Group 2:

Vendor independent PA Imaging System Enabled with Asynchronous Laser source

Student: Yixuan Wu

Mentors: Haichong "Kai" Zhang, Emad Boctor

Abstract

Photoacoustic (PA) imaging is an innovative imaging modality with the advantage of high penetration and high resolution. However, the application is confined owing to the high cost of PA machines, and a lack of standard among venders. This project focuses on a bold and innovative idea, that implement PA imaging on conventional ultrasound (US) imaging machines, where synchronization between US probe's line trigger and laser pulse is primarily investigated. Meanwhile, a new beamform method named SPARE approach[1] invented by MUSiiC lab, which applies the beamformed US data as pre-beamformed RF data to form PA images is integrated. Algorithms are developed to correct phase delay and frequency in US probe's line trigger, ensuring a one line one laser pulse synchronized situation. Both simulation and experimental results indicate feasibility of implementing PA imaging on US machines.

Introduction

Photoacoustic (PA) imaging is an imaging modality that derives image contrast from the optical absorption coefficient of the tissue being imaged[2]. Owing to its deep penetration, high resolution and safety, it is intensively and widely applied in fundamental, preclinical and clinical studies[3] as a very effective optical imaging modality. However, hardware of PA imaging hinders a universal application of this technology. Implementation either relies on low-efficiency Ultrasound (US) beamformers or vender-variant PA platforms. If conventional US scanner implementing PA imaging is viable, then the cost of PA imaging will be lower so that more life will be saved. Thanks to the effort of Medical UltraSound Imaging and Intervention Collaboration (MUSiiC) Lab[1], an innovative photoacoustic re-beamforming approach has been developed to make real-time PA implementation on conventional US platforms possible. However, this approach is applied on an ultrasound platform where frame rate and probe's beamline sweeping rate are manually set. Whereas, conventional clinical ultrasound scanners don't possess such "triggers" for frames and sweeping. In another word, the phase and frequency of the laser pulse are unknown, leading to a random-looking image where the transmitted signal is asynchronous with the received signal. Hence, a reconstruction method which measures the laser frequency and the laser phase, and correct the obtained US image, is significant and crucial for implementing PA imaging on conventional US platform.

This project develops a peak-detection-based method to correct frequency errors. Some imaging processing techniques, such as Hilbert transform, band pass filter and Savitzky–Golay filter are used to pre-process the image to get the envelop of the RF signal and smooth it. Then, a z-windowing peak detection is implemented to find the peak position in each line of samples. By counting the distance between peak positions, the ratio of line trigger's frequency to laser pulse repetition frequency is somehow estimated. As for phase delay correction, a binary search approach is explored. The phase delay is detected within a range of 50% of line trigger period. Recursively, the maximum intensities between beamformed images in two binary bins are compared. After iterations, the maximum intensity in the beamformed image reaches the highest, indicating that signals are fully focused. Thus, phase delay is found. Finally, two errors are combined and added into the image simultaneously. To correct both errors, a "coarse to fine" method is developed. By using linear search to find the optimum sample number within a small range after estimation of frequency and phase using methods above, the right PA image is ultimately recovered.

Both simulation and experiments are investigated to verify the algorithm. The algorithms are robust and reasonably efficient in simulation within a range of 20% frequency error and 20% phase error, and works in most cases within a range of 50% frequency error and 50% phase error. But it is still limited within a range of 5% for both frequency and phase errors to recover the real images. However, both simulation and experiment results reveal a feasibility to implement PA imaging on US system.

Theory

Image and signal processing technique

1. Z-score peak detection

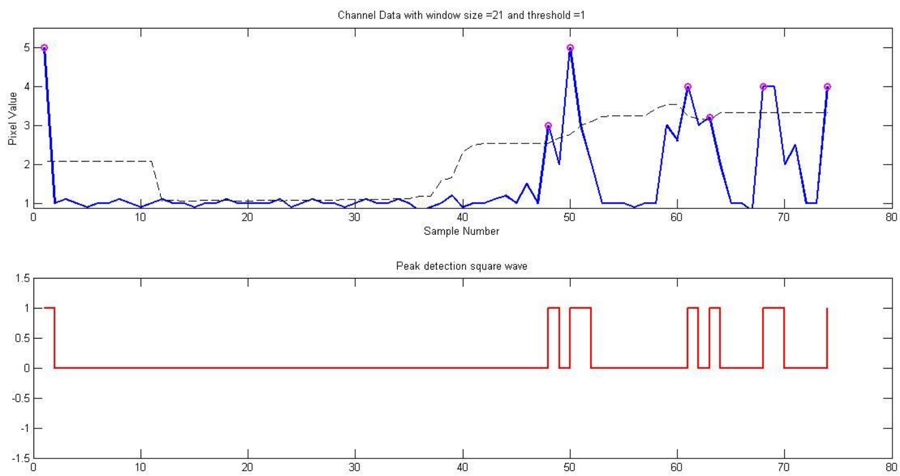
A simple maximum intensity detection is not a proper method to find peaks in each line of ultrasound images when frequency errors exists. When PRF is higher than line frequency, there will be multiple pulses appear in some lines. If a simply maximum intensity detection is applied, multiple peaks will not be detected. Similarly, when PRF is lower than line frequency, there should be no pulse in some lines, but maximum intensity detection will always find one.

The idea of this z-score peak detection technique is to find the values that are variances apart from the average of the window. A window is shifted through the signal, calculate average and variance of values within the window for each shift, and find out values larger than average plus variance multiplied by a threshold. An indicator is created first,

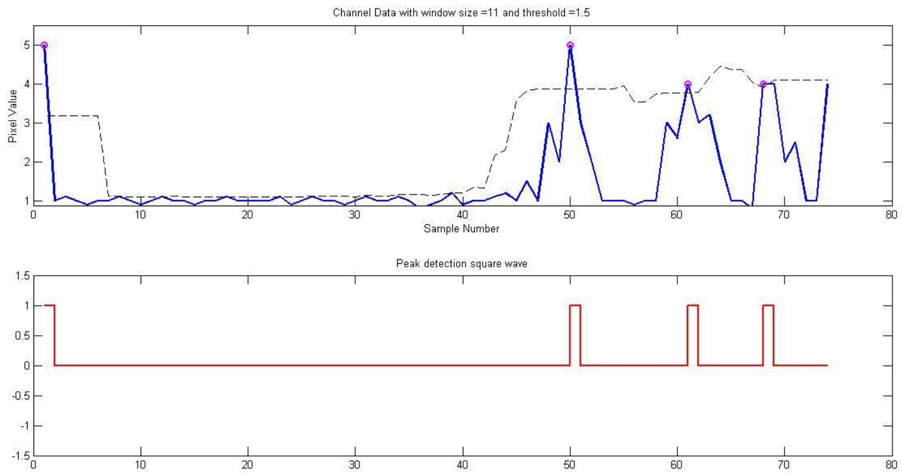
$$I = \begin{cases} 1 & \text{if signal} > \text{avr+thres*std} \\ 0 & \text{otherwise} \end{cases}$$

A bulge of the indicator is defined as regions with consecutive ones. After the window shift process is completed and bulges are found, the peak value and peak position are found within bulges.

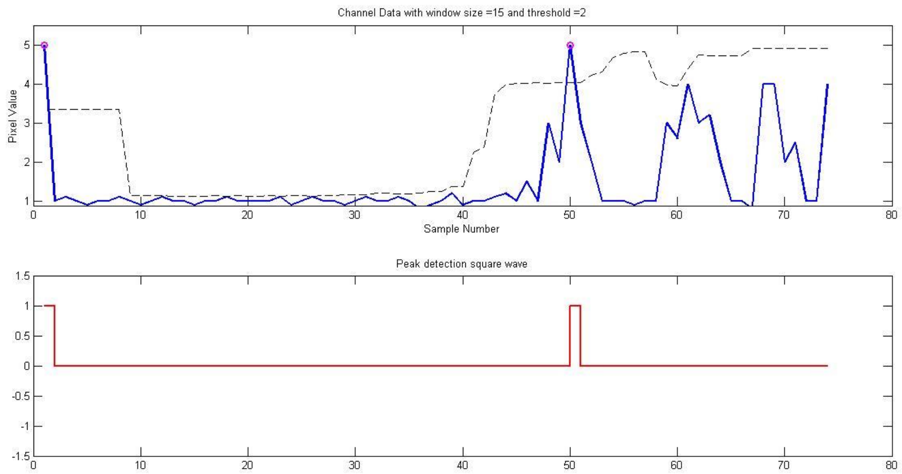
The size of the window and the threshold value is user defined. A window size of the period of signal and a threshold of 3 are good choices.



