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Technical note

A desktop electrohydrodynamic jet printing system

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ABSTRACT

This paper discusses the design and integration of a desktop system for electrohydrodynamic jet (E-jet) printing. E-jet printing is a micro/nano-manufacturing process that uses an electric field to induce fluid jet printing through micro/nano-scale nozzles. This enables better control and resolution than traditional jet-printing processes. The printing process is predominantly controlled by changing the voltage potential between the nozzle and the substrate. The push to drive E-jet printing towards a viable micro/nano-manufacturing process has led to the design of a compact, cost effective, and user friendly desktop E-jet printing system. The hardware and software components of the desktop system are described in the paper. Experimental results are presented to validate the performance of the system.

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1. Introduction

As the demand for micro- and nano-scale devices in electronics, biotechnology and microelectromechanical systems has increased, efforts have been made to adapt current graphic art printing techniques to address this need. Conventional methods for graphic art printing such as inkjet printing include applying heat to induce a vapor bubble to form and eject a droplet of ink through a nozzle, and piezoelectric printers which squeeze a glass tube to eject ink [1]. The minimum printing resolution that can be created reliably for these methods ranges from 20–30 µm. This course resolution is due to a combination of nozzle sizes and droplet placement. Smaller nozzle sizes may become clogged due to the ink viscosity, while the vibrations caused by the piezoelectric actuators often lead to variations in the droplet placement [11]. These traditional graphic art approaches cannot be used for high-resolution manufacturing due to size and accuracy limitations.

Electrohydrodynamic jet (E-jet) printing is a technique that uses electric fields to create fluid flow necessary to deliver ink to a substrate for high-resolution (<10 μ m) patterning applications [8]. E-jet has been gaining momentum in the past few years as a viable printing technique, especially in the micro- and nano-scale range [4,15,14]. As the advantages of E-jet printing become more apparent (e.g. the potential for purely additive operations, the ability to directly pattern biological materials for biosensors, drop-ondemand functionality for chemical mixing and sensor fabrication, and high-resolution printing for printed electronics), the necessity for compact, affordable, and user friendly E-jet printing systems increases.

The drive to miniaturize production systems is not a new concept. Efforts to conserve space and energy, while reducing investment and operation costs, have led to a new approach to designing and building manufacturing systems [6]. These systems aim to provide low cost, compact, and accessible alternatives to the large, expensive, and user intensive systems that are generally available. For example, Dimatix is a low cost (<\$75,000), commercially available inkjet printing system which is capable of printing multiple inks with a droplet resolution of approximately 40 µm. Following this minimization approach, we designed and built a low cost, compact system for high-resolution printing.

Previous work demonstrated high-resolution E-jet printing [8] using expensive custom-built equipment. This paper presents a desktop system for E-jet printing, designed from commercial offthe-shelf technology (COTS) components, competitive in terms of cost with many of the commercially-available printers but capable of much higher resolutions. The system consists of the necessary hardware and software for standard E-jet printing. More specifically, this paper will focus on (1) the design and fabrication of a micro/nano-manufacturing testbed for E-jet printing, and (2) the development of an integrated user interface enabling manual and automated printing. The remainder of the paper is organized as follows. Section 2 provides a description of the E-jet process. Sections 3 and 4 introduce the hardware and software components of the desktop E-jet system. Experimental results validating the performance capabilities of the E-jet printer will be given in Section 5. Section 6 provides concluding remarks and future directions.

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2. Electrohydrodynamic jet printing

