



Design and Fabrication of Flexible Circuits Connected by Plug-and-play Modules

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Abstract. Flexible electronics refers to the innovative field of technology that utilizes bendable materials for electronic circuits, enabling the development of lightweight, portable, and conformable devices that can integrate seamlessly into various applications, from wearable health monitors to advanced sensors, thus enhancing human-computer interaction. An important development in the field of flexible electronics is the design and construction of highly integrated flexible circuits with plug-and-play modules, allowing for easy replacement while maintaining the lightweight and conformable characteristics essential for applications in wearable technology and biomedical devices. Still, flexible plug-and-play modules in flexible circuits often face challenges such as limited electrical conductivity, difficulty in customized design and fabrication, and difficulties in achieving reliable connections that can withstand varying operating conditions. In this research, a double-layer flexible plug-and-play module, which is constructed with miniature magnets showing great conductivity and mechanical durability, is proposed. Meanwhile, the manufacturing process of flexible plug-and-play modules is improved, and the CAD-based model slicing process for customized conductive patterns is optimized to improve efficiency and accuracy during fabrication. Besides, the fabrication materials are modified and analyzed to enhance the adherence between the conductive ink and the substrate. In addition to this, the paper discusses the screen printing of double-layer flexible plug-and-play modules and the fast direct writing of customized, highly integrated flexible sensing circuits, which inform the realization of future mass production. The flexible capacitive strain gauges designed in this study have a stable capacitance value of $27.3 \pm 0.5 \text{ pF}$ after being connected through the plug-and-play modules, and the sensing values are not interrupted when the overall circuit is arranged to detect the human joints, proving the stability and reliability of the flexible plug-and-play modules. The proposed fabrication strategy and modular structure not only demonstrate exceptional electromechanical stability through real-time human body application test but also establish a possible circuit connection for wearable

electronics by successfully implementing double-layer plug-and-play modules in human motion sensing. This work fundamentally advances flexible circuit integration methodologies while providing an industrialized solution framework for next-generation intelligent health monitoring systems.

Keywords: Flexible Electronics, Flexible Circuits Integration, Plug-and-Play, Model Slicing Planning, Human Factors.

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1 INTRODUCTION

With the great demand in human sensing[1], medicine engineering[2] and soft robotics[3]Conventional rigid sensing circuits are no longer able to meet the demands of practical applications; thus, flexible sensing circuits are proposed to fill this application gap. Flexible circuit integration is an advanced technology that involves the development and design of individual flexible devices, the selection of high-precision printing equipment required, and the development of ink materials that are suitable for the printing equipment and the substrate to be carried[4]. In addition, to realise the rapid interconnection and replacement of different flexible circuit modules in real application scenarios, the design of flexible plug-and-play modules is particularly important. Prof. Zhenan Bao reported a new plug-and-play structure for stretchable device interconnections, which can be easily applied as interconnections between different flexible circuit modules for human organ monitoring[5]. The plug-and-play module allows for seamless interchangeability of components, enabling users to customize their devices based on specific needs. Additionally, the modular approach simplifies repairs and upgrades, extending the lifespan of electronic devices[6,7]. Despite the advantages described above, flexible plug-and-play modules in flexible circuits frequently encounter challenges, including restricted electrical conductivity, complexities associated with customized design and fabrication, and difficulties in establishing reliable connections that can endure diverse operating conditions. Besides, how to integrate the existing processing methods to complete the mass industrial production of customized highly integrated flexible circuits while maintaining the functions and quality still deserves attention and discussions[8].

In this study, a double-layer flexible plug-and-play module composed of miniature magnets that exhibit excellent electrical conductivity and mechanical durability is presented. Additionally, the manufacturing process of flexible plug-and-play modules is enhanced, and the CAD-based path planning to refine the model slicing procedure is carried out to facilitate the creation of customized conductive patterns, thereby improving fabrication efficiency and accuracy[9]. In addition to this, screen printing of double-layer flexible plug-and-play modules and fast direct writing of customized highly integrated flexible sensing circuits are discussed in this paper, providing a reference for achieving mass production in the future[10]. To assess the reliability of flexible circuits integrated with flexible plug-and-play modules in practical applications, our research affixed them to fabric utilizing miniature magnets for the purpose of human motion detection.