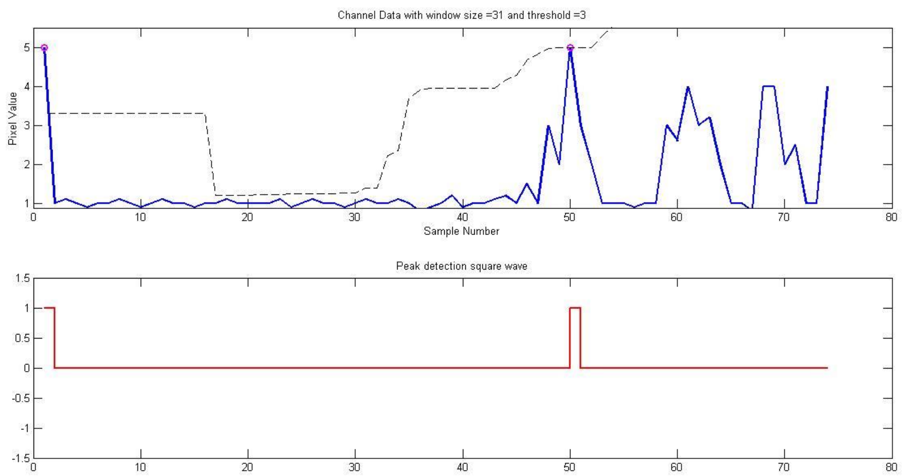
(a)


Channel Data with window size =11 and threshold =1.5
Pixel Value
Sample Number
Peak detection square wave

(b)


Channel Data with window size =15 and threshold =2
Pixel Value
Sample Number
Peak detection square wave

(c)


Channel Data with window size =31 and threshold =3
Pixel Value
Sample Number
Peak detection square wave

(d)

Figure a tool signal to illustrate z-score peak detection. Blue lines in the upper axis indicate the signal, dashed black lines reveal a divide of average + threshold*std, pink spots indicate peak detected. Red square waves in lower axis are indicators, showing the position of bulges. The window size and threshold for each image is: (a) window size 21, threshold 1. (b) window size 11, threshold 1.5. (c) window size 15, threshold 2. (d) window size 31, threshold 3.

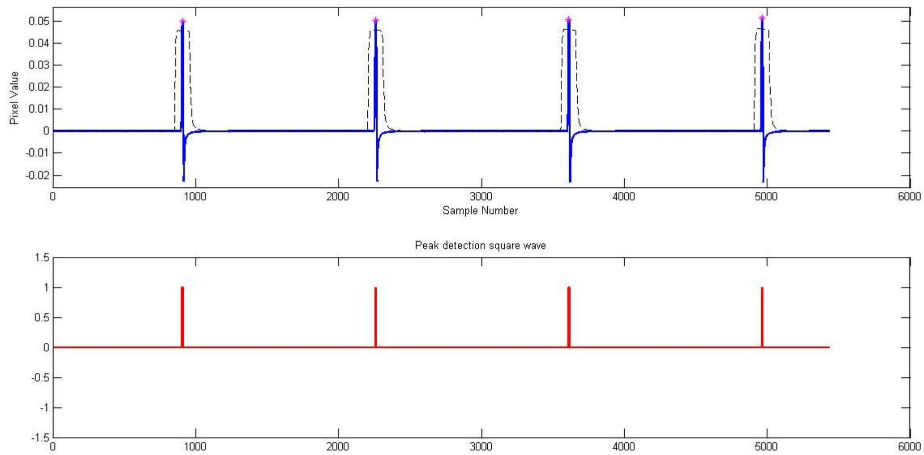


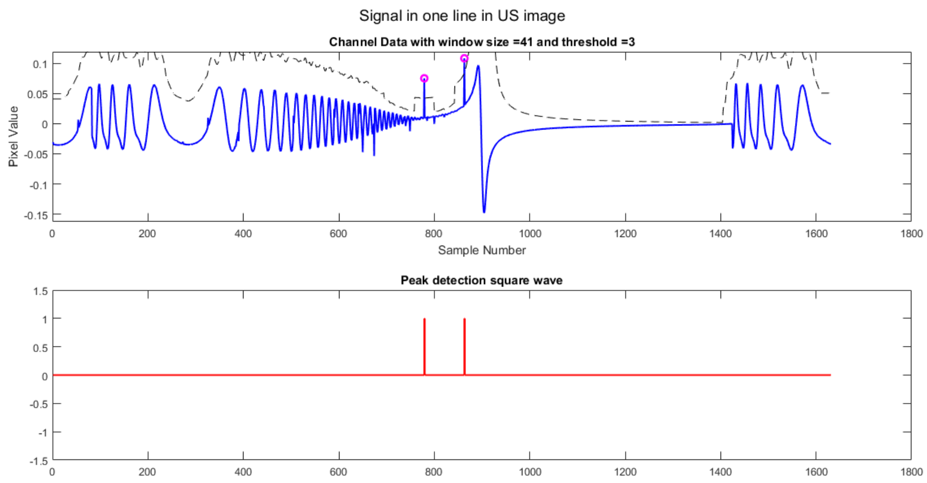
Figure a sequence of N-shape pulses are tested with a window size 101 and threshold 3. Peaks of pulses are successfully found.

This peak detection method is generally very robust for multipeak detection when signal is free of high frequency noise. However, it is very sensitive to noise. Thus, Improvement of SNR is very important, and it will be discussed in Savitzky–Golay filtering and band pass filtering

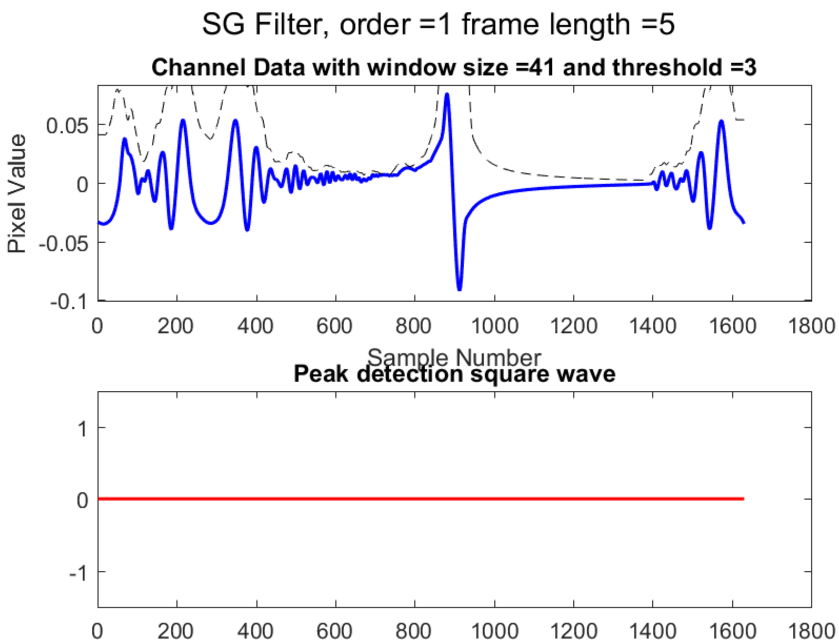
Savitzky–Golay filtering

This method is first brought up by Savitzky and Golay[4] in *Analytical Chemistry*[5] in 1964. They mainly brought up a spreadsheet for convolution coefficients. Savitzky–Golay filter is a digital filter with the aim of smoothing the data to increase SNR but without distorting the data.

The experimental data obtained from ultrasound machine contains very sharp "spinal" signals. This is not tolerable for peak detection in frequency correction. Comparting to other methods, Savitzky–Golay filter well solves this problem without changing or minorly changes the peak position. It is illustrated in the figures below.



(a)



(b)

Figure (a) Signal before and (b) signal after processed by Savitzky–Golay filter. Spinal signals are eliminated, and some high frequency parts are also filterd.

Band pass filtering

The purpose of band pass filter is to (1) filter the low frequency acoustic reflection signals and (2) reduce noise to improve SNR. The critical issue of designing band pass filter is to choose reasonable cut-off frequencies ω_1 and ω_2. The process is to Fourier transform the signal into frequency domain, multiply by the filter function, then Inverse Fourier transform the multiplied signal.

Ideally, if a simple $rect$ function is applied for bandpass filter, suppose the function of signal is $f(t)$, then the bandpass filtered signal is

$$f_{bp}(t) = F^{-1}\{F(f(t)) \cdot \mathrm{rect}(\frac{u - \frac{\omega_1 + \omega_2}{2}}{\omega_2 - \omega_1})\} = f(t) * ((\omega_2 - \omega_1)\,\mathrm{sinc}(t) e^{j\pi\omega_1 + \omega_2 t}$$

Where ω_1 and ω_2 are lower cut-off frequency and higher cut-off frequency, respectively. In digital signal processing, FFT and IFFT are applied to Fourier and inverse Fourier transform the signal.

2. SPARE beamforming method

The goal of Synthetic-aperture based re-beamforming (SPARE) method is to develop a new PA image reconstruction approach based on ultrasound RF data that has already been beamformed by the system.

