MOTION CONTROL OF PLANAR OBJECTS USING LARGE-AREA ARRAYS OF MEMS-LIKE DISTRIBUTED MANIPULATORS*

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Abstract:
This paper presents an overview of the Xerox PARC levitating media transport, including initial experimental results. The levitating media transport is a closed-loop MEMS-based motion control system that employs 12 in. x 12 in. arrays of directed air jets to levitate and control the motion of planar objects, such as sheets of paper, without contacting them. An array of 32,000 optical sensors (photodiodes) senses the position of the media in real-time, while 1,152 air jet actuators apply distributed control forces to the object being transported. Initial results have demonstrated closed-loop positioning accuracies on the order of 50 microns. Trajectory tracking accuracies are substantially larger in this very preliminary data, reflecting the primitive controller used for these initial experiments.

1. INTRODUCTION

The creation of large-area *active surfaces* that can sense, compute about, and act upon their surroundings has long been a goal for MEMS technology development. This paper reports on a prototype active surface in which an array of batch fabricated, electrostatically-actuated valves, interleaved with optical sensors, is used to levitate and precisely control the motion a flexible planar object, such as a sheet of paper, without contacting it. This system, which contains 1,152 pneumatic valves and jets over a 144 in^2 area, is made practical through the use of a novel thin-film lamination technique to produce MEMS-like valve arrays on a printed-circuit-board substrate. Coordinated action of these air jets produces distributed actuation with scales of force, energy, and spatial extent suitable for manipulation of macro-scale objects, such as sheets of paper.

In industrial applications, it is often necessary to manipulate and transport materials with fragile surface textures, such as uncured rubber, silicon wafers, and paper coated with unfused toner or wet ink. In these situations, a non-contact transport method is highly desirable. For nearly-planar objects, air bearings can be used to enable low-friction motion without contacting the surface. The same air jets used to create the air bearing can be angled to produce tangential viscous forces that accelerate the object laterally. For appropriately chosen dimensions, the air jets are highly collimated (Fig. 1), and apply a highly localized force, as described in (Biegelsen 1999b). Examples of previous air jet work include (Berlin 1999, Biegelsen 1997, Konishia 1994, Paivanas 1979, and Taylor 1966). The approach described in this paper is novel in that a MEMS-like binary valve fabricated for each directed jet permits a distributed array of high bandwidth, non-contacting directional control forces to be applied to the moving object.

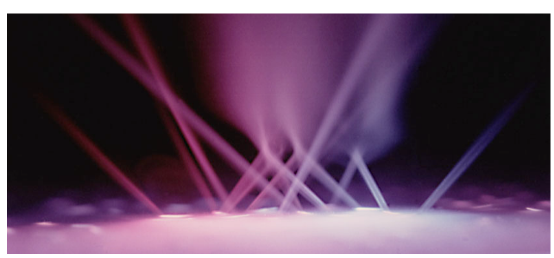

Fig. 1. Air flow visualisation. Visualisation (using water vapour) shows that air flow emerging from an array of angled jets is highly collimated.

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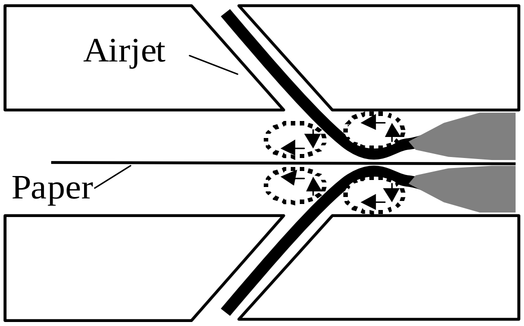

Fig. 2. Air jet actuation cross-section. Schematic cross-section of tilted holes in jet plates, levitated paper, air streams impinging obliquely on sheet then diverging and slowing in 3-dimensions, and recirculation and detachment vortices.

