Sequence-Pair-Based Placement and Routing for Flow-Based Microfluidic Biochips

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Outline

- Background
- Problem Formulation
- Contributions
- Overall Design Flow
- Placement and Routing Method
- Routing Feedback and Placement Adjustment
- Experimental Results
- Summary
Flow-Based Microfluidic Biochips

- One of the many different types of biochips
- Based on multilayer soft lithography technology
- Functional units are fabricated by elastomer material (polydimethylsiloxane, PDMS)

http://groups.csail.mit.edu/cag/biostream/
Schematic of flow-based biochips

(a) 3D view.

(b) Top and side views.
Microvalve

- Used to control the movement of flow
- Located between control and flow channels at their intersection region

1. Load sample on top
2. Load sample on bottom
3. Rotary Mixing

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Design of Flow-Based Biochips

**Flow-Layer Design**

(1) Sequencing graph

(2) Scheduling

(3) Placement & Routing

**Control-Layer Design**

(4) Microvalve position

(5) Microvalve addressing

(6) Control-layer routing
Flow-Layer Design

(1) Sequencing graph
A directed acyclic graph specifying the sequential order of operations

(2) Resource binding and scheduling
Choosing the specific component for each operation
Computing the starting and finishing time of each operation

(3) Component placement & channel routing
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Requirements:
(1) Minimum component spacing
(2) Minimum channel width
(3) Minimum channel spacing

Objective: Minimize weighted cost of
(1) Chip area
(2) Number of intersections
(3) Total channel length
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Contributions

- Integrated placement and routing method is proposed
- Sequence-pair-base placement with simulated annealing optimization
- Negotiation-based routing method is adopted for channel routing
- Placement adjustment method
- Routing feedback mechanism
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Overall Design Flow of Our Approach

- Placement and Routing
- Biochemical Assay
- Initial Sequence Pair Generation
- Negotiation-Based Routing
- Design Result
- Placement Adjustment
- Scheduling
- Component Library
- Input Module

Placement representation

Placement optimization

Single-layer routing with path intersections allowed

Congestion problem
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Sequence-pair (SP) representation

- SP enables a solution space polynomial-admissible
  1. The solution space is finite
  2. Every solution is feasible
  3. Realization of a code is possible in polynomial time
  4. There exists a code corresponds to one of the optimal solutions

- Set of components: \( M = \{a, b, c, d, e, f\} \)

- SP code: \((s_1, s_2)\)

- Rule for explaining the SP code
  A. If \( a \) is before \( b \) in both \( s_1 \) and \( s_2 \), then \( a \) is on the left side of \( b \)
  B. If \( a \) is before \( b \) in \( s_1 \), and after \( b \) in \( s_2 \), then \( a \) is above \( b \).
Sequence-pair (SP) representation

(s1, s2) = (ecadfb, fcbead)
Simulated annealing-based placement (1)

- Initial code $SP = (s_1, s_2)$
- Expanded spacing vector
  - $EX = \{ ex_i \}$  $EY = \{ ey_i \}$  $e_{\text{min}} \leq ex_i$  $ey_i \leq e_{\text{max}}$
- Placement state $ST = (s_1, s_2, EX, EY)$
- Initial temperature $T$
- Energy function $E(ST)$ for placement $ST$
- If $E(STM') < E(ST)$ or $p < p_0$, accept the new solution $STM'$

$$p_0 = e^{\frac{E(ST) - E(ST')}{T}}$$

$p \in [0, 1]$
Simulated annealing-based placement (2)

Randomly generate placement ST

- Randomly generate binary (0/1) value $b$
  - $b=0$
    - Choose component $m_i$
    - Choose $e_x^i$ or $e_y^i$
    - Increase or decrease it by 1
  - $b=1$
    - Choose $s = s'_1$ or $s'_2$
    - Swap two components $m_i, m_j$

If $E(ST') < E(ST)$ or $p < p_0$

- Accept $ST'$
- Abandon $ST'$
Simulated annealing-based placement (3)

- Energy function of placement state $ST$

$$E(ST) = \alpha \cdot A + \beta \cdot C + \gamma \cdot L + \theta \cdot L_2$$

- $A$: area of the minimum bounding box of all placement components
- $C$: total number of crossings between line segments corresponding to the nets
- $L$: sum of Manhattan distances of the nets
- $L_2$: sum of square of Manhattan distances corresponding to the nets
Negotiation-Based Routing

- Cost function for history cost

\[ C_h(g)^{r+1} = C_b + \lambda \cdot C_h(g)^r \]

- \( C_h(g)^{r+1} \) is current history cost of routing grid \( g \) for iteration \( r + 1 \)
- \( C_b \) is the base history cost
- \( C_h(g)^r \) is the history cost in iteration \( r \)
- \( \lambda \) is set to be 0.1
Negotiation-Based Routing

Route a net

success

Set path obstacle

Update history cost

Step 1 finished

Yes

Modified A-star searching $F(g) = G(g) + C(g) + H(g)$

No

No
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Routing Feedback and Placement Adjustment

SP code keep the same

Corresponding components are pushed away
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With and without placement adjustment

Number of channel intersections


50%  67%  43%  20%  57%
With and without placement adjustment

With and without placement adjustment

Chip area

Comparison with the other method


Comparison with the other method


Comparison with the other method


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Summary

- An effective integrated placement and routing flow
- Using sequence-pair-based iterative placement
- Routing feedback and placement adjustment
- Real-life biochemical applications validate the presented method effectiveness

Thank you!