USING FEEDBACK CONTROL AND MICRO-FLUIDICS TO STEER INDIVIDUAL PARTICLES

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ABSTRACT
We show how it is possible to combine micro-fluidics and feedback control (sense, compare, and apply corrective actuation) to steer many particles at once. The particles are steered by creating a spatially complex and time-varying fluid flow that carries all particles along their desired trajectories. We demonstrated experimental results for steering of a single yeast cell and realistic simulation results for the steering of many particles at once.

INTRODUCTION

We show how it is possible to combine micro-fluidic devices and feedback control methods to enable new behavior in MEMS systems. In particular, we demonstrate steering of individual particles, without the need for lasers and optical traps, by using flow control, vision sensing, and common electroosmotic actuation. Since cameras are already available in miniaturized format (for example in cell phones), this will allow us to replicate the capability of laser tweezers in a hand held format. This technology also allows us to steer particles and objects that cannot be captured by laser tweezers such as particle with the wrong dielectric properties and objects that are too big to fit inside optical traps.

Figure 2 shows the basic idea: a micro-fluidic device, an optical observation system, and a computer are connected in a feedback loop. The vision system observes the position of all the particles in real time, the computer then compares the location of the particles (which are determined by real time vision algorithms) with the desired (user input) particle positions, control algorithms compute the necessary actuator voltages that will create the fluid flow that will carry the particles from where they are to where they ought to be, and these voltages are applied at electrodes in the micro-fluidic device. The process repeats at each time instant and forces all particles to follow the desired paths. Both neutral and charged particles can be controlled in this way: charged particles react directly to the imposed electric fields while neutral particles are carried along by the flow that is created by electroosmotic forces.

EXPERIMENTAL RESULTS FOR STEERING OF A SINGLE PARTICLE

We have recently demonstrated this concept experimentally for steering of a single cell in a cross channel. Figure 3 shows multiple time snapshots of a yeast cell being steered along a ‘UMD’ (University of Maryland) cursive script path. The micro-fluidic device was fabricated by molding PDMS to an SU8 template and then bonding the PDMS to a glass slide. The device geometry consists of a cross-channel actuated by four electrodes.

The optical system is composed of a Vision-Component 2038 DSP camera and an Axiostar microscope. The real time position of the yeast cell is determined as follows: a previously taken background device image is subtracted from each incoming pixilated camera image, this separates the cell pixels from the background view; the resulting image is now filtered and thresholded; and the center of mass of each blob in the image gives the current position of the yeast cell or cells.

The control algorithm now commands an actuation to move the yeast cell from its current position to the desired position on the ‘UMD’ path. Two of the electrodes create flow in the North or South direction, and the other two electrodes create an East or West flow. If at the current time the yeast cell is to the North/West of its desired position, then the electrodes are commanded to create a South/East flow. Perfect flow accuracy is not required because the feedback system will correct for any errors in the particle position at the next instant in time.

SIMULATION RESULTS FOR STEERING MULTIPLE PARTICLES

We have also demonstrated the independent steering of *multiple* particles in realistic simulations that include the effects of sensor noise and actuator uncertainty (see Figure 4).

Here we create complex, time-varying, micro-fluidic flows that carry all particles at once along their desired trajectories. A schematic of a micro-fluidic system that can achieve this kind of multi-particle steering is shown in Figure 1.

The behavior of this more complex system can be explained in physical terms as follows. The multiple electrodes can actuate different micro-fluidic modes in the system. For example, if we turn on all the East electrodes up and all the West electrodes down, this would create a bulk East to West flow. To create more complex fluid modes we can turn the North half of the East electrodes up, the South half of the East electrodes down, the North half of the West electrodes down, and the South half of the West electrodes up. This will create a quartered flow. It is clear that many electrodes will be able to actuate many different modes in the micro-fluidic system. Different modes will carry different particles in different directions. By judiciously choosing which modes to actuate at any given moment, we can steer particles independently of one another.