2. AIRJET ACTUATION

2.1 Architecture

The levitating media transport (see Fig. 9 at end of paper) uses a two-sided actuation scheme, as illustrated in Figure 2, in which air is directed towards both sides of the transported object in a symmetric fashion. One array of actuators is located below the medium (sheet), while a second array is located above the sheet. Each of these actuator arrays consists of 576 directed jets, with an independent MEMS-like valve controlling the flow for each jet. Corresponding valved jets in the upper and lower arrays share a common control signal, so that both actuator arrays act in synchrony with one another, applying a localized directed force to both the top and the bottom of the transported object simultaneously.

The directionality of the jets is fixed, and is distributed evenly between each of four orthogonal directions, with a total of 144 pairs of jets in each cardinal direction. This arrangement enables software activation of various combinations of directed jets so as to provide control of three degrees of freedom of the transported object: translation in two-dimensions, as well as in-plane rotation.

As described in (Biegelsen 1999c), the flow rates and geometries of the jets operate in a regime where the coupling between the air and the transported object is primarily a consequence of viscous drag, rather than momentum transfer. This form of coupling avoids disturbing any delicate surface coatings on the media, such as unfused toner. The air flow dynamics is further enhanced by arranging the layout of the actuator array so that jets having directions that are opposed by 180° are never located directly adjacent to one another.

2.2 Jet fabrication and structure

The valve array is fabricated at relatively low-cost on a printed-circuit-board substrate using a fabrication process ("PCB/mEMS") that is based on lamination of laser-patterned thin films (Biegelsen *et al.* 1999a flap valve paper). An aluminized mylar sheet is patterned and deposited above a patterned electrode on the PC-board substrate to form the structure shown in Fig. 3. The valve operates via electrostatic attraction when there is a voltage difference (~300V) between the flap electrode and the substrate electrode. The flap itself is constructed of aluminized mylar, where the aluminum acts as the electrode and the mylar acts as an insulating dielectric layer.

When the voltage is set to 0V, the pressurized air in the plenum below blows the flap open, permitting air to exit through the directed jet towards the paper. A directed jet, located just above the mylar flap, is formed by laminating a laser-patterned piece of acrylic that contains angled holes onto the pc-board that contains the flap valve array. This structure, in which the flap is constructed from a very thin (6 micron) mylar film, has very low inertia and is thus capable of switching extremely rapidly (on the order of 1-2 kHz).

3. SENSING

The system includes a sensor board containing an array of 25 CMOS optical sensor bars, each of which contains 1280 CMOS photodiodes. These photodiodes provide grey-level data that are used to detect the edges of the transported sheet. The actuation board contains interleaved gaps to provide optical visibility to the sensors, which are located beneath the actuators on a separate sensor board, as illustrated in Fig. 4. SELFOC lenses mounted on top of the sensors bring the plane of the moving medium into focus. In a multilayer construction, the SELFOC lens assembly fits directly into cutouts in the actuator board, as shown in Fig. 4. The sensors look up through the gap in the lower actuator board, through the transparent jet plate, to the sheet being

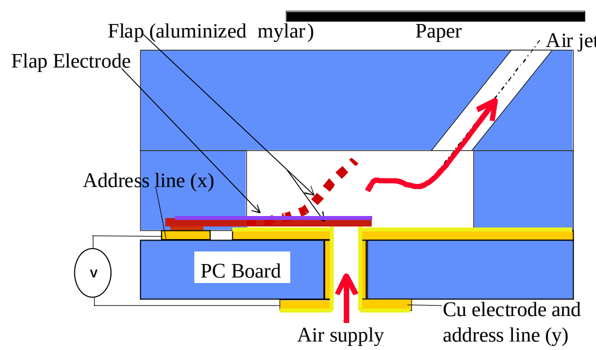

Fig. 3. Cantilevered valve structure. An electrostatic voltage between the flap electrode and the substrate electrode (labelled 'CU electrode' above) causes the flap valve to close. When the voltage difference is removed, the flap blows opened and air flows through the jet orifice towards the paper.