Conventional PA imaging needs channel data for beamforming. Since US probes only provide beamformed data, re-beamform the beamformed data becomes the potential method.

The re-beamforming process for SPARE approach is demonstrated below. First, the US probe receives US waves and generate channel data. Then, it beamforms the channel data into pre-beamformed data, which can be achieved from the platform. Finally, SPARE approach is applied to re-beamform the data.

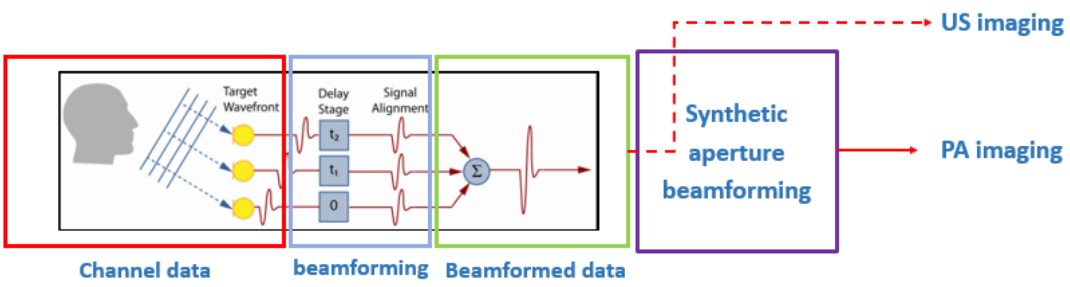
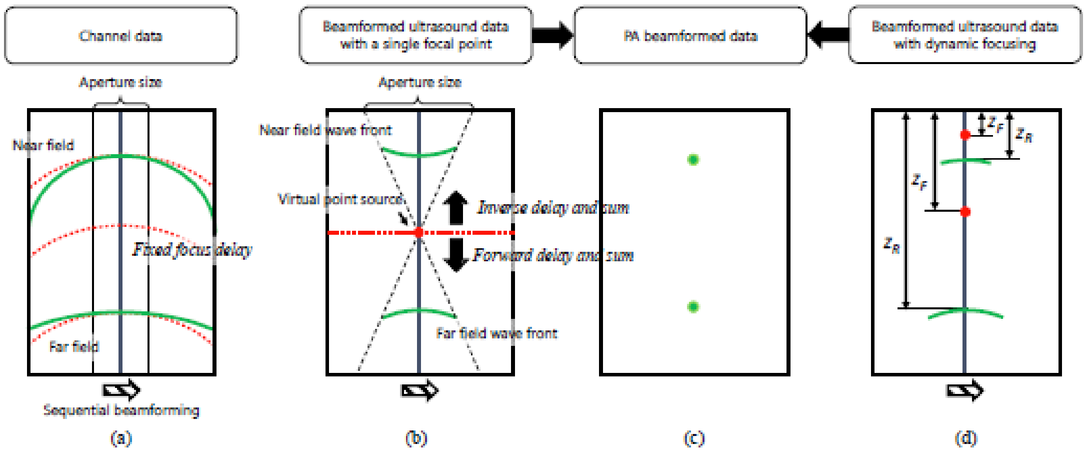


Figure Procedure for conventional US imaging and PA imaging based on SPARE method

More specifically, the shapes of two point sources are illustrated in the figure to show the process of SPARE beamforming. The wave front of received RF signal is shown as the green curve in (a). After applying the fixed focusing delay as red dashed curves in (a), it becomes somewhat more but not totally focused in (b). Regard the focal point in (b) as a virtual point source and apply inverse and forward delay and sum, the signal is fully focused as shown in (c). (d) illustrates the situation for dynamic focusing, in which the virtual element depth z_F is the half distance of re-beamforming focal depth z_R.



Figure[1] A detailed procedure of SPARE beamforming.

3. Frequency and phase correction algorithms

Before a depiction of correction algorithms, several concepts of data acquisition should be clarified. Frame, line, phase delay, and frequency errors are to be elaborated.

The time of one frame of B-mode imaging ranges from the start of the first line to the end of the last line. The time of one line is the time from the start of the first sample and the end of the last sample received by an element. Phase delay indicates the phase difference between the pulse repetition and the line trigger. Frequency error refers to the difference between PRF and the line trigger frequency.

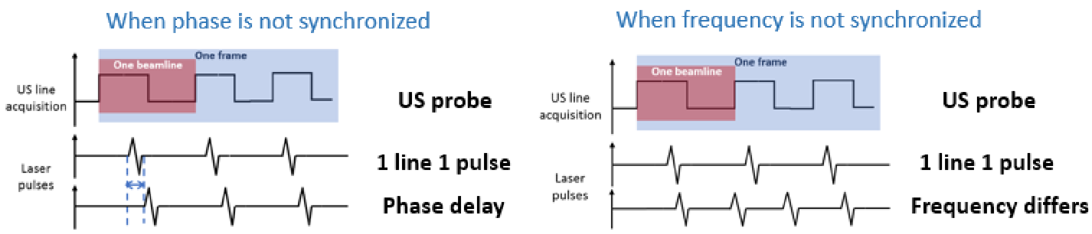


Figure Relationship between line trigger, frame, phase delay, and frequency error.

Frequency correction

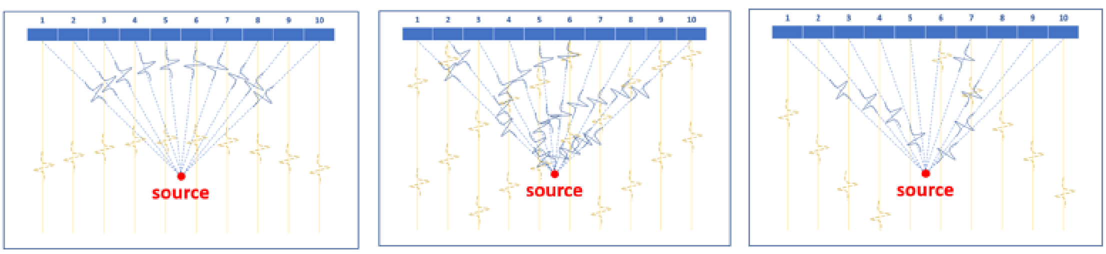
In general, two situations will occur

(1) PRF is larger than line trigger frequency, one line one/multiple pulses.

(2) PRF is smaller than line trigger frequency, one line one/no pulse.

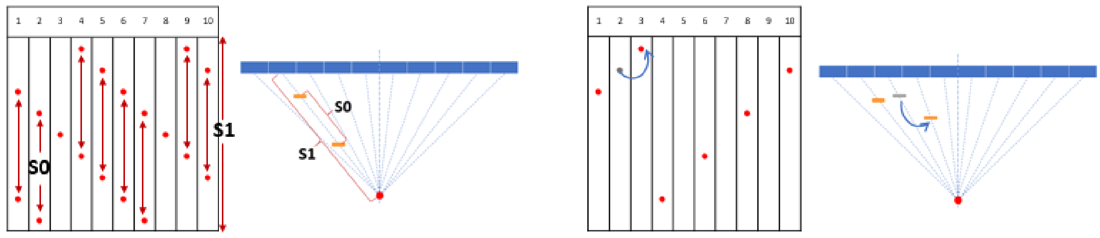
For the first case, it is relatively easy to find PRF. Since there are multiple peaks in some lines, the distance between each two adjacent peak pairs in one line represents pulse repetition period. By counting the sample number S_1 between two peaks (peaks showing up in the same line instead of two peaks in different lines), a ratio of PRF to line trigger frequency is easily derived as S_0 / S_1, where S_0 is the sample number of one line.

A more robust way is to count distance between every peak pair in each line, then average them to get the ratio.



(a) (b) (c)

Figure (a) PRF equals line trigger frequency, one line one pulse. (b) PRF is larger than line trigger frequency, one line one or multiple pulses. (c) PRF is smaller than line trigger frequency, one line one or no pulse.



(a) (b)

Figure (a) An illustration of peak distribution in lines when PRF > line trigger frequency. (b) An illustration of peak distribution in lines when PRF < line trigger frequency.

For the second case, distance between two adjacent peaks is not a good measurement for pulse repetition period, since these two pulses are received by different elements, so a difference of time of flight (TOF) should be compensated. Nevertheless, how much is the difference of TOF between two adjacent peaks in different lines is in fact not estimable, since it depends on the axial position and depth of the source.

The method proposed here only depends on axial position of the source. If we know the axial position of the source, we can use information revealed by peaks in lines that are symmetric to the source, for they have the same acoustic TOF.

Suppose N is the number of elements, p_i is the pulse position in line i, p_j is the pulse position in line j, i and j are symmetric about the source. Suppose d_i is the distance between p_i and p_j, n_i is the number of pulses between p_i and p_j, we can get

$$d_i = (S_1 - pi) + [(N+1-i) - i - 1]S_1 + p_j = (N+1-2i)S_1 - p_i + p_j$$
$$S_{0i} = d_i / n_i$$

By counting all the S_{0i} and average them, we have $\frac{1}{M}(\sum S_{0i})$, where M is the total number of peak pairs.