Current trends in the fields of electronics, bioengineering and microelectromechanical systems are leading to increased demands for high-resolution manufacturing capabilities. E-jet printing uses electric field induced fluid flows through microcapillary nozzles to create devices in the micro/nano-scale range [8]. The first patented use of E-jet printing came from the Natural Imaging Corporation under US Patent 5838349 claimed by D.H. Choi and I.R. Smith (1998). The printer and printing process detailed in this patent were designed to dispense different colored ink droplets into uniform patterns on a substrate. While these methods easily surpassed the 2-D printing capabilities of ink jet printers at that time, droplet resolution, ink variations, and potential applications for E-jet printing were not fully addressed. In January 2009, the University of Illinois was granted a patent (WO2009/011709) for high-resolution E-jet printing for manufacturing systems. The research detailed in this patent focused on using the E-jet process to print high-resolution patterns or functional devices (e.g. electrical or biological sensors) in the sub-micron range. The patterning of wide ranging classes of inks in diverse geometries, as well as printed examples of functional circuits and sensors demonstrating the diverse applications of E-jet printing are provided in [8]. In addition to a wide ranging class of liquids, this process has been used to deposit suspensions containing particulates such as zirconia, DNA, and silver nanoparticles as demonstrated in Wang et al. [13]; Park et al. [7]; Lee et al. [5]. Along with the ability to print electrical and biological sensors, these suspensions can be used to fabricate 3D structures without supporting material as demonstrated in [10].

Fig. 1 presents a schematic of the E-jet printing process. The main elements for E-jet printing include an ink chamber, controlled pressure supply, glass nozzle tip, substrate, and positioning

system. The printing conditions are controlled through the back pressure (air applied to the nozzle), the offset height, and the applied voltage potential between a conducting nozzle tip and substrate. Changes in back pressure, stand-off height, and applied voltage affect the size and frequency of the droplets. These changes result in different jetting modes (e.g. pulsating, stable jet, e-spray) which can be used to achieve various printing requirements. Choi et al. [3] proposed the following relationship for frequency of jetting f with the voltage potential V and stand-off height h:

$$f = K \left(\frac{V}{h}\right)^{3/2} \tag{1}$$

where K is a scaling constant dependent on the viscosity of the ink, the nozzle diameter, applied back pressure, and permittivity of free space. For a detailed derivation of this relationship, the interested reader is referred to [3].

For E-jet printing, an applied voltage potential is generated between a conducting nozzle and substrate. Note that the nozzle tip and substrate are generally coated with metal to ensure conductivity. Additionally, if the surface of the desired substrate in nonconductive, one can use a conductive layer under a nonconductive substrate provided that the thickness of the nonconductive substrate is within a certain range. A voltage applied to the nozzle tip causes mobile ions in the ink to accumulate near the surface at the tip of the nozzle. The mutual Coulombic repulsion between the ions introduces a tangential stress on the liquid surface that, along with the electrostatic attraction to the substrate, deforms the meniscus into a conical shape (called the Taylor cone after Sir Geoffrey Ingram Taylor who first reported it in 1964) as described in [8]. At some point, the electrostatic stress overpowers the surface tension and droplets eject from the cone. Fig. 2 illus-



Fig. 1. Schematic of the E-jet printing setup. Taken from [8].



Fig. 2. Illustration of the change in the meniscus of the fluid due to an increase in voltage potential between the nozzle tip and the substrate.



Fig. 3. Desktop E-jet system with specific hardware requirements identified. Note that the major positioning and jetting components for the desktop E-jet system are sized to fit a typical lab desktop.

Table 1		
Purchased	hardware components.	

Part	Manufacturer	Part no.	Resolution
X, Y stages	Parker	MX80LT03MP	0.1 μ
Z stage	Parker	MX80MT02MS	1μ [`]
Rotary stage	Parker	M10000	6 arc
Pump-vacuum	Cole-Parmer	EW-79610-02	N/A
Pump-pressure	McMaster	4176K11	1 psi
Infinity 2-2	Lumenera	NT59-051	2 Mpixel
Zoom lens	EdmundOptics	NT55-834	$2.5 \times -10 \times$
Illuminator	EdmundOptics	NT55-718	N/A
Breadboard	ThorLabs	MB6060/M	N/A
Enclosure	ThorLabs	TQ0004627-3	N/A

trates the change in the apex of the ink meniscus due to an increase in voltage.

The pinching off of the fluid from the apex of the cone results in droplets that are typically smaller than the nozzle (micro-pipette) diameter. Initial implementation of this process was performed on a custom built air bearing positioning testbed. This system was designed as a research platform, which subsequently resulted in a large, expensive, and modular system that is suitable for experimental studies but not for use as a printing tool.

In an effort to package and simplify the process and make E-jet printing more accessible to researchers working on potential printing applications in micro/nano-manufacturing, a desktop printing



Fig. 4. Nozzle mount for the E-jet process. Note the electrical connection used to apply a high-voltage signal to the treated micro-pipette.