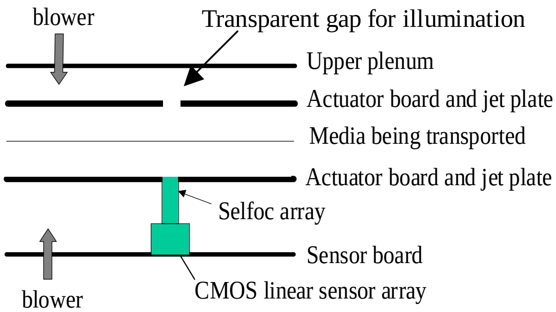

Fig. 4. Schematic cross-section of air jet media transport. The sheet being transported is sandwiched between two actuator arrays that direct air from pressurized plenums towards the media.

transported. Illumination is provided by an overhead light source. Light passes through the transparent upper plenum seal, through the gaps in the actuator board, and through the transparent jet plate, to illuminate the media and sensor array.

4. INFORMATION FLOW

4.1 Sensor fusion

A new sensor reading is taken, interpreted, and acted upon every 2 milliseconds. Each sensor bar is a linear array containing 1280 photodiodes at 400 dpi[1] that are simultaneously latched into a clock-shifted output register. Sensor data are locally clocked out, thresholded, and filtered by a field programmable gate array (FPGA). This converts the grey-level sensor data into a set of edge crossing locations, which are then transmitted to a central DSP processor. Local filtering results in both data compression and improved scaling properties, as communication is dependent on the size of the object rather than the size of the board, which may grow if the board is used as a tile in a larger system.

In the centralized DSP, a least-squares fit is used to determine the current size, location, and orientation of the media based on the edge crossing data. Where multiple interpretations of sensor readings are plausible, historical position data are used to achieve position continuity.

4.2 Control

The media location and orientation are passed on to a 1st order lead controller. This controller compares the media position and orientation to a target trajectory, and computes the translational control forces and rotational torque to be exerted on the media in order to have the media's motion match the pre-specified target trajectory. For the preliminary results presented in this paper, this controller includes only proportional and derivative terms, has a fixed knowledge of the media areal density (g/cm^2), and does not adapt its operating parameters over time.

4.3 Force Allocation

The control module provides the force allocator with a *request* for specific translational forces (Fx, and Fy), as well as a torque (Tz). The role of the force allocator is to determine which directed jets to activate in order to provide forces that best approximate these requested forces. The orientation of the requested translational forces corresponds directly to the orientation of the directed jet actuators, so that Fx and Fy are determined by the net force exerted by all active jets acting in the X and Y directions. Applying torque requires activating jets in opposing directions on either side of the center of mass of the paper. Thus in deciding whether to activate a particular directed jet, the allocator must take into account both that jet's effect on the net X/Y force, as well as the net effect on torque.

The force allocator first determines which jets engage the media at its current position and orientation. Many strategies for allocating the jet forces are possible. For example, an allocation strategy could favor use of jets that lie far from the center of mass of the media. This will maximize the effect of each jet on torque, thereby permitting fewer jets to be used, which minimizes net air flow. However, such a strategy would also increase the susceptibility of the system to the failures of individual jets. The strategy currently implemented involves a hierarchical decomposition that allocates forces to groups of jets at multiple spatial scales. The strategy that works best to date includes a randomization feature that attempts to make use of different jets during each control cycle, so as to minimize the impact of a failed or weak actuator. In order to maintain a high quality air bearing, the allocator begins with the goal of having all jets open (which implies a net force of approximately zero, since an equal number of jets are directed in each direction), and then decides which jets to close to achieve the requested net force and torque.

5. EXPERIMENTAL RESULTS

This first prototype of the levitating media transport that is based on the PCB/mEMS fabrication technology has just become operational. The characterization results presented in this paper are preliminary, and performance is expected to improve once the 1st-order lead controller has been further tuned, sensor alignment errors have been compensated, and once more sophisticated control strategies have been implemented.

5.1 System dynamics

Initial results indicate that for typical flow rates (corresponding to plenum pressures on the order of 0.4 kPA), the lateral force exerted by each pair of jets

[1] At present, only half of these pixels (200dpi) are utilized by the sensor fusion algorithm.

is on the order of 17 dynes. The observed dynamics of the system include a net bias force driving the paper towards the edges of the board and increasing as one proceeds outwards. This bias force varies across the board, and appears to be related in part to the proximity of the jet to the perimeter of the valve array. This is hypothesized to be caused by air exiting through the perimeter of the valve array creating an aggregate net force towards the nearest edge, but further characterization is required to verify this hypothesis. In addition, asymmetries in aggregated forces of multiple jets facing in opposing directions have been measured to be on the order of 20%.