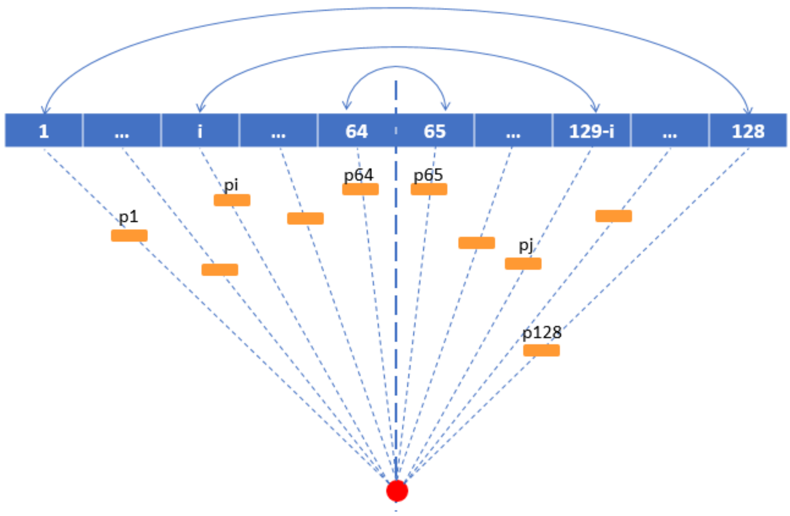


Figure Pulses appear in symmetric lines about the source have same TOF

There are two deficiencies of these two frequency correction algorithm. The first is these methods do not take delay between two lines into consideration. Fortunately, the delay between two lines is a small constant number and can be estimated via experiment, so this is not a big issue. We need simply add this measured delay to the sample number we estimate from algorithms to derive the true line trigger frequency. The second is when PRF is smaller than the line trigger frequency, source position information is still needed. Currently, whether there is a direct access of the axial position or whether it can be derived is unknow to me. In addition, PRF is usually higher than line trigger frequency in practice. Hence, this method is not applied in the tests.

Phase correction

Since beamforming method for photoacoustic imaging is fixed focusing, as long as the position of the source changes, the beamformed signal will not be fully focused. Thus, the maximum intensity will be lower. Phase correction method uses binary search to iteratively change phase delay, beamform the RF data, and find the maximum intensity in the beamformed image.

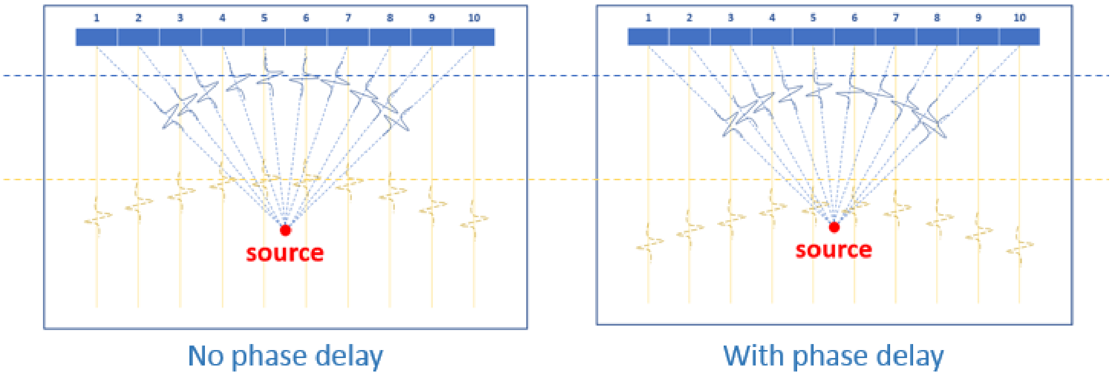


Figure An illustration of phase delay. Figure on the left is the original channel data and figure on the right is the delayed channel data.

By constraining the phase delay in a certain range (upper bound is 1), binary search is efficient to converge.

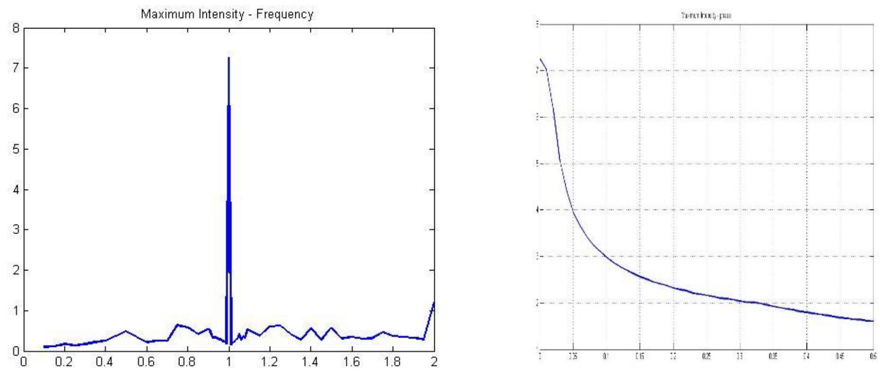
Frequency and phase correction combined

When these two errors are combined, frequency correction becomes tricky since distance of peaks may change because of phase delay. For instance, a pulse originally at the end of one line may now goes up to the top of the image. Suppose when there is no phase delay, the distance between these two peaks in the same line is d_0 . Now with phase delay, it becomes $S - d_0$, where S is the total sample number in one line.

If we only consider the situation that maximum peak number in one line is two, we can use $\max\{S - d_0, d_0\}$ as the distance between two peaks. So now the method is confined to a frequency correction with the upper bound of PRF to be 3 times of line trigger frequency. In practice, this still can be recognized as a large range, so the algorithm is still applicable.

4. Analysis of infeasibility of conventional image processing criterion

Intensity-based methods are the most common techniques applied for imaging processing. However, many criterions, like mutual information (MI), sum of squared difference (SSD), and normalized cross correlation (NCC) are not applicable in the problem we are solving.



(a) (b)

Figure Change of maximum intensity of beamformed image when (a) frequency and (b) phase vary.

The figure reveals that maximum intensity in the beamformed image monotonically decreases when phase error is becoming error. This is because the effect of phase delay is a shift of the image, and this is a linear change. However, frequency correction is nonlinear, and the maximum intensity has no rule to trace, showing from the figure that only when PRF is close enough to line trigger frequency will the intensity increase sharply. If we apply the maximum intensity of beamformed image as a criterion for iteration, it won't converge in a correct direction. If we correct the frequency by linear search, this becomes needle in a haystack problem.

Eventually, we use a "coarse to fine" strategy to correct the image. First, we estimate the frequency error by using frequency correction error first, and binary search for phase delay second. Thereafter we linear search the frequency error within a small range around the estimated frequency. Within each linear search iteration, we correct phase error by still using binary search, and compare the maximum intensity of the beamformed image recursively.

Methods

1. Workflow

The idea of the investigation is from simulation to experiments, from channel data to US beamformed data, and from Matlab to C++.

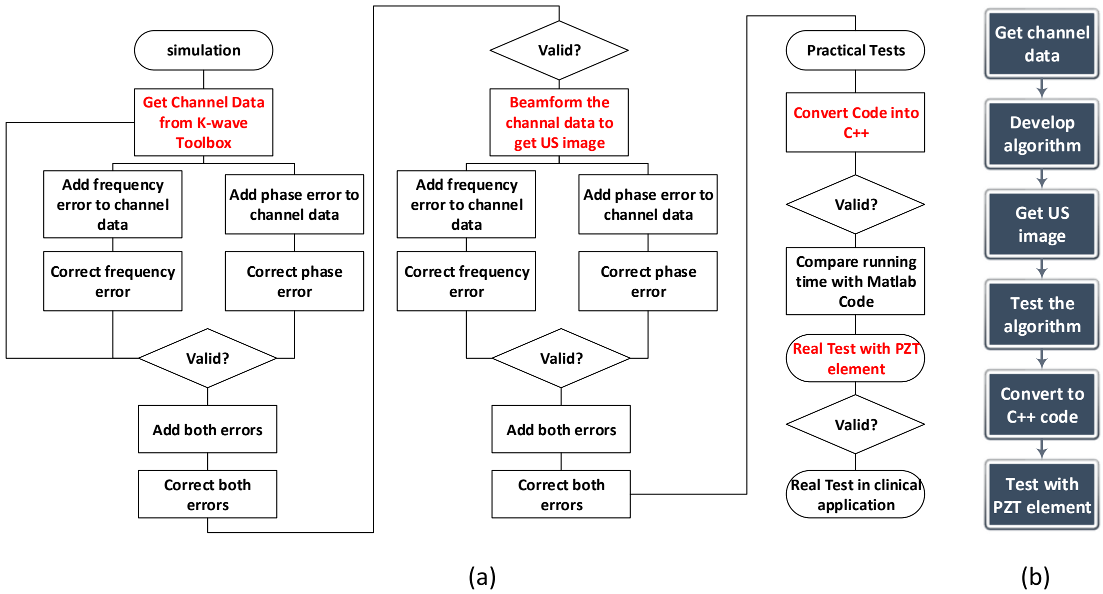


figure (a) A detailed workflow and (b) a general workflow

2. Channel data generation in k-wave

In fact, channel data are not achievable from every US platform. Instead, beamformed RF data are achievable. The reason for using channel data first is:

- Almost identical algorithms are applicable to both channel data and beamformed RF data.
- 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.

