Multi-Angle Bended Heat Pipe Design Using X-Architecture Routing with Dynamic Thermal Weight on Mobile Devices

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Outline

• Introduction
• Thermal simulation on smartphone with heat pipe
• XHPR: X-architecture thermal driven heat pipe routing engine
• Experimental results
• Conclusions
Motivation (1/3)

• The application processor (AP) in high-end smartphones is *overheated*
  – High performance
  – Die shrink

• Why consider thermal issues on smartphones?
  – Decreasing carrier mobility slows down the device and degrades the performance of die
  – High skin/screen temperature cause the thermal burn
Motivation (2/3)

• Thermal solutions for smartphones
  – Graphite sheet
  – Metal back cover
  – Heat pipe
Motivation (3/3)

• Why heat pipe is suitable for smartphones?
  – High thermal conductivity (1000~100000 W/(m·K)) [7]
  – Light
  – Cheaper (USD$ 1.5) [8]

• The smartphones in industry

There are still few discussions about automatic heat pipe routing design tools
Heat Transfer Equation

- Heat transfer equation for steady state

\[ \nabla \cdot (\kappa(\mathbf{r})\nabla T(\mathbf{r})) = p(\mathbf{r}) \]

The total heat transferring out of the control volume

Heat generation in the control volume

- Boundary condition

\[ \kappa(\mathbf{r}_b) \frac{\partial T(\mathbf{r}_b)}{\partial n_b} + h_b T(\mathbf{r}_b) = f_b(\mathbf{r}_b) \]

Heat transfer equation is partial differential equation

It is difficult to be solved

Finite difference method

\( \mathbf{r} \): Arbitrary position
\( \kappa \): Thermal conductivity
\( T \): Temperature
\( p \): Heat generation
\( \mathbf{r}_b \): Arbitrary position in boundary
\( n_b \): Outward normal to boundary
\( h_b \): Heat transfer coefficient on boundary
Compact Thermal Model

- Thermal resistance between two adjacent grids $q$ and $w$ [12]

$$r(q, w) = \frac{1}{A_{q,w}} \left( \frac{d_q}{k_q} + \frac{d_w}{k_w} \right)$$

- Boundary thermal resistance

$$r_b = \frac{1}{h_b A_b}$$
Heat Pipe Cooling Technique (1/2)

• What is heat pipe?
  – A two-phase heat transfer device that has the good ability to transmit heat

• Principle of heat pipe
  – The working fluid evaporates by heat absorption in hot region
  – Vapor travels to the cold region
  – Vapor condenses into fluid by dissipating heat in cold region and flows back through wick structure
Heat Pipe Cooling Technique (2/2)

• Why do we need multiple angle bended heat pipes?
  – Smartphone’s structure
  – The thermal resistance increases with increasing the bending angle [13]
    1. Reduction in the vapor core
    2. Disruption in the path of liquid flowing back to the evaporator
A* Search Algorithm (1/2)

- An effective pathfinding algorithm that finds the least cost path from source to sink
  - Be extended from the Dijkstra algorithm
  - Apply heuristic estimation to improve searching quality
A* Search Algorithm (2/2)

- The mechanism of A* algorithm
  - The evaluation function decides the promising grid

\[ f(n) = g(n) + h(n) \]

- The exact movement cost (start → n)
- The estimated movement cost (n → destination)

Examine the most promising unexplored location it has seen

Is location the goal? yes no

Make note of all that location’s neighbors for further exploration

Finish
Thermal Simulation on Smartphone with Heat Pipe

Thermal Simulation Flow

- Multi-angle bended heat pipe modeling
  - Heat pipe effective thermal conductivity
  - Cuboids approximation for bended heat pipe structure
Thermal Simulation on Smartphone with Heat Pipe

Heat Pipe Effective Thermal Conductivity

$g_5 = \frac{p_{hp}}{\Delta T}$ and $g_5 = \frac{kA_{hp}}{L}$

$\rightarrow k = \frac{p_{hp}L}{\Delta T A_{hp}}$

*$p_{hp}$: The power of AP, $\Delta T=2.5^\circ C$ [15]
*L: The length of vapor channel
*A$_{hp}$: The cross-section area of vapor channel
*k: Thermal conductivity of straight vapor
$n_{45}/n_{90}$: The number of 45/90-degree bend

- Degrading rate are 86% and 80% of 45-degree bend and 90-degree bend, respectively [13]

$$k_{vapor,45/90} = \frac{p_{hp}L}{\Delta T A_{hp}} \times 0.86^{n_{45}} \times 0.8^{n_{90}}$$
Thermal Simulation on Smartphone with Heat Pipe

