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Multi-Nozzle Pneumatic Extrusion-Based Additive Manufacturing System for Printing Sensing Pads

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Abstract: This paper developed a multi-nozzle pneumatic extrusion-based additive manufacturing (AM) system and applied it to print multi-material polymers and conductive sensing pads. We used pneumatic extrusion nozzles to extrude the liquid material and then cured it by an ultraviolet (UV) light source. The multi-nozzle pneumatic extrusion-based additive manufacturing system mainly integrates both PC-based HMI and CNC controller to operate the three-axis motion and the extrusion flow control. Moreover, the peripheral I/Os include both positive and negative pressure and also the curing light source. A D/A controller is also applied to control the value of the pneumatic pressure. The coding part utilizes the numerical control software along with the PLC planning to operate the AM machine automatically. Our experiment is conducted by using Simplify3D, a commercial 3D printing slicing software. Different requirements were set for extrusion nozzles with different materials, and then we executed the path controlling G-code data by Python Language. Our system successfully prints multi-material polymer structure pads which include the hard and soft material pad fabricated in double-layers, triple-layers and also the grid structure. Finally, we find that the printed pad has conductivity.

Keywords: additive manufacturing; Pneumatic extrusion system; Smart sensing; graphene; Vat Polymerization

1. Introduction

Rapid prototyping (RP), currently known as three-dimensional printing (3-D printing) or additive manufacturing (AM) was proposed in the 1980s. According to ISO/ASTM 52900:2015, it defines the terms used in AM technology, that applies the additive shaping principle and then builds the physical 3D geometries by successive addition of material. By using a slicing software, a 3D model is converted into a series of image files which present a digitalized layer information. After that, each layer can be repeatedly piled up until the product is accomplished by utilizing an AM system. In comparison with conventional subtractive manufacturing, AM also brings a lot of advantages such as customized, rapid, novelty and zero inventory besides lowering the waste of materials and processing constraints [1]. There are many reports about the smart robot market and gripper sensors, which show the tremendous commercial benefit and prospect [2–5]. A newly established company, ICobots, currently provides different sizes and quantities of flexible grasping mechanisms to solve a large number of requirements of the US food and merchandise pick-and-place applications [6]. A Swiss company, F&P Personal Robotics, encloses the traditional mechanical arms with flexible materials and detects whether arms touch an external object by a strength sensor.

On the other hand, the robot market also promotes collaborative robots which can sense contact with humans. So far, additive manufacturing is the only technology that can combine multiple complex structure, mechanical properties and functionalities of materials together. Suppose a mechanical object with sensing or electronic performance can be printed out by AM technology, this may bring a big advance not only in the smart gripper part but also in intelligent robots. Utilizing sensors made of flexible materials and embedding a lot of sensors into robot's skin may make the electronic skin gain more sensitivity [7]. Many research works about manufacturing sensing pads have been launched through 3D printing PDMS (Poly-dimethylsiloxane) molds and this has to go through post-processing [8]. In this paper, sensing pads can be printed out directly without a PDMS mold and thus this can also reduce post-processing. A pneumatic extrusion-based additive manufacturing system with a multi-nozzle is introduced in this paper. It is applied to print a sensing pad with soft and hard material structure. It can potentially satisfy the concept of the flexible finger for robotic applications in the future [9–17].

2. Theoretical Analysis and System Construction

2.1. Theoretical Analysis

To construct a pneumatic extrusion-based additive manufacturing system, a pneumatic dispensing controller is used in this paper. The pneumatic extrusion nozzles are operated by a three-axis gantry mechanism. The material drop per unit time can be controlled by a proper given command from the controller during the printing process. Because the motion of pneumatic dispensing controller depends on the mechanical platform constructed, if we want to assure whether our given extrusion pressure can maintain a stable flow or not, we should check Poiseuille's Law and obtain a constant pressure during the dispensing process. Poiseuille's Law in fluid mechanics is shown below in Figure 1. According to Poiseuille's Law (1), the relationship between the given pressure ΔP and outlet flow rate v can be calculated as the following:

$$\Delta P = \frac{8\mu v l}{r^2} \tag{1}$$

where

ΔP = pressure drop (kPa)
μ = viscosity coefficient (N.s/m^2)
v = outlet flow rate (m / s)
l = length of pipe diameter (m)
r = diameter of the pipe (m)