K-wave is a powerful toolbox integrated in Matlab for wave propagation study. Generally, four key input structures should be defined: kgrid, medium, source and sensor. Kgrid defines the computational grid, medium defines the material properties, source defines location of acoustic sources and sensor defines the properties and locations of the sensor points. kspaceFirstOrder1D, kspaceFirstOrder2D, and kspaceFirstOrder3D are the main simulation functions for different dimensions.

3. Simulation with channel data

The process of simulation with channel data is (1) add error to channel data, (2) correct error. The error only includes frequency or phase error first, with correction verified separately, then comprises both frequency and phase error.

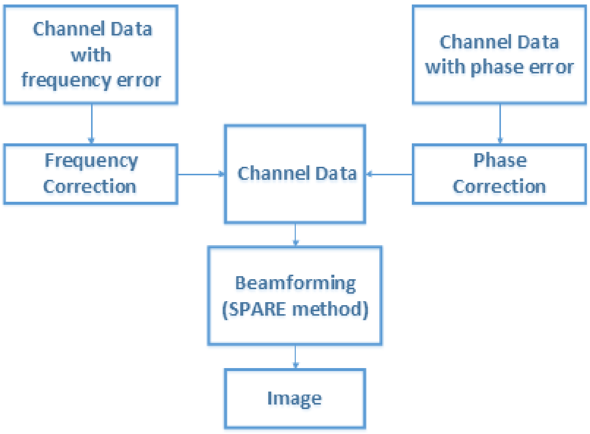


Figure Workflow of simulation with channel data

4. Simulation with ultrasound beamformed data

The difference here compared to channel data simulation is we use US beamform method to first get the RF data, then add errors on the RF data, finally use correction methods (also the beamform method in phase correction is modified to be the SPARE method) to correct images.

5. Convert Matlab Code into C++ code

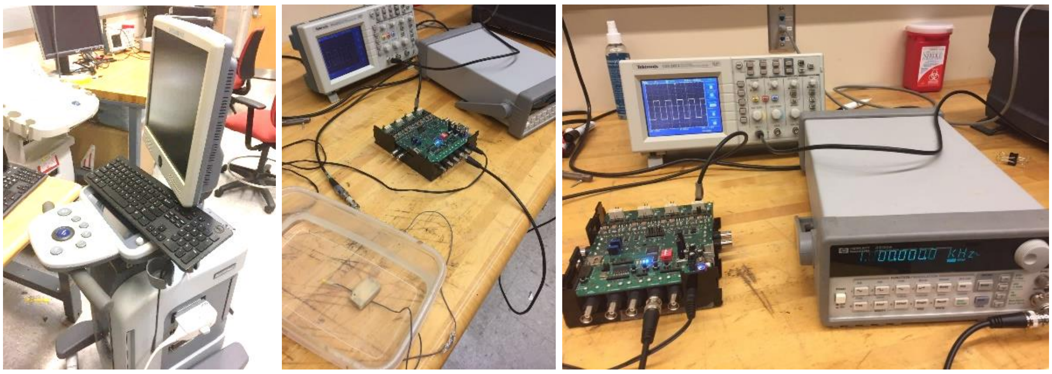
In order to improve the speed of computation, and apply the algorithms on real US machines, Matlab code is converted to C++ code.

As planned before, the US system environment needs support from Cmake and QT, which I installed and set up. However, that system is unstable, so another system where Matlab can be run is backed up. The aim of converting Matlab code into C++ code becomes comparing the running time between these two.

6. Experimental tests

Experiment setup:

(1) Ultrasonix machine
(2) HP 33120A function generator
(3) Tektronix TDX 2010 oscilloscope
(4) PZT element
(5) Custom-made circuit board



(a) (b) (c)

Figure experiment setup. (a) Ultrasonix ultrasound machine. (b) PZT element in the water tank, custom made circuit board, function generator and oscilloscope. (c) custom-made circuit board, function generator and oscilloscope.

Instead of using laser pulses generated by laser, a PZT element is first applied to mimic the laser pulse. It can be deemed as a single source, with signal transmitting in a constant frequency. This element is easy to manipulate and is a good tool before real photoacoustic imaging tests.

The PZT element is controlled by the custom-made circuit. The voltage of PZT element is decided by the output of the circuit, which is higher than 200V. The frequency of PZT element is controlled by input trigger 1 on the board, and usually a square wave generated by the function generator ranges from 0-3.5V is the input.

The experiment procedure to get synchronized images includes (1) choose right imaging mode and properties for the US probe, set it as receiving only, (2) measure the line trigger frequency by connecting a port from US machine to the scope and observing the signal, (3) connect the port from US machine to the custom-made board and make it as an input to synchronize line trigger and pulses produced by the PZT element, (4) get the synchronized image from US machine.

Results

Simulation: test with channel data

Generation of channel data:

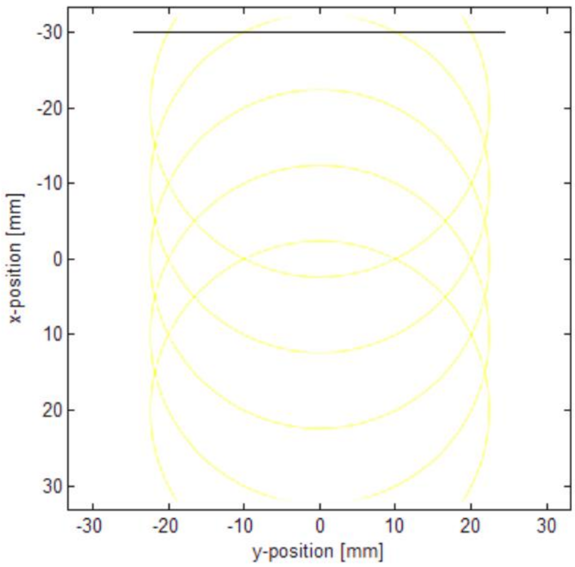
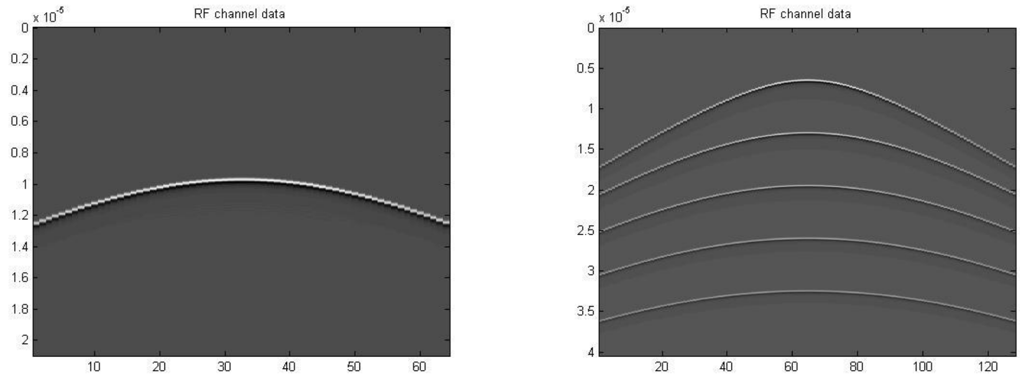


Figure Wave propagation process for five sources dispersed at 10mm, 20mm, 30mm, 40mm and 50mm in depth along the line x = 0.



(a) (b)

Figure Waveform of channel data for (a) one source, and (b) five sources

Add frequency error:

From the results, we can see that frequency is very sensitive to errors. There is no certain rule to estimate what the beamformed image will look like, but the source is better focused in the beamformed images at a ratio of 1.5, 1.2 or 0.75 than ratio of 0.99, 1.03, 1.47, etc.

