CrossRouter: A Droplet Router for Cross-Referencing Digital Microfluidic Biochips

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Outline

1. Droplet Routing in Cross-Referencing Biochip
2. Formulation of Droplet Routing
3. CrossRouter: Idea and Implementation
4. Experiment and Evaluation
5. Conclusion
Droplet Routing Problem & Previous Works

- Similar to Motion Planning in Robotics
- NP-hard even for only two robots!
- Existing methods
  - A* Search, [Bohringer TCAD’06]
  - OSPF, [Griffith IJRR’05]
  - Pattern Selection, [Su DATE’06]
  - Network-Flow, [Yuh ICCAD’07]
  - Bypassibility, [Cho ISPD’08]
  - Graph-Coloring, [Griffith TCAD’06]
  - Clique-Partitioning, [Xu DATE’07]
  - Progressive ILP, [Yuh DAC’08]
Electrode Manipulation in Cross-Referencing DMFB

Apply a sequence of Voltage Assignment

Special and hard problem:

- Routing several droplets simultaneously - Electrode Interference

[Cite from [1]]

Electrode Interference and Solution

Supposed movements

Electrode Interference

Solution

- **High voltage**
- **Low voltage**
- Droplet
- Cell
Example of Routing Result

Extra-activated cells without causing interference (no droplet nearby)

Figure 1: time=0
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Problem Formulation

- **Input:**
  - A $W \times H$ 2D array
  - A netlist of $N$ net, either 2-pin or 3-pin
  - $K$ blockages
  - Waste disposal location $WAT$
  - Time limit $T$

- **Output:**
  - A *schedule of voltage assignment* for each time step
  - Fail if cannot finish routing before timing constraint

- **Objective:**
  - Route all droplets to their destinations
  - Minimize time used
  - (Minimize cell used)

- **Constraint…**
Voltage Assignment – A Snapshot

Voltage assignment for this time step:

(Row)
H: 6
L: 2, 5, 9, 20

(Column)
H: 0, 5, 11, 14
L: 8
Routing Result – Schedule of Voltage Assignment

Figure 1: time=0
Constraints

1. Timing Constraint (Hard constraint)
   - All droplets be moved within time $T$

2. Fluidic Constraint
   - A minimum spacing of one cell should be kept

3. Electrode Constraint
   - While activating some electrodes simultaneously, no interference is caused
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Overview of CrossRouter

START

Compute net order

All Routed?

N

Propagate next unrouted net

SUCCESSFUL?

N

First net?

Y

Ripup & Reroute

FAILURE

Backtrack

FINISH

Y

FINISH
Five possible movements

A 'droplet movement status'

At $P=(2,5)$, time=3

Backtrack path

Some previously routed net

$\text{Weight}(P,t) = t + \text{MD}(P, \text{sink}) + U(P) + \text{Len}(P,t)$

$N - \#\text{netuse}$

Current path length

Need to perform Fluidic/electrode check!
Fluidic Constraint

- To avoid unexpected mixing
  - Static fluidic constraint
    - $|x_1^t - x_2^t| \geq 2$ or
    - $|y_1^t - y_2^t| \geq 2$
  - Dynamic fluidic constraint
    - $|x_1^{t+1} - x_2^t| \geq 2$ or
    - $|x_1^t - x_2^{t+1}| \geq 2$
    - $|y_1^{t+1} - y_2^t| \geq 2$ or
    - $|y_1^t - y_2^{t+1}| \geq 2$
Electrode Constraint

- A crucial part in CrossRouter

- A constraint graph is used to determine if the simultaneous movements of a set of droplet is implementable

- Constraint Graph $G$
  - Vertices are electrodes that need to be assigned a H/L voltage
  - Two types of edges:
    - SAME and DIFF

- Two-colorability
  - High->RED  Low->BLUE
  - Each coloring corresponds to a voltage assignment

A Constraint Graph and a two-coloring
Constraint Graph by Example

Scenario: $d_3$ is NOT present

NO valid assignment for the graph!

Scenario: $d_3$ is present

Two colorable components

Forbidden cells

SAME Edge!

Interference!
Speed Up Technique - Incremental Coloring

- At every time step, a constraint graph is maintained.
  - No need to construct graph from scratch
  - Incrementally color the nodes
  - Can perform electrode check very efficiently!

[Diagram showing different cases and colorings for constraint graphs]
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Experiment Setup

- **Environment:**
  - Implemented in C++ language
  - Run on department’s Linux server
    - Intel Pentium IV 3.20GHz
    - 2GB Ram

- **Benchmarks:**
  - Real world benchmark including:
    - *in-vitro, in-vitro2, protein, protein2*

- **Compared with two previous works**
  - Yuh’s Progressive ILP
  - Cho’s High Performance Droplet Router (in terms of cell used)
## Experimental Result – Comparison I

<table>
<thead>
<tr>
<th>Circuit</th>
<th>#sub.</th>
<th>Progressive ILP [1]</th>
<th>CrossRouter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max/Average cycle</td>
<td>CPU time (sec.)</td>
</tr>
<tr>
<td>In-vitro_1</td>
<td>11</td>
<td>24/13.09</td>
<td>2.55</td>
</tr>
<tr>
<td>In-vitro_2</td>
<td>15</td>
<td>22/11.00</td>
<td>2.53</td>
</tr>
<tr>
<td>Protein1</td>
<td>64</td>
<td>26/16.15</td>
<td>15.36</td>
</tr>
<tr>
<td>Protein2</td>
<td>78</td>
<td>26/10.23</td>
<td>6.70</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>-/12.62</td>
<td>-</td>
</tr>
</tbody>
</table>

- The timing constraint of these benchmarks are all 20 steps
- In some subproblems, [1] exceeds the constraint, while CrossRouter completes all with smaller average cycle

Experimental Result – Comparison II

<table>
<thead>
<tr>
<th>Circuit</th>
<th># sub.</th>
<th>Size</th>
<th># cell used</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HPDRA [2]</td>
</tr>
<tr>
<td>In-vitro_1</td>
<td>11</td>
<td>16x16</td>
<td>258</td>
</tr>
<tr>
<td>In-vitro_2</td>
<td>15</td>
<td>14x14</td>
<td>246</td>
</tr>
<tr>
<td>Protein1</td>
<td>64</td>
<td>21x21</td>
<td>1688</td>
</tr>
<tr>
<td>Protein2</td>
<td>78</td>
<td>13x13</td>
<td>963</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>788.75</td>
</tr>
</tbody>
</table>

- HPDRA is for direct-addressing DMFB, in which no electrode constraint and thus easier
- We achieve a better cell used rate
  (For *In-vitro_2*, HPDRA found an earlier merging point for a 3-pin net and hence better)

Note: [1] does not provide # cell used

Conclusion

- The graph **two-coloring** based method is very succinct and powerful in handling the electrode constraint for droplet routing

- CrossRouter is an efficient router for droplet routing problem on cross-referencing biochip
  - Explores the degree of parallelism of moving droplets
    - Comparing to the state-of-the-art Progressive ILP method, it can solve the problems within timing constraint and achieves shorter routing time
  - Effectively **minimizes** the cell used during routing
    - Comparing to HPDRA, better cell used rate acquired
Thank You!