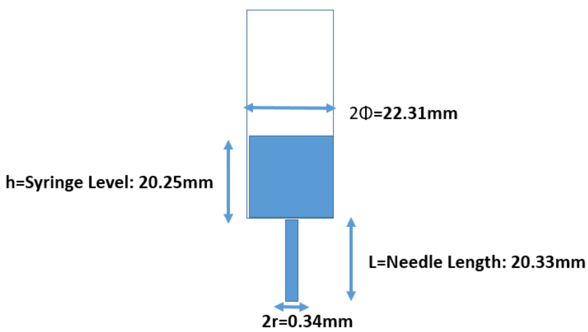

Figure 1. Needle extrusion structure.

2.2. System Construction

To design a system for multi-material printing such as embedded graphene wire, multi-material polymers and so on, we develop a multi-nozzle pneumatic extrusion additive manufacturing system with four nozzles for printing different materials.

2.2.1. System Configuration

The system configuration is mainly based on a SynTec controller (HC-8C) which provides complete G/M codes so that we can customize control program by ourselves. A manual controller is also equipped through a RS232 interface. To control the axis motors, the controller will connect to the motor driver and send the applied pulses. On the other hand, the register R is utilized to control the switches in peripheral IO. A DA controller is also added to control the electronically proportional valves for regulating the pressure. The system configuration is shown below in Figures 2 and 3.

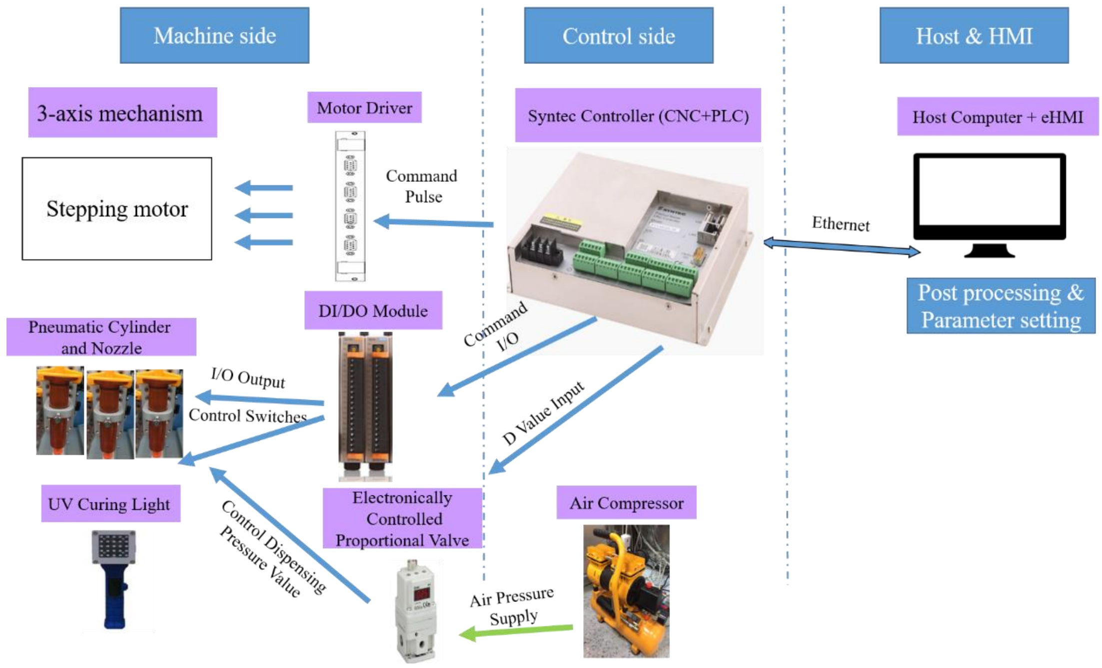

Figure 2. System configuration.