The research will be illustrated in the following sections. The design of flexible capacitive sensing circuits and flexible plug-and-play modules will be covered in Section 2.1, Customized highly integrated flexible sensing circuits design. The customized flexible pattern slicing methods will be shown in Section 2.2, Optimized CAD-based pattern slicing methods. Highly integrated flexible circuit processing is demonstrated in Section 2.3, Fabrication process and results. The materials used in the manufacture of flexible circuits will be discussed in Section 2.4, Material analysis. The feasibility of large-scale production will be discussed in Section 2.5, Scalability of the manufacturing process. The application of the designed circuits in human motion monitoring will be discussed in the Test and Application. Finally, the whole study and relevant future works will be illustrated in the conclusions.

2 METHODOLOGY

2.1 Customized Highly Integrated Flexible Sensing Circuits Design

In this study, flexible capacitive strain sensors are used as an example to optimize the design of flexible capacitive sensing modules[11]Multi-layer flexible plug-and-play modules are designed to realize the connection between flexible Arduino control boards and capacitive sensing modules. The detailed structure of the designed flexible capacitive sensor test circuits is shown in Fig. 1 (a) and (b) below. The whole module includes two parts: the capacitive sensor part and the capacitive sensor test circuit part. The test circuit contains a NE555 DR polytunnel oscillator timer, a 103pF filtering capacitor, two resistors with resistance of 680K ohm and 1M ohm, and a 0-ohm resistor as the circuit connection wire. To ensure ease of soldering and taping, the larger size 1206 model is chosen for all components. Based on the principle of circuit measurement, the final capacitance value can be calculated by the output oscillation frequency from the 555 polytunnel oscillator shown in Equation 1.

$$C = \frac{1}{f \times 0.7 \times (R_1 + 2 \times R_4)} \quad (1)$$

Considering fast interconnection between flexible circuit modules, this study proposes a magnetic multi-layer connection plug-and-play module. The detailed design structure is shown in Fig. 1 (c). The stretchable conductive silver paste is directly printed with a certain pattern on the polyimide substrate. The conductive magnets are attached to the electrode pins with conductive silver glue. The epoxy resin is used around the conductive magnets to fasten conductive magnets and substrates while maintaining electrical conductivity. Besides, there is a polydimethylsiloxane protection layer between the upper and bottom conductive layers. To meet the customization of flexible capacitive test circuits with complex patterns using customized conductive ink materials, this research modified the Creality Ender-3V2 3D printer into a pneumatic direct writing machine, as shown in Fig. 1 (d). 24-volt switching power supply, driving an air source treatment precision pressure regulator, is used to control the external input air pressure. Controlled airflow with constant air pressure regulated by a precision pressure regulator is led to the pneumatic extrusion nozzle through a 2-way pneumatic solenoid valve controlled by the G-code of the 3D printer consumables, extruders, and fans. Finally, the conductive silver paste in the syringe is extruded on the polyimide substrate through a 90-micron nozzle by controlled airflow with constant air pressure.

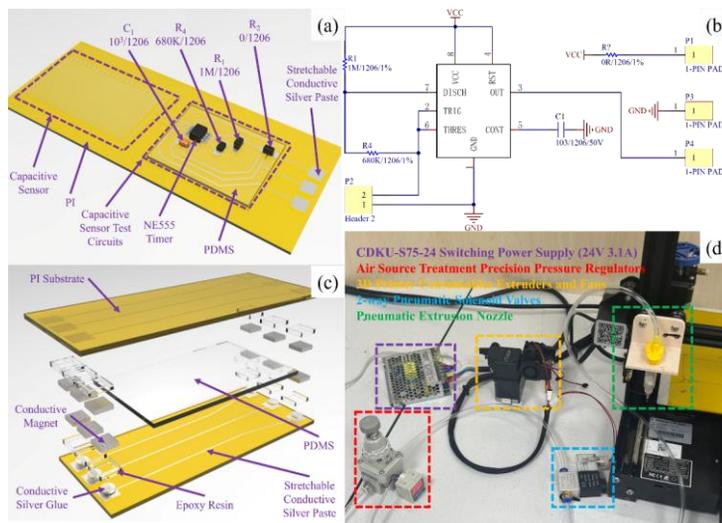


Figure 1: (a) Capacitive Sensing Module, (b) Capacitive Sensing Test Circuit Diagram, (c) Double Layer Plug-and-Play Module Structure, (d) Self-modified Pneumatic Direct Ink Writing Printer.

