Checkpoint 03/30

Vendor Independent PA Imaging System Enabled with Asynchronous Laser Source

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PLAN SUMMARY

Overview

Idea
Implement photoacoustic (PA) imaging on conventional ultrasound (US) systems.
- Make PA systems vendor-independent.
- Popularize PA imaging and lower the cost.

Challenge
In clinical scanners:
1. US line trigger is not accessible
   - line RF data acquisition frequency unknown.
2. US frame acquisition timing is not accessible
   - Laser pulse phase delay is unknown.

1. **Correct frequency**: synchronize laser pulse and ultrasound line acquisition (algorithm 1)
2. **Correct phase delay**: synchronize image frames (algorithm 2)
3. Use synchronized signals to implement real-time PA imaging.

**PA imaging on conventional US platform**

When phase is not synchronized

- US probe
- 1 line 1 pulse
- Phase delay

When frequency is not synchronized

- US probe
- 1 line 1 pulse
- Frequency differs
WORK TO DATE

Overview

• Simulation
  1. Ground truth channel data
  2. Asynchronous signal (error data)
  3. Develop algorithm to get
     (1) pulse repetition frequency
     (2) pulse phase delay
  4. Recover the data and get image

• Software environment preparation
  Cmake, VS 2010, OpenCV, Ultrasonix

Workflow: Correct frequency error and phase error separately.
2 WORK TO DATE

2.1 Ground Truth Channel Data

Why first using channel data?
- Channel data are not achievable from every US platform.
- Instead, beamformed RF data are achievable, but would be applied later.

Reason:
• Almost identical algorithms are applicable to both.
• The process of using channel data is simpler and direct.
• Channel data is readily available from k-wave simulator.
• Once algorithm works on channel data, code would be updated to optimize ultrasound beamformed RF data.
2 WORK TO DATE

2.1 Ground Truth Channel Data

1. Manually set impulse response
   - Fast, but less accurate

2. Use \textbf{k-wave}, an acoustic toolbox for time domain acoustic and ultrasound simulations
   - Define kgrid, medium, source and sensor
   - compute wave propagation
   - More realistic and accurate, but slow

Waveform from manually set impulse response

Waveform from k-wave (N-shape)
Results:

1 source

Channel data from manually set impulse response

Channel data from k-wave

Wave propagation process

Channel data of five sources
2. WORK TO DATE

2.2.1 Simulate Frequency Error

Compare pulse repetition frequency (PRF) and ultrasound line frequency (LF)

1 line 1 pulse
PRF = LF

1 line multiple pulses
PRF > LF

1 line 1 or 0 pulse
PRF < LF
Channel data and beamformed images with frequency errors (single source)
One false step will make a great difference. Correction demands a high accuracy.

Limitation: when the pulse shoots into another element, different time of flight (TOF) is not considered. Difference is slight, but will affect correction. Hard to solve!
2.2.2 Simulate Phase Error

No phase delay

With phase delay

source
Channel data and beamformed images with phase errors (single source)
WORK TO DATE

2.3.1 Correct Frequency Error

**Known:** pulse repetition frequency (PRF); **Unknown:** line frequency (LF)

**Target:** Get the ratio \( r = \frac{\text{PRF}}{\text{LF}} \), then set \( \text{LF}_0 = \text{LF} \times r \).

1. **PRF > LF**
   - Multiple pulses in one line
   - \( \frac{\text{PRF}}{\text{LF}} = \frac{S_1}{S_0} \)

2. **PRF < LF**
   - Problem: Time of flight (TOF) of the same pulse changes.
2. WORK TO DATE

2.3.1 Correct Frequency Error

PRF > LF

Peak detection with a shift window
- Count peak numbers and find peak position.

A tool for test

Signal in one line when PRF = 4*LF
2.3.1 Correct Frequency Error

**PRF > LF**

Once get peak positions, measure distance between adjacent peaks in each line, then average them to get $S_0$.

**Result**

Ground truth

Frequency error: $\text{PRF} = 1.05 \times \text{LF}$

Recovered image
WORK TO DATE

2.3.1 Correct Frequency Error

PRF < LF

Axial position of the source is easy to determine: it is at the position of the element which first receives signal.

Use line pairs with the same TOF

For instance, if source is in the middle of the element array:

\[ N : \text{number of elements} \]
\[ p_i : \text{pulse position in line } i \]
\[ p_j : \text{pulse position in line } j \]
\[ d_i : \text{distance between } p_i \text{ and } p_j \]
\[ n_i : \text{number of pulses between } p_i \text{ and } p_j \]
\[ d_i = (S_i - pi) + [(N + 1 - i) - i - 1]S_i + p_j \]
\[ = (N + 1 - 2i)S_i - pi + p_j \]
\[ S_{0i} = d_i / n_i \]
\[ S_0 = \text{mean}(\sum S_{0i}) \]

Image has not been recovered due to a lack of consideration of TOF. But method should work.
2.3.2 Correct Phase Error

Phase delay ranges from 0 to 1 line period
Method: **binary search**
Judging condition: maximum intensity of beamformed image

the smaller the delay →
the more focused the beamformed image →
the higher the maximum intensity
## 2 Work To Date