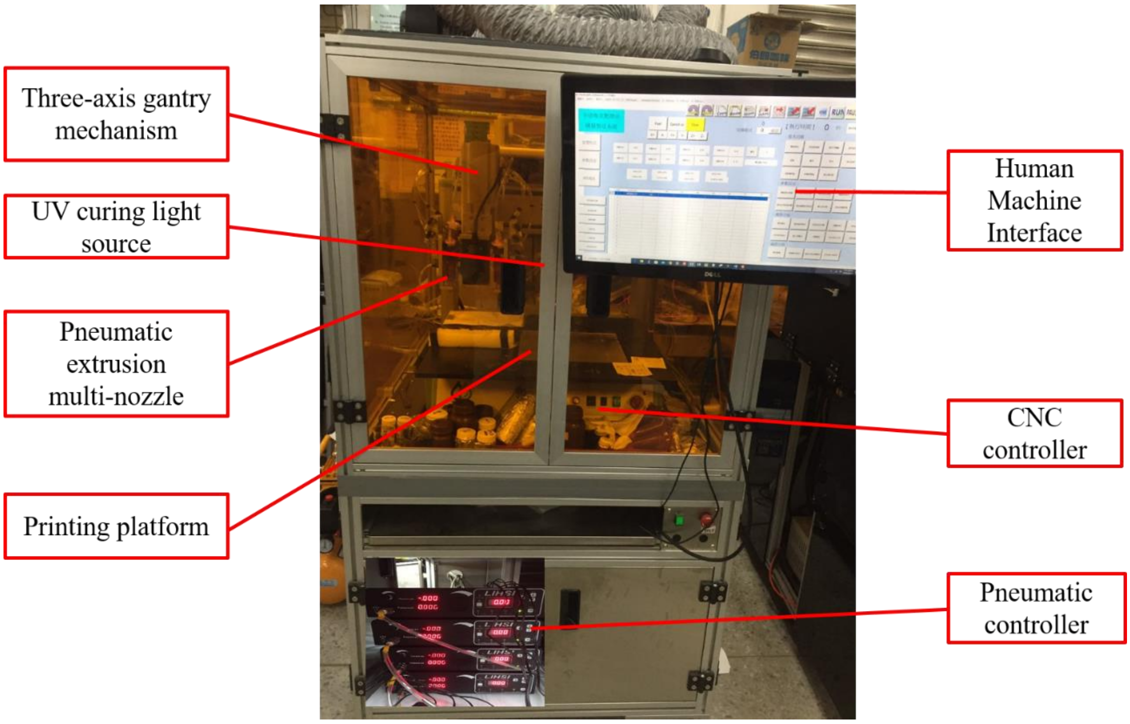

Figure 3. A photo of the hardware system architecture.

2.2.2. System Software Development

The multi-nozzle pneumatic extrusion based additive manufacturing system is developed on a PC Windows system. We integrate a PLC with a CNC simulator, making it control the system properly. A CNC simulator is mainly for setting the coordinate of multinozzle and parameters of step motors, while eHMI is for customizing the interface which can meet different requirements. Also, a PLC is required for the operation of the I/Os or the transmission of data.

2.2.3. Multi-Nozzle Operating Coordinates Setting: G54–G59

The commands G54~G59 can be applied to select up to six different working coordinate systems for different nozzles in a CNC controller. The offset of six different coordinates is shown below in Figure 4. Thus, if we need different nozzles working at the same time, we can simply apply the commands to control different nozzle position.