2.2 Optimized CAD-based Pattern Slicing Methods

As shown in Fig. 2, the exact controlling for pneumatic solenoid valves method is illustrated and divided into 5 steps. At the beginning, after finishing the former pattern printing, the solenoid valve is turned off to stop the extrusion of conductive silver paste by G-code "M107". Then, the nozzle will be raised to the same coordinate to avoid the nozzle collision during motor motion. After the nozzle is at a safe height, the XY motor is controlled to move to the next printing location, followed by lowering the nozzle to the printing height, which is around 500 microns above the substrate. This is the height at which the material can be continuously extruded under the control of fluid tension and viscosity while ensuring that the nozzle does not collide with the substrate. Finally, when the nozzle is at the next printing location with the correct printing height, the solenoid valve is turned on to start the extrusion of conductive silver paste by G-code "M106 S255".

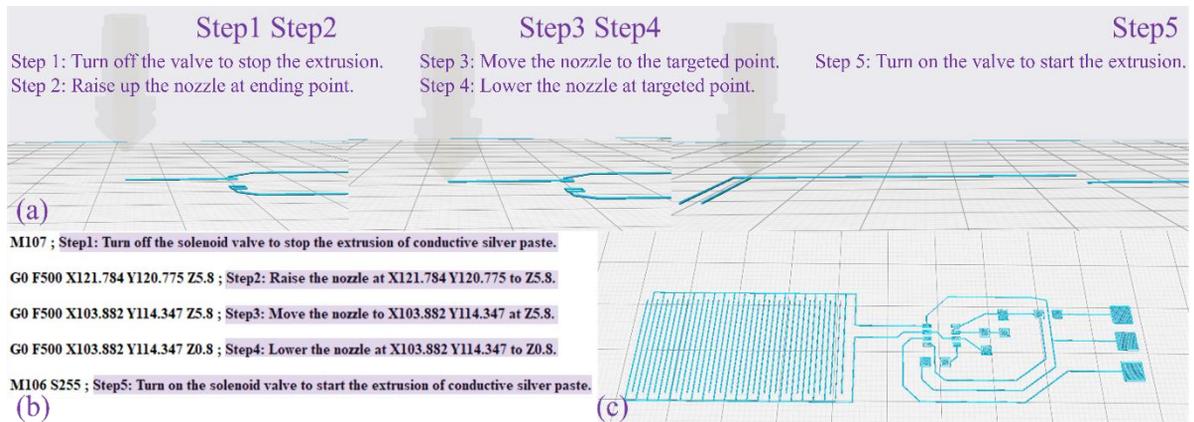


Figure 2: (a) 5 Steps for Pneumatic Solenoid Valves and Motors Controlling the Motion and Extrusion of Pneumatic Nozzle, (b) G-code for Pneumatic Solenoid Valves and Motor Motions, (c) Flexible Capacitive Sensing Circuits Slicing Simulation.

2.3 Fabrication Process and Results

The whole capacitive sensor test circuits module and pneumatic direct writing process are shown in Fig. 3 (a) and (c) below. The capacitive sensor test circuit is printed with the 90 microns pneumatic direct writing nozzle and sintered at 120 degrees Celsius for 40 minutes. After printing and sintering are complete, the electronic components needed for the measurement need to be integrated into the entire circuit. The electronic components are first secured to the circuit using a small amount of epoxy resin. Then, after the epoxy resin has cured and the electronic components have been stably bonded to the printed substrate at specific locations, conductive silver glue is applied to the pins of each electronic component so that the pins of the electronic components are tightly connected to the circuit electrode pins to ensure strong electrical conductivity of the overall circuit. This study does not use traditional circuit board soldering techniques because the solder wire used for soldering does not adhere well to silver, and high-temperature soldering can lead to burn-through of the polyimide substrate, affecting subsequent conductivity. The polydimethylsiloxane protection layer is also attached to the final printed circuits to ensure the connection during the bending test. With the same manufacturing method, the stretchable conductive silver paste is directly printed with a certain pattern on the polyimide substrate. The conductive magnets are attached to the electrode pins with conductive silver glue. The epoxy resin is used around the conductive magnets to fasten conductive magnets and substrates while maintaining electrical conductivity. Besides, there is a polydimethylsiloxane protection layer between the upper and bottom conductive layers. The final plug-and-play modules structure is shown in Fig. 3 (b) and (d) below.