It is surprising that this is possible. For a single particle, we simply caused the flow to go North/West when the particle was to the South/East of its desired position. For multiple particles, the nature of micro-fluidic flows enables particle steering capabilities that are simply not possible on the macro scale. On macro scales, fluid momentum effects create extremely complex fluid flows. But on the micro scale, it is easier to predict the fluid behavior. Specifically, the low-Reynolds limit of the Navier Stokes equations gives a linear set of equations that can be effectively inverted: we can determine the necessary input voltages that will steer many particles at once in the desired directions. The limit on the number of particles that can be steered at once is determined by actuator and sensor accuracy considerations more so then by the number of actuators. To steer N particles, we must be able to actuate N fluid modes, but successive modes require more delicate and accurate sensor and actuator resolution. Given our current control algorithms and reasonable (5% accuracy) vision sensing and electroosmotic actuation, we can steer approximately ten particles at once.

The particle control algorithm can be explained in mathematical terms as follows. The micro-fluidic device of Figure 1 uses electroosmotic actuation to create fluid flow. The thin Debye moving layer of charges drags the fluid by viscous forces. This means that the micro-flow will follow the electric field that is active at the floor and ceiling of the device. In our case, the electric field is uniform in the vertical direction but it has complex patterns in the horizontal (x,y) plane. The resulting micro-flow will exhibit these same complex horizontal patterns

$$\vec{V}(x,y,z) = (\varepsilon\xi/\eta)\vec{E}(x,y) = -(\varepsilon\xi/\eta)\nabla\phi(x,y) .$$

Here $\vec{V}$ is the flow velocity, $\vec{E}$ is the electric field which is uniform in the vertical direction, ϕ is the electric potential as created by the actuators of Figure 1, ε is the permittivity of the liquid, η is its density, and ξ is the zeta potential (essentially the voltage) at the liquid/solid interface.

The floating neutral particles are simply carried along by the flow. Thus the particle positions are convected by $\dot{\vec{P}}_j = \vec{V}(\vec{P}_j) + \vec{w}$ where $\vec{w}$ is Brownian noise and $\vec{P}$ is the vector of particle x and y positions. The electric potential is described by Laplaces equation $\nabla^2\phi = 0$ with Dirichlet boundary conditions at the electrode boundaries $\phi(\partial D_j) = u_j$ where ∂D_j denotes the liquid/ electrode interface location and u_j is the jth applied voltage. Insulating Neumann conditions hold at all other surfaces. The solution of Laplaces equation is linear in the applied voltages so

$$\dot{\vec{P}} = \vec{V}(\vec{P}, z) + \vec{w} = -(\varepsilon\xi/\eta)\nabla\phi(\vec{P}) + \vec{w}$$
$$= A(\vec{P})\vec{u} + \vec{w}$$

where Φ_j is the solution to Laplaces equation when electrode j has a unit applied voltage and all other electrodes are at zero voltage, and $\vec{u}$ is the time-varying vector of applied voltages. Note that the velocities of the particles depends on where they are with respect to the electric potential ϕ(x,y). For the same set of voltages, two different particles in two different locations will execute different motions. In summary, the equations to be controlled are linear in the control and nonlinear in the particle positions: $\dot{\vec{P}} = A(\vec{P})\vec{u} + \vec{w}$.

We split the multi particle steering control into two tasks: open loop control for path generation and closed loop feedback control to correct for noise and sensing/actuation errors. The open loop control is based on a least squares inversion of the model equations $\dot{\vec{p}} = A(\vec{p})\vec{u}$. Our first task is to find the set of voltages $\vec{u}(t)$ that will generate a set of velocities $\vec{v}_D(t) = \dot{\vec{p}}_D(t)$ along the desired particle paths $\vec{p}_D(t)$. The least squares solution $\vec{u}(t) = \left[A^T(\vec{p}(t))A(\vec{p}(t))\right]^{-1} A^T(\vec{p}(t))\vec{v}_D(t)$ finds the set of open loop control voltages $\vec{u}(t)$ that will minimize the 2-norm error between the actual and the desired particle velocities $\left\|\dot{\vec{p}}(t) - \vec{v}_D(t)\right\|_2$. However, as stated, the least squares problem is ill-conditioned: even a 2% change in particle positions or velocities will lead to 200% changes in control voltages. We use singular value decomposition (SVD) modes to condition the least squares problem. (This essentially projects the problem onto the micro-fluidic modes given above in the physical explanation.)

