Acoustic Ink Printing: Photographic Quality Printing At High Speed

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Abstract

We have used Acoustic Ink Printing (AIP) to produce photographic quality prints using aqueous based inks on special coated papers. In AIP, an ultrasonic beam is focused on the free surface of the ink to eject discreet droplets of controlled diameter. This "nozzleless" process enables generation of extremely small drops without sensitivity to small defects in nozzle geometry because the drop size is determined by the lateral dimensions of the acoustic beam. We have used 1.5 pl drops and produced images at a quality level approaching standard silver halide processes. The printing is done at a spatial addressability of 600 spots per inch and the printed spot size can be varied by firing from 0 to 10 drops per pixel to achieve multiple gray levels at high resolution. The printheads were fabricated using thin-film processes along with specially developed mechanical assembly techniques. Printheads with 1024 ejectors were built at a nozzle density of 600 per inch to enable printing of a 1.7-inch-wide swath, operating at a drop ejection rate of 25 kHz. Several novel techniques were demonstrated to seamlessly stitch multiple swaths without degrading image quality or print speed.

Introduction

Direct marking potentially offers an environmentally friendly, lower cost and higher speed alternative to silver halide processes for printing photographs. In particular, ink jet printing has the capability to meet the stringent quality requirements when small drops of ink are used for printing. Today there are several commercial products in the market that offer a quality level comparable to the standard silver halide process. For example, Epson Stylus Photo printers[1] and Hewlett-Packard Photosmart printers[2] meet these requirements. Due to the artifacts produced by drop misdirectionality in many standard ink jet processes, however, it has been found to be very difficult to achieve high quality single pass printing at the high print speeds which would enable a low-cost alternative to silver halide for speeds useable for Minilab type productivity.

Recently Acoustic Ink Printing (AIP) has been proposed as an alternative to the standard ink jet printing processes to achieve very high quality photo prints at a relatively high speed and low cost.[3] This paper describes the results of research and development efforts at Xerox PARC to achieve a cost effective solution to direct marking for photographic printing.

AIP Droplet Ejection Process

AIP uses acoustic waves focused onto a fluid surface to eject droplets from the liquid.[4] Fig. 1 shows the principles of the droplet ejection process in AIP. A piezoelectric transducer is attached to one end of a solid rod. On the other end of the rod, a spherical cavity filled with a liquid is located and this cavity serves as the lens element to focus the acoustic waves. When the transducer is excited with a tone burst of RF energy, it generates sound waves that propagate in the solid rod towards the lens. The lens focuses the sound waves towards the liquid surface, which is adjusted to be at the focal plane of the converging beam. Impact of the sound burst will cause a mound of liquid to rise from the surface due to the radiation pressure of the acoustic waves. If the energy of the incident sound beam is high enough, a droplet will break free from the top of the mound due to Rayleigh-Taylor instability. The droplet is expelled away from the surface at a velocity of several meters per second. After ejection, the fluid surface relaxes as capillary waves generated near the mound propagate radially outwards. The ejected droplets have been found to be very stable in size, velocity and directionality. A more detailed account of the physics of droplet ejection and modeling of this process can be found in Ref. 3.

The diameter of the drops generated using AIP has been found to be comparable to the lateral dimensions of the focused sound beam. Since the focusing of the sound waves is typically diffraction limited, the ejected drop size is then on the order of the wavelength of sound in the fluid. For example, at an acoustic frequency of 150 MHz, the wavelength of sound in most aqueous fluids is 10 microns and the generated drops are about a picoliter in volume. Figure 2 shows the relationship between drop volume and acoustic frequency. One can obtain extremely small droplets without using small nozzles, leading to excellent directionality which is relatively insensitive to geometry errors in aperture fabrication. The drop ejection rate is limited by how fast the capillary waves settle down after ejecting drops. Typical drop ejection rates are on the order of several tens of kHz.

