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Development of a multi-nozzle drop-on-demand system for multi-material dispensing

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ABSTRACT

Besides its application in media printing, drop-on-demand (DoD) printing is becoming an attractive alternative to traditional micro-fabrication to build 3D structures with wide applications. In DoD printing, each type of nozzle (ejector) has its uniqueness and limitation in the dispensing material properties, driving parameters, and the ejected droplet dimension. This paper presents a multi-nozzle DoD printing machine to satisfy the increasing demand for multi-material dispensing in industry. On the hardware aspect, a microcontroller-based synchronizer is designed to synchronize the printing process from multi-nozzles with respect to a movable positioning stage. This real-time control contributes to accurate micro-droplet deposition. On the software aspect, a three-layer framework is proposed, including user interface, system manager, and hardware interface layer. This proposed structure greatly improves the system flexibility with which the user can dynamically configure the desired dispensers for 3D structure printing. Integrating these techniques into the printing system, the developed DoD system can achieve a flexible and friendly user interface, while dispensing a wide range of functional materials using various types of dispensing nozzles.

1. Introduction

The advancement of micro-dispensing technologies has been driven by the need for manufacturing process for miniaturization, dynamic design change, time and cost reduction, and environmental friendliness. It is promising to adopt drop-on-demand (DoD) micro-dispensing of functional materials to accrete solid 3D structures in various fields of applications, including electronics (Ko et al., 2007), optics and sensors (Wallace et al., 2002), biotechnology (Khalil et al., 2005), light-emitting devices (Chang et al., 1998), ceramics and so on.

In rapid prototyping field, a DoD machine is to dispense microdrops at desired positions layer-by-layer to form the 3D structure models. DoD printing technology can provide much benefit in functional application compared to traditional subtractive processes and other RP methods. For example, its additive nature with capability to dispense minute material to pico-liters provides a great potential in lower material wastage of expensive materials and more environmental friendliness. The data-driven nature offers high flexibility to cater for changing design with minimum or no tooling change in fabrication. It is also a non-contact fabrication process that eliminates cross-contamination and avoids mechanical wear on the print-head.

In the literature, there are extensive studies to investigate the actuating mechanism to dispense mcirodrops for DoD machines, e.g., piezoelectric (Sweet, 1965) bubble (Nielsen, 1985), micro-valve (Khalil et al., 2005), flextensional aperture (Percin and Khuri-Yakub, 2003), and others. Each mechanism is unique in its operating principle, and has its advantages and limitations in applicable materials, droplet size, driving parameters, and so on. To extend the potential of DoD printing technology, it is better to have a system to dispense multiple materials with multiple actuating modes of nozzles. MicroFab Technologies Inc. (2008) provides a four-channel piezoelectric nozzle set with a controller Jetdrive III. Ibrahim et al. (2006) modified a commercial inkjet printer to fabricate 3D multi-material patterns layer-by-layer. Both systems can dispense multiple materials, while are limited to use one type of actuating mode. Khalil et al. (2005) proposed a multi-nozzle deposition system to build porous tissue engineering scaffolds. Their system is capable of simultaneously depositing amounts of cells, growth factors or other bioactive compounds to form complex constructs by using multiple nozzles with different actuation modes. However, it is designed for the fabrication of 3D tissue scaffolds with four different nozzles. No explicit details are provided on how to develop the multi-nozzle DoD system and extend it to other application field with dynamic configuration of applied dispensers. Dynamic configuration is very important in actual application, and especially so in experimental study which requires a DoD system with enough flexibility to

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try different dispensing and actuating modes for optimal process search.

This paper presents the early development stage of a multi-nozzle DoD printing system for multi-material dispensing with dynamic configuration. The system consists of two major distinctive characteristics. Firstly, it is to dispense multiple materials with various actuating modes of micro-dispensing nozzles. This can extend the applicable functional material range and improve the practicability of the proposed DoD printing system. Secondly, it allows the user to dynamically configure the used nozzles with a friendly interface. This dynamic configuration is achieved by the special design of the hardware and software in the printing system. On the hardware aspect, a synchronizer is designed to produce the real-time multiple TTL actuating signals for nozzle dispensing control. On the software aspect, a three-layer framework is designed to isolate the influence of hardware modification to the user interface, and enables dynamic configuration. Section 2 will discuss the design detail, including the framework of the DoD printing system, the hardware design for multiple material dispensing and the software design with dynamic configuration of applied hardware. Finally, discussion and conclusion are given in Section 3.

