Continuous-Tone Color Prints by the Electrohydrodynamic Ink-Jet Method

Dong Ho Choi and Francis C. Lee
IBM Research Division Alameda Research Center, San Jose, California

Introduction

The phenomenon of ink ejection from a capillary nozzle by the application of an electrostatic field has been known since the turning of the century and represents, nowadays, a branch of the broader field of electrohydrodynamics. Lord Rayleigh and Sir G.I. Taylor, among others, have left their exploratory footprints in this subject. Only recently, however, has electrohydrodynamic jetting received any significant attention on the part of technical entrepreneurs, with the appearance of powder coating techniques, space thrusters and mass spectrometry based on this process. The geometry, the properties of the liquid, and the electrical excitation scheme required to optimize this jetting process for printing purposes were outlined previously[1]. Printing of gray-scale (256 levels per print spot) black and white images at a resolution of 300 dpi has been demonstrated as well[2]. The current article describes the production of the first continuous-tone color print samples using an array of four nozzles independently driven by the electrohydrodynamic (EHD) principle.

Fundamentals of Operation

We have addressed the specific requirements of: (a) continuous-tone print production and (b) insensitivity to printing media, while maintaining a high print quality, comparable to that of electrophotographic printers. The electrohydrodynamic jetting method is suited to satisfy requirement (a), while the use of solid hot-melt inks (used in some currently available ink-jet printers) was the solution to requirement (b).

Electrohydrodynamic Jetting

Consider the configuration shown in Figure la, which consists of a liquid meniscus pending at a capillary nozzle and facing a flat platen. The meniscus' dynamics result-

Originally published in *Proc. of IS&T's Ninth International Congress on Advances in Non-Impact Printing Technologies,* October 4-8, 1993, Yokohama, Japan.

ing from the application of an electric potential between the nozzle and the platen has been classified and phenomenologically described by Cloupeau[3]. Under appropriate conditions, a fine jet streams out of the meniscus, as shown in Figure lb. The voltage ranges for which this occurs for 2-Propanol was reported by Choi and Lee[1]. The present understanding of the basic electrohydrodynamic transport process is still limited, active research being pursued in different parts of the world.

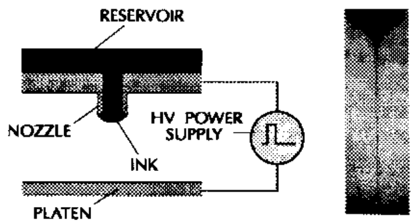

Figure 1. (a)Schematic of the basic configuration for electrohydrodynamic jetting; (b)Photograph of jetting in the stable EHD regime

Typically, the electric conductivity, dielectric constant, viscosity, surface tension and density of the liquid dictate the magnitude of the electric fields needed for jetting. The geometry can be optimized to minimize the electric potential difference required to produce such fields. Application of this transport process for ink jet printing has been demonstrated by Choi and Lee[2]. This method can produce a continuous variation of tones (gray scales) without sacrificing the overall resolution as is the case with conventional ink jet printing technologies that use halftoning (dithering) processes.

Ink Characteristics

The irregular feathering of water or oil-based inks on papers produces poor quality prints. This is one of the major limitations of current ink jet printing technologies. As a result, many ink jet printers (especially the color ones) require special papers to perform their best. An alternative is the use of hot-melt solid inks which reduce paper sensitivity of the output print quality.

Commercially available, hot-melt inks were used to produce the color print samples shown in this article. They come in four colors: cyan, magenta, yellow and black, and are solid at room temperature. The ink reservoir/maintenance system and the nozzle(s) need to be heated up to ≈ 100°C in order to melt the "solid„ ink (the melting point was around 80°C). The density and viscosity at 100°C were 0.77kg/ m^3 and 10cP, respectively.

The dielectric constant and electric conductivity of the black ink in the liquid state were reported in Reference [2]. The dielectric constant was around 2.7 and electric conductivity approximate 5umho/cm at 100°C measured with an AC excitation at lkHz. The different colored inks exhibited no difference in the dielectric constants but did exhibit a perceptible (though small) difference in the electric conductivities. This is presumed to be due to the fact that the former property is a measure of the bulk polarizability of the waxy substrate, while the latter property reflects the effect of the different dye materials (ionic agents) used to produce the different colors. Again, the reported values are intended to be taken as rough estimates of their true behavior in electrohydrodynamic jetting conditions.

Print Robot

The print robot consists of a rotating drum of diameter 7.62cm (3.0") and length 29.2cm (11.5") attached onto a translation table. It is the same robot reported in Reference [2], used to produce the black-and-white print samples. A four nozzle electrohydrodynamic ink jet "print head„ was adapted above the rotating drum, in place of the old single nozzle head. Each color plane was printed sequentially, requiring four passes in order to produce the final color print. We intend to implement, in the near future, a controller box and corresponding software that drives the four nozzles simultaneously, thereby reducing printing time by a factor of four.