The number of particles that we can steer at once is fixed by our actuator and sensor accuracy: as we attempt to steer more particles, we have to include more SVD modes, and this amplifies the sensor errors into larger control voltage fluctuations. For realistic system settings of noise and sensing/actuation errors, we can steer about ten particles at once in simulations.

Feedback linearization is used to correct for particle deviations away from the nominal trajectories due to Brownian noise and actuator/ sensor errors.

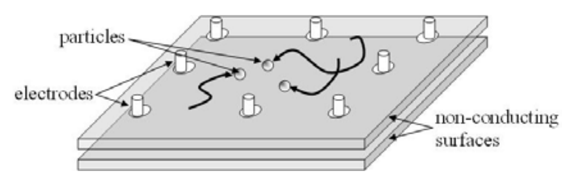

Figure 1: Schematic of the particle steering micro-fluidic system. The vertical inserted electrodes create complex time-varying planar fluid flows by electroosmotic forces. These flows can be used to cary many particles at once along desired trajectories.

CONCLUSION

This paper shows how to use feedback control of a micro-fluidic system to steer particles, without the need for laser tweezers. We have demonstrated steering of a single particle experimentally and independent steering of multiple particles in simulations. Future work will focus on steering many particles at once experimentally.

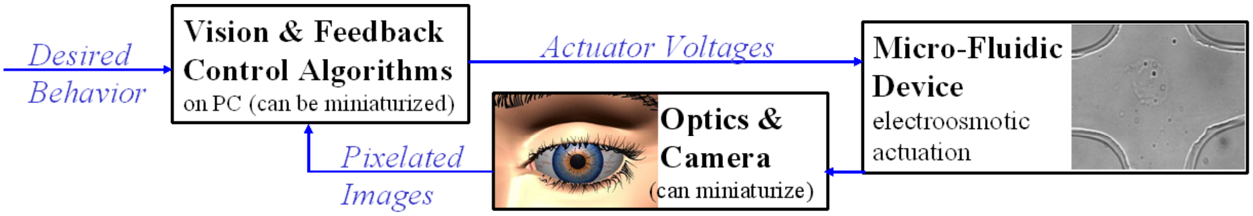

Figure 2: A micro-fluidic device with standard electroosmotic actuation is observed in real time by a camera that is connected to a computer. The PC has algorithms that find the location of the particles, compares them to the desired locations, and then computes the necessary actuator voltages that will cause the particles to move from where they are to where they ought to be.