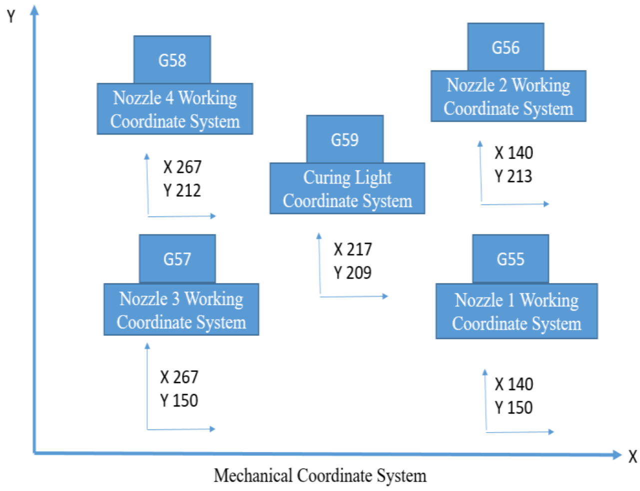

Figure 4. Multi-nozzle operating coordinate setting.

2.2.4. e-HMI System Design

In the HMI part of multi-nozzle pneumatic extrusion based additive manufacturing system, the design includes manual tunable pressure valve and manual I/Os switches that are handy for users. Moreover, in the automatic part, the system will load the files according to the setting which G-Code file name has already been loaded into the Line Command to do certain work as in Figure 5.

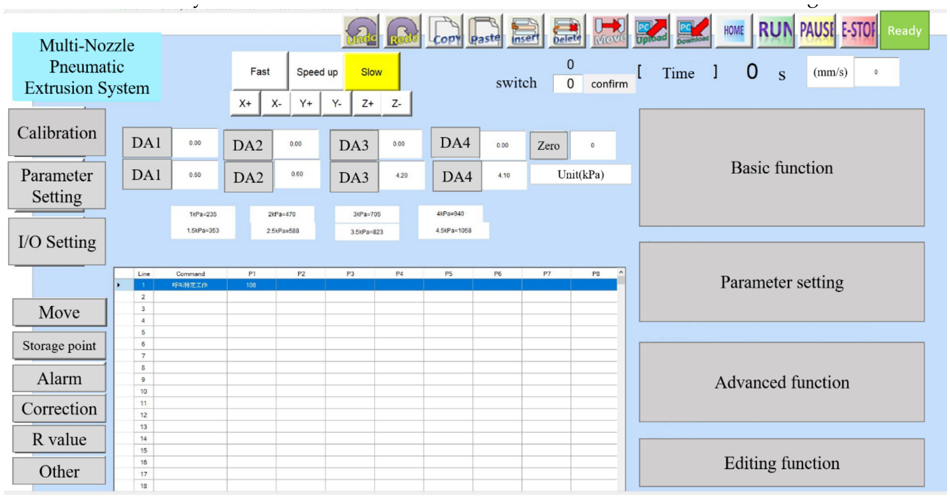

Figure 5. e-HMI system design.

2.2.5. The Combination of Slicing Software and G-Code Post-Processing

The Simplify 3D is a commercial slicing software that can support almost all 3D printers on the market. There are a lot of slicing parameters that can be adjusted such as layer height, wire width and so on. The user interface is convenient and easy to operate. We can design printing parameters for different extrusion heads. The slicing process flowchart is shown in Figure 6. After the wire diameter and the inner filling parameters are set, the software will output its G-code file that can be operated by most of the FDM machines [18,19].

Figure 6. Slicing flowchart by Simplify 3D.

In this paper, those G-code files cannot be directly operated by the system. So we need to do some post-processing to convert them into an available file. The Python Pandas was invented to solve data analysis tasks. The Pandas includes a large amount of built-in libraries and some standard data models which provide us with the solutions to process data much more quickly. Figure 7 below shows the process flowchart. First of all, we load into the Pandas data structure object, and the pre-processing of the data such as data supplementation, null removal or replacement can be performed quickly by the structural material. It can read the excel file by using the read_excel function. After that, the excel file becomes the DataFrame object of pandas. DataFrame is a two-dimensional structure with lists and line labels [18].

