SOUND VALVE-CONTROL FOR PROGRAMMABLE MICROFLUIDIC DEVICES

Andreas Grimmer¹, Berislav Klepic¹, Tsung-Yi Ho², Robert Wille¹
¹ Johannes Kepler University, Linz, Austria
² National Tsing Hua University, Taiwan

Contact: andreas.grimmer@jku.at
MICROFLUIDIC LABS-ON-CHIP

- Reduced sample volume
- High-throughput
- Complex applications: protein crystallization, immunoassays, DNA-synthesizing, etc.

Source: http://miter.mit.edu/articlecommercial-microfluidicswandering-desert-or-entering-promised-land/
Each node consists of four valves (red blocks)
A node provides a full control of the flow to and from adjacent nodes
A node is used as reaction vessel
Realization consists of 64×300 pico-liter nodes
Controlled by 114 individually addressable valves

REALIZING APPLICATIONS ON PMDS

- Considered Task: Control valves
- In order to push the sample through the grid, a continuous flow path is required
- In one time step, a sample is pushed one node further in the flow path
- Flow paths must not intersect
- Overall: Push all samples to their target positions by determining flow paths in each required time step
MOTIVATION AND RELATED WORK

- Determining a valve-control is a difficult task because of
  - limited resources
    (area, operations, inputs, outputs)
  - overall time steps should be minimized

→ Use of automatic design solution

Development of a **sound** valve-control for PMDs

Result obtained from "A routability-driven flow routing algorithm for programmable microfluidic devices" by Yi-Siang Su et al. in *ASP-DAC*, 2016.
PROPOSED APPROACHES

Exact

Satisfiability Modulo Theories Solver

Solver

SAT

UNSAT

Heuristic

Standard VLSI Maze routing
EXACT: SYMBOLIC FORMULATION

For each sample \( s \) and time \( t \):

- **Positions:** \( pos^t_s = \{(pos^t_s[i].x, pos^t_s[i].y) : 0 \leq i < l\} \)
- **Inputs and Outputs:** \( in^t_s, out^t_s \)
- **Bends:** \( bend^t_s = \{(bend^t_s[i].x, bend^t_s[i].y) : 0 \leq i < 2 \times k\} \)

**Example:**

\[
\begin{align*}
pos^0_s &= \{(1,2), (1,1)\} \\
in^0_s &= 2, \quad out^0_s = 15 \\
bend^0_s &= \{(2,0), (1,0), (1,5), (5,5)\}
\end{align*}
\]

\[
\begin{align*}
pos^0_s &= \{(3,2), (3,1)\} \\
in^0_s &= 3, \quad out^0_s = 14 \\
bend^0_s &= \{(3,0), (3,0), (3,4), (6,4)\}
\end{align*}
\]
EXACT: CONSTRAINTS

All samples $s$ have to

- start on their starting position

$$\bigwedge_{s \in S} pos_s^0 = src_s$$

- reach their target at some time $t_t$

$$\bigwedge_{s \in S} \exists t_t \left( 0 \leq t_t < T \land \bigwedge_{t_t \leq t < T} pos_s^t = tgt_s \right)$$

Discussion:

- stay on the grid

$$\bigwedge_{s \in S} \bigwedge_{0 \leq t < T} (pos_s^t \cdot x < W \land 0 \leq pos_s^t \cdot y < H)$$

- can flow to an adjacent node

$$\bigwedge_{s \in S} \bigwedge_{0 \leq t < T} \left( pos_s^t[0] \cdot x = pos_s^{t-1}[0] \cdot x \land pos_s^t[0] \cdot y = pos_s^{t-1}[0] \cdot y - 1 \right)$$

\[ U_p^t \]

\[ \lor (\ldots) \lor (\ldots) \lor (\ldots) \lor (\ldots) \]

\[ Down_s^t, Left_s^t, Right_s^t, Pause_s^t \]

\[ \Rightarrow \] Results in huge search space

\[ \Rightarrow \] Applicable only for small instances

BUT: Useful for evaluating heuristic solutions
PROPOSED APPROACHES

Exact

Satisfiability Modulo Theories Solver

Solver

SAT

UNSAT

Heuristic

Standard VLSI Maze routing
# HEURISTIC

### Applied simplifications:
- Samples flow continuously from source to target
- Determine flow path for each sample one after another

### Implications:
- Cannot guarantee a solution within a certain amount of time steps
- But this solution is still sound!

### Procedure:
Three sub-paths are required:
- From any input to the "tail" of the sample source
- From the "head" of the sample source to the "tail" of the sample target
- From the "head" of the sample target to any output

→ Application of a standard routing algorithm, namely **maze routing with a rip-up and reroute method**
EVALUATION – QUALITY

Number of timesteps

- 2 Samples 3 Samples 4 Samples 2 Samples 3 Samples 4 Samples 2 Samples 3 Samples 4 Samples
- 6x6 8x8 10x10

Required 3 hours

Required 0.092 seconds
EVALUATION – COMPARISON TO RELATED WORK

<table>
<thead>
<tr>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x10; 5 Samples</td>
</tr>
<tr>
<td>10x10; 10 Samples</td>
</tr>
<tr>
<td>20x20; 20 Samples</td>
</tr>
<tr>
<td>30x30; 30 Samples</td>
</tr>
<tr>
<td>40x40; 40 Samples</td>
</tr>
<tr>
<td>50x50; 50 Samples</td>
</tr>
</tbody>
</table>

CONCLUSION

Two complementary approaches:

- **Exact Satisfiability Modulo Theories Solver**
  - SAT
  - UNSAT

- **Heuristic Standard VLSI Maze routing**

Limitations:
- Does not consider physical properties (i.e. applied pumping pressure, fluids, ...)
- Considers only valve-control

Open Source:
http://www.jku.at/iic/eda/pmd
SOUND VALVE-CONTROL FOR PROGRAMMABLE MICROFLUIDIC DEVICES

Andreas Grimmer¹, Berislav Klepic¹, Tsung-Yi Ho², Robert Wille¹
¹ Johannes Kepler University, Linz, Austria
² National Tsing Hua University, Taiwan

Contact: andreas.grimmer@jku.at