JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

Paper Seminar

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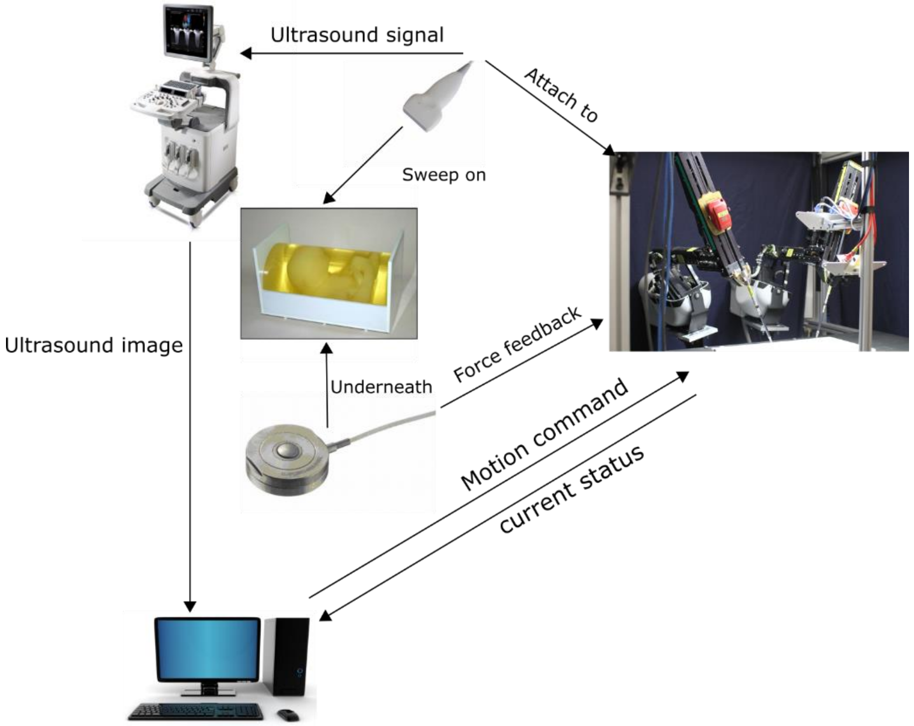
Group 18: Force Controlled Elastography with DaVinci Toolkit
Mentors: Preetham, Dr. Boctor, Dr. Taylor

Project Overview

Goal

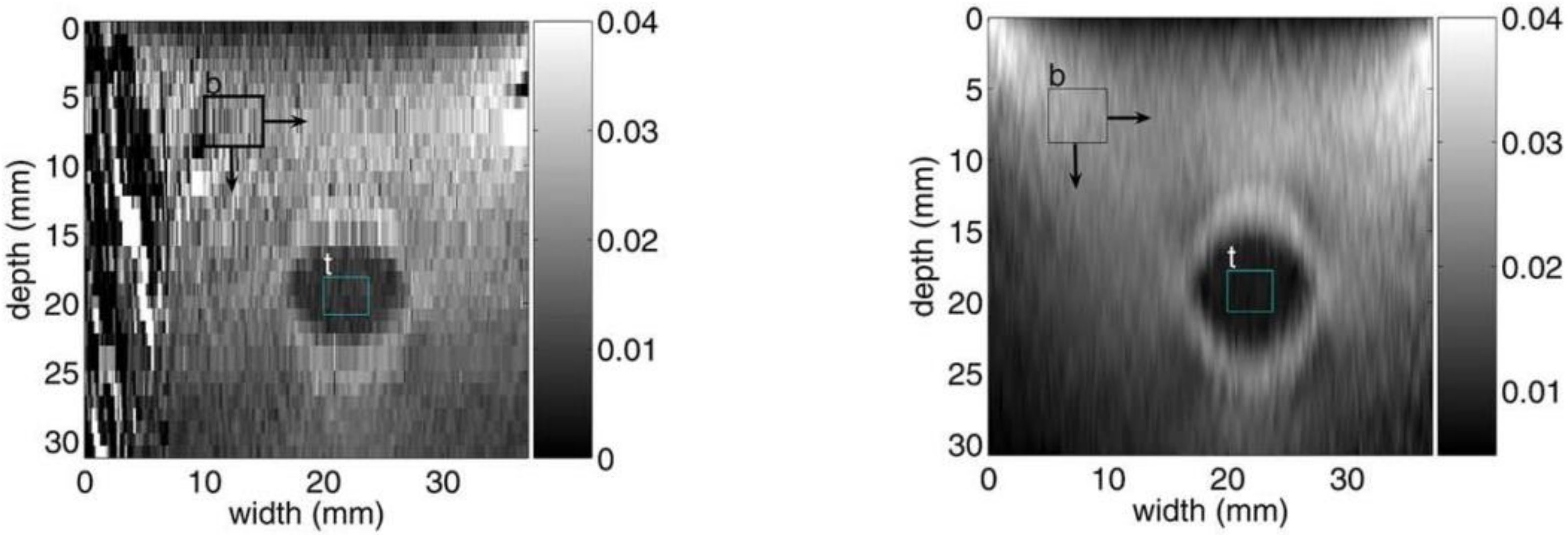
- Integrate ultrasound probe and software into the DVRK robot system.
- Use DVRK robot system to generate ultrasound elastography image and locate stiff features in a phantom based on that.