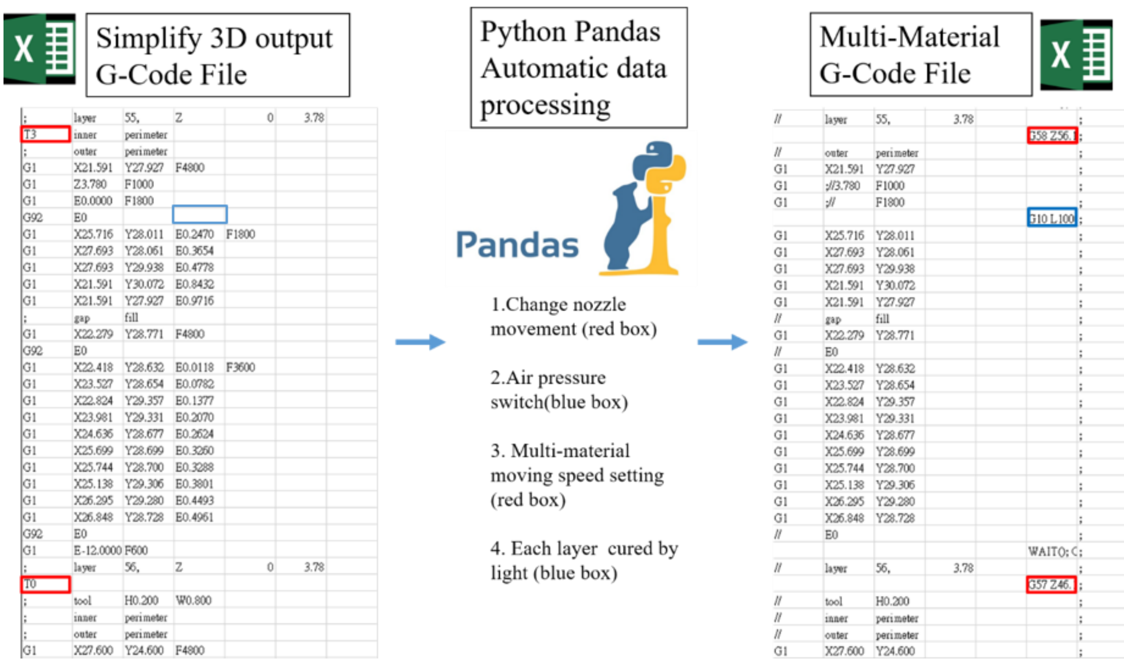

Figure 7. Post-processing flowchart by Python Pandas.

3. Results and Discussion

3.1. Multi-Material Printing Pad Experimental Results

To verify the flexible gripper, we print double layers multi-materials pads and triple layers multi-materials pads as initial models. We use hard material (HAA) and soft material (CT4) made by our research group. HAA is a new type photocuring hard resin of high hardness, which its mechanical strength is high enough to simulate human finger bones. And soft material CT4 is a new type of photocuring TPU(Thermoplastic polyurethanes) resin of high flexibility, which can simulate how muscles protect finger bones. The information of material and printing parameters are as Tables 1 and 2, and the results are as shown in Figures 8 and 9.

Table 1. Hard material (HAA) and Soft material (CT4) Material parameters [20].

Property	Hard Material (HAA)	Soft Material (CT4)
Young's modulus (MPa)	600	2.7
Elongation (%)	2.8	104
Tensile strength (MPa)	15.75	3.73
Viscosity (CP) (T = 25 °C)	338	1666
Shrinkage (%)	3.5	1.7
Density (g/cm3)	1.209	1.18

Table 2. Printing parameters of multi-materials pads.

