Synthetic Aperture Ultrasound Imaging

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Synthetic Aperture Ultrasound Imaging with Robotic Tracking Technique

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Seminar Presentation

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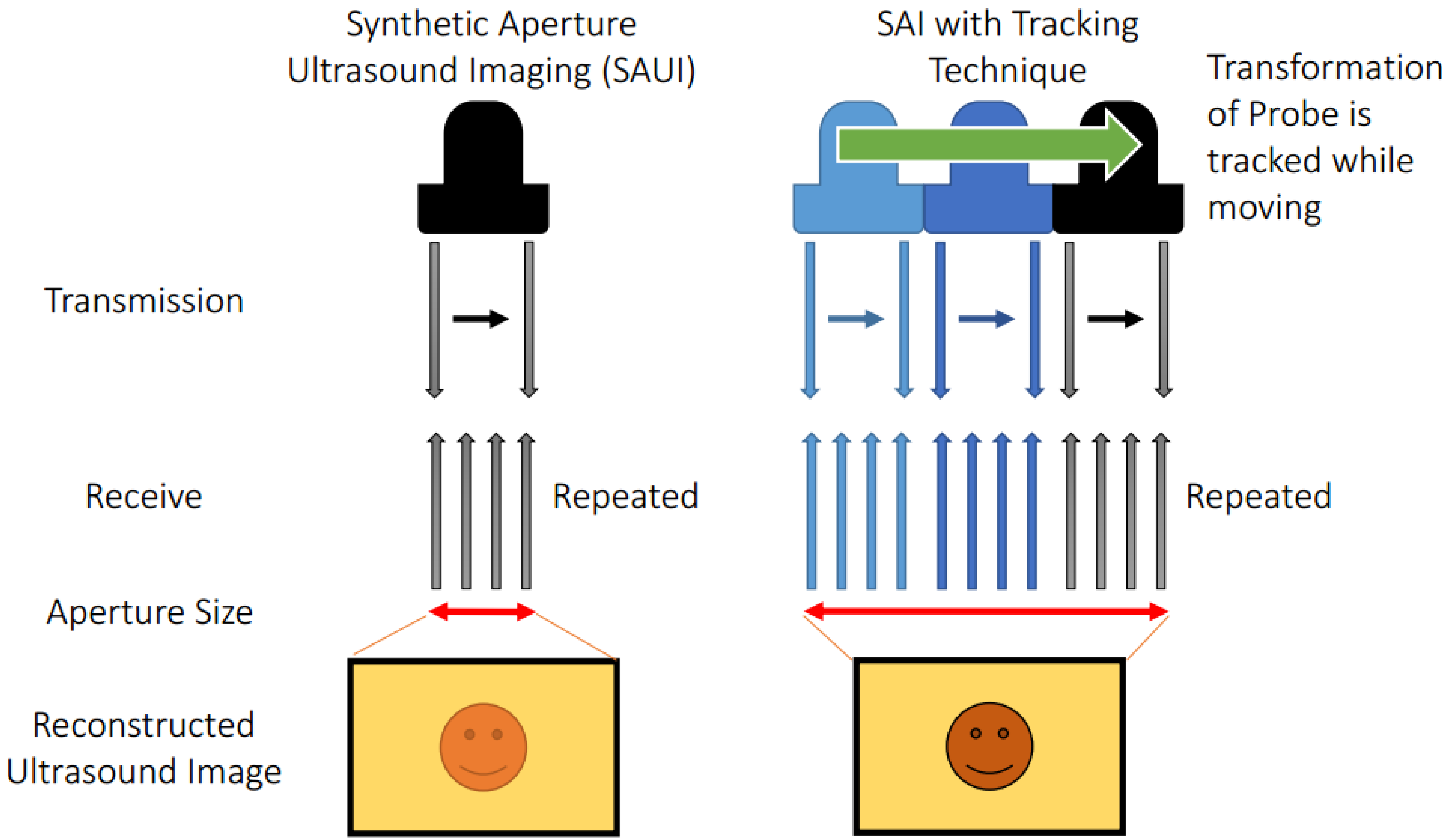
Project Background

- Aim: combine robotic tracking technique into synthetic aperture ultrasound imaging and to achieve higher resolution images
- Synthetic apertures improve the resolution of deep sight by utilizing expanded aperture size. The robotic tracking system can generate imaginary elements, which eventually expand the aperture size even more
- During the process, we also would work for inventing a new ultrasound calibration method with sub-millimeter error, which is necessary to reach our goal.


