

Paper Transport Using Modulated Airjet Arrays

Andrew Berlin, David Biegelsen, Patrick Cheung, Markus Fromherz, David Goldberg, Warren Jackson, Elias Panides, Bryan Preas, James Reich, and Lars Swartz
Xerox Palo Alto Research Center
Palo Alto, California, USA

Abstract

If the cost of transducers for sensing and actuation can be brought into line with the cost of computation and communication, qualitatively new functionalities and machine architectures can be enabled. In this paper we describe a spectrum of air jet arrays for moving paper. Such systems can support and accelerate flexible media without physical contact and move the sheets without disturbing unfused, toned images, wet ink, etc. Approaches described here span from open-loop flexible, high speed paper transports using multiple jets in fixed aggregation, to arrays of individually addressable jets integrated with paper position sensing under tightly coupled, closed-loop control. The latter approach allows for arbitrary paper trajectories with three degrees of freedom parallel to the array. It is also compatible with batch fabrication and its consequent Moore's law decreases in cost per functionality. We present results of an exemplary platform based on printed circuit board technologies, having an array of 576 electrostatic flap valves and associated oriented jets, and an integrated array of 32,000 optical sensors for high resolution detection of paper edge positions. The fabrication and control of the system is described.

Introduction

Air flows have long been used to support and transport flat objects including flexible objects such as sheets of paper, film glass, etc. A schematic illustration of tilted airjets impinging on a sheet of paper is shown in Figure 1. Airjets obliquely incident on the surface of an object can produce sizable, localized forces, both normal and tangential.[1,2,3] The normal forces repel the object from the jets while, at the same time, attractive forces can arise[4] from the reduction of pressure within a channel formed between the object and the plate through which the jet emerges. The reduced pressure can be due both to detachment vortices, as indicated in Figure 1, and the Bernoulli effect of lateral air flows. The lateral, viscous drag-induced forces created by arrays of oblique jets can provide low friction, low inertia, contactless drives for moving and manipulating sheets in several degrees of freedom. Multidimensional trajectories can be effected in limited spaces. Furthermore, the boundary layer (the region in which the air velocity transitions from the velocity of the paper to that of the high air speed in the channel) is generally large compared with the height of paper surface texture, toner pile thickness, or thickness of ink or paint. Therefore shear force gradients across the surface features are small. As a result, the motive forces on sheets are largely independent of surface texture; surface coatings, having a threshold for displacement, can be left undisturbed. Thus, airjet actuation has many beneficial attributes for paper paths in printers, as well as other applications.

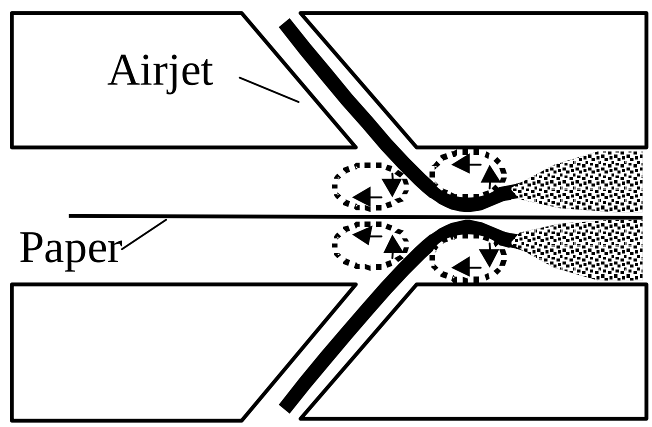

Figure 1. Schematic cross-section of tilted holes in jet plates, levitated paper, air streams impinging obliquely on sheet then diverging and slowing in 3-dimensions, and recirculation and detachment vortices.

A taxonomy of airjet paper movers would include static arrays of jets providing a vector field of forces, dynamically variable flows, selectable jet directions, etc. In this paper we describe three systems. The first two consist of a 2-sided array of jets aggregated into separately controlled forward and backward thrusters, and the third is a fully programmable configuration in which a large number of jets, pointing in the four cardinal directions are individually modulatable by integrated electrostatic valves.