Parameter	Hard Material (HAA)	Soft Material (CT4)
Extrusion pressure	300 kPa	400 kPa
Needle diameter	23G (inner 0.33 mm)	22G (inner 0.41 mm)
Printing velocity	80 mm/s	116.6 mm/s
Extrusion diameter	0.65 mm	0.4 mm

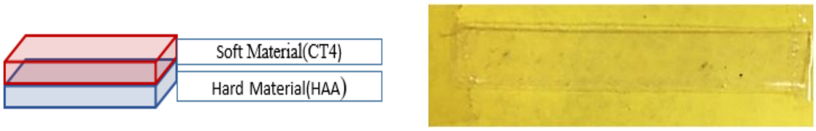

Figure 8. Double-layers multi-materials pads.

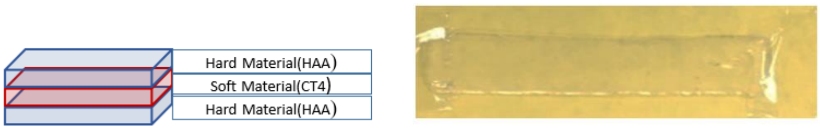

Figure 9. Triple-layers multi-materials pads.

To prove the advantage of additive manufacturing, we can find that the accuracy is high when printing both HAA and CT4 on the same layer. The wire diameters of both can be 0.4 mm, as shown in Figure 10.

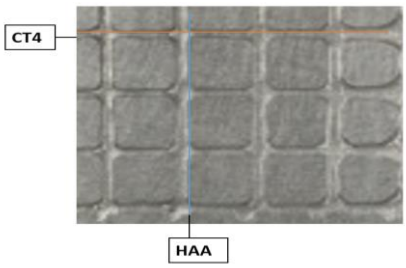

Figure 10. The mesh photo of HAA and CT4.

Another merit of additive manufacturing is that it can print out 3D mold rapidly which dispenses with complicated traditional cutting steps. Thus, Figure 11 shows a simple mold.

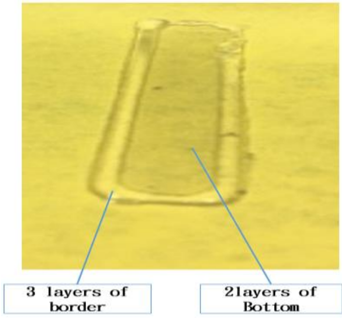

Figure 11. Rapid printing of 3D mold.

3.2. Piezoelectric Sensing Pads

To make two PVDF(Polyvinylidene difluoride)/graphene (NMP(Methylpyrrolidone) mix with CT4 and to cure the NMP with a UV light source as we expected, the proportion of the photocuring agent we blend into is optimal in the ratio of (PVDF/graphene/photocuring agent) (5:5:1).

After the double-layer structure pad is produced, in the future application, the design of the soft material's bottom layer is mainly for the purpose of causing the cross-linking reaction between the heat generated by the light source and make the soft material accelerate the curing of the sensing layer. In order to protect the PVDF/graphene (NMP) physical properties of the fragile part, we design a square soft material protection, and make a three-layer structure pad of complete sandwich interlayer with the positive and negative plates, as shown in Figure 12, with the printing parameters shown in Table 3.

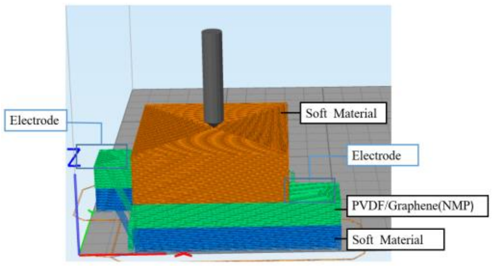

Figure 12. Piezoelectric sensing pad schematic.

Table 3. Parameters of piezoelectric sensing pad.