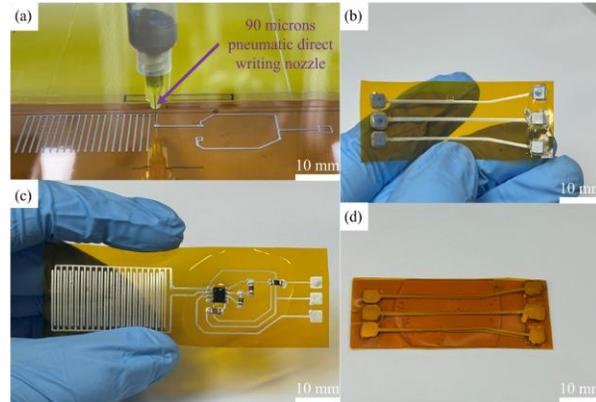


Figure 3: (a) Pneumatic Direct Writing Process, (b) Single Layer Plug-and-Play Modules, (c) Final Capacitive Sensing Module. (b) Single Layer Plug-and-Play Modules, (d) Double-layer Connection Plug-and-Play Module.

2.4 Material Analysis

To ensure the high flexibility of the capacitive sensor test circuits and the fine conductivity of the printed pattern, the conductive silver paste is used as the direct writing ink material with 10% dibasic ester (DBE) solvent, which is used to reduce the viscosity of the ink to facilitate the smooth extrusion of ink at lower air pressure to avoid clogging of the printheads. As shown in Fig. 4, the diameter and thickness of the single silver flake are measured to ensure smoothness in the printing process while maintaining the conductivity.

The conductive silver paste used here is a bright silver colored paste with $62 \pm 5\%$ silver flakes content. The diameter of the single silver flake is around 1 to 10 microns, with a thickness of around 150 nanometers. To ensure the high conductivity and high adherence to the PI substrate, the printed silver paste is sintered at 120 degrees Celsius for 40 minutes. The following Fig. 4 shows the Scanning Electron Microscope of the printed silver paste electrodes. By using the environmental scanning electron microscope, the percentage of individual elements in conductive silver paste is well indicated in Fig. 5. From the analysis, the silver content of the conductive silver paste is up to 89.9%, which guarantees high conductivity of the printed pattern.

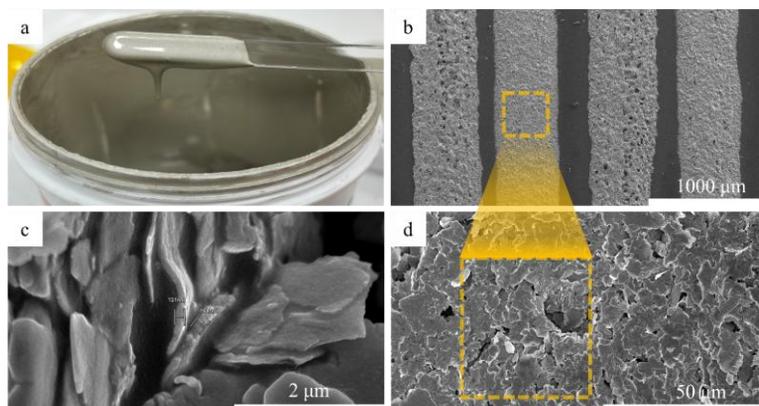


Figure 4: (a) Conductive silver pastes with 10% dibasic ester (DBE) solvent. (b) SEM for silver paste electrodes. (c) SEM for the thickness of the single silver flake in the silver paste. (d) SEM for silver flakes in the stacked state in silver paste electrodes.