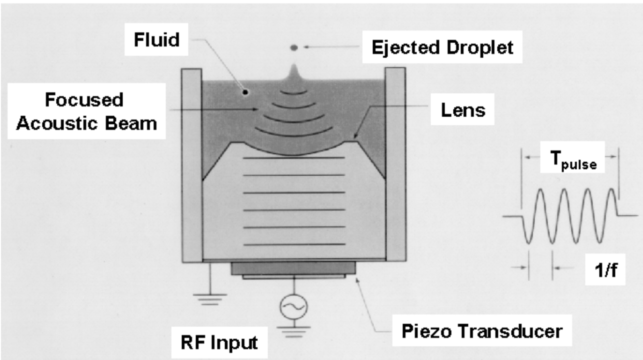

Figure 1. AIP drop ejection process

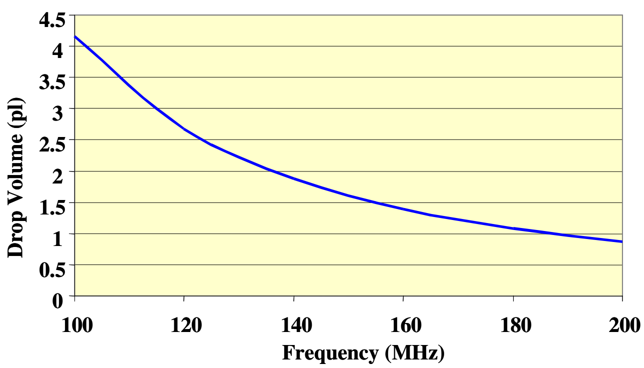

Figure 2. Relationship between drop volume and acoustic frequency

Printhead Construction

In order to provide a cost effective alternative to silver halide processes, there is need to integrate a large number of ejectors into one printhead, using techniques that lend themselves to low cost manufacturing. Figure 3 shows a diagram of the technique we have utilized for achieving such results, with the performance parameters summarized in Table I. An array of ejectors is fabricated in a planar substrate, with the acoustic energy focussed by an array of Fresnel lenses fabricated on the back side of the substrate. The printhead consists of two plates. The bottom substrate is a 1.1 mm-thick glass plate with the acoustic transducers and planar Fresnel lenses attached to the back and front surfaces, respectively. A second substrate, called the liquid level control plate, is attached to the glass plate to maintain the ink height at the focal plane of the acoustic lenses.

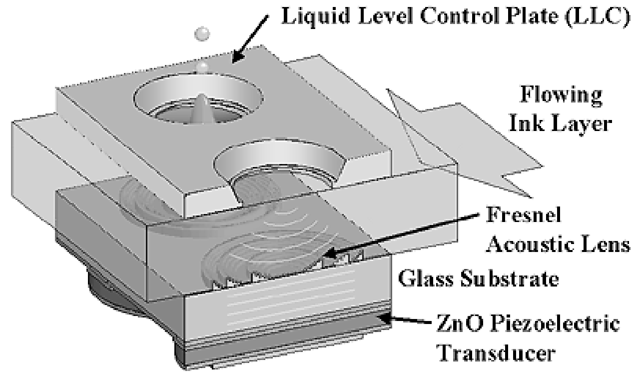

Figure 3. Cross-section of an AIP drop ejector used for printing experiments

Table 1. Summary of Printhead Specifications

Resolution	600 SPI
Pixel size	42 microns
Max drops per pixel	10
Print zone width	43 mm
Number of ejectors	1024
Ejector pitch per row	336 microns
Number of staggered rows	8
RF frequency	145 MHz
Drop volume	1.5 pl
Transducer diameter	300 microns
Lens focal length	325 microns
Drop ejection rate	25 kHz

The acoustic transducer is one of the key components of Acoustic Ink Printing. We have previously reported5 a process to deposit high-efficiency thin ZnO films for generation of sound waves. In this case, a 10 micron thick layer of Zinc Oxide is deposited and patterned with standard photolithographic techniques to define individual transducers.

In order to focus the acoustic energy in the ink layer diffractive Fresnel lenses have been used. Fresnel lenses offer the advantages of planar geometry and relative ease of fabrication over other forms of lens making techniques. The lens array is fabricated using photolithographic techniques[6] utilizing a four phase lens geometry.

