OPTIMAL STRATEGIES FOR MOVING DROPLETS IN DIGITAL MICROFLUIDIC SYSTEMS

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Abstract

In digital microfluidic systems, analyte droplets (volume typically $\ll 1\mu l$) are transported on a planar electrode array by dielectrophoretic and electrowetting effects. While recent work has demonstrated feasibility mainly with single droplets on small arrays, these systems hold promise for commercial-scale applications by simultaneously moving many droplets on large arrays. This paper introduces a broadly applicable approach to optimally control digital microfluidic systems, *i.e.*, software algorithms that generate a sequence of control signals for moving one or many droplets from start to goal positions in the shortest number of steps, subject to constraints such as minimum required separation between droplets, obstacles on the array surface, and limitations in the control circuitry.

Keywords: digital microfluidics, droplet manipulation, control strategy, lab on a chip

1. Introduction

Several groups have demonstrated the movement of small droplets across a planar surface by electrostatic fields [*e.g.,* 1-5] and other means [*e.g.,* 6-8]. As an alternative to microfabricated networks consisting of reservoirs, channels, valves, and pumps, these digital microfluidic systems promise advantages through (1) greater flexibility – analyte handling may be reconfigured simply by re-programming rather than by changing the physical layout of the microfluidic components; (2) high droplet speeds – reportedly up
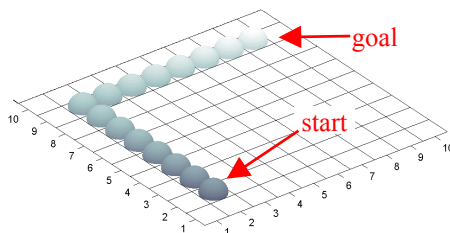

Figure 1a: Droplet moving on a 10×10 array from cell (2,2) to cell (9,9). The trace of the droplet is shown, with darker color indicating earlier steps.
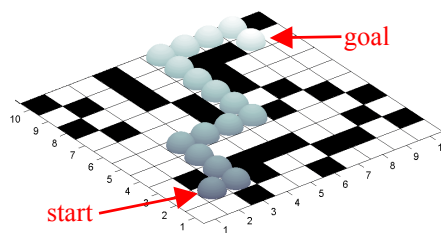
Figure 1b: Droplet moving from cell (2,2) to (9,9) while avoiding obstacles (shown as black cells). Here, an optimal strategy requires 16 steps, two more than in Figure 1a.

to 25cm/s [4]; (3) no dilution and cross-contamination due to diffusion and shear-flow; and (4) the possibility for massively parallel microfluidic circuits.

The research goal of this paper is to generate optimal sequences of control signals to move droplets from start to goal positions in the shortest number of steps. With growing array size and number of droplets, this becomes increasingly challenging: closely related optimizations are the travelling salesman problem and motion planning with multiple moving robots [9], which are known to be computationally complex (*i.e.*, NP-hard [10]).

2. Example

Figure 1 shows examples of control strategies for simple digital microfluidic systems. On a 10×10 array, a single droplet must be moved from cell (2,2) to cell (9,9). Figure 1a shows an optimal strategy consisting of 14 steps. In the system in Figure 1b, "forbidden" cells marked as black squares must be circumnavigated, resulting in a slightly longer solution sequence. The following section describes how these solutions can be generated automatically, and generalizes the approach to more complex scenarios with multiple moving droplets and additional constraints stemming from the physical implementation.

3. Modelling and Software Implementation

We first specify the physical properties of the digital microfluidic system:

Layout: typically a rectangular m×n array, but, *e.g.*, an arrangement of hexagonal cells is also possible.

Control circuitry for electrowetting: *e.g.*, individually addressable electrodes in each cell, or simpler row/column addressing.

Location of cells with special functions: reservoirs, sensors, waste, *etc*.

Then, we identify the number of droplets and their start and goal locations. Given this information, we can generate the optimal control strategy: a sequence of electrode signals that simultaneously steer all droplets from start to goal.

Our software provides a data structure to represent the array (inclusive special cells and obstacles), and keeps track of droplet locations at any specific time. Rules on how droplets can move from one cell to the next are added, taking into account constraints, *e.g.,* to avoid accidental merging of droplets. A systematic search is performed, using an A* algorithm known from artificial intelligence programming [11]. This method is guaranteed to always find an optimal solution if one exists, and indicate failure otherwise.