Parameter	Soft Material (CT4)	PVDF/Graphene (NMP)
Lower layers	4 layers	1 layer photocuring time: 10 min (60 °C) 3min (60 °C), attain half curing status
Upper layers	1 layer	
Pressure	400 kPa	300 kPa
Needle size	22G (inner diameter 0.41 mm)	22G (inner diameter 0.41 mm)
Printing speed	116.6 mm/s	28.3 mm/s
Wire diameter	0.4 mm	0.3 mm
Thickness	0.4 mm	0.3 mm
Whole size: 30 × 30 × 1.5 mm		

Originally, it was hoped that the PVDF (NMP)/graphene was cured by mixing with a photocuring agent, and the curing effect was poor. Therefore, we capitalized on the volatilization characteristics which experience high heat generated by the UV light source for PVDF (NMP)/graphene as shown in Figure 13. This process must use a small piece of aluminum to illuminate it, making it slower to dissipate heat. Because the thickness of the upper layer cannot be ensured in the process, printing PVDF/graphene (NMP) will increase the original thickness by 0.14 mm, and at the same time increase the pressure and reduce the printing speed.

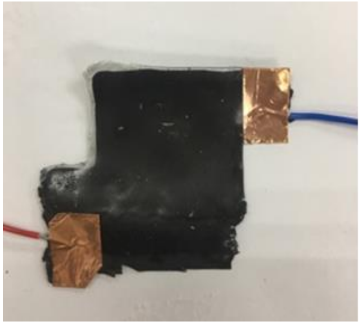

Figure 13. Printing result of a piezoelectric sensing pad.

The proposed system can print a structure with multi-material polymers and graphene-based sensing material which can be cured with a UV light source. A multi-nozzle head module is mounted a 3-axis NC servo controlled platform. For a material with different viscosity, the extrusion outlet flow rate is dependent on the used nozzle parameter and applied pneumatic pressure. However, for a fixed outlet flow rate, the layer thickness and width of the printed wire will be affected by the printed speed, since the shape of the printed material depends on the material properties such as viscosity, surface tension and curing speed. Therefore, for a given material and proper needle head, a desired width of the printed wire can be obtained by choosing proper control parameters such as pneumatic pressure and printed speed which can be controlled by the system. From the experimental result, a printing wire with a diameter of 0.28 mm can be achieved [20]. Hence, this system is used to print rectangular pads with soft and hard materials including two-layer and three-layer structures with PVDF/graphene-based sensing material. A more complicated structure can be printed by involving a support material.

4. Conclusions

This research develops a multi-nozzle pneumatic extrusion-based additive manufacturing system, completes the overall system design, and designs a suitable process to print a rectangular pad of soft and hard materials. The detailed results are as follows.

(1) We develop a multi-nozzle pneumatic extrusion-based additive manufacturing system which can select different inner diameters of needle and positive or negative pressure according to different material characteristics and viscosity, and also we integrate a numerical controller and design man-machine interface with PLC to undertake I/O logical control and control the moving speed of three-axis motor.

(2) The software part is combined with the commercial 3D printing slicing software Simplify 3D, and then through the Python Pandas data analysis library for rapid post-processing of a large amount of data, and then accelerate the operation the multi-threading module parallelization program, in line with the study of the multi-nozzle pneumatic extrusion-based additive manufacturing system.

(3) The multi-nozzle pneumatic pressure extrusion additive manufacturing system prints rectangular pads with soft and hard materials including two-layer and three-layer structures and rapid printing molds. In addition, printing soft and hard material of mesh and beehive structures can achieve a minimum printing wire diameter of 0.28 mm.

(4) We design a piezoelectric sensing pad including a bottom soft resin material which uses a PVDF/graphene/light curing agent (5:5:1) and an upper protective soft material, and produce a three-layer structure sensing pad with piezoelectric characteristics.

(5) The novelty of this study is that a piezoelectric sensing pad can be printed out directly through the pneumatic extrusion-based system instead of printing a PDMS mold, thus it reduces a lot of post-processing. The system can also print soft and hard materials together through Python Pandas post-processing.

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Conflicts of Interest: The authors declare no conflict of interest.

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