2. Multi-nozzle printing system

Fig. 1 illustrates the framework of the multi-nozzle DoD system with regard to the development procedure. The system input is the 3D model data with standard formats, which can be directly produced in any 3D design software, e.g., unigraphics. The system output is the built 3D pattern via layer-by-layer printing. There are two major parts in the DoD printing system interacting with each other to transfer the model data to the built pattern, i.e., software control system and hardware components. The software control is to produce a set of commands to drive the hardware based on the input model data, available hardware devices, and their status, and user-desired configuration. The hardware components consist of physical devices to eject the required microdrops to form required 3D structures. Note that the data flow in this system is not unidirectional from the software control to hardware components. The hardware also sends back signals on hardware status for dynamic configuration and real-time control. In this section, we will first discuss the hardware design and software control design, followed by considering that software design to accommodate the specific characteristics of the hardware components.

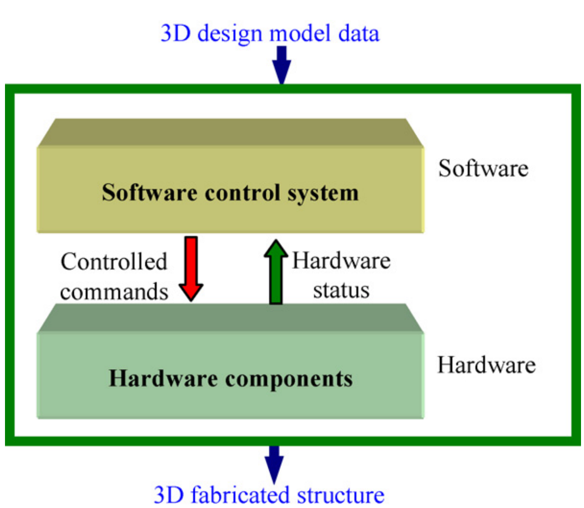

Fig. 1. Framework of DoD system.

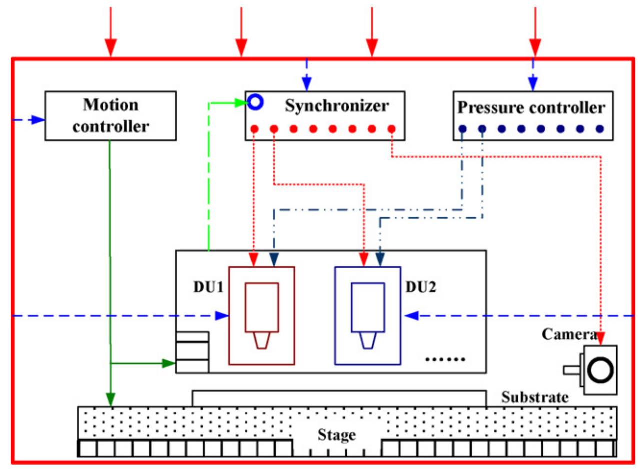

Fig. 2. Schematic diagram of hardware in the multi-nozzle DoD system. (⊟) Parts with horizontal translation (left/right); (⋯) parts with vertical translation; (◫) parts with horizontal translation (inward/outward); (– – – ▶) command data from control system; (–·–·▶) pressure channel; (——▶) motion command; (⋯⋯▶) activated signals; (–·–·▶) encoder data.

