Title:
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 conductive ink and substrate. 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 also discussed in this paper, which informs the realization of mass production in the future. The flexible capacitive strain gauges designed in this study have a stable capacitance value of 27.3 ± 0.5pF 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.

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

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Introduction:

With the great demand for human sensing[1], medical engineering [2] and soft robotics [3]. Conventional rigid sensing circuits can no longer 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 used [4]. In addition to realizing 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 circuits 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.

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 [8] is carried out to facilitate the creation of customized conductive patterns, thereby improving fabrication efficiency and accuracy. 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 circuit and flexible plug-and-play modules will be covered in methodology. The customized flexible pattern slicing methods will be shown in methodology and the application of the designed circuits in human motion monitoring will be discussed in conclusion.

Methodology:

In this study, flexible capacitive strain sensors are used as an example to optimise the design of flexible capacitive sensing modules, and multi-layer flexible plug-and-play modules are designed to realise 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 10^3pF 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.

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

Considering fast interconnection between flexible circuit modules, this study proposes a magnetic multi-layer plug-and-play connection 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 the 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 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 precision pressure regulator is led to the pneumatic extrusion nozzle through 2-way pneumatic solenoid valve controlled by 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.

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 at 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 following by lowing the nozzle to the printing height, which is around 500 microns to 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 correct printing height, the solenoid valve is turned on to start the extrusion of conductive silver paste by G-code “M106 S255”.

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 under 120 degrees Celsius for 40 minutes. After printing and sintering is 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 electrodes 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 on the final printed circuits to ensure the connection during 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 layer. The final plug-and-play modules structure is shown in Fig .3 (b) and (d) below.

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.

Conclusions:

In this study, 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. 4. 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.

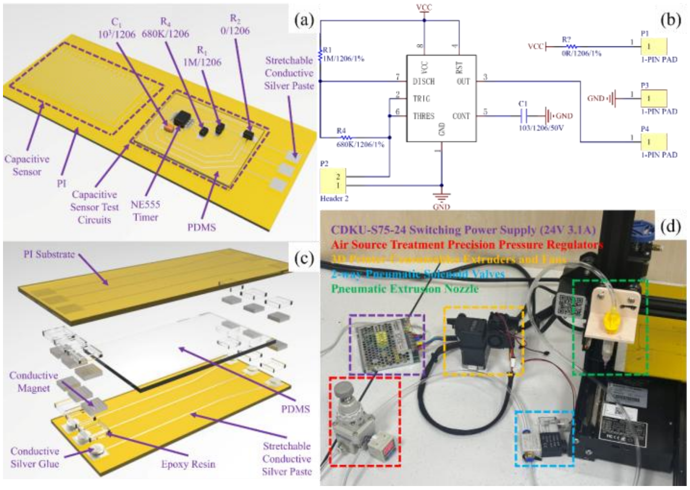

Fig. 1: (a) Capacitive Sensing Module, (b) Capacitive Sensing Test Circuit Diagram, (c) Double Layer Plug-and-Play Module Structure, (d) Self-modified Pneumatic Direct Ink Writing Printer.

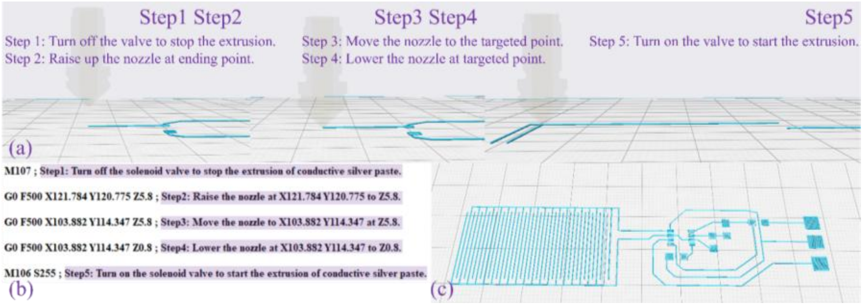

Fig. 2: (a) 5 Steps for Pneumatic Solenoid Valves and Motors Controlling the Motion and Extrusion of Pneumatic Nozzle, (b) G-code for Pneumatic Solenoid Valves and Motor Motions, (c) Flexible Capacitive Sensing Circuits Slicing Simulation.

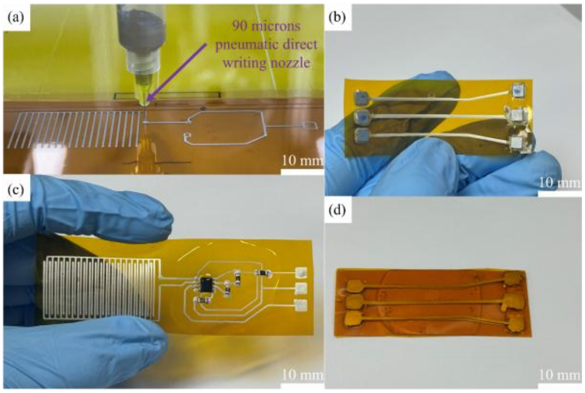

Fig. 3: (a) Pneumatic Direct Writing Process, (b) Single Layer Plug-and-Play Modules, (c) Final Capacitive Sensing Module. (b) Single Layer Plug-and-Play Modules, (d) Double-layer Connection Plug-and-Play Module.

Besides, in this study, highly customized flexible circuit patterns are printed by building a pneumatic direct-write printer with targeted adjustment of model slicing paths. This provides a new solution 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. Meanwhile, the highly integrated flexible circuits realized by flexible plug-and-play modules will have a broader prospect in the field of human health testing and soft robotics applications.

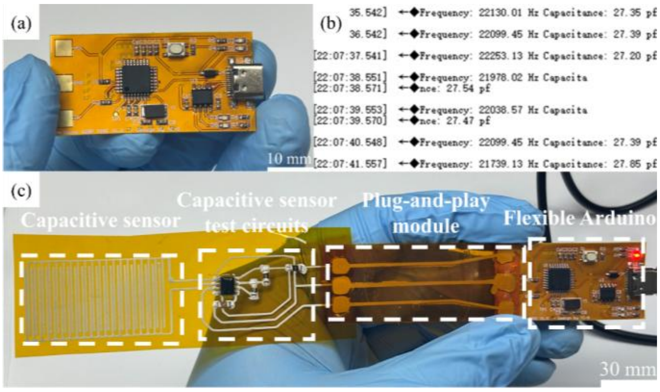

Fig. 4: (a) Flexible Arduino Nano Board. (b) Serial Monitor Measurement Showing Real-time Capacitance Values. (c) Capacitive Sensor Test Modules Plug-ang-Play with Flexible Arduino Nano Board.

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