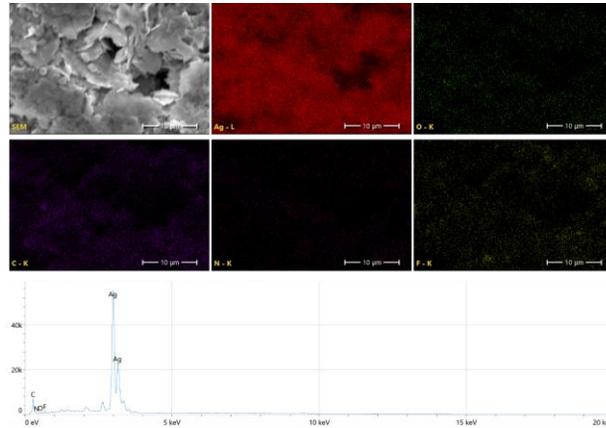


Figure 5: Environmental scanning electron microscope shows the percentage of individual elements in conductive silver paste.

2.5 Scalability of the Manufacturing Process

For the large-scale processing of customized, highly integrated, flexible circuits, this paper makes theoretical assumptions and demonstrations. Screen printing can realize the circuit processing of large size and simple contour structure, to improve the processing productivity. To ensure the customization and precision of the print pattern, direct printing and aerosol inkjet printing are used here. By leveraging the high-throughput characteristics of large-area screen printing for batch fabrication of foundational conductive/dielectric layers, while simultaneously employing aerosol jet direct-writing technology for integration and topology-optimized layout of functional units, this approach achieves dynamic adaptation between standardized interface modules and personalized sensing networks. The former ensures production stability under economies of scale, while the latter enables real-time reconfiguration of three-dimensional interconnect architectures through digital modeling systems. This methodology demonstrates unique advantages in reconciling mass-production scalability with customization requirements, particularly suitable for wearable electronics and smart epidermal applications requiring both structural conformability and functional programmability.

3 TEST AND APPLICATION

In this section, the designed flexible plug-and-play module is tested for its practicality. The flexible plug-and-play module is connected to a flexible Arduino board and a flexible capacitive sensing module, as shown in Fig. 6. The initial capacitance of the capacitance sensor is 27pF, as shown by the serial monitor, and no breakage is seen during the testing process, which indicates that the designed flexible plug-and-play module is highly practical.

For the designed capacitive sensor circuit module, this study tests the overall circuit response speed during bending and touching. Shown in Fig. 7, in the bending test, the tester, wearing insulated gloves on his hands, performs a 180-degree bending operation on the capacitive sensor. It is evident in the serial monitor that the capacitance value increases from 26pF to 40pF. After that, the tester touched the capacitance sensor with a bare finger and clearly observed that the capacitance value increased from 26pF to 145pF. When the capacitive sensor is touched by the tester wearing insulated gloves, the sensor value increases from the initial 26pF to 63pF.

The whole designed capacitive sensor test circuits with plug-and-play modules and a flexible Arduino Nano board are applied on the clothes with conductive magnets shown in Fig. 8. The flexible Arduino Nano board is connected with a capacitive sensing module with a plug-and-play module. Conductive magnets are used for connections between testing circuits and clothes. The elbow

bending process is shown in Fig. 8 (b) to illustrate the stability and practicality of the conductive magnets' connection.

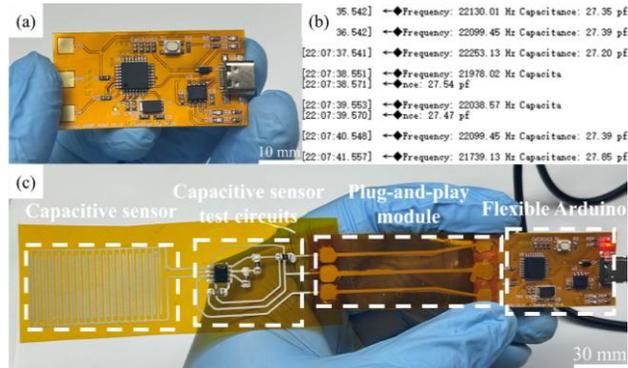


Figure 6: (a) Flexible Arduino Nano Board. (b) Serial Monitor Measurement Showing Real-time Capacitance Values. (c) Capacitive Sensor Test Modules Plug-and-Play with Flexible Arduino Nano Board.