2.1. Hardware design of multi-nozzle DoD system

The main objective of multi-nozzle DoD system is to dispense multi-material micro-droplets at command positions. Fig. 2 illustrates the schematic diagram of the hardware design, which is a modification of our single-nozzle DoD micro-dispensing system (Feng et al., 2005). Firstly, the motion controller receives the command from the software control, and drives the motorized stage to move as commanded. The motorized stage position is then sent to the synchronizer, which produces the synchronizing TTL signals to activate the corresponding dispenser units (DU) and supplementary components. When activated, the DU is to dispense the required micro-droplets to the substrate. In the dispensing procedure, back-pressure control is one crucial factor for successful production of satellite-free droplets from DUs. The back pressure can be a fluid pushing pressure (e.g., micro-valve nozzles) or a negative fluid holding pressure (e.g., piezoelectric nozzles) in a DU. Thus, the developed DoD printing system is also equipped with a pressure controller which provides the positive and/or negative pressure to the DUs. In addition, other supplementary devices might be included; for example, a camera to calibrate and monitor the process, the curing device to fabricate the 3D structures and so on. In this section, we focus on the modified hardware components, including the motorized stage with mechanical mounting, dispenser units, and the synchronizer. The detail of other components can be found in (Feng et al., 2005).

2.1.1. Motion control system

Motion control concerns the movement of the attached nozzles and the substrate such that the dispensed droplets are deposited at the command positions. In the developed DoD machine, the motion control system consists of a Galil controller embedded in the computer, and a motorized stage with *X*-, *Y*-, and *Z*-axis movements as shown in Fig. 3a. After receiving the movement command from the software control, the motion controller translates the command to a set of signal pulses, which drive the three stage motors to move to the command position at specific speed. The resolution of the motorized stage is 1.25 μm in *X*- and *Y*- axis directions and 0.673 μm in *Z*-axis direction. There is an attached encoder on each motor to record the actual motor movement. These captured data can be applied for the motor feedback control, which depends on the motion controller design. In addition, these data are sent to the synchronizer to regulate in real time the operation of dis-

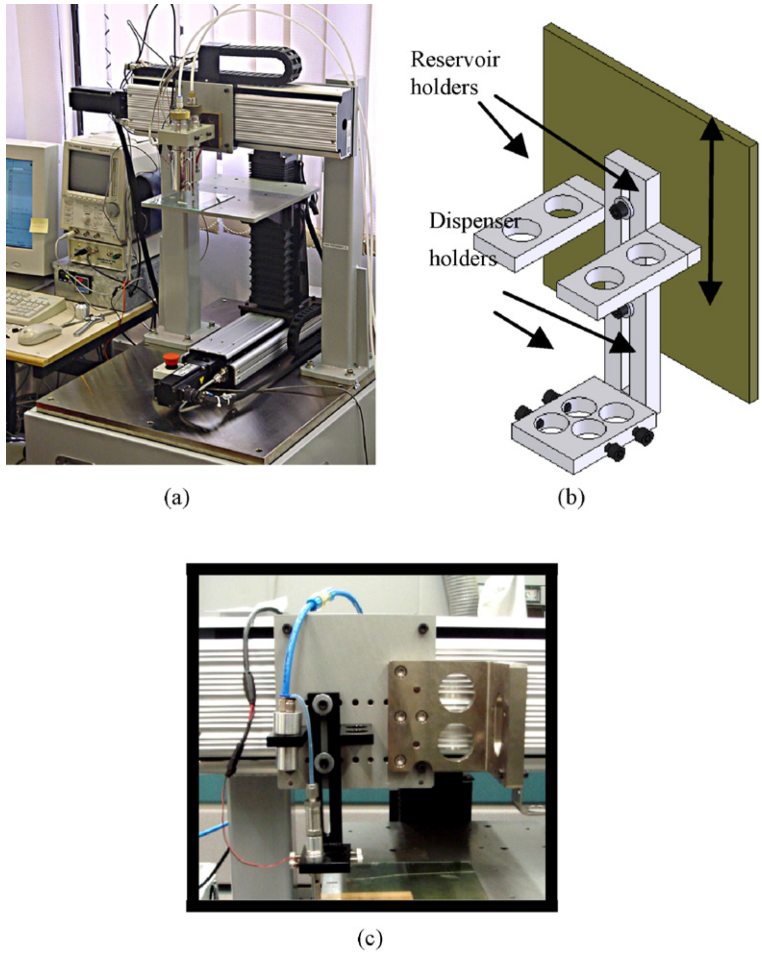

Fig. 3. The moving mechanism in the multi-nozzle DoD system. (a) The motorized stage, (b) the mechanical mounting for the multiple dispenser holding, and (c) a dispenser unit mounted on the mounting.

penser units and other components in this developed multi-nozzle DoD system. Besides the controller and the motorized stage, a good mechanical mounting for the dispenser units is also required to minimize erratic dispensing operation. Fig. 3b and c illustrate the designed mechanical mounting which is capable of holding four dispenser units in place. In this design, the reservoir and dispenser are mounted separately.