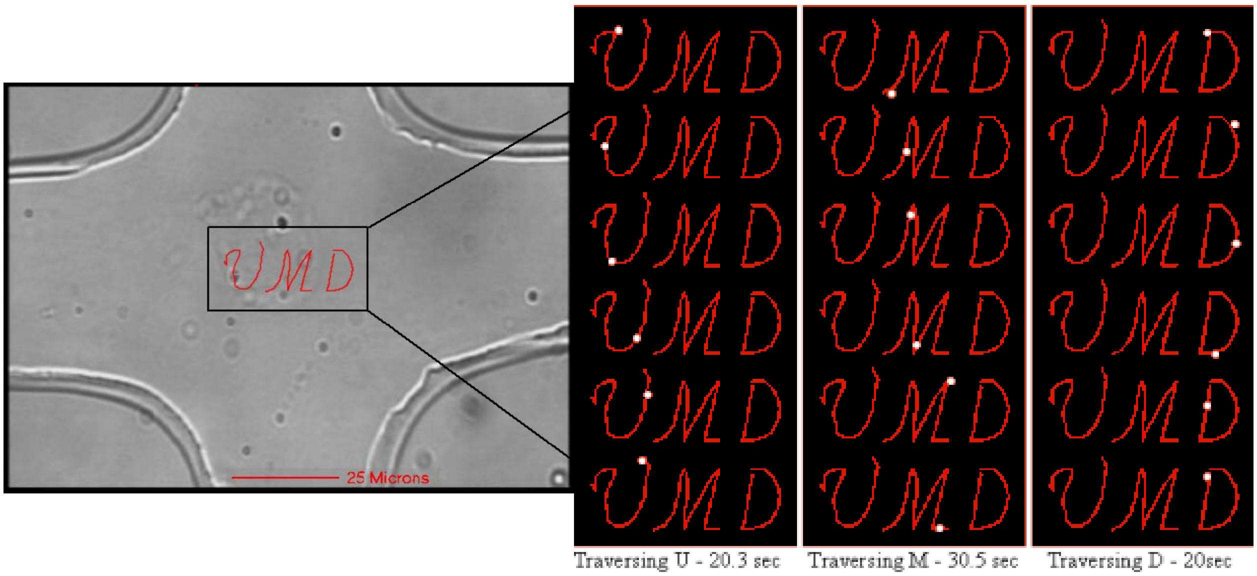

Figure 3: Left: Photograph of the micro-fluidic devices with the cursive 'UMD' path super-imposed on the image. Right: The actual path of the particle (white dot) in the feedback control experiment.

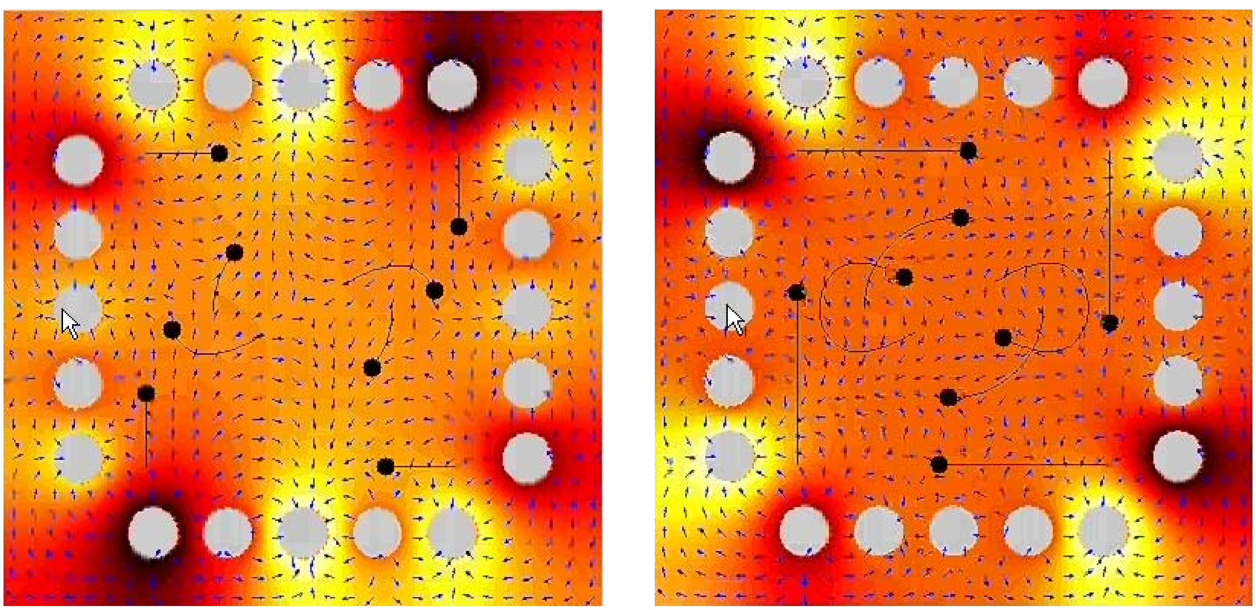

Figure 4: Simulation of multi-particle steering through electroosmotic fluid actuation and feedback control. The view is from above; two time instants are shown; the grey circles are the actuating electrodes; the small black circles are the eight particles to be controlled; the color field corresponds to the instantaneous voltage field; blue vectors are the resulting fluid velocities; and the black curves trace out the paths of the particles which match the desired paths commanded to the system.