Synthetic Aperture Ultrasound Imaging (SAUI)
SAI with Tracking Technique
Transformation of Probe is tracked while moving
Transmission
Receive
Repeated
Repeated
Aperture Size
Reconstructed Ultrasound Image

- While using synthetic aperture:
  - The performance is still restricted by physical limitation of the number of elements.
  - The approach of this project is to take away the limitation of aperture size by tracking the ultrasound transducer
- The performance of reconstructed synthetic aperture images is depending on the accuracy of the transformation between images and the probe.
- In order to move the probe for a designated position, unknown rigid-body transformation on the transducer from sensor to image needs to be calibrated. -> ultrasound calibration
- We aim to improve the tracking accuracy using robot and create a new ultrasound calibration method to utilize accurate transformation from probe to image.

Today's paper

- Synthetic Aperture Ultrasound Imaging
  - Jensen J., Nikolov S., Gammelmark K., Pedersen M.
  - Ultrasonics 44 (2006) e5–e15
  - Technical University of Denmark, Center for Fast Ultrasound Imaging

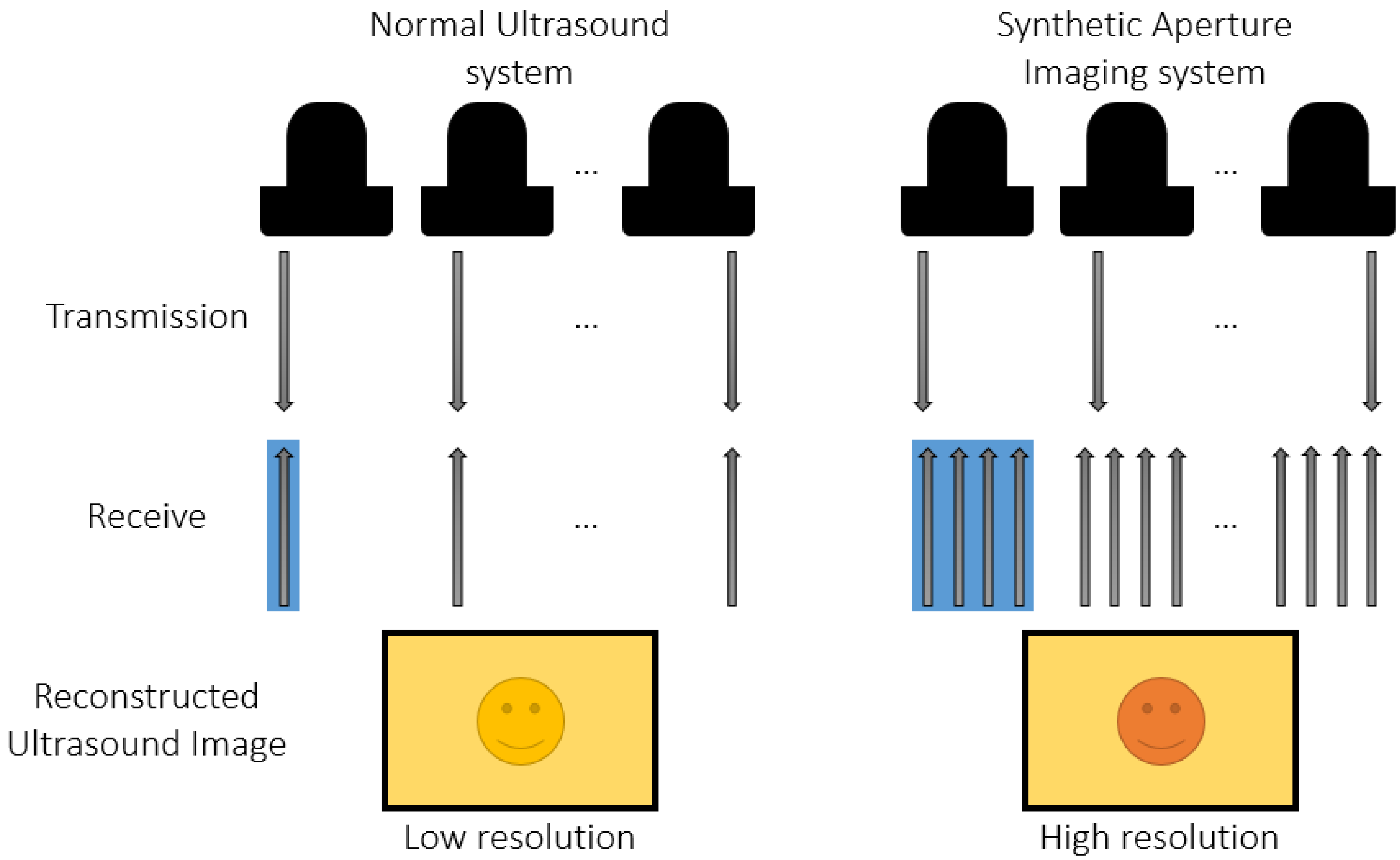
Conventional ultrasound imaging

- High frequency sound waves
- Waves travel through tissue and partly reflected at each tissue interface
- B-mode: multiple lines of interrogation over a wide area, each returning echo is assigned a brightness on a grey scale based on amplitude

12 week fetus
http://www.qlife.jp/dictionary/item/i_030840000/

- High frequency -> lose energy faster, less penetration depth
- Axial resolution is determined by frequency of ultrasound system.
- Lateral resolution is restricted by aperture size of ultrasound transducer.
- Images are acquired sequentially one image line at a time
- The acquisition rate is limited by the speed of sound c
- Two problems:
    - Single transmit focus
    - Low frame rate for velocity estimation

Introduction to synthetic aperture imaging



- A single element in the transducer aperture is used for transmitting a spherical wave covering the full image region.
- The received signals can be used for making a low resolution image
- Focusing is performed by finding the geometric distance from the transmitting element to the imaging point and back to the receiving element
- When a short pulse is transmitted and the echo signal is received, a round-trip delay is:

$$t_{\mathrm{p}}(i,j) = \frac{|\vec{r}_{\mathrm{p}} - \vec{r}_{\mathrm{e}}(i)| + |\vec{r}_{\mathrm{p}} - \vec{r}_{\mathrm{r}}(j)|}{c}$$