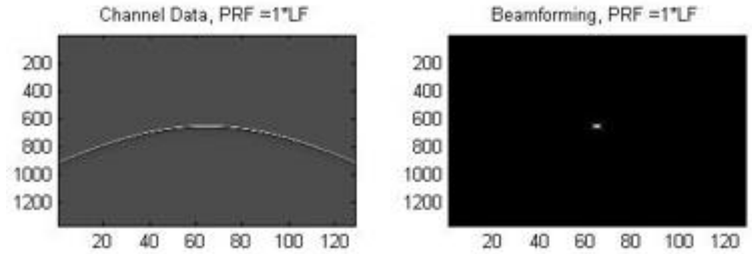


Figure Ground truth of channel data and the beamformed image

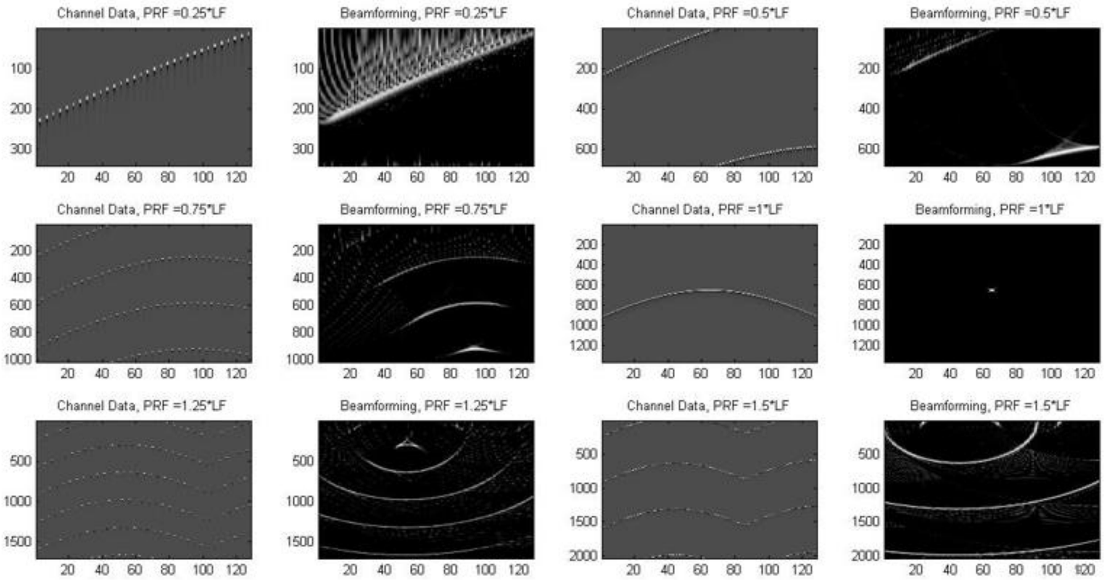


Figure frequency error shown in channel data and the beamformed images. The first and the third columns are channel data with error, and the second and fourth columns are the beamformed images. PRF ranges from 0.25 to 1.5 times of line trigger frequency, with an interval of 0.25.

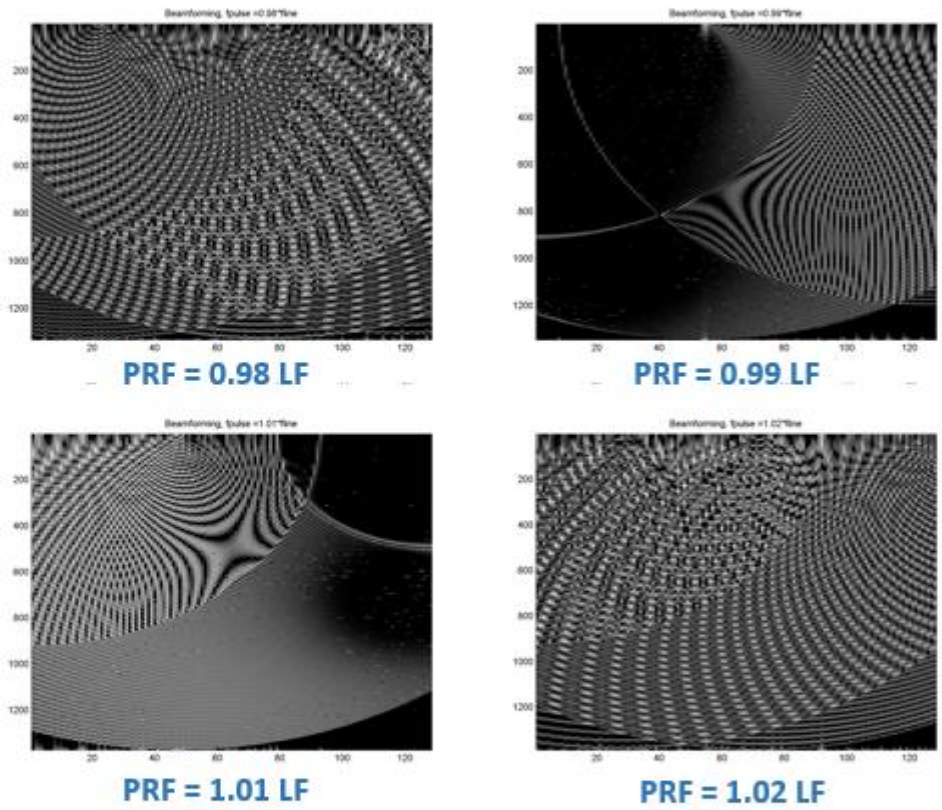


Figure Beamformed images when the ratio of PRF to line trigger frequency is close to 1. A single source becomes very sporadic in these cases

Add phase error:

Since phase delay is a shift progress of the image, the beamformed images become increasingly unfocused as phase delay rises.

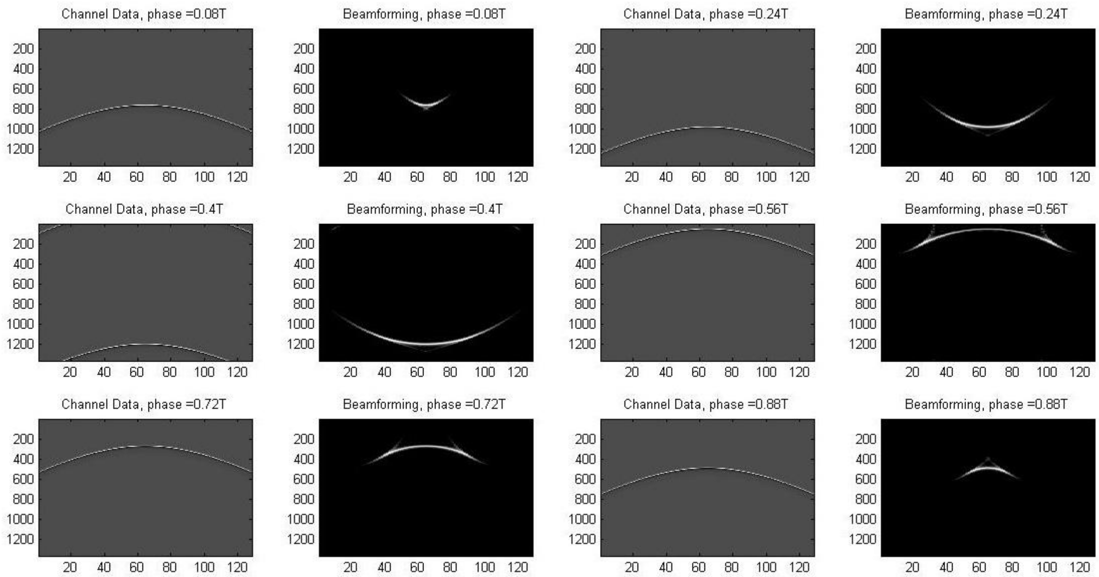


Figure Phase delay shown in channel data and the beamformed images. The first and the third columns are channel data with error, and the second and fourth columns are the beamformed images. Delay ranges from 0.08 to 0.88 times of line trigger period, with an interval of 0.16.

Correct frequency errors and phase errors separately:

The algorithms work very well for phase correction and frequency correction.

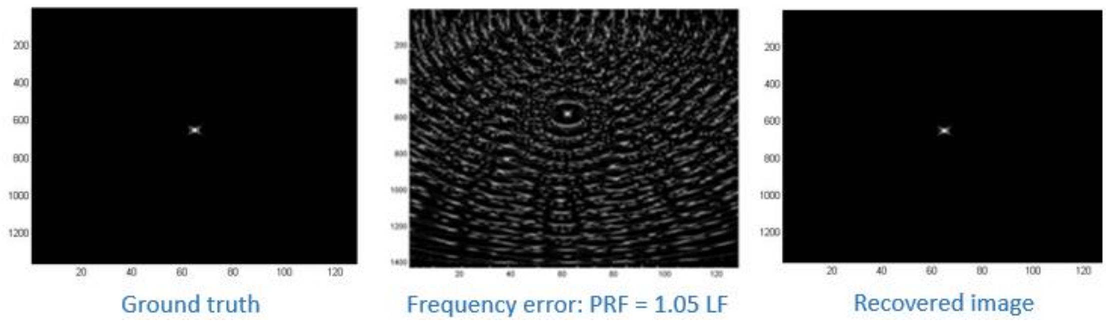


Figure Frequency correction when PRF is 1.05 to line trigger frequency

Table phase correction result

Actual phase delay	Calculated phase delay	Mean squared error
0.05	0.0459	0.1115
0.1	0.0959	0.1115
0.15	0.1459	0.1115
0.2	0.1959	0.1115
0.25	0.2459	0.1115
0.3	0.2959	0.1115

Add both frequency and phase errors:

When adding both errors, the image will be firmly corrected, but some artifacts appear in the corrected channel data. These artifacts are produced because of the sequence of correction. When adding errors, frequency error is first added, then phase error. If we want to totally correct the image, we need to do frequency correction after phase correction. However, it is not possible recursively find maximum intensity in the beamformed image without a right sample number estimated, so frequency correction first is necessary. Therefore, the pulses originally position at the bottom of the line and shifted to the top because of phase delay remain at the top during frequency correction, and finally form the artifact in the corrected channel data.