4. Results

In this section we show two additional examples of optimal control strategies. In Figure 2, two droplets require 8 steps to switch their positions while circumnavigating an obstacle. This strategy assumes that the electrodes in each cell can be activated independently from all other cells. The two droplets are always separated by at least one empty cell, such that accidental merging is avoided. Note that the darker droplet moves

more than necessary (steps 4 and 5), but this does not affect the overall number of steps. Future software improvements will eliminate this programming artefact.
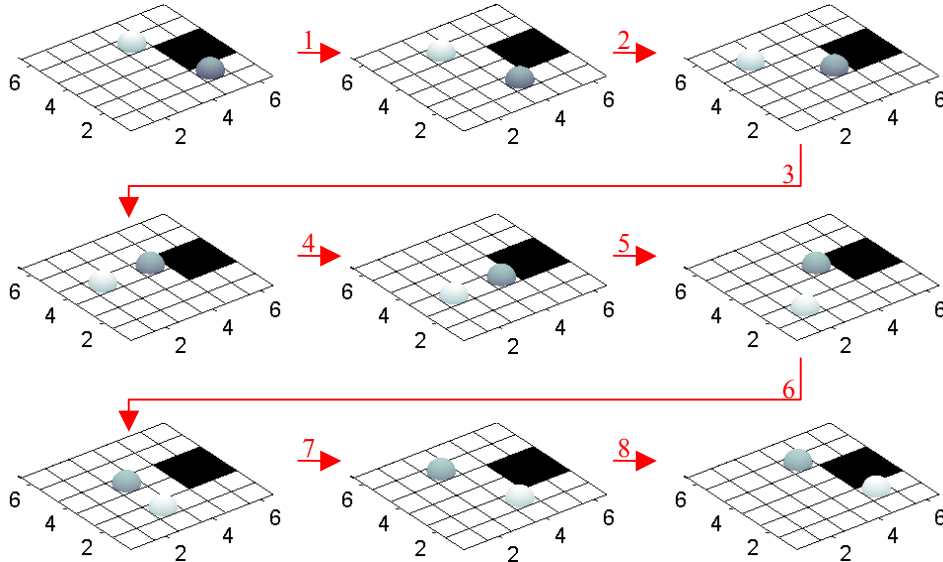

Figure 2: Two droplets moving simultaneously on a 6×6 array while avoiding an obstacle (black cells). The two droplets start at cells (5,2) and (4,5), and require 8 steps to trade places.

The previous examples (Figures 1 and 2) assumed that each cell in the array is individually addressable. However, [12] introduced a simpler addressing scheme based on a top layer of row electrodes and a bottom layer of column electrodes. This scheme creates additional constraints on the droplet motion. Figure 3 shows the same task as Figure 2 but performed only with row-column addressing, resulting in a longer sequence.

5. Conclusions and Future Work

Digital microfluidic systems based on droplet manipulation are promising because of their flexibility and reconfigurability: they shift complexity from microfluidics hardware to control software. We introduce a general approach for optimal control of digital microfluidic systems, and demonstrate its applicability to various scenarios.

Several directions for further research are under investigation: (1) Extending the software to handle other common operations in digital microfluidic systems, such as splitting and merging of droplets. (2) There may be a large number of droplets, but only a small number of different types of droplets; this could simplify the control strategies. (3) Currently, optimal solutions are generated but the implementation is exponential in the number of droplets; finding more efficient algorithms will be important for massively parallel digital microfluidic systems.
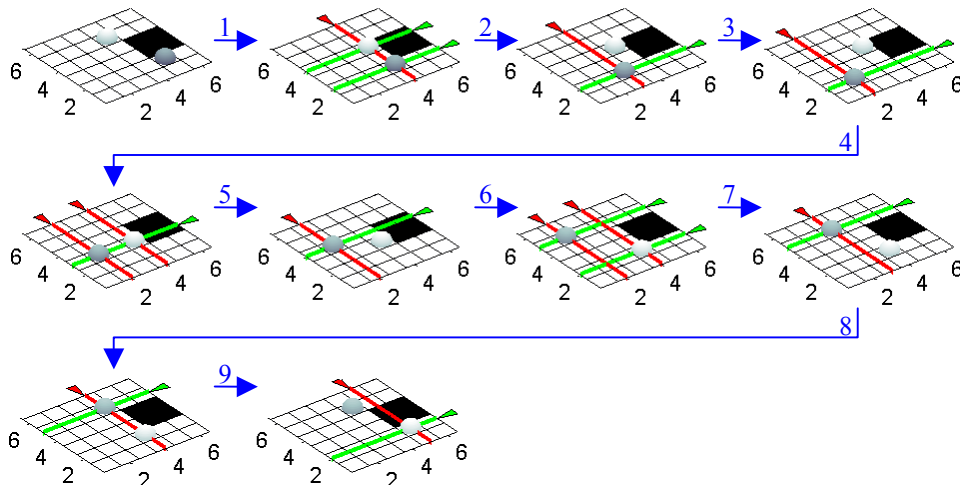
Figure 3: Two droplets trading places as in Figure 2 above, but here droplets move only to cells whose *row and column address* has been activated (indicated by triangular arrows). An optimal strategy now requires 9 steps, one more step than in Figure 2.

Acknowledgements

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The software is available at www.ee.washington.edu/research/mems/digitalfluidics.