Apparatus and Results

Figure 2 shows the computed velocity field for an array of jets typical of those described below.[3] Figure 3 indicates the corresponding fluid dynamic computations of the shear stress fields at the paper surface and projected path lines. It is readily seen that the forces acting on the paper are quite localized. This is a desirable characteristic when programmable torques are required. Figure 3(C) further reveals regions of lateral counterflow. Figure 4 exemplifies a minimal but useful architecture using aggregated airjets for transport in three dimensions, but with only one degree of freedom, namely distance in the process direction. The illustration consists of two frames from a video recording of a sheet of 78 gram/meter^2 paper being accelerated by a 2-sided array of forward/backward acting jets. In the left frame the paper is tethered with the leading part levitated within the jetted section. The right hand frame shows the sheet 160 ms later. The sheet has been accelerated at 25 m/sec^2 to a velocity of 4 m/sec and steered around a vertical 180^o turn by a curved plastic sheet. The downstream air flow in this un-jetted region continues to bear the paper around the turn then propels the paper through the "free air" without tumbling. The latter effect is enabled by the planar jet which emanates from the device.

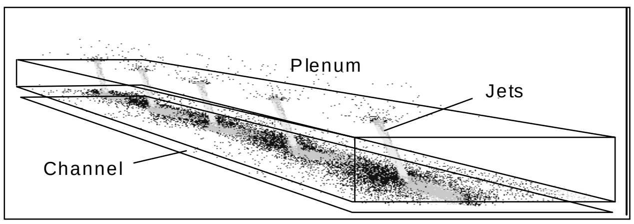

Figure 2. Computed velocity field for array of 1 mm diameter, 45^o jets separated by 25 mm. Sheet is spaced 1.5 mm from jet plate. Plenum pressure is 0.2 kPa above atmosphere.

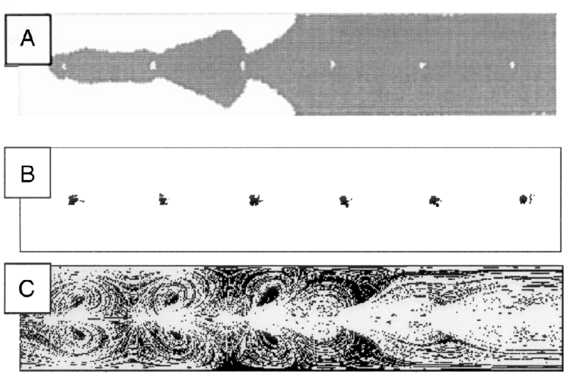

Figure 3. Simulated shear stress and path line maps for 45o tilted, 1 mm diameter jets, 0.2 kPa plenum gauge pressure, and 1.5 mm paper height. Array is periodically repeated in the direction perpendicular to channel. A: Gray (white) indicates positive (negative) shear stress regions. Note counter flow regions just upstream of the jet impingement zones. B: Gray indicates regions containing 90% of the total shear stress. C: Path lines showing lateral counter flows for upstream jets.

In Figures 5 and 6 a full size paper path unit is shown. The apparatus, 1/2 meter from paper inlet (left) to outlet, and 1/2 meter in width (into page), consists of three modules. The left and right modules are passive elements with 45^o jets oriented in the process direction (to the right.) Air pressurizing the plenum of each module to ~1/100 atmosphere (gauge pressure) streams through the jets where it levitates, stiffens and impels the paper forward. The sheet is unconstrained laterally or azimuthally. The middle module has interdigitated rows of jets pointing alternately forward and backward. All forward (reverse) jets are sourced in common by the internal plumbing indicated. Four valves in parallel control the flow in a given direction. Each valve has an orifice of different diameter so that 4 bits of gray scale can be digitally selected. To sense and control paper position, linear position sensitive detectors (PSDs) are embedded in the walls of the jet plates on one side of the channel. On the other side electroluminescent strips are embedded to illuminate the PSDs. Paper shadows the light, the PSDs output a signal proportional to the centroid of the resultant illumination, and the computer obtains a linearized estimate of the sheet position. The closed loop is controlled by a P-I-D program with parameter-learning to null errors between the sensed position and the desired trajectory. An example of the system performance is shown in Figure 7. At t=0 the system starts to learn the mass of the sheet. Maximum errors occur where the sheet velocity is near zero (at extrema of sine waves). Here the friction changes both magnitude and sign. The problem is thus quite non-linear in these parts of the trajectory. The rms error of the entire trajectory is ~600 microns.