2.1.2. Dispenser units

A DU ejects a micro-droplet when receiving an activating signal. Generally, a dispenser unit includes a dispenser controller, a reservoir, a nozzle, and other fluid connecting items, such as filter, hose tube, adaptor and so on. Fig. 4 shows a piezoelectric dispenser unit used in our multi-nozzle DoD system. When activated, the dispenser controller MicroJet III from MicroFab Technologies Inc. (2008) generates the voltage pulse with specific waveform shape, which is sent to the piezoelectric transducer in the nozzle to eject the droplet. The reservoir and the nozzle are connected by a hose tube and through a filter with 7 μm element from Swegelok Company.

Currently, we only employ two types of nozzles to show the effectiveness of the developed DoD system. One is our developed piezoelectric-actuated nozzle in which a piezoelectric element is used to change the volume of the fluid container to produce the fluid ejection and retraction pressure pulse, as shown in Fig. 5a. The pressure pulse rise and fall times can be tailored to optimize drop production and dynamically alter the diameter of the ejected drops (Lee, 2003). Since the amplitude of the pressure pulse from the piezoelectric elements is limited, the piezoelectric-actuated nozzle is generally used to dispense fluid with low viscosity (Khalil et al., 2005). Another is the solenoid-actuated micro-valve nozzle in which an electro-mechanical valve opens and closes the orifice via an applied voltage pulse, which is illustrated in Fig. 5b. In ejecting process, a voltage pulse is applied to open the valve by lifting the piston against the spring. The material is then extruded out of the nozzle tip under an applied back pressure. Since the back pressure is directly from the easily adjustable pressurized air, the micro-valve actuated nozzle can be applied to dispense fluid of higher viscosity compared to that from piezoelectric-actuated nozzle. Besides these two types of nozzles, our system also can extend to include other actuated modes of commercial nozzles by simply configuring the hardware interface module in the software control, which is discussed later.

2.1.3. Synchronizer

The synchronizer is to regulate the operation of dispenser units and other supplementary components with regard to the stage positions (x, y, z). The working principle of the synchronizer includes three steps: (1) acquire the stage position data from the rotary encoders coupled to the stage motors; (2) compare the position data with the desired values from software control; and (3) generate the multiple TTL signals to activate the respective hardware components. In our previous system, these three steps are implemented by using a software API (advance programming interface) inside the motion controller. The implementation is simple and flexible to reconfigure. However, the output channel of the

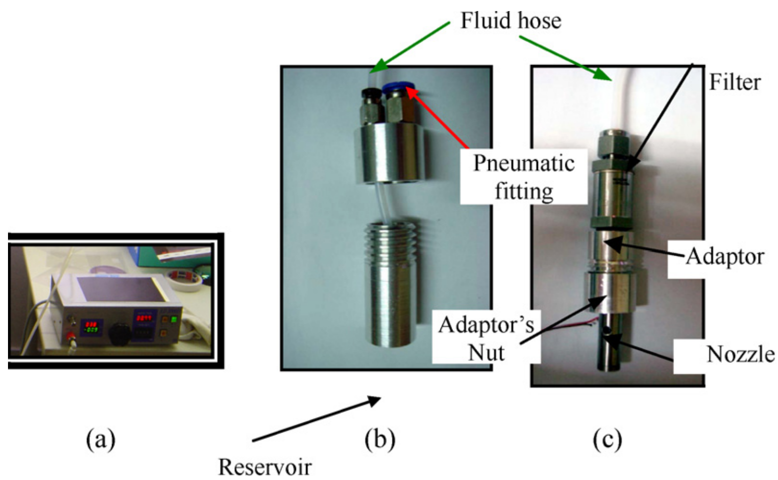

Fig. 4. The dispenser unit (including (a) controller MicroJet III, (b) reservoir, and (c) nozzle and fluid connecting items).