Cuboids Approximation for Bended Heat Pipe Structure

- Integrate the developed compact thermal model of multi-angle bended heat pipe into the compact thermal model of system
  - Chop the heat pipe and use several cuboids to approximate its original shape

\[ \Delta x \] is the width of each rectangle.
XHPR
Design Flow

• Goal
  – Maximize the temperature reduction of AP by designing the 45/90-degree bended heat pipe path

• Overview
  – X-architecture thermal driven routing algorithm
  – Learning based dynamic thermal weight calculator
  – Thermal simulation of heat pipe
Dynamic Thermal Weight Calculator

• Why do we need to build dynamic thermal weight function?
  – The phenomenon of two-phase heat transfer with heat pipe is difficult to estimate while routing heat pipe
    1. Bending angle
    2. Bending number
    3. Routing position

• We adopt a supervised machine learning method to build a dynamic thermal weight function
Dynamic Thermal Weight Calculator

Machine Learning Framework

Heat pipe routing patterns with the bending numbers (0 to 3) and two bending angles (45 and 90 degrees)

Input file
- Smartphone profile: Geometry, Material, Boundary condition
- Power profile: Steady-state power
- Heat pipe patterns

Output file
- Dynamic thermal weight function for heat pipe routing

Flowchart:
- ANSYS Fluent
- Temp.
- Distance
- Label
- Bending number
- Model Selection
- Maximum error < threshold
- yes
- no
- Model Testing
- Model Training
Dynamic Thermal Weight Calculator

**Feature Variable List**

- Obtain the thermal distribution of smartphones with heat pipe routing patterns
- Extract the feature variables that would cause some thermal effects from each grid in thermal map as our data
  - The *rising temperature* of source and sink of heat pipe
  - The *distance* between the grid and the source grid
  - The *label* whether the heat pipe passes the grid
  - The *bending number* of heat pipe in 45 or 90 degrees
  - The *rising temperature* of grid without employing the heat pipe cooling technique
  - The *temperature reduction* of each grid
Dynamic Thermal Weight Calculator

Learning Model Building

• \( y_p(x, w) = \sum_{k_1+\cdots+k_7 \leq 6} w_{k_1,\ldots,k_7} \prod_{j=1}^{7} x_j^{k_j} \)
  \( \forall k_i \in 0 \cup \mathbb{N} \)

  – \( y_p(x, w) \) is our predicted target value
  – \( x = (x_1, x_2, \ldots, x_7)^T \) is the vector of input variables
  – \( w = (w_0, \ldots, 0, w_1, \ldots, 0, \ldots, w_0, \ldots, 6)^T \) is the vector of function parameters

• Gaussian distribution assumption for data
  – \( p(t|x, w, \beta) = N(t|y_p(x, w), \beta^{-1}) \)
  – \( t \) is corresponding target value of \( x \)
  – \( \beta \) is the precision of distribution

• Using maximum likelihood function to determine \( w \)

We use six order multivariate polynomial function as our learning model
X-Architecture Thermal Driven Routing
Routing Algorithm Basic Introduction

• X-architecture thermal driven routing is based on A* algorithm
  – The predicted process improves the result and searching quality
• X-architecture thermal driven routing manipulates the routing grids for finding the path has maximum total accumulated temperature reduction (accumulated heat)
• Definition of terms using in X-architecture thermal driven routing
  – expanded grid: The grid chose as promising grid
  – neighbor grid: The grid propagated from expanded grid
  – openList: A list of grids that has been propagated but not yet expanded
  – closedList: A list of grids which has been expanded
X-Architecture Thermal Driven Routing

Path Scores Definition

• Total accumulated temperature reduction from source to sink through the grid \( r_i \) is composed of
  - Accumulated temperature reduction from source to \( r_i \)
  - Predicted accumulated temperature reduction from \( r_i \) to sink
  - \( f(r_i) = g(r_i) + h(r_i) \)

• Accumulated temperature reduction function
  \[ g(r_i) = \sum_{j \in \text{src} \rightarrow r_i} y_p(j, \mathbf{x}, \mathbf{w}) \]

• Predicted accumulated temperature reduction function
  \[ h(r_i) = \sum_{j \in r_i \rightarrow \text{sink}} y_p(j, \mathbf{x}, \mathbf{w}) \]

\( y_p(j, \mathbf{x}, \mathbf{w}) \): The dynamic thermal weight function
\( j, \mathbf{x} \): The feature variable of grid \( j \)
\( \text{src} \rightarrow r_i \): The searching path from the source grid to current grid \( r_i \)
\( r_i \rightarrow \text{sink} \): The predicted path from the current grid \( r_i \) to sink grid
X-Architecture Thermal Driven Routing