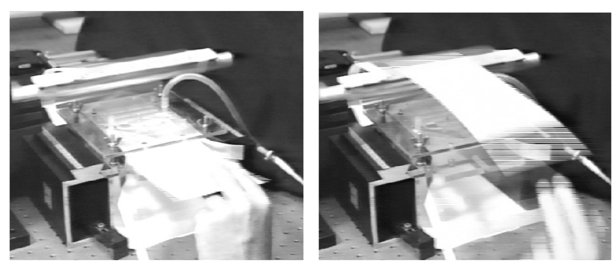

Figure 4. Photographs of small paper mover module with 2-sided forward acting jets, followed by plastic 180^o reversion guide. Note that paper flies stably through "open air".

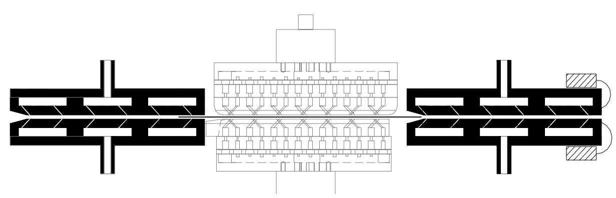

Figure 5. Paper handling unit consisting of three modules. Left hand module is a passive unit for transferring paper to middle, active module. Right hand unit supports paper to hand-off point. Both middle and right hand units incorporate thin film illumination and continuous position sensing.

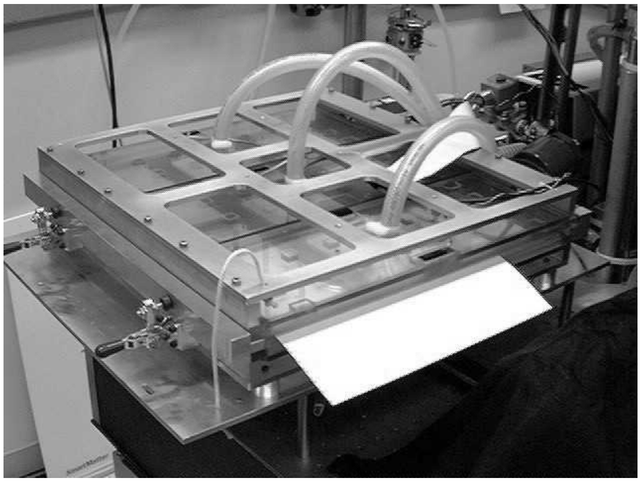

Figure 6. Photograph of 3-module paper mover.

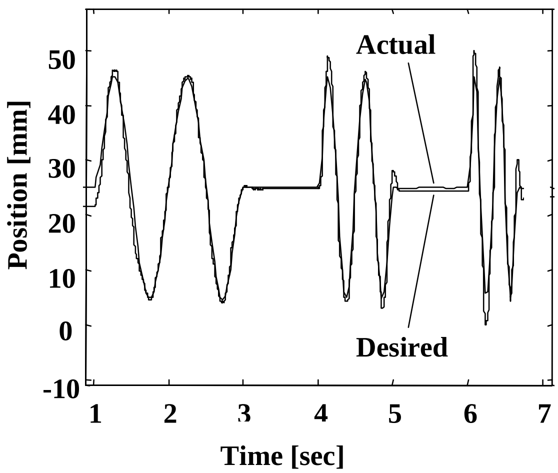

Figure 7. Plot of desired and actual paper edge positions.