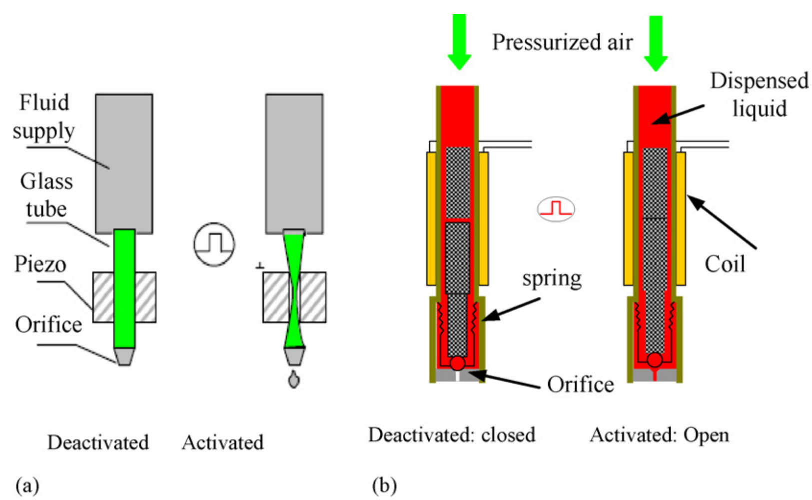

Fig. 5. Two actuating modes of dispensing nozzles. (a) Schematic of piezoelectric actuated nozzle and (b) schematic of micro-valve actuated nozzle.

motion controller is limited, i.e., it can control only one nozzle. To achieve multiple nozzle dispensing control, a hardware synchronizer circuit board has been developed to handle the synchronizing process. It is low-cost but able to perform synchronization task in real-time.

2.2. Software design of multi-nozzle DoD system

The software control system in the proposed DoD machine serves to produce a set of control signals to drive the hardware components for desirable printing given a 3D model from commercial CAD software. Fig. 6 illustrates the schematic diagram of the proposed three-layer control framework. The control system needs to handle the issues related to user requirements and the hardware operations, which are represented as user interface (UI) layer and the hardware interface (HI) layer, respectively. In addition, a middle layer, referred as system manager (SM), is added to isolate the influence of hardware modification to the user interface, which facilitates the dynamic configuration of applied hardware components. This section discusses these three layers respectively with focus on the data and signal flows.

2.2.1. User interface

UI provides the user a friendly interface to specify the attributes in the printing process, and transmit these requirements to SM layer. UI generally includes three primary tasks: (1) interact with the user; (2) convert the input standard CAD model to layer-by-layer model for printing; and (3) communicate with SM layer. Fig. 7 shows the schematic diagram of the UI framework. Three modules are designed to realize the three primary functions. Firstly, *user interaction* module is to provide the user an interface to specify the printing attributes, for example, the printing model file, the applied hardware components, the desirable driving parameters for hardware, the corresponding dispenser units for multi-material part,

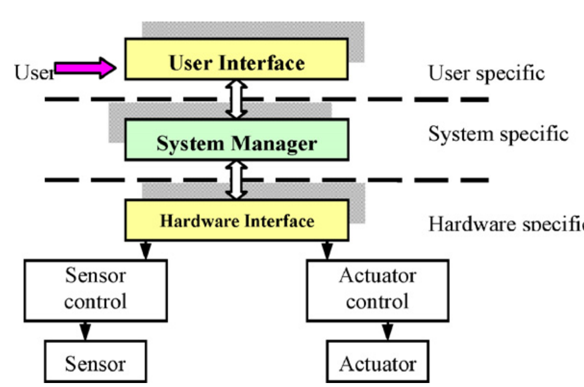

Fig. 6. Schematic diagram of system framework for software design.