Fig. 5. Multi-nozzle mount for the E-jet process. The design is an extension of the single nozzle mount with integrated high-voltage electrical connections in each individual nozzle holder.

system has been developed. Details describing the necessary hardware for this system are provided in the following section.

3. Hardware for e-jet printing system

From the previous section, the hardware requirements for the desktop E-jet system consist of: the positioning elements, the pressure and vacuum pumps, the visualization system, the toolbit and substrate mounts, the electrical connections for generating the required voltage potential, and the housing elements. The various components have been identified in Fig. 3.

As can be seen from Fig. 3, the positioning system consists of x- and y-axis electronic positioning stages, a manual z-axis, and a manual rotary axis. Manual z and rotary axes were used to minimize costs. Back pressure and voltage potential compensate for any height irregularities using the relationship provided in Eq. (1). The pressure pump applies back pressure to the syringe, while the vacuum pump is used to attach the substrate to the substrate mount. The visualization system includes a high-resolu-



Fig. 6. Substrate mount for the E-jet process. Note the electrical connection to ground on the treated substrate. This is used to create a voltage potential between the treated substrate and nozzle.

tion camera and magnification lens mounted to a 180° rotary track, as well as a fiber optic light with adjustable arms. The housing is made up of a breadboard and glass enclosure (shown in Fig. 8). All of the items described thus far have been purchased as off-the-shelf components from various vendors. Table 1 lists the components, along with the vendor and any relevant information.

The remaining hardware consists of components that are specific to the E-jet printing process. The toolbit and substrate mounts and the electrical connections residing within these components are critical to the E-jet process and require custom designs. Fig. 4 illustrates one of the toolbit mounts. This mount is designed for single nozzle deposition. An off-the-shelf syringe containing the deposition ink is connected to the pressure pump and a Luer lock micro-pipette ranging in tip size from 300 nm to 10 um. The micro-pipette (nozzle) is sputter coated with metal prior to assembly to ensure an electrical connection along the length of the nozzle [9]. Additionally, the pipette tip is treated with a hydrophobic coating to minimize wicking of the ink along the nozzle. The conductive base of the pipette makes an electrical connection with the mount using built-in contact pins. In addition to the single nozzle mount in Fig. 4, a multi-nozzle toolbit has been designed (Fig. 5). This toolbit enables multiple inks to be used on a single part by manually rotating the nozzle mount.

The substrate mount shown in Fig. 6 contains a raised section designed for a generic glass slide. The slide, which has been sputtered with a metal coating for conductivity, is seated in a cutout within the raised section and held in place by a vacuum chuck. The electrical connection is maintained through contact between the conductive slide and a metal clip held in place by a plastic fly screw (Fig. 6).

The hardware components for E-jet printing make up half of the working system. In order to print, specific software requirements must be met. These are described in the following section.

4. System interfacing

The interfacing of the desktop system through LabVIEW was designed to integrate the two major subsystems: (a) the positioning system (linear motors and the motor drivers) and (b) the electrical system (high voltage amplifier). LabVIEW was chosen for software interfacing due to its easy to use front end graphical interface and



Fig. 7. Desktop E-jet system software-hardware interface.



Fig. 8. Electrohydrodynamic jet printing system designed to minimize cost (<\$50,000), system dimensions, and set-up time, while maintaining high resolution E-jet printing capabilities.



Fig. 9. Process diagram of the E-jet printing system.

the accessibility and modular capabilities of its back end platform. There are two modes of operation for the software. In manual mode, the user has control over position and voltage signals. This mode is used to test the E-jet process for determining suitable voltages for consistent jetting conditions. In the automated operation mode, a set of pre-programmed commands can be loaded and executed sequentially to generate a specific pattern on the substrate through coordination of the voltage and position commands. The voltage commands, however, can be over-written by the user while in the automated operation mode.

Fig. 7 shows a schematic of the software-hardware interfacing. The voltage amplifier is controlled and monitored through analog communication via an NI-6229 DAQ board. On the other hand, the motor drivers are controlled over a serial port (RS 232) communication link. The front end GUI enables the user to monitor safety signals and send control signals for operation over these communication links.