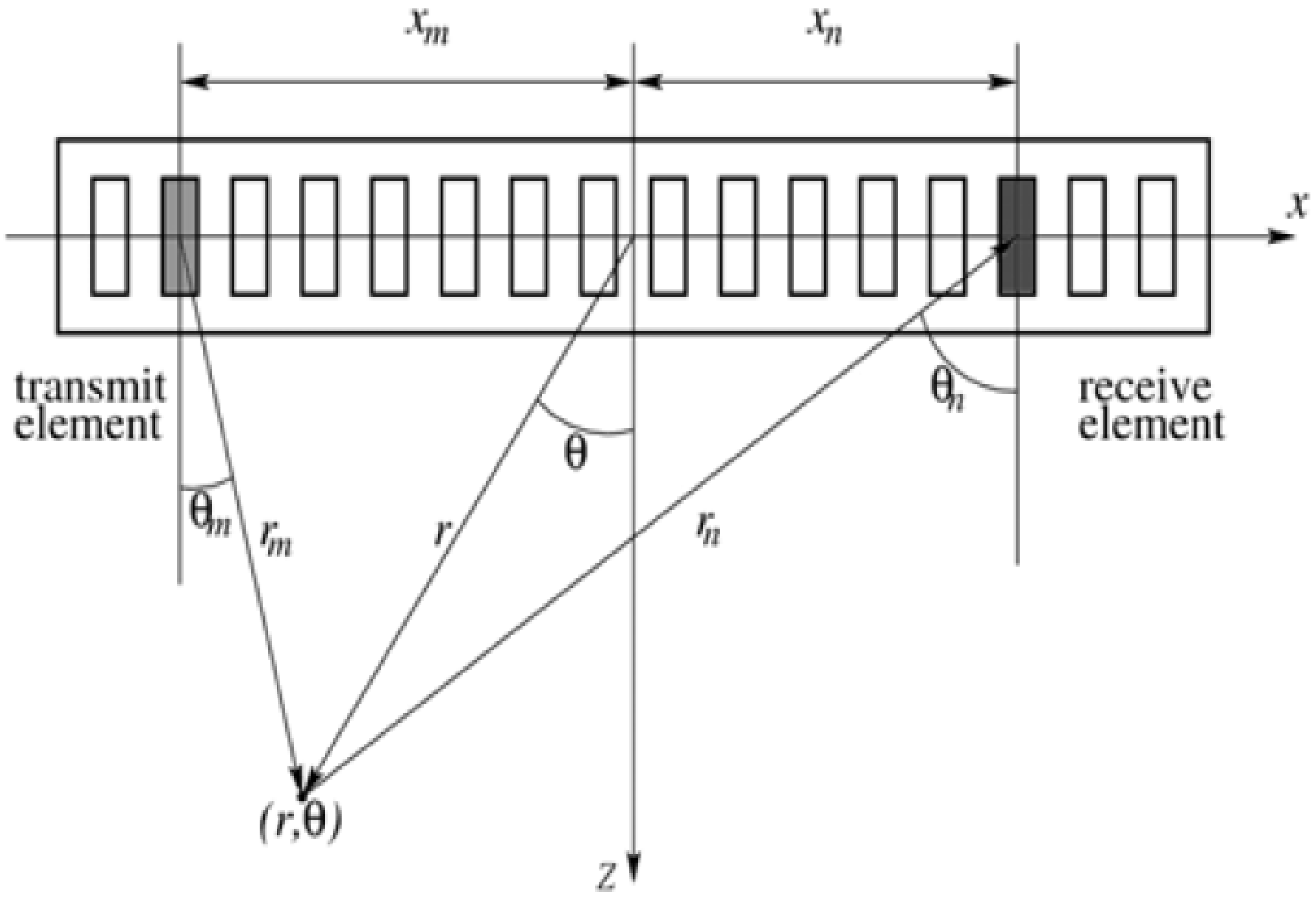