Basic Operation of Routing Algorithm

1. Choose the grid which has maximum $f$ scores in openList as expanded grid

2. Move expanded grid from openList to closedList

3. Find the neighbor grid of expanded grid and check the condition of it
   - In closedList: skip following operations
   - In openList: calculate $g$ scores
   - Otherwise: put it into openList, and calculate $g$ scores

4. Update the neighbor grid if the current expanding is better than before
   - Update $g$ scores
   - Execute the predicted process to get $h$ scores
   - Calculate $f$ scores
# X-Architecture Thermal Driven Routing

## Routing Process (Part 1)

### Source and sink grid assignment

1. **Initialization of searching map**
2. **Putting src into openList**
3. Choosing the promising grid in openList as expanded grid and putting into closedList

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**src**

### Pointer to parent grid

- \( g \): Index
- \( h \): 
- \( f \): 

**sink**

**Put src into openList**

**Choosing the promising grid in openList as expanded grid and putting into closedList**
# X-Architecture Thermal Driven Routing

## Routing Process (Part 1)

1. **Source and sink grid assignment**
2. **Initialization of searching map**
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*sink*

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# X-Architecture Thermal Driven Routing

## Routing Process (Part 1)

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Source and sink grid assignment

Initialization of searching map

Putting src into openList

Choosing the promising grid in openList as expanded grid and putting into closedList

- `sink`
- `src`
### X-Architecture Thermal Driven Routing

**Routing Process (Part 1)**

1. **Source and sink grid assignment**
2. **Initialization of searching map**
3. **Putting src into openList**

Choosing the promising grid in *openList* as *expanded grid* and putting into *closedList*.

#### Source and Sink Grid Assignment

- **src**
- **sink**

#### Initialization of Searching Map

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X-Architecture Thermal Driven Routing
Routing Process (Part 2)

Choosing the promising grid in openList as expanded grid and putting into closedList

- Backtracking the path
  - Yes: Is the expanded grid the sink?
  - No: Finding the neighbor grid of expanded grid
    - No: Is the neighbor grid not in closedList?
      - Yes: Is the neighbor grid not in openList?
        - Yes: Putting the neighbor grid into openList
        - No: Calculation for acc. temp. reduction (accHeat) of the neighbor grid
          - accHeat > g
            - Yes: Updating g scores to accHeat and recording predecessor

sink

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X-Architecture Thermal Driven Routing
Routing Process (Part 2)

Backtracking the path

Choosing the promising grid in openList as expanded grid and putting into closedList

Is the expanded grid the sink?

no

Finding the neighbor grid of expanded grid

Is the neighbor grid not in closedList?

no

Is the neighbor grid not in openList?

no

Putting the neighbor grid into openList

Calculation for acc. temp. reduction (accHeat) of the neighbor grid

accHeat > g

Update g scores to accHeat and recording predecessor

sink

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X-Architecture Thermal Driven Routing
Routing Process (Part 2)

Choosing the promising grid in openList as expanded grid and putting into closedList

Finding the neighbor grid of expanded grid

Updating g scores to accHeat and recording predecessor

Calculation of h scores

Calculation of f scores

Are all neighbor grids done?

yes

no

sink

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X-Architecture Thermal Driven Routing
Routing Process (Part 2)

Choosing the promising grid in openList as expanded grid and putting into closedList

Finding the neighbor grid of expanded grid

Updating g scores to accHeat and recording predecessor

Calculation of h scores

Calculation of f scores

Are all neighbor grids done?

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src
X-Architecture Thermal Driven Routing
Routing Process (Part 2)

Choosing the promising grid in openList as expanded grid and putting into closedList

Finding the neighbor grid of expanded grid

Updating g scores to accHeat and recording predecessor

Calculation of h scores

Calculation of f scores

Are all neighbor grids done?  no

yes
X-Architecture Thermal Driven Routing

Routing Process (Part 2)

Choosing the promising grid in openList as expanded grid and putting into closedList

Finding the neighbor grid of expanded grid

Updating g scores to accHeat and recording predecessor

Calculation of h scores

Calculation of f scores

Are all neighbor grids done?

no

yes
X-Architecture Thermal Driven Routing

Routing Process (Part 2)

1. Choosing the promising grid in `openList` as expanded grid and putting into `closedList`.
2. Finding the `neighbor grid` of expanded grid.
3. Updating `g` scores to `accHeat` and recording predecessor.
4. Calculation of `h` scores.
5. Calculation of `f` scores.
6. Are all `neighbor grids` done?
7. If `no`, repeat from step 1. If `yes`, proceed with the next step.