### 2.3.2 Correct Phase Error

#### Result

<table>
<thead>
<tr>
<th>Actual phase delay</th>
<th>Obtained phase delay</th>
<th>Mean squared error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.0459</td>
<td>0.1115</td>
</tr>
<tr>
<td>0.10</td>
<td>0.0959</td>
<td>0.1115</td>
</tr>
<tr>
<td>0.15</td>
<td>0.1459</td>
<td>0.1115</td>
</tr>
<tr>
<td>0.20</td>
<td>0.1959</td>
<td>0.1115</td>
</tr>
<tr>
<td>0.25</td>
<td>0.2459</td>
<td>0.1115</td>
</tr>
<tr>
<td>0.30</td>
<td>0.2959</td>
<td>0.1115</td>
</tr>
</tbody>
</table>

Ground Truth

Corrected Image (phase delay = 0.1)
2.3.2 Correct Phase Error

Conclusion:
• The obtained source on the image is highly focused.
• The absolute error is always 0.0041. The mean squared error is always 0.1115
  - when phase delay is very small, relative error can be high
  - reconstructed image is not strongly sensitive to the error.

Reason:
• The maximum intensity of ground truth image is 7.24, while the image obtained is 7.38.
• There might be some better judging condition in addition to maximum intensity, but maximum intensity is reasonably good.
# PROBLEMS & EXPOSURES

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of flight was not considered when adding frequency error, which makes image correction when PRF &lt; LF imprecise in simulation.</td>
<td>To get a totally correct “errored” data is tricky. Will try in simulation. May directly test via PZT element.</td>
</tr>
<tr>
<td>Phase correction: a better criteria to determine the image quality.</td>
<td>Coherence factor (CF) and minimum variance (MV) may be applied.</td>
</tr>
<tr>
<td>When phase and frequency errors both exist.</td>
<td>Correct frequency error then phase error step by step.</td>
</tr>
<tr>
<td>Channel data is not achievable from some of the ultrasound systems, should try pre-beamformed data</td>
<td>The actual step would be almost identical. Will adapt the code once validity verified.</td>
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</table>
### Completed Tasks

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Milestone.1 Simulation</strong></td>
<td></td>
</tr>
<tr>
<td>Acquire PA real time re-beamforming algorithm + US Imaging SDK.</td>
<td>Before 2/1</td>
</tr>
<tr>
<td>Reading on PA imaging and document methods and algorithms.</td>
<td>Before 2/1</td>
</tr>
<tr>
<td>k-wave installation and manual reading</td>
<td>2/1 – 2/15</td>
</tr>
<tr>
<td>Simulate and get ground truth data.</td>
<td>2/10 – 2/24</td>
</tr>
<tr>
<td>Develop brute-force searching algorithm to synchronize frames and laser pulses.</td>
<td>2/10 – 3/5</td>
</tr>
<tr>
<td>Simulate PA imaging with k-wave tool box in Matlab.</td>
<td></td>
</tr>
<tr>
<td>Validate the algorithm and improve it.</td>
<td>3/6 – 3/12</td>
</tr>
<tr>
<td>Add noise to frames and beamlines, validate the algorithm.</td>
<td>3/12-3/19</td>
</tr>
<tr>
<td>Set up Ultrosonix SDK, QT creator, CMake and open CV.</td>
<td>2/15 – 3/26</td>
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</tbody>
</table>
Future Tasks

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Date</th>
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</thead>
<tbody>
<tr>
<td>Correct data with both frequency and phase error in Matlab</td>
<td>3/30 – 4/7</td>
</tr>
<tr>
<td>Develop method to work on US beamformed RF data instead of channel data</td>
<td>3/30 – 4/12</td>
</tr>
<tr>
<td><em>Milestone.2 C++ algorithm</em></td>
<td></td>
</tr>
<tr>
<td>Convert frequency and phase correction programs into C++</td>
<td>4/13 – 4/20</td>
</tr>
<tr>
<td>Convert SPARE beamforming method into C++</td>
<td>4/13 – 4/20</td>
</tr>
<tr>
<td><em>Milestone.3 Integration of synchronization &amp; real-time imaging</em></td>
<td></td>
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<tr>
<td>Validate the algorithms via PZT element</td>
<td>4/21 – 5/5</td>
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<tr>
<td>Combine synchronization part and real-time part to achieve PA imaging on US platform</td>
<td>4/21 – 5/5</td>
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<tr>
<td>Prepare demo and final report/paper</td>
<td>5/5 – 5/18</td>
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4 PLAN UPDATE

Deliverables

Minimum
1. Ultrasound system environment setup.  
   In progress
2. Simulation in Matlab with k-wave tool box:
   (1) Algorithm to correct frequency error
   (2) Algorithm to correct phase error

Expected
1. Incorporate Matlab code in C++ and transplant it onto Ultrasonix.
2. PZT element tests for verification of the algorithm

Maximum
1. Algorithm improvement: higher accuracy and efficiency.  
   In progress
2. Summary of PA imaging using clinical US scanners in a paper for submission.
3. An in-class demo of PA imaging using clinical US scanners.

Some problems:
The Ulterius system adaptive to C++ is not stable.
Backup plan: write C++ code, run it inside a Matlab-based software