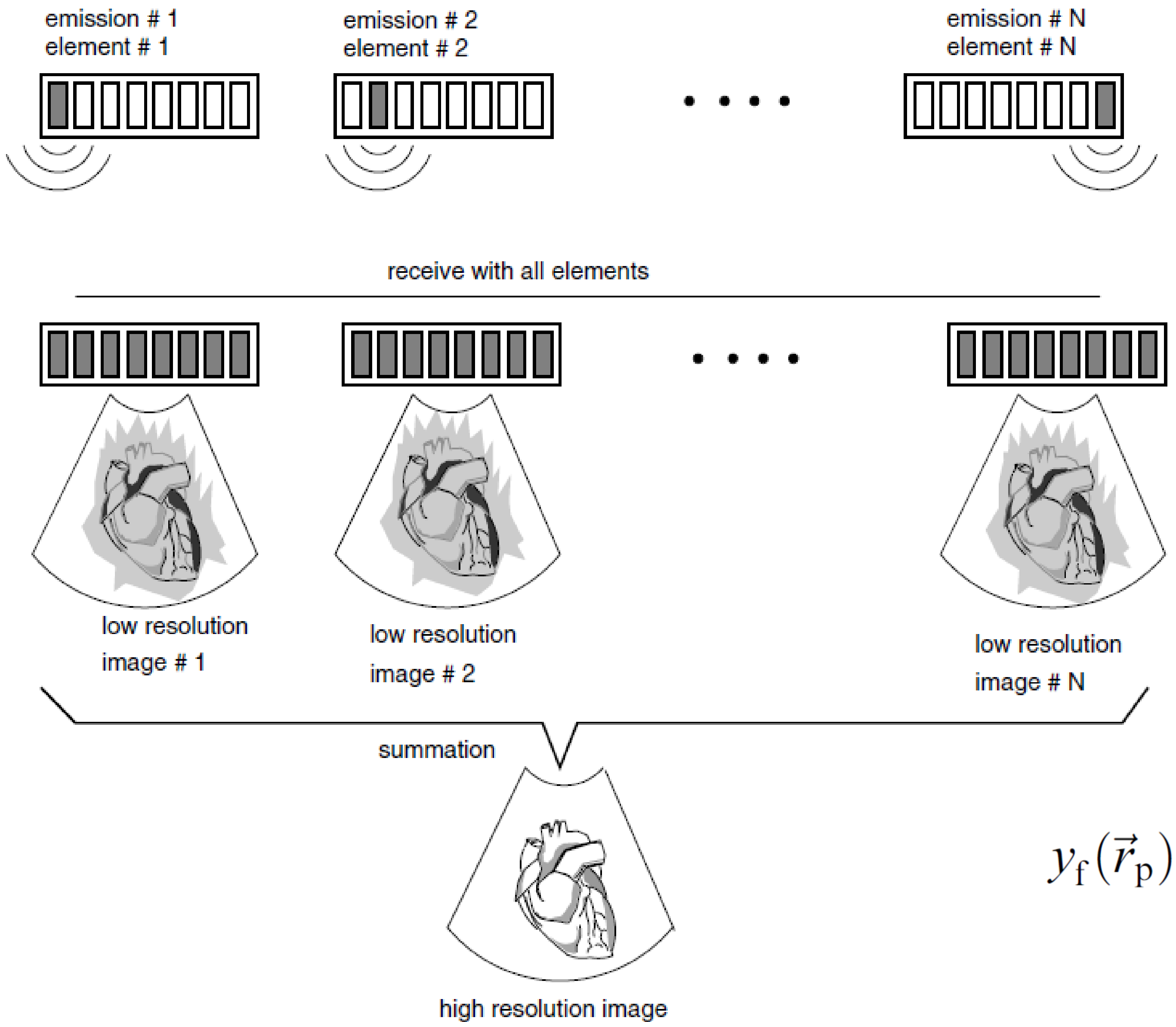