**Example Table:**

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# X-Architecture Thermal Driven Routing

Routing Process (Part 2)

1. Choosing the promising grid in `openList` as expanded grid and putting into `closedList`
2. Finding the neighbor grid of expanded grid
3. Updating $g$ scores to `accHeat` and recording predecessor
4. Calculation of $h$ scores
5. Calculation of $f$ scores

---

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- Are all neighbor grids done?
  - **yes**
  - **no**

---

Diagram showing the routing process with the grid and nodes connected by arrows, indicating the path. The grid has nodes labeled with numbers, and the arrows show the flow or direction of the thermal driven routing process.
X-Architecture Thermal Driven Routing
Routing Process (Part 3)

- Choosing the promising grid in openList as expanded grid and putting into closedList
- Backtracking the path
  - Is the expanded grid the sink?
    - yes
    - no
      - Finding the neighbor grid of expanded grid
        - Is the neighbor grid not in closedList?
          - yes
          - no
            - Is the neighbor grid not in openList?
              - yes
              - no
                - Putting the neighbor grid into openList
                  - Calculation for acc. temp. reduction (accHeat) of the neighbor grid
                    - accHeat > g
                      - yes
                      - no
                        - Updating g scores to accHeat and recording predecessor
- 19  4
- 0   23
- 1   22
- 2   24
- 3   25
- 14  4
- 4   18
- 5   19
- 6   22
- 7   24
- 8   0
- 9   20
- 10  10
- 12  10
- 13  11
- 0   0
- 8   12
- 5   25
- 7   18
- 0   0
- 11  8
- 4   17
- 15  15
- src
X-Architecture Thermal Driven Routing

Routing Process (Part 3)

Choosing the promising grid in openList as expanded grid and putting into closedList

Is the expanded grid the sink? yes

Finding the neighbor grid of expanded grid

Is the neighbor grid not in closedList? yes

Is the neighbor grid not in openList? yes

Putting the neighbor grid into openList

Calculation for acc. temp. reduction (accHeat) of the neighbor grid

accHeat > g yes

Updating g scores to accHeat and recording predecessor

Backtracking the path
Experimental Results

Environmental Settings

• Program language: C++
• Personal computer (PC)
  – RAM: 16G
  – CPU: Intel (R) Core (TM) i7-2600 CPU @3.40GHz
• Experimental target
  – Samsung Galaxy 4 (GS4)
  – Google Nexus 5 (N5)
• Case of power profile, C1-C5 [16]
## Experimental Results

### Pipe Thermal Model Validation

The results are with the temperature of center application processor (AP), and maximum temperature of skin (Sk), and screen (Sc).

<table>
<thead>
<tr>
<th>Case</th>
<th>Bends</th>
<th>Fluent</th>
<th>Proposed thermal simulator</th>
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<td>Runtime (s)</td>
<td>Error (%)</td>
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**Maximum error:** 4.79%, 10.85%, and 13.58% (AP, skin, screen)

**Speedup is with two order of magnitude (311×)**

GS4: Samsung Galaxy 4; N5: Google Nexus 5
Experimental Results

Temperature Reduction with Heat Pipe Designs

<table>
<thead>
<tr>
<th>Case</th>
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<th>I-MR-D</th>
<th>XHPR</th>
<th>Exhausted method</th>
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<td>AP</td>
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**XHPR can reduce the temperature of AP at least 13.20%**

It shows that XHPR achieves the better cooling ability than others.

SP-A*: shortest path A* routing algorithm [17]; I-MR-D: the 90-degree maze routing method in [18]; XHPR: X-architecture thermal driven routing; Exhausted method: [19]
Experimental Results

Thermal Maps & Heat Pipe Routing Paths

**NOHP**

**SP-A**

**I-MR-D**

**XHPR**

Exhausted method

GS4-C1

N5-C1
Conclusion

• In this work, we present
  – A compact thermal model of multi-angle bended heat pipe for accurate and fast thermal simulation
  – A developed X-architecture thermal driven routing algorithm for heat pipe design
  – A thermal weight calculator using in the heat pipe routing stage to support heat pipe design
  – The proposed X-architecture thermal driven heat pipe routing engine can reduce the temperature at least 13.20% in application processors
Reference

[1] https://phandroid.com
[12] ISAC: Integrated Space-and-Time-Adaptive Chip-Package Thermal Analysis Yonghong Yang, Student Member, IEEE, Zhenyu (Peter) Gu, Student Member, IEEE, Changyun Zhu, Student Member, IEEE, Robert P. Dick, Member, IEEE, and Li Shang, Member, IEEE
Thanks for listening 😊