The acoustic waves used in the print head are sharply focused, with the depth of focus on the order of tens of microns. To achieve the location of the ink surface at the focal plane of each lens with such precision, a second substrate is attached to the glass plate. This liquid level control plate is about 100 microns thick and contains apertures fabricated by photo etching. When the space between the two substrates is filled with ink, the surface tension of the ink across the aperture opening holds the liquid level near the top surface of the aperture plate. It should be noted that the aperture opening (100 microns) is much larger than the diameter of the ejected drops (10 microns), so that the exact shape and fabrication of these apertures have a relatively small impact on the size and directionality of the droplets.

Since the pitch of ejectors in a single row is 336 microns whereas the spot size is 42 microns, eight staggered rows of ejectors are utilized to be able to print a continuous region without making multiple passes. This is shown in the ejector layout shown in Figure 4. A matrix drive architecture including drive chips mounted on the glass, and an attached printed circuit board enable sequential driving of each of the eight rows of transducers within a single print line time.

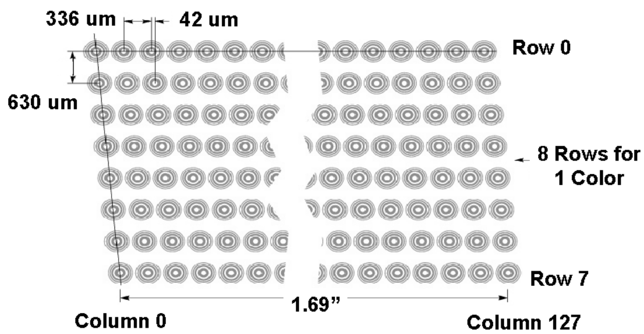

Figure 4. Staggered row ejector layout

A photograph of a finished print head assembly is shown in Fig. 5. The lifetime of the printheads have been found to be over several million prints.

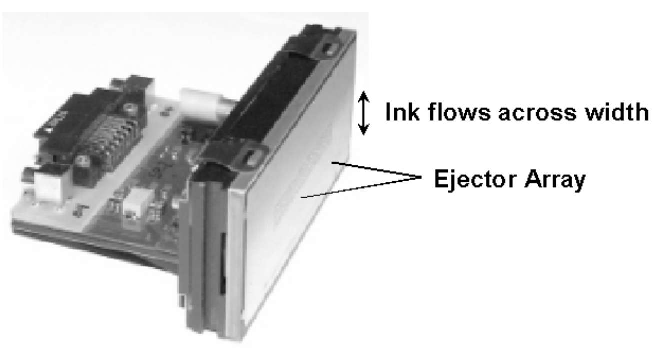

Figure 5. Photograph of a packaged printhead

Printing Algorithm

Photographic printing has very stringent requirements on quality. In addition, the printing has to be done at a relatively high speed to provide a cost effective solution for photo reproductions. Standard ink jet printers has to make a significant number of passes to print each swatch in order to make the artifacts due to droplet misdirectionality and swath stitching less visible to the eye.

We have developed a technique to produce very high quality prints that show no visible degradation due to the artifacts mentioned above and without degrading print speed significantly. The technique used is shown in Fig. 6. First, the tone reproduction curve is done such that we print 0 to 10 drops of each color on each pixel. Using multiple drops per pixel gives additional gray levels and makes contouring almost invisible. The printhead makes two passes to produce each swath. In each swath half of the drops that are supposed to be placed on each pixel are ejected. Therefore, except for a small overhead for acceleration and deceleration at the end of each swath, there is no significant decrease in print speed due to two-pass printing. The printhead is shifted by half-a-swath between each pass to reduce the artifacts of slight droplet misdirectionality.

In order to reduce the visibility of errors in switching, the last 100 or so pixels at the ends of the swaths are modulated in a saw tooth pattern. The printhead shifting is done then in such a way that these saw tooth patterns overlap. This technique results in the blur of transition between each swath making the stitch error almost invisible to the eye. The degradation in the print speed due this overlap region is small, given the transition zone is less than 10% of the width of the printhead.

