Image Super-resolution for Ultrafast Optical Time-stretch Imaging

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Presentation Outline

• Introduction of Time-stretch Imaging
• Modeling the Image Sampling
• Super-resolution with Subpixel Shift
• Evaluation Simulation
• Experiment Results
• Summary & Future Work
Time-stretch Imaging

• **Application**
  - Ultrafast optical microscopy
    - High-throughput microfluidic (8 m/s)
    - 100,000 cells/s
    - >10 MHz line scanning rate
    - Real-time imaging
  - Connected with digital system
    - Cancer cell detection
    - Precision Medicine

• **Challenges**
  - Expensive oscilloscope
    - HKD 1,000,000
  - Huge data processing
    - 80 GB/sec

• **Next:** Home-built system
Time-stretch Imaging System

Phase 1: Spectral Encoding
- Microfluidic flow, ~100,000 cells/sec
- Line-scan laser

Phase 2: Time-stretch
- Time-stretch via few-mode fiber
- Amplify with an optical gain

Phase 3: Digitize
- Transformation from optical to electronic signal
- Continuous signal sampling
- 2-D Cellular image formation on FPGA
Modeling of Image Sampling

- **Line Scanning and Time Stretch (Optical System)**
  - Fixed frequency line scanning (colorful bands on the cell image)
  - Time-stretch the spatially-encoded signal, generate the continuous signal

- **Normal Line-aligned Sampling (High-speed ADC)**
  - Uniformly sampling the time-stretched signal (3 sampling points per line in following example)
  - Digitize the samples from analog signal to 8-bits grey-scale pixel data

- **2D Image Stack (FPGA, Field Programmable Gate Array)**
  - Construct the cell image
Sampling Model Parameters

- Parameters set in line-aligned sampling

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Denotation</th>
<th>Sample Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Pulse Frequency (fixed)</td>
<td>$f_{\text{laser}}$</td>
<td>11.4 MHz</td>
</tr>
<tr>
<td>ADC Sampling Frequency</td>
<td>$f_{\text{sampling}}$</td>
<td>3.99 GHz</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>$v_{\text{flow}}$</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Imaging Width</td>
<td>$\text{Width}$</td>
<td>250 µm</td>
</tr>
</tbody>
</table>

- Calculation of digitized image resolution (unit: pixel/µm)

$$R_{\text{horizontal}} = \frac{f_{\text{sampling}}}{\text{Width} \times f_{\text{laser}}} \quad R_{\text{vertical}} = \frac{f_{\text{laser}}}{v_{\text{flow}}}$$

<table>
<thead>
<tr>
<th>Variables</th>
<th>Denotation</th>
<th>Sample Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Resolution (Horizontal)</td>
<td>$R_{\text{horizontal}}$</td>
<td>1.4 pixel/µm</td>
</tr>
<tr>
<td>Image Resolution (Vertical)</td>
<td>$R_{\text{vertical}}$</td>
<td>11.4 pixel/µm</td>
</tr>
</tbody>
</table>

The slower, the more information be caught in vertical
Spatial imaging range in horizontal

$\sim$8x unbalanced H/V resolution

350x Sampling 350 points per line
Unbalanced H/V Resolution

Demonstration of unbalanced H/V resolution image, image is sampled more tightly in vertical direction

MCF-7 (breast cancer cell) imaging with line-aligned sampling method, sampling frequency is 3.99 GHz. Jagged-edge is apparent in horizontal direction

• How to optimize the sampling?
  • Method Constraints
    • Only slightly adjust the ADC sampling frequency, but still sampling line scans uniformly
    • No computation overhead (complicate interpolation computation), because of the ultrafast throughput (4GB/s)
    • Acceptable data increment
  • Method Assumption
    • Combine several lines into one line
    • Different with line-aligned sampling, sampling points between lines should be shifted / interleaved
Super-resolution with Subpixel Shift

- Adjust the sampling frequency (T to T+ΔT)
  - Previous line-aligned sampling: 3 points per line (in previous example picture)
  - Super-resolution sampling: 8 points per 3 lines (in this example picture), not integer sampling points per line
  - new co-prime parameters: \{p, q\}