Paper Selection

1. Rivaz, H., Boctor, E., Foroughi, P., Zellars, R., Fichtinger, G., & Hager, G. (2008). **Ultrasound elastography: A dynamic programming approach**

- 2-D strain imaging technique based on minimizing a cost function using dynamic programming
- More robust to signal decorrelation in comparison to the standard correlation techniques
- 1 second processing time per frame, potentially suitable for real time elastography

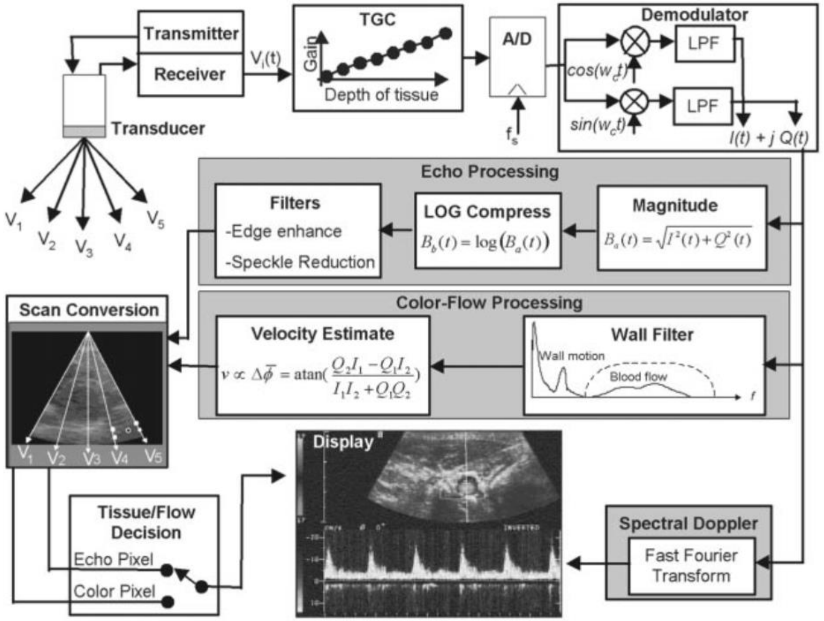


Rivaz, H., Boctor, E., Foroughi, P., Zellars, R., Fichtinger, G., & Hager, G. (2008). Ultrasound elastography: A dynamic programming approach. *IEEE Transactions on Medical Imaging*, *27*(10), 1373–1377. https://doi.org/10.1109/TMI.2008.917243

Background – Ultrasound

- **Ultrasonography** uses a probe containing multiple acoustic transducer to send pulses of sound into a material. Whenever a sound wave encounters a material with a different density (acoustical impedance), part of the sound wave is reflected back to the probe and is detected as an echo. The time it takes for the echo to travel back to the probe is measured and used to calculate the depth of the tissue interface causing the echo. The greater the difference between acoustic impedances, the larger the echo is.
- **A-mode**: A-mode (amplitude mode) is the simplest type of ultrasound. A single transducer scans a line through the body with the echoes plotted on screen as a function of depth.
- **B-mode**: In B-mode (brightness mode) ultrasound, a linear array of transducers simultaneously scans a plane through the body that can be viewed as a two-dimensional image on screen.

- This paper uses pre-compressed and post-compressed A-mode lines to calculate elastography images



York, G., & Kim, Y. (1999). Ultrasound processing and computing: review and future directions. *Annual Review of Biomedical Engineering*, *1*, 559–588. https://doi.org/10.1146/annurev.bioeng.1.1.559

Background – Elastography

- **Elastography** is an emerging medical imaging method with medical applications such as tumor detection, which computes the spatial variation of the elastic modulus of tissue.
- **Quasi-static methods**
  - Constant stress is applied to the tissue
  - Hooke's law: $\delta = E\varepsilon$
  - Pros: easy to implement
  - Cons: unknown stress distribution prevents precise estimation of the local Young modulus in kilo-Pascal
- **Dynamic methods**
  - A time-varying force is applied to the tissue -- short transient mechanical force or an oscillatory force with a fixed frequency.
  - Shear waves propagation: $E = 3\rho V_s^2$
  - Pros: can produce quantitative and higher resolution Young's modulus map
  - Cons: require a more complex system which can generate the shear wave and able to image the small displacements induced by the shear wave.

- This paper focuses on static elastography, a well-known technique that applies quasi-static compression of tissue and simultaneously images it with ultrasound.

