challenging and could potentially increase production costs.

Interference Issues: In environments with other electronic devices or strong electromagnetic fields, the sensor's readings might be interfered with, affecting its accuracy.

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