Fig. 2. Geometric relation between the transmit and receive element combination and the focal point



- After combining the low resolution images, the final signal is:

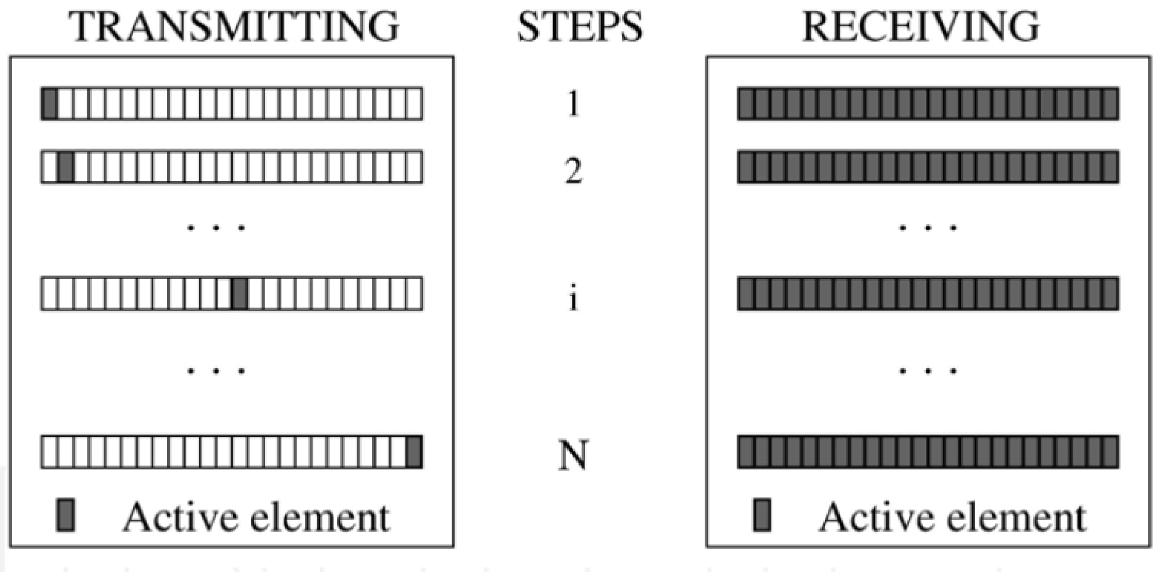
$$y_{\mathrm{f}}(\vec{r}_{\mathrm{p}}) = \sum_{j=1}^{N} \sum_{i=1}^{M} a(t_{\mathrm{p}}(i,j),i,j) y_{\mathrm{r}}(t_p(i,j),i,j)$$