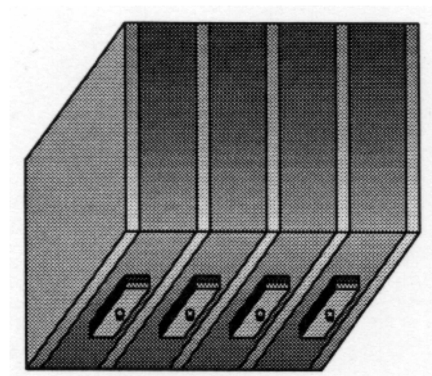

Figure 2. Prototype printhead with four nozzles.

The prototype "print head" consists of four single-nozzle printing modules assembled side-by-side. Each module consists of an aluminum reservoir with its own cartridge heater and temperature sensor as well as the high voltage connection to drive the nozzle. Machinable ceramic and Teflon materials are used to electrically and thermally isolate the modules from each other thereby causing as little cross-talk as possible. The four nozzle assembly is shown in Figure 2. The temperature of the reservoir is controlled to within ±2°C of the set values. The initial (un-energized) height of the capillary meniscus can be controlled by imposing different hydrostatic heads (from 31.5 to 70.0 mm of ink).

Departing from the previous approach of adapting commercially available hypodermic needles (for medical application) as the emitting nozzle, the four-color prototype printhead is equipped with conventionally machined nozzles which started from bulk aluminum blocks. The dimensions of the new nozzles are listed in Table l.

Print Samples

The printing conditions are summarized in Table 1. As done previously with the black-and-white printhead, each of the nozzles in the new print head was calibrated to

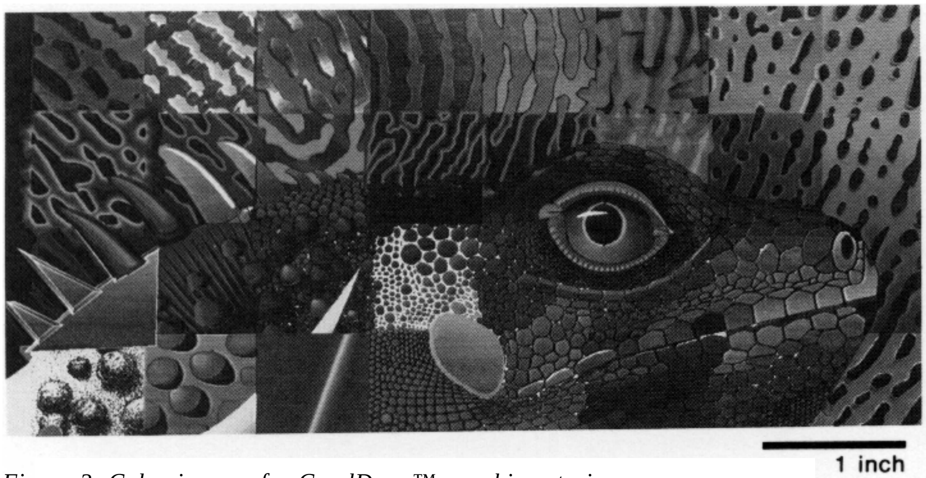

Figure 3. Color image of a CorelDraw™ graphic art piece printed with the electrohydrodynamic method.

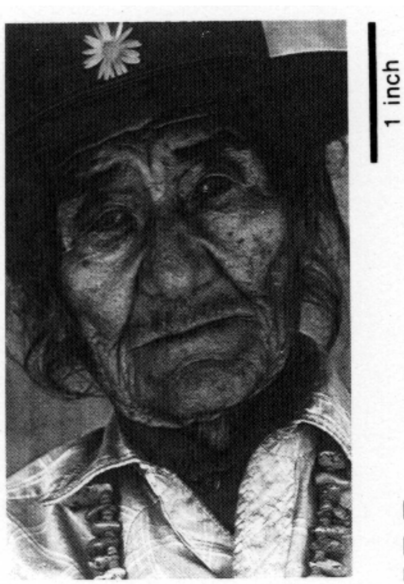

Figure 4. Color photographic image printed with the electrohydrodynamic method.

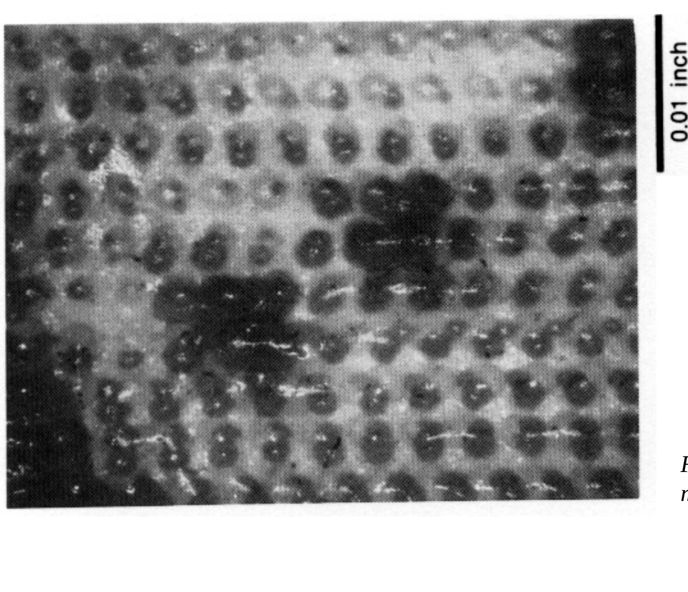

Figure 5. Magnified portion of Figure 3, showing spot size modulation.

correlate intensities with pulse widths. The –correl-ations are then used to generate lookup tables (for each color) that consist of 256 pulse width elements (PWs,i = 1,2,..256). The i-th element, PWj, corresponds to the pulse width needed to generate the ith gray level on a scale of 1 to 256, gray level=256 being white (no ink) and gray level=1 being maximum optical density (full area fill).