The paper mover unit above is designed for 1-dimensional transport of sheets. However, uncontrolled degrees of freedom create translational errors in the controlled direction. Also, demanding large flows through a few valves results in high supply pressures, bulky, expensive valves, and long supply lines. By constructing a system in which each jet has its own small valve[5] high flows can be achieved at low source pressures. To control motion with three paper degrees of freedom (x, y, θ) the system must sense paper position and apply forces and torques in two dimensions. To fabricate such systems as inexpensively as possible we have developed methods for extending printed circuit board (PCB) technology from providing simply electronic substrates to creating an electro-mechanical medium. This extension is qualitatively similar to the relation between MEMS (Micro Electro Mechanical Systems) and silicon chip fabrication.

Figure 8 illustrates the first version we have built of a PCB-based paper moving system. An array of electrostatic flap valves is fabricated by laminating patterned, aluminized mylar sheets to the PCB. [6] The valves are individually driven with a voltage of ~300V to close and seal the corresponding orifice. Setting a valve to zero volts allows the pressurized air in the plenum below the board to blow the 6-micron thick flap open and to exit through a directed jet towards the paper. The time constants for force turn on and turn off are each about 1 ms. The present PCB-based paper mover also has linear CMOS sensor arrays surface mounted on a second PCB about 1 cm below the valve board. Selfoc arrays transfer an image of the sheet onto the sensors.

Figure 9 is a photograph of the PCB airjet module that is 35 cm on a side. The 576 valves are ~1 cm apart. The bars in the inter-woven pattern are the Selfoc arrays over the CMOS sensors. Each sensor consists of 1280 CMOS photodiodes simultaneously latched into a clock-shifted output register. Sensor data are clocked out, thresholded, and filtered by a field programmable gate array (FPGA), then converted into paper centroid coordinates every 1 ms by one or more digital signal processor chips (DSPs). The same DSP(s) then compares the actual and desired paper position, computes the necessary forces and torques and the valve transitions necessary to best approximate the forces and torques subject to various constraints. The loop closure time is slightly longer than 1 ms.

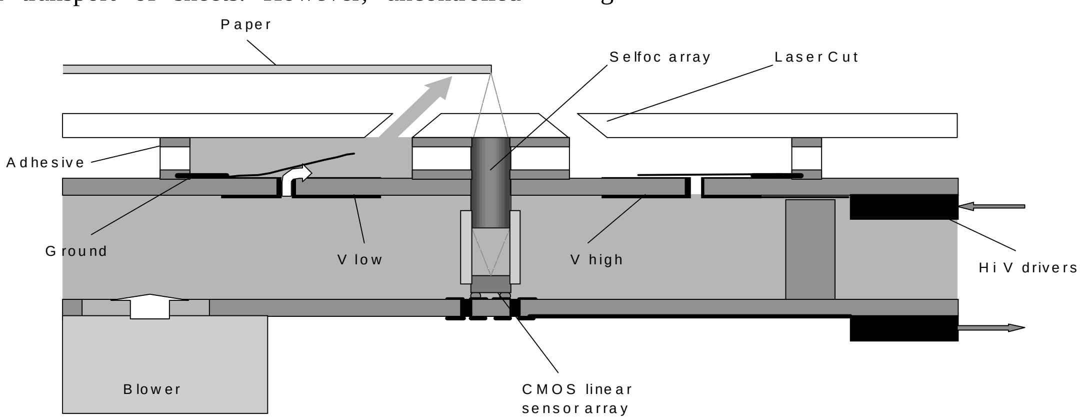

Figure 8. Schematic cross-section of PCB-based paper mover. Actuator is assembled using a PCB and laminated aluminized mylar flaps to form electrostatic valves. Valve body plate and jet plate are laminated to PCB using transfer film adhesives. Selfoc arrays transfer the image of the paper to the CMOS arrays on the lower PCB.