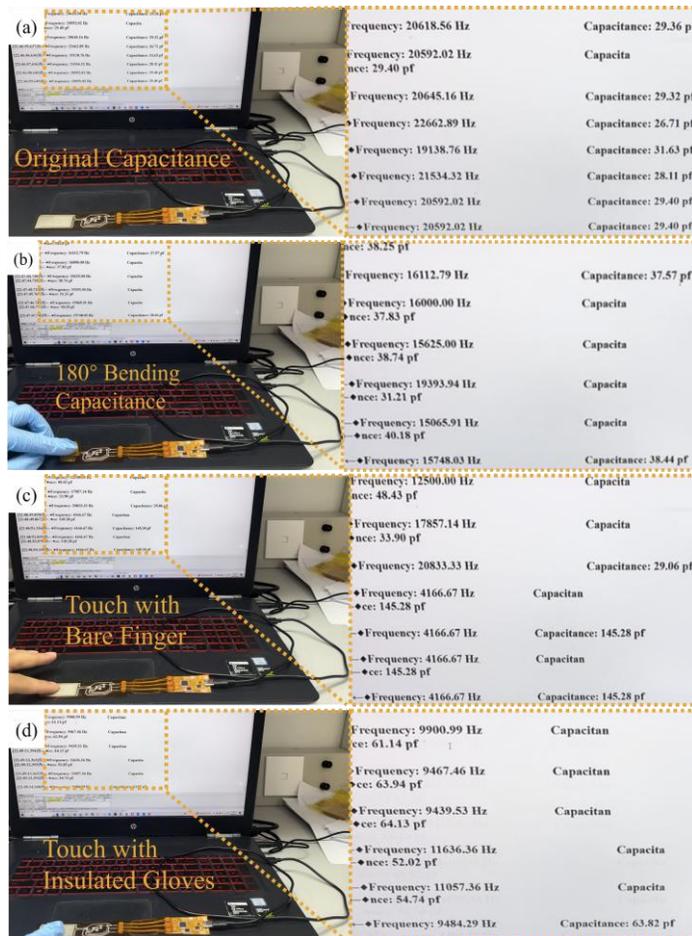


Figure 7: (a) Original capacitance of the capacitive sensor. (b) 180-degree bending capacitance of the capacitive sensor. (c) Touch with a bare finger the capacitance of the capacitive sensor. (d) Touch with insulated gloves, the capacitance of the capacitive sensor.

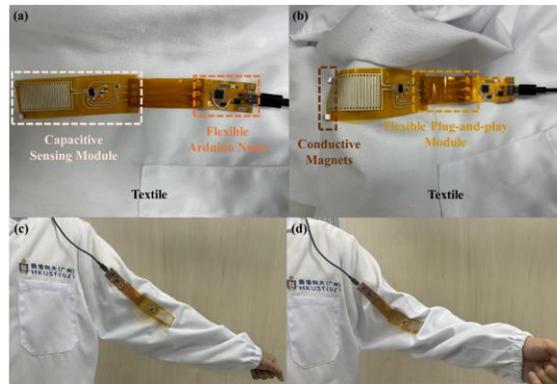


Figure 8: (a) Capacitive sensor test circuits with plug-and-play module and flexible Arduino Nano board connected to the textile with conductive magnets. (b) The elbow bending process is performed while capacitive sensor test circuits with a plug-and-play module and a flexible Arduino Nano board are connected to the cloth with conductive magnets. (c) Whole circuits are applied to the sleeve to test the elbow bending. (d) Capacitive sensor bending with elbow bending.

4 CONCLUSIONS

In this study, the printing of highly customized flexible circuit patterns is achieved by building a pneumatic direct-write printer with targeted adjustment of model slicing paths. This provides a new solution idea for the design and processing of more flexible test circuits afterwards. The screen printing of double-layer flexible plug-and-play modules and fast direct writing of customized highly integrated flexible sensing circuits are discussed in this paper, providing a reference for achieving mass production in the future. The materials used for flexible circuits fabrication are mentioned in this study, and the scanning electron microscope is applied to refine the observation of particle diameters. Meanwhile, the fabricated structure is tested, which illustrates good flexibility and high sensitivity while maintaining electrical conductivity. Finally, the highly integrated flexible circuits realized by flexible plug-and-play modules are applied to the human body and fabrics to show the real-life application, which demonstrates a broader prospect in the field of human health testing and soft robotics applications.

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