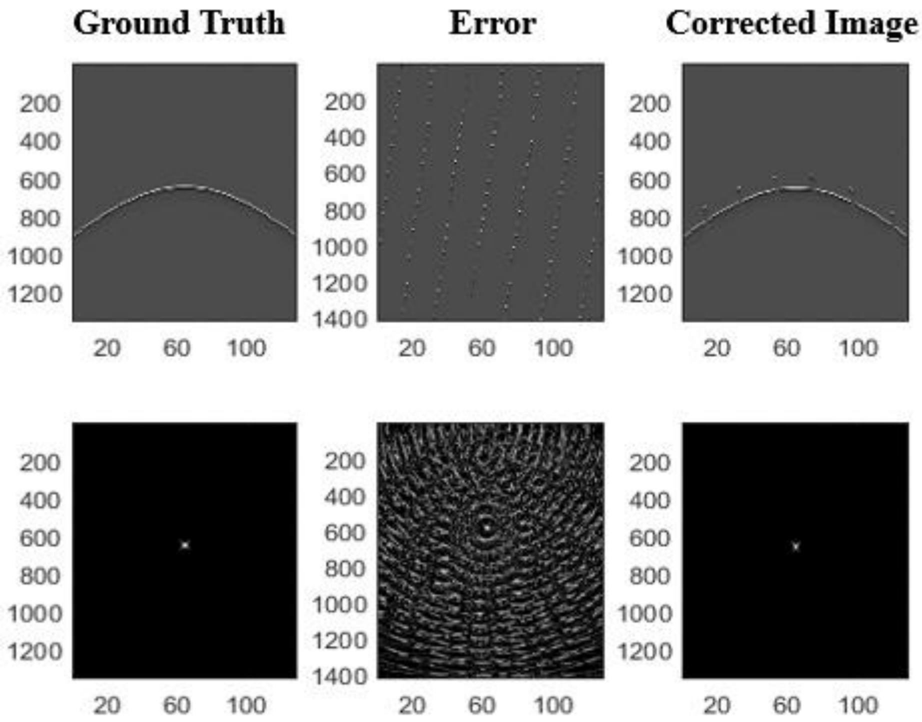


Figure Corrected images when PRF is 1.05 to line trigger frequency, and a phase delay of 0.1 is added. Images in the first row are channel data, and images in the second row are beamformed data

Simulation: test with US data

The procedure of tests of US data is very similar to channel data. However, the data becomes much noisier with US beamform applied, so SG filter is applied prior corrections. The correction methods become less robust for US data, so the coarse to fine method is tried here, that first estimate frequency and phase errors by using algorithms developed, then linear search within a small range to improve accuracy. Coarse to fine method is more accurate as the result indicates, but also much more time-consuming.

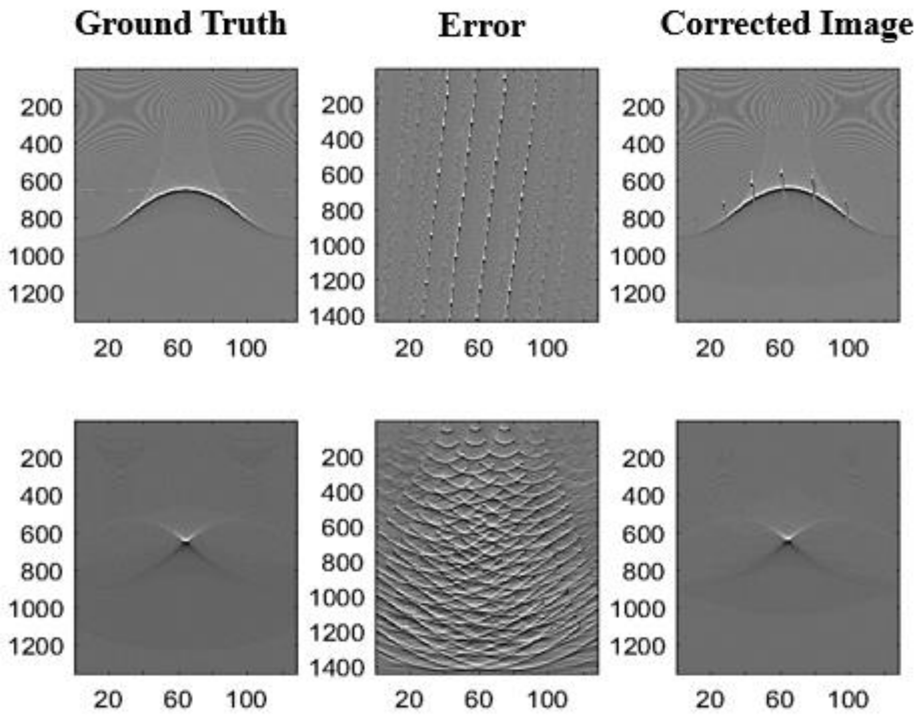


Figure Correction of US beamformed data, with phase delay error 6% and frequency error 6% added.

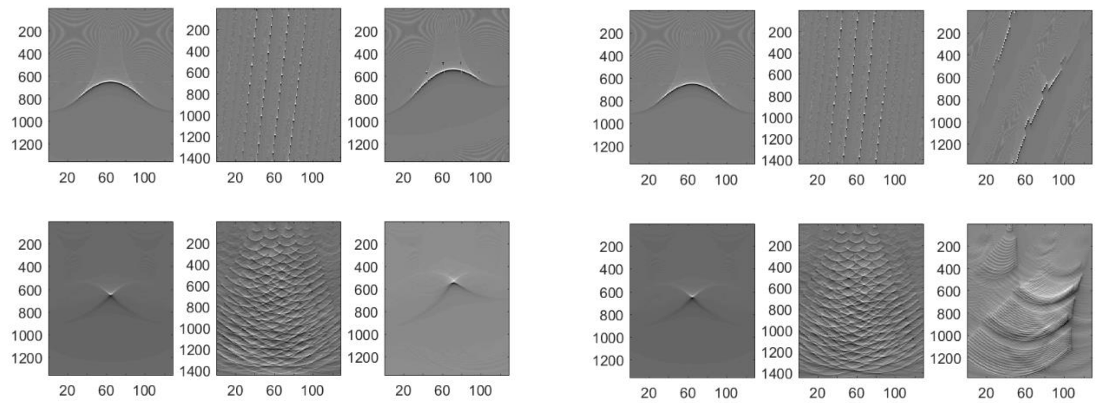


Figure (a) frequency error 6% and phase error 2%, source position shift in the corrected image. (b) frequency error 6% and phase error 32%, a failure in correction happens.

Table Comparison of corrected sample number between images with linear search in the end and without linear search

Ground truth sample number = 1359

Frequency error	Phase error	Sample number without linear search	Difference	Sample number with linear search	Difference
1%	6%	1355	-4	1355	-4
2%	6%	1360	+1	1359	0
3%	6%	1372	+13	1372	+13
4%	6%	1359	0	1358	-1
5%	6%	1359	0	1358	-1
6%	6%	1358	-1	1359	0
7%	6%	1360	+1	1359	0
8%	6%	1360	+1	1359	0
9%	6%	1357	-2	1357	-2
10%	6%	1361	+2	1360	+1
11%	6%	1361	+2	1360	+1
12%	6%	1361	+2	1360	+1
13%	6%	1361	+2	1360	+1
14%	6%	1357	-2	1359	0
15%	6%	1383	+24	1360	+1
16%	6%	1361	+2	1360	+1
17%	6%	1383	+24	1360	+1
18%	6%	1361	+2	1360	+1
19%	6%	1361	+2	1382	+23
20%	6%	1386	+27	1361	+2

Comparison between C++ code and Matlab code

Theoretically, C++ is faster than Matlab. But since there is a huge amount of numerical calculation, the SPARE beamforming method is surprisingly slow in C++, takes more than 300 seconds for running once. Since we are calling SPARE method twice in iteration of phase correction, and binary search takes 7 to 8 iterations on average, in addition we are doing around 20 iterations for linear search in the end, this running time becomes unacceptable. In Matlab, SPARE method runs 3096.35s for 385 iterations, namely, 8 seconds for one iteration on average. So Matlab is applied to process experimental data.