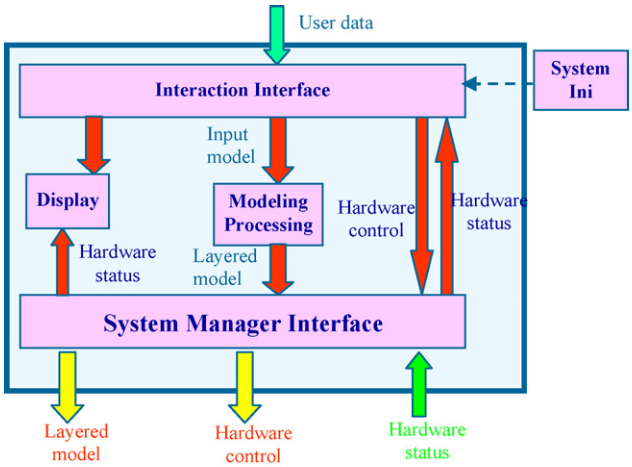

Fig. 7. Schematic diagram of user interface layer.

and so on. Note that to balance between high flexibility and system use simplicity, a variable authority access control is provided for different user groups. The manager of the DoD machine can access the interface to configure the hardware components and the types of hardware control signals as requirements, while the machine operator only needs to provide the input model and some driving parameter values to conduct the printing process. Secondly, *model processing* module is to convert the 3D model to a desired layer-by-layer printing model. This is a necessary step for any rapid prototyping (RP) system due to its material additive nature. Thirdly, *system manager interface* module takes charge of communicating with SM layer, i.e., collecting the hardware status, and sending the model data and driving parameters. In addition, a display module is added for user-friendliness to show the input model, the slicing result, the printing progress and so on.

2.2.2. System manager

SM is taken as the communication through-pass between the UI and HI. There are two categories of flowing data in SM according to the flow direction. One is the up-to-bottom printing data, including the layered 3D model data and the user specified driving parameters for hardware. Starting from UI, the printing data is firstly transmitted to SM, which interprets the data to a set of commands and sends the commands to corresponding HIs to drive the hardware components. Another category is the bottom-to-up hardware status data. Starting from HI, the hardware status is fed back to SM and then to UI. The hardware status data is used to specify the applicable hardware components, or indicate the progress of printing process. Two different mechanisms are applied for the data transmission between layers: a shared data buffer between UI and SM, and TCP/IP protocol between SM and HI. The reason for using TCP/IP protocol between SM and HI is the consideration of the extendible system, i.e., the system can be extended to a web-based distributed system with UI and SM running in an office computer and HI running in a factory computer linked with the hardware components. As the middle SM layer is able to isolate the influence of hardware change to the user interface, the user is provided a simple and friendly interface which does not involve the detailed hardware attributes, and on the other hand hardware replacement can be easily implemented by configuring them in HI without changing the UI codes.

2.2.3. Hardware interface

HI layer generates the commands to drive physical hardware components to build the desired 3D structures. Each hardware component is unique in the driving parameter types and values. In our system, separate HIs are designed to correspond to different hardware components. For example, the driving parameter for the motorized stage is the moving speeds and positions, and stage HI will produce one stage path file to manipulate the stage movement. The synchronizer needs the input position data and related information to synchronize the operation of dispenser units, and its HI will generate a set of data about the activation information corresponding to the stage position. A piezoelectric dispenser unit is driven by a voltage pulse, and its HI will generate the pulse waveform shape data accepted by the controller. A micro-valve dispenser unit is also driven by an applied voltage pulse but of different shape, and its HI will generate the data on voltage amplitude and actuation spike time. With the separate HIs structure, a new hardware can be easily added into the system by configuring a new HI and linking it with SM layer. In this way, the developed DoD system has high flexibility to dynamically configure the applied hardware components to satisfy the versatile requirement from the experiment science and industry.

3. Conclusions

This paper presents the development of a multi-nozzle DoD system which is able to dispense multi-material micro-droplets on demand to build 3D structures. The development is implemented from two aspects. On the hardware aspect, a single nozzle DoD machine, our previous work, has been modified to dispense multiple materials from multiple actuating modes of nozzles. A hardware synchronizer has been designed to improve deposition accuracy by real-time synchronization of the operation of the motorized stage and the droplet dispensing by the nozzles. On the software aspect, the three-layer framework achieves high system flexibility for dynamic hardware configuration, and friendly user interface for printing specification.

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