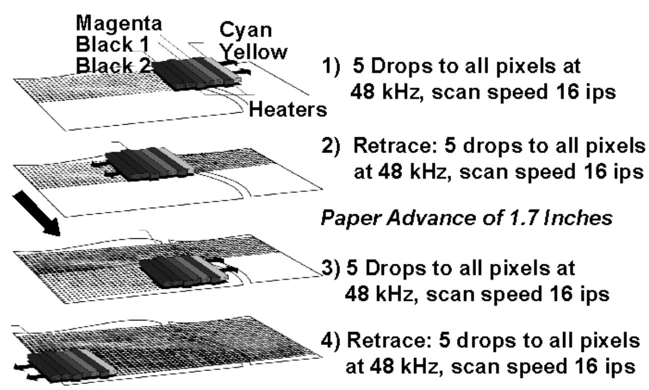

Figure 6. Spot filling and stitching process used for printing photos

Print Results

For printing photographic imaging we used dye-based aqueous inks of Cyan, Magenta, Yellow and Black. The printing was done on specially coated glossy paper. The paper is mounted on a flat computer-controlled translation stage assembly and scanned unidirectionally at a distance of approximately 1 mm from the print head.

A typical print made with the technique described above is shown in Fig. 7. The time required to print each 4”x6” print is approximately 4 seconds. The quality of photos is comparable to silver halide reproductions.

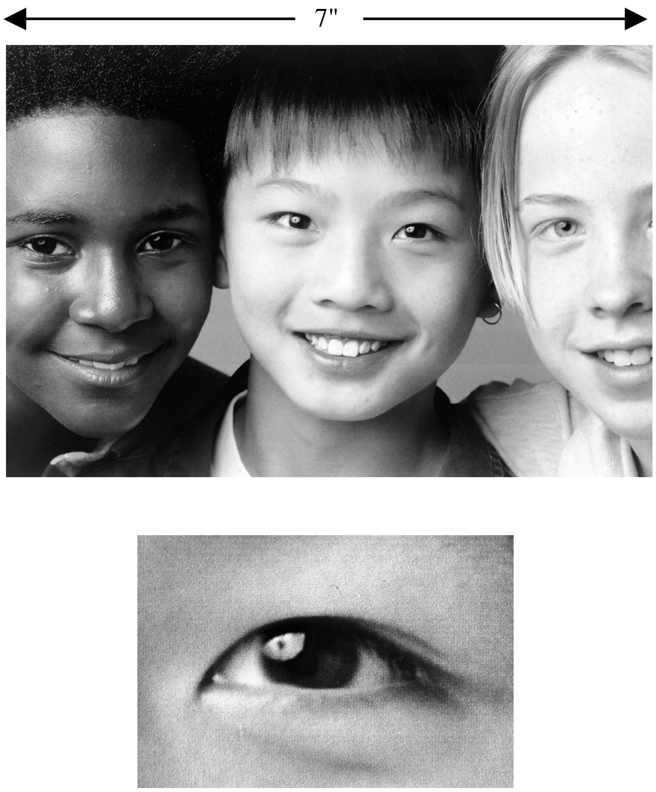

Figure 7. An AIP print taken in the photo mode of operation

Conclusion

We have developed a novel printing technology for high-resolution printing. Acoustic Ink Printing has many advantages including: 1) the absence of a droplet-defining nozzle; 2) the precision with which uniform small droplets of ink can be ejected; 3) the potential for a high degree of integration of a large number of ejectors using low-cost manufacturing techniques in the print head structure; and 4) a relatively long printhead lifetime. Given these advantages, Acoustic Ink Printing has a potential to provide a cost effective alternative to silver halide for printing photographs at competitive speeds in Minilab type operation.

References

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Biography

Robert Sprague received a B.S. and a Ph.D. in Optics from the University of Rochester. He has been at Xerox Palo Alto Research Center (PARC) since 1976 managing activities in advanced ink jet printing, electronic imaging, and electric paper. Dr. Sprague is currently the Chief Technical Officer of Gyricon Media Inc., a spinout of PARC, to commercialize a new paper-like display technology. He is a Fellow of SPIE and the Optical Society of America.