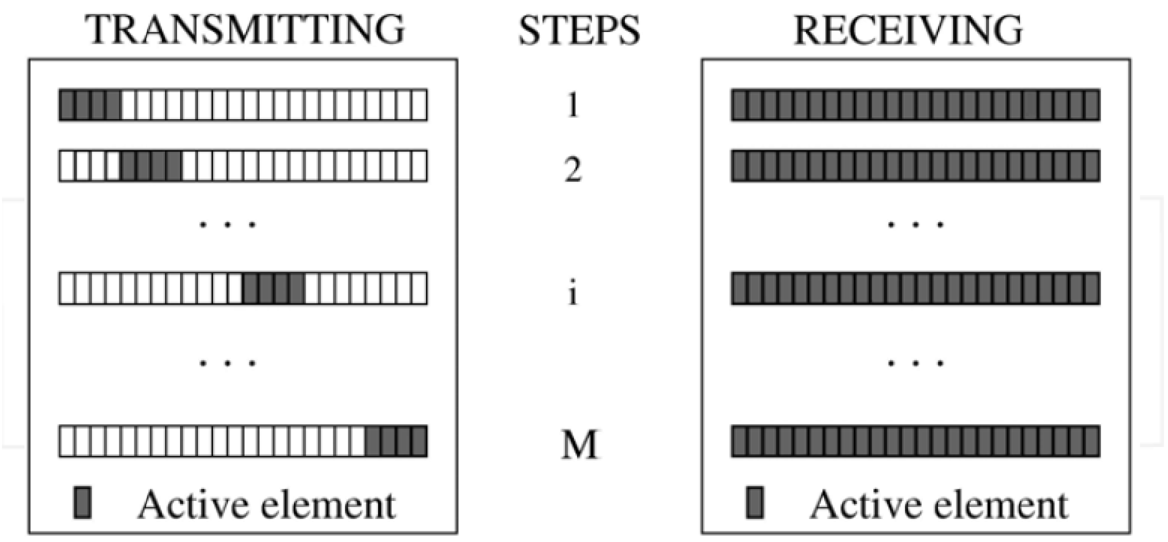
Recursive Imaging

- Very fast imaging can be achieved by using recursive imaging techniques
- SA acquisition sequence is repeated, a new frame is created after every pulse emission
- A new frame is created by adding the new RF lines to the RF lines from the previous frame
- Such an approach can yield very high frame rates and can be used for velocity imaging.

Penetration problem

- In SA imaging only a single element emits energy, so penetration depth is limited.
- This problem can be solved by combining several elements for transmission and using longer waveforms emitting more energy.





Equipment and implementation

- The authors have developed a software (RASMUS) to acquire SA images.
- All conventional ultrasound imaging methods can be implemented with this system, but real-time SA imaging is not possible.
- The data is stored in the RAM and later processed on a Linux cluster.

Flow estimation in conventional ultrasound

- Velocity estimations in conventional ultrasound is done by finding the shift in position of the scatterers over time.
- Lines are acquired from the same direction (8-16 times) and then the data is correlated to find the shift in position between lines
- Dividing the spatial shift by the time gives the velocity
- This method can only find the velocity along the ultrasound direction
- The standard deviation is often high
- The frame rate is lowered by the number of emissions per direction

Flow estimation in SA

- In SA imaging, it is possible to focus the received data in any direction and in any order. It does not have to be along the direction of the emitted beam, since the emission is spherical and illuminates the full region of interest.
- Note that the focused signal is a function of space, and that this can be anywhere in the image.

$$y_{\mathrm{f}}(\vec{r}_{\mathrm{p}}) = \sum_{j=1}^{N} \sum_{i=1}^{M} a(t_{\mathrm{p}}(i,j),i,j) y_{\mathrm{r}}(t_p(i,j),i,j)$$