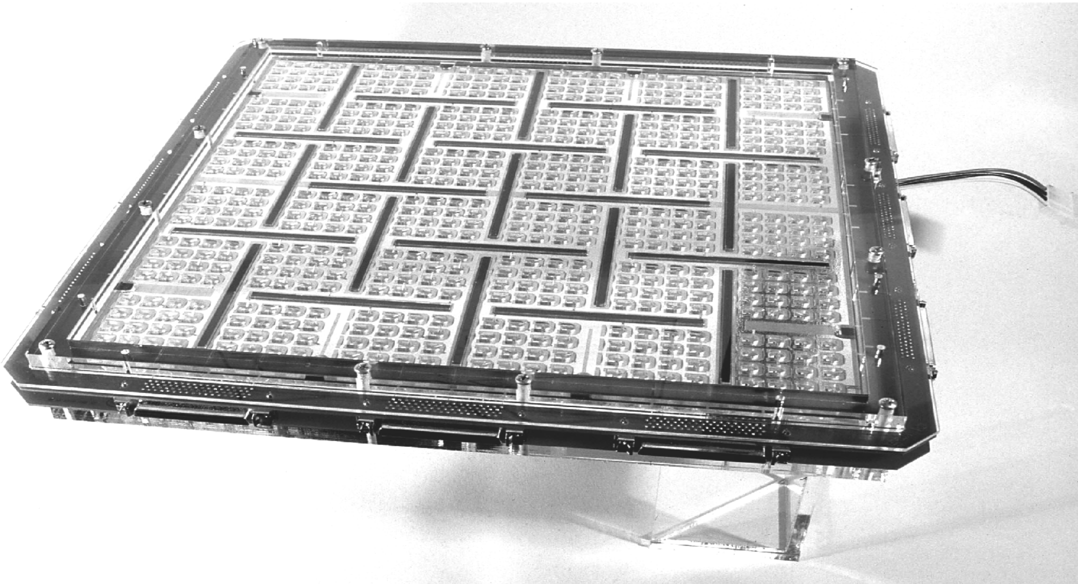

Figure 9. Photograph of 35 cm x 35 cm airjet paper mover module. Sixteen element arrays are flap valves and associated jets. Black bars are Selfoc arrays.

Conclusion

Airjet arrays are useful in enabling novel architectural elements of printer paper paths. The contactless forces allow for manipulating sheets with unfused or wet images, effecting multidimensional trajectories in confined spaces, and providing easy coupling between modules. Printed circuit board electromechanical integration could enable inexpensive, yet complex, systems. One goal of such an approach is a printer/scanner assembled simply from PCBs and solid state, surface mounted and/or laminated components.

Acknowledgement

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References

1. Sir Geoffrey Taylor, Oblique impact of a jet on a plane surface, *Philosophical Transactions of the Royal Society*, **260A**, pp. 96-100 (1966).
2. David Biegelsen, Warren Jackson, Andrew Berlin, and Patrick Cheung, Air jet arrays for precision positional control of flexible media, *Proc. International Conference on Micromechatronics for Information and Precision Equipment*, Tokyo, Japan, Vol. 97-207, pp. 631-634 (1997).
3. David Biegelsen, Elias Panides, Lars Swartz, Warren Jackson, Andrew Berlin, Characterization of Shear Stress Field Induced by Obliquely Impinging Airjets, *Proc. IMECE99*, ASME, to be published (1999).
4. J. A. Paivanas and J. K. Hassan, Air film system for handling semiconductor wafers, *IBM J. Res. Develop*., **23**, pp. 361-375 (1979).
5. S. Konishi and H. Fujita, A conveyance system using air flow based on the concept of distributed micro motion systems, *J. MEMS*, **3**, pp..54-58 (1994).
6. David Biegelsen, Patrick Cheung, Lars Swartz, warren Jackson, Andrew Berlin, and Rachel Lau, High performance electrostatic air valves formed by thin-film lamination, *Proc. IMECE99*, ASME, to be published (1999).

Biography

David Biegelsen is a Principal Scientist at the Xerox Palo Alto Research Center. Past areas of research include acousto-optic materials and interactions, the physics and applications of amorphous semiconductors, laser crystallization of silicon thin films on glass for high speed, large area device arrays and 3d integration, surface science and heteroepitaxial systems, analog computation at the pixel level, and smart matter systems.