In addition to the bias force variation, there is a coupling between dimensions, in which a set of jets (e.g. X) directed in one direction yield a small net force in the orthogonal (e.g. Y) direction. This creates an unintended coupling between dimensions that appears to be repeatable and should be possible to compensate for via appropriate control actions.

5.2 Position Hold

Fig. 5 shows the results of a control experiment where the control goal was to keep a levitated 15 cm x 13 cm sheet of flexible plastic (having mass of 3 grams and flexibility similar to that of paper) stationary at a target position. The control algorithm employed included the randomization feature mentioned earlier, which seeks to utilize different jets during each 2 millisecond control cycle. Fig. 5 clearly shows the effect of the bias force. The bias force led to a mean displacement from the target position of 53 microns in the X direction, 39 microns in the Y direction, and a mean rotation of 1.3 milliradians. A slightly more advanced controller (such as one that included an integral term) should be able to effectively eliminate this 'mean displacement'.

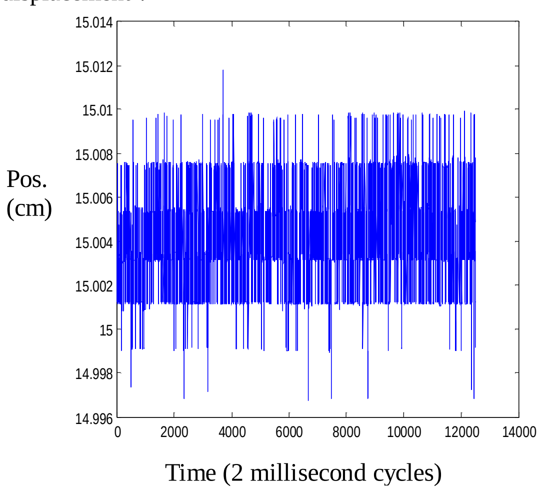

Fig. 5. Plot of Y position vs. time for a position hold experiment of duration 25 seconds. The target of the hold was (X,Y)=(15.0,15.0). The actual result is offset from the target as a result of the bias force.

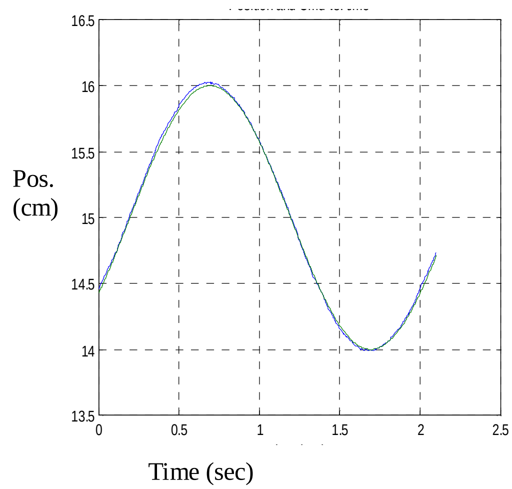

Fig. 6. Tracking a sinusoidal trajectory. The dashed line shows the target trajectory, while the solid line shows the actual trajectory as reported by the sensors.

The standard deviation of the position error was 21 microns (X), 22 microns (Y), and 0.5 milliradians (θ), which is a fairly good indicator of a more fundamental closed-loop performance limit of the system. RMS error was (X,Y,θ) = (57 microns, 45 microns, 1.4 milliradians).

5.3 Tracking a sinusoidal trajectory

Fig. 6 shows the results of a control experiment where the control goal was to move a plastic sheet (the same 15 cm x13 cm sheet as in the position hold experiment) along a 1-dimensional (X) sinusoidal trajectory, while holding rotation and Y-axis position fixed. The rms tracking error was 204 microns, with a mean error of 117 microns and a standard deviation of 167 microns.