Table 1. Operating Parameters of the Print Robot.

Parameter	Range
No. Nozzles	4 (1 per color)
Nozzle Outside Diam.	203µm (0.008in)
Nozzle Inside Diam.	102µm (0.004in)
Nozzle Length	508 µm (0.090in)
Print Speed	8hr/A4 (300dpi graphics)
Gray Scale	Dot diameter control
Dot Diameter	Pulse width control
Pulse Voltage	1000*V*
Bias Voltage	900*V*
Nozzle-platen gap	550µm (0.020in)
Ink temperature	110°C
Pressure head	44.2*mm* of ink

Currently, the smallest printable dot (15Hm) corresponds to an optical density ~ 0.1. The printing algorithm clipped off gray scales higher than 249, eliminating the very light grays from the print samples.

Two images are presented: a graphic art piece produced with CorelDraw™ (Figure 3) and a photograph digitized at a resolution of 300dpi and 24-bit color (Figure 4). A magnified portion of Figure 3 is also shown in Figure 5 to better characterize the prints.

The dots composing the images range from 15 to 140µm in diameter, their shape being nearly circular as shown in Figure 5—even though the paper on which the prints were made did not have any special coating. The lack of “feathering” translates into a higher perceived print quality—with sharp edge transitions—compared to prints made using water-based inks. Other main features of the print images are summarized below:

i) Comparisons of the image sample obtained by the electrojet method with those obtained by the HP Deskjet 500C and the Tektronix Phaser III ink jet printers (all using digital half-toning) provide a vivid contrast, exemplifying the advantages of a true gray-scale printing method.

ii) The image sample printed on ordinary bond paper and on special ink jet papers were not perceptively different from each other, re-confirming the paper independence attribute.

iii) Magnified strips of the images show misregistration, i.e., the different color dots comprising a single pixel are not concentric. This is a result of the sequential way the prints were made, one color plane being laid at a time. Alignment of the dots had to be done manually and repeatability suffered as a consequence. We expect to get an order of magnitude improvement in this respect with the implementation of the simultaneous driver box.

iv) Comparison of the photographic prints with their originals revealed differences in hue and balance. This is due to a lack of calibration between the color separation algorithm and the color lookup tables used for printing. This problem can be easily remedied as scanner/printer manufacturers provide software means of matching the color of the printed images to their originals by taking into account the transfer function (lookup tables) of the printer in their color separation schemes.

v) The temperature control in the four-color prototype printhead was more difficult than in the single-color head (used to produce the black-and-white continuous gray-scale prints reported in Reference [2]). The latter was heated by a foil heater that distributed the heat more uniformly. The four-color head incorporated cartridge (cylindrical) heaters buried vertically, close to one of the edges of the reservoir, producing a more non-uniform temperature distribution inside. As a result, temperatures in the four-color head oscillated by ± 2°C while the single-color head exhibited only ± 0.3°C variations. The print sample shows slight striations (variation in the overall intensity) which correspond to the periodic temperature fluctuations. A better design of the heating system is expected to improve this situation.

The two major limitations of this printing method were mentioned in Reference [2]: (i) high voltage driver requirement and (ii) low print speed. Although these two arenas are seeing steady technical progress, they still represent the major hindrance to a successful commercialization of this technology.

Conclusions

Continuous-tone color printing with the electrohydrodynamic jetting method was demonstrated on a variety of papers, with no apparent change in print quality. The superior quality advantage of continuous-tone color printing compared to half-toning methods was demonstrated. Several departures from non-ideal performance were seen to persist with the new, multi-nozzle printhead. Nonetheless, no new “serious” limitation or problem arose with the multi-nozzle feature.

The current performance is, by no means, the best attainable. Careful specifications of the ink and the print head design can lead to significant improvements.

References

1. Choi, D. H., and Lee, F. C., *Principles of Electrohydrodynamic Inkjet Printing*, IBM Report RJ 8311 (75672), August 27, 1991.
2. Choi, D. H., and Lee, F. C., *Continuous Gray-scale Printing with the Electrohydrodynamic Inkjet Principle*, IBM Report RJ 8913 (80000), August 10, 1992.
3. Cloupeau, M., and Prunet-Foch, B., Electrostatic spraying of liquids: main functioning modes, *J. of Electrostatics*, **25** (1990), pp 165-184.