Since the fidelity of the E-jet process relies heavily on the coordination of the two subsystems, the primary functionalities of the software system interface were:

I. The front end graphic user interface (GUI): Provides the user with an interactive panel for control of the hardware components in terms of the position of the *XY* axes and the voltage potential between the nozzle tip and the substrate. In manual operation mode, these are controlled by the user. In automated operation mode, the user loads up a series of commands that are executed sequentially to deposit a prescribed pattern on the substrate by coordination of the voltage on-off and positioning of the *XY* stages. The GUI also enables the user to visualize current position and printing on a virtual work-plate. II. The back-end hardware interface of the software: Aims at monitoring, controlling, and coordinating the hardware components of the E-jet system. The encoder position readings, motor faults, voltage output monitor, and voltage overload readings are monitored over a fixed time-interval repeating loop. In the automated operation mode, the software simultaneously controls and coordinates voltage and position commands to generate jetting of droplets and specific locations on the substrate.

5. Experimental results

In order to validate the performance capabilities of the desktop E-jet printing system (Fig. 8), a sample image was drawn using the process diagrammed in Fig. 9.

Operating from the manual mode on the GUI, an initial calibration was performed to determine suitable *XY* position, *z*-axis offset height, back pressure and voltage input for a desired jetting frequency. Switching over to the automated mode, a series of position

Table	2	
Experi	imental	setup.

Variable	Setup Value
Ink	Glycerol and H ₂ O solution
Nozzle diameter	5 μm
Pump-pressure	0.25 psi
Image size	$1 \text{ mm} \times 1 \text{ mm}$
X position	-3.5 mm (absolute)
Y position	-0.5 mm (absolute)
Z position	0.030 mm (offset height)
Feedrate	0.39 mm/s
Voltage input	418 V
Printing time	10 min

K. Barton et al./Mechatronics 20 (2010) 611-616



Fig. 10. Block "I" printed using the desktop E-jet system. Image was printed from a nozzle diameter of 5 µm resulting in printed droplets with an average measured diameter of 2.8 µm. Typical ink jet droplets with a 20 µm diameter have been superimposed on the printed image for comparison purposes.

and voltage commands were uploaded into the GUI. Using the experimental values listed in Table 2, sequential implementation of the uploaded commands resulted in a block 'I' image shown in Fig. 10.

Using a 5 µm nozzle tip (micro-pipette), the desktop system printed droplets with an average measured diameter of 2.8 µm. The droplet size is correlated to several process variables including: nozzle tip, ink viscosity, offset height, back pressure, and applied voltage potential between the conducting nozzle tip and substrate [3,12,2]. Changes in these conditions will result in variations in the droplet diameter and jetting frequency. For the system in Fig. 8, the process variables were shown to be consistent over a printing area of 5 mm x 5 mm, thereby indicating minimal built-in tilt offset with the printer. The block 'I' was printed by rastering back and forth along the y-axis with a fixed jetting voltage determined during the initial calibration. By applying a constant DC voltage, the natural pulsating jet mode of the meniscus resulted in slight discrepancies in droplet placement. Control techniques which address high-resolution droplet size and placement requirements are currently being pursued by the authors. For droplet size comparison, droplets representing a typical ink jet printing resolution of approximately 20 µm have been superimposed on the E-jet printed image in Fig. 10. These results clearly indicate the ability of E-jet printing to surpass the printing resolution of typical ink jet printers.

6. Conclusion and future work

The availability of compact, affordable, and user friendly test platforms for micro/nano-manufacturing processes is a critical part of enabling the transition of these processes into mainstream manufacturing systems. The major challenge is providing affordable test platforms for researchers to further develop the process and associated applications. E-jet printing is an emerging manufacturing technology that has potential in widespread applications. This paper presented a small and affordable desktop system for E-jet printing.

The significant hardware and software components of a desktop E-jet printing system were described in Sections 3 and 4. In order to simplify the experimental setup, novel toolbit and substrate mounts with built-in electrical connections were designed and fabricated. A two part GUI enables manual and automated printing modes. Experimental results verified the printing capabilities of the desktop E-jet system.

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