The visible error at the extremes of the sine wave is caused in part by miscalibration and slight misalignment of the sensor array. Further characterization of the performance of the system during direction changes, sensor calibration, and modelling of interactions between actuator selection and airflow dynamics, should lead to improved performance.

6. CONCLUSIONS

The levitating object mover is now operational and exhibits highly repeatable behavior and generates forces large enough to manipulate sheet media in meaningful ways. Three-degree of freedom control has been demonstrated, and the overall design of the system appears to be sound. Experience with earlier air jet based systems (not based on MEMS valves) indicates that the position hold experiment is an indication of the tracking accuracy that can be expected when sophisticated adaptive control strategies are applied to more complex trajectories.

There are several directions for future work. Adding various model-based functionality to the controller to compensate for bias force and the effects of air dynamics is critical. This will require further analytical studies to ascertain the nature of the bias force, the relationship between actuator allocation decisions and airflow dynamics, and the nature of the coupling between degrees of freedom. Second, it is highly desirable to add a truth sensor to the system. All of the current measurements are based on the same sensors being used for control, making it difficult to accurately quantify sensor calibration or alignment errors. Third, exploring alternative control approaches to the current centralized fuse-control-allocate model, such as associating specific jets with specific sensors and using local controllers to implement trajectory tracking. In this approach, data fusion would occur in part through the dynamics of the sheet motion, rather than through a centralized control algorithm.

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8. ACKNOWLEDGMENT

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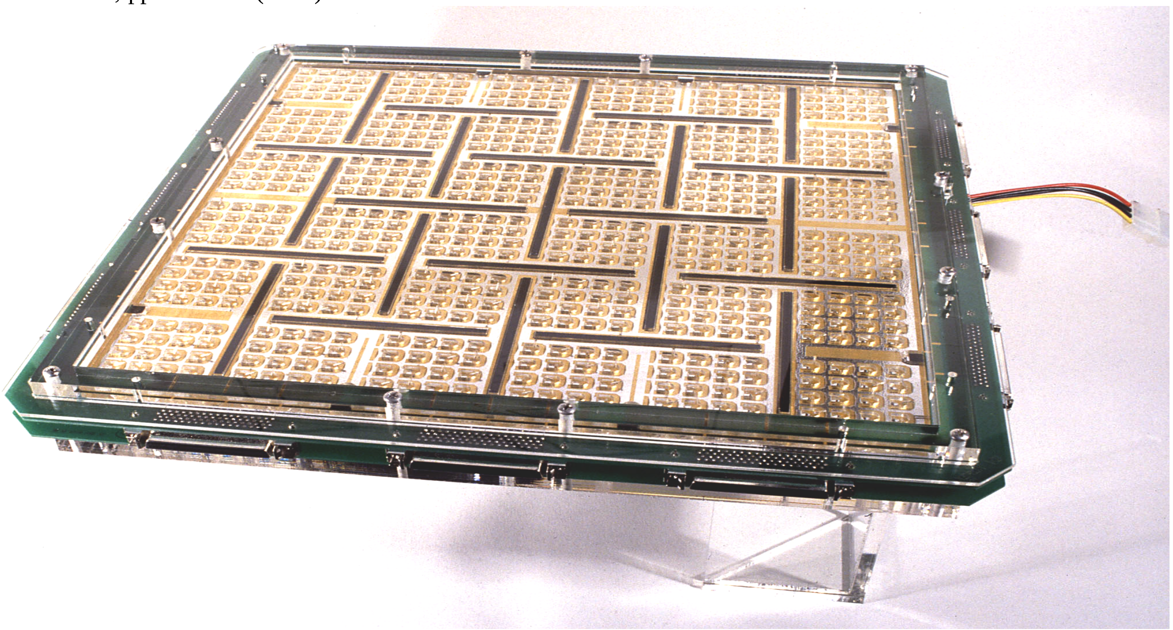

Fig. 7. Photograph of 12 in x 12 in levitating object mover module. Sixteen element arrays are flap valves and associated jets. Black bars are Selfoc lens arrays with optical sensors mounted beneath them. This module applies forces to the bottom side of the transported object. An additional assembly of jets (not pictured) is mounted above this module to apply forces to the top side of the transported object.