- The received data can be focused along the direction of the flow

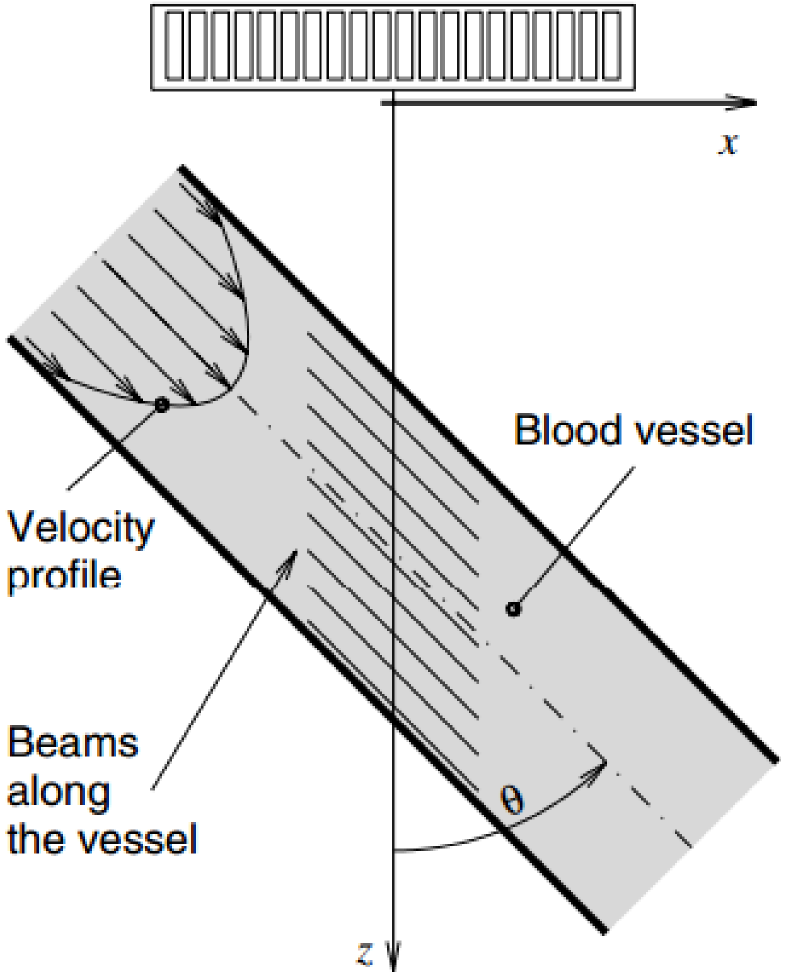


Fig. 1. Beamforming is made along the laminar flow.

- If the data collection is repeated, data from two high resolution images can be correlated to obtain the velocity of the blood or tissue
- It is here important that the two images are acquired in a short time interval
  - Data for the first image line is $y_1(x')$, and next image line is $y_2(x') = y_1(x' - \Delta x')$
  - Cross correlation between y_1 and y_2 gives a peak at $\Delta x'$ Cross correlation between y_1 and y_2 gives a peak at $\Delta x'$
  - Find velocity using the formula: $\Delta x' = |v|MT$
  - M: # emissions, T: time between emissions
  - Flow angle be estimated from the actual data.
    - At the actual direction the correlation of the data $y_1(x')$ and $y_2(x')$ is highest. For other directions the correlation will drop, since the velocities along that line are different due to the velocity profile of the blood.

- SA flow imaging has several advantages compared to traditional ultrasound flow imaging
  - Continuously available data for all points in the image.
  - Data can be focused in any direction
- The accurate velocity estimation can also be used for compensating for tissue motion during the SA acquisition process.

Clinical results

- Acquired in vivo real-time data
- Off-line processing for finding the clinical performance
- Tested both conventional ultrasound and SA
  - Using same region of interest, transducer, and measurement system at the same time
- Seven human volunteers were scanned at two positions (28 videos)
- Three experienced medical doctors in a double blinded experiment and they were asked to evaluate the images in terms of penetration depth and relative performance between the two images
- 0.48 cm increase in penetration depth ($p = 0.008$)
- Improved image quality ($p < 0.001$)

Thank you for your attention!

- Images are from:
  - Synthetic aperture ultrasound imaging
    - Jensen J., Nikolov S., Gammelmark K., Pedersen M.
  - Trots, Nowicki, Lewandowski, Tasinkevych
    - Institute of Fundamental Technological Research, Poland