Although SPARE algorithm is not a task in this project, it needs future improvement.

Experiment: Test with experimental data

Since the real data is very noisy, SG filter, bandpass filter and Hilbert transform are applied to smooth the image and improve SRN. In addition, since the PZT element is put in a water tank with no wave absorption material enclosed, there are many reflections. Figure below shows how noisy the image is. The upper curve in the ultrasound image in (a) is the PZT element, and the bottom thin panel is the bottom of water tank and the table. The bright oblique line on the right is the wire of PZT element. (b) indicates the PA image with real geometry of the objects. We can see that the reflection at the bottom is also very bright, which is not desirable. By first apply bandpass filter, then Hilbert transform and SG filter, and finally properly crop the image, the region of interest is selected as demonstrated in (c).

The algorithm is limited for experimental test. If the frequency error or phase error is large, it takes long to compute and accuracy is low. Up till now, it is relatively robust for frequency and phase errors both within a range of 5%. Still there is some situation that the method does not work. When the frequency error is close to 0, false correction will appear. This is because the error is small enough that we can only find one pulse one line situation within one frame. At this point, a simple linear search from the very beginning is good.

In total, 25 situations are explored, with phase error ranges from 1% to 5% and frequency error ranges from 1% to 5%. The algorithm works well except when phase error is very close to 0 (1% in the experiments)

(a) (b) (c)

Figure (a) Ultrasound image of a PZT element in a water tank. (b) The SPARE beamformed image. (c)The filtered and cropped US image with only region of interest remaining.

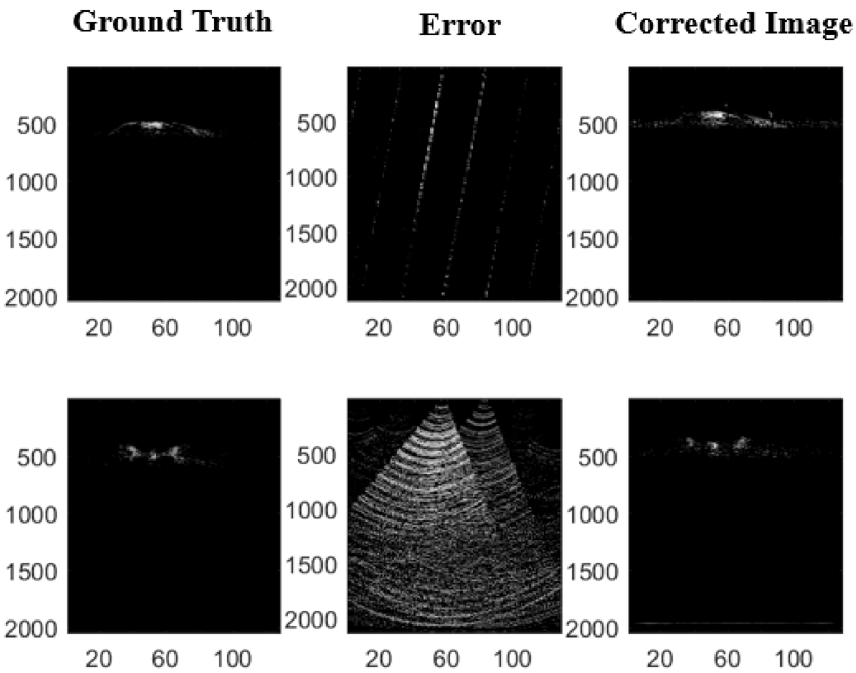


Figure 4% of frequency error and 4% of phase error are added. The first column are the US sound data obtained from US machine. The second column is the images with errors added. The third column is the corrected image. The first row of images are US images and the second row of images are SPARE beamformed images, which are identical to PA images.

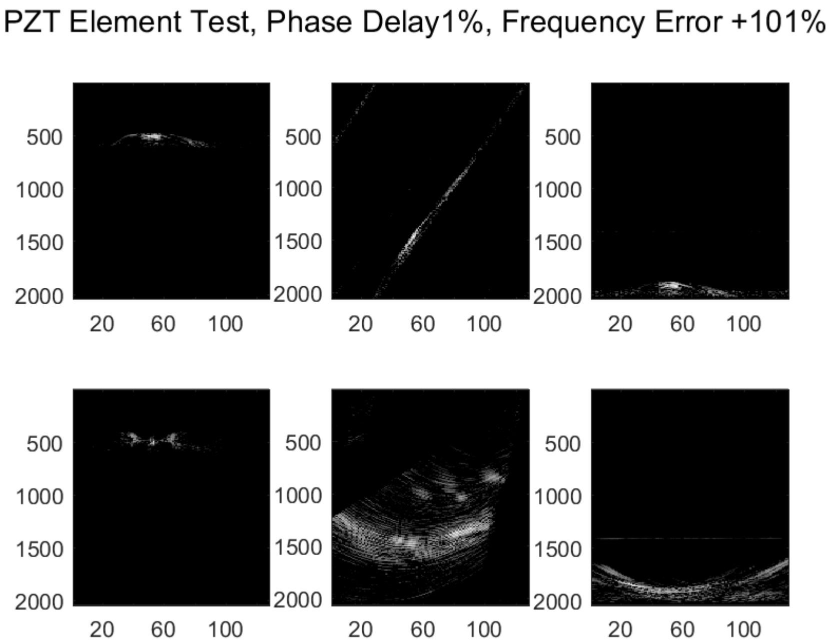


Figure Correction that fails when frequency error is close to 0.

Conclusion

To implement photoacoustic imaging on conventional ultrasound machines, synchronization problem between the line trigger in the ultrasound probe, and the laser pulse from the laser source is investigated. To correct frequency and phase errors, binary search for phase delay and peak detection for frequency correction are developed. SPARE beamforming method is also integrated and applied in beamforming RF data.

Results indicates feasibility of offline US image to PA image correction. With only US image given, PA image can be achieved by first correct frequency error, then correct phase error.

Management summary

The proposed timeline and deliverables:

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

Backup plan:

1. If delays are encountered in milestone 1, keep focusing on developing the synchronization algorithm. Make incorporation of Matlab program in C++ as a maximum deliverable.

2. As previous experience from group 13 last year, hardware problems may occur on US platform. If delays occur in milestone 3, leave more time to tests and put off integration of synchronization and real-time imaging.

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

Deliverables

Minimum	1. Ultrasound system environment setup.	✓
	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.	

Summary of management plan

The backup plan 1 indeed happens in this project. Many problems encountered during verification process. Since this project is a good extension to a master thesis, I didn't change my deliverables since these tasks are to be achieved in the end. An in-class demo of PA imaging using clinical US scanners is not achieved, for the reason that (1) only off-line correction is possible now, and (2) the algorithm has high time complexity to correct the images. In all, a lot of work has been done and they are significant to eventually achieve real-time PA imaging on US machines.

Acknowledgement

Thank Dr. Emad Boctor for providing me an innovative project. It is hard but I really enjoy exploring the truth. It is always a good time to talk with Dr. Boctor, for he is illuminated, open-minded, and with fancy ideas. I really appreciate Haichong Kai Zhang for his guidance in this project. Thank him for a weekly meeting, and patient replies to my stubborn questions, and all the encouragement and inspiration. In addition, I should also thank Howard Huang for helping me setting up software environment and giving me very helpful instructions on this course. Thank Younsu Kim for guidance on experimental tests and help for experimental setup.

Finally, thank Dr. Taylor's guidance, critiques and compliments for the whole course. I really learned a lot on presentations and making management plans. Thank Alexis for dedicated TA work. Wish Alexis a promising future and a happy life in his new job.

Bibliology

---

[1] Zhang, Haichong K., et al. "Synthetic-aperture based photoacoustic re-beamforming (SPARE) approach using beamformed ultrasound data." Biomedical Optics Express 7.8 (2016): 3056-3068.
[2] Su, Jimmy L., et al. "Advances in clinical and biomedical applications of photoacoustic imaging." Expert opinion on medical diagnostics 4.6 (2010): 497-510.
[3] Nikitin, Sergey. Laser ultrasonics in a diamond anvil cell for investigation of simple molecular compunds at ultrahigh pressures. Diss. Université du Maine, 2015.
[4] Savitzky, Abraham, and Marcel JE Golay. "Smoothing and differentiation of data by simplified least squares procedures." Analytical chemistry 36.8 (1964): 1627-1639.
[5] Larive, Cynthia K.; Sweedler, Jonathan V. (2013). "Celebrating the 75th Anniversary of the ACS Division of Analytical Chemistry: A Special Collection of the Most Highly Cited Analytical Chemistry Papers Published between 1938 and 2012". Analytical Chemistry. 85 (0): 4201–2. doi:10.1021/ac401048d