- Interleave samples of every q lines to one super-resolution line
  - Interleave pattern repeats every q lines
  - In the example picture, horizontal resolution will be \(~3x\) higher (with the subpixels); vertical resolution will be \(~3x\) lower
Super-resolution Sampling

• Relations of parameters in super-resolution sampling
  • Sampling frequency is decided by \{p, q\} and laser frequency, also should be constrained at \(~4\text{GHz}\).
  • q decides spatial line number that used to generate the super-resolution line. Case q=1 is equivalent to the normal line-aligned sampling
  • Hence, p is a proper number that constrained by q and sampling / laser frequency.

\[
\begin{align*}
  f_{\text{sampling}} &= f_{\text{laser}} \times \frac{p}{q} \\
  R_{\text{horizontal}} &= \frac{p}{\text{Width}} \\
  R_{\text{vertical}} &= \frac{f_{\text{laser}}}{v_{\text{flow}} \times q}
\end{align*}
\]

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<th>Parameters</th>
<th>Previous</th>
<th>Super-resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>p, q</td>
<td>350, 1</td>
<td>1024, 3</td>
</tr>
<tr>
<td>(f_{\text{sampling}})</td>
<td>3.99 GHz</td>
<td>3.89 GHz</td>
</tr>
<tr>
<td>(R_{\text{horizontal}})</td>
<td>1.4 pixel/\mu m</td>
<td>4.1 pixel/\mu m</td>
</tr>
<tr>
<td>(R_{\text{vertical}})</td>
<td>11.4 pixel/\mu m</td>
<td>3.8 pixel/\mu m</td>
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• Next Step: Choose a proper q
Evaluation of different \{p, q\}

- **Sampling simulation with different \{p, q\}**
  - **Motivation of this evaluation:** Choose a proper q value
  - Source image: sampled with **80GSa/s oscilloscope**, crop the cell area, **340** pixel/line
  - **Down-sampling** the image ~20x to ~4GSa/s, ~17 sample points / line, \((p/q \cong 17)\)
    - Reshape the 2D image to a whole line and do **1D down-sampling**
    - Case \(\{p=17, q=1\}\) is the normal line-aligned sampling
    - The other cases are super-resolution with subpixel shift, with different \{p, q\} set, similar sampling frequency

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80GSa/s, Oscilloscope, HKD 1,000,000

Choose q=3, Trade-off between Resolution & Computation Cost

If q>6, Image distortion appears

4GSa/s, ADC + FPGA Super-resolution HKD 50,000
Frequency Domain Analysis

• Analyze the previous simulation results in frequency domain
  • Motivation of the analysis:
    • Verify that the high frequency information is revealed by the super-resolution (make cell texture clearer)
    • Evaluation the error that introduced by the sub-pixel shift (theoretically error increase as the q becomes bigger)
  • Fourier Transform in analysis
    • Firstly, reshape the 2D image to a whole 1D line
    • 1D Fourier Transformation to 1D frequency domain, because the image is sampled line by line
  • Based on Nyquist-Shannon sampling theorem
    • MAX frequency in source image = 40 GHz (sampling frequency is 80 GHz)
    • MAX frequency in line-aligned sampled image (q=1) = 2 GHz (sampling frequency is 4 GHz)
    • MAX frequency in image with super-resolution = 2*q GHz (With the super-pixels, we assume the equivalent sampling frequency increases)
  • Error Analysis
    • Replace the shifted sub-pixels with the original ones in the corresponding position of source image
    • Do the same Fourier Transform to get accurate frequency domain information
    • Calculate the error introduced by sub-pixel shift
Frequency Analysis Results

q=3, reveal the high frequency information, with acceptable error

If q>6, most high frequency information are covered by error and is not effective
Experiment Results

MCF-7 (breast cancer cell) imaging with line-aligned sampling method, sampling frequency is 3.99 GHz.

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<td>Interleave</td>
<td>No</td>
<td></td>
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MCF-7 imaging with the proposed super-resolution method, sampling frequency is 3.89 GHz.

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Summary & Future Work

• Super-resolution in cellular imaging
  • Slightly adjust the sampling frequency
  • No sampling data increment
  • Acceptable interleave computation
  • Obvious image quality improvement

• Future Work
  • Proper interpolation to eliminate the jagged edge
Thanks.