Gennisson, J. L., Deffieux, T., Fink, M., & Tanter, M. (2013). Ultrasound elastography: Principles and techniques. *Diagnostic and Interventional Imaging*, *94*(5), 487–495. https://doi.org/10.1016/j.diii.2013.01.022

Background – Dynamic Programming

- **Dynamic programming** is a method for solving a complex problem by breaking it down into a collection of simpler sub-problems, solving each of those sub-problems just once, and storing their solutions. The next time the same sub-problem occurs, instead of re-computing its solution, one simply looks up the previously computed solution, thereby saving computation time at the expense of a modest expenditure in storage space.

- Small example: Maximum Value Contiguous Subsequence

https://en.wikipedia.org/wiki/Dynamic_programming

https://people.cs.clemson.edu/~bcdean/dp_practice/

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One-Dimensional Displacement Estimation using DP

The cost function C at a point i and associated displacement d_i is defined as a recursive function

$$C(i, d_i) = \min_{d_{i-1}}\{C(i-1, d_{i-1}) + wS(d_i, d_{i-1})\} + \Delta(i, d_i)$$

The difference between pre and post-compressed corresponding signals:

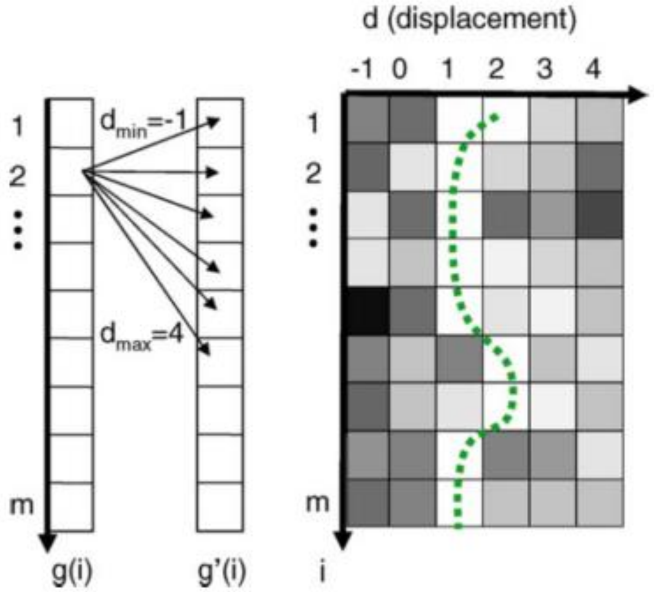
$$\Delta(i, d) = |g(i) - g'(i+d)|$$

The smoothness of the displacements for adjacent locations in strain images:

$$S(d_i, d_{i-1}) = (d_i - d_{i-1})^k$$

The value of d_{i-1} that minimizes cost function C is stored in function M for backtracking optimal solution,

$$M(i, d_i) = \operatorname*{argmin}_{d_{i-1}}\{C(i-1, d_{i-1}) + wS(d_i, d_{i-1})\}$$



$d_i \in [d_{min}, d_{max}]$, Searching space of d_{i-1} is limited to $d_i - 1, d_i, d_i + 1$ to speed up computation

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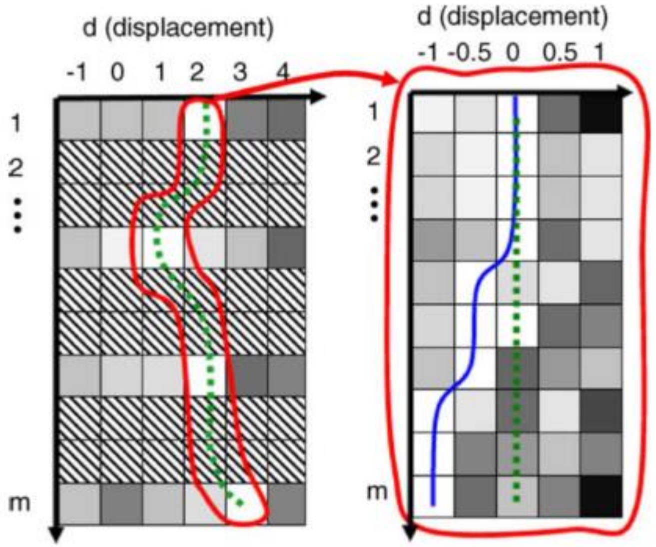
Hierarchical Search and Subpixel Displacement Estimation

Step 1. Further speedup is achieved by downsampling the signal $g(i)$ by a factor of β and comparing it with the original post-compressed signal $g'(i)$.

Step 2. Skipped samples are approximated by linear interpolation as initial guess for the next step.

Step 3. Original pre-compressed signal $g(i)$ is compared with $g'(i)$ upsampled by a factor of γ to refine displacement estimation.

Step 4. Repeat Step 3 n times to achieve a refinement factor of $1/\gamma^n$.



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Two-Dimensional Displacement Estimation

The cost function C at a point i, associated axial displacement d_a and lateral displacement d_l is defined as a recursive function

$$C_j(d_a, d_l, i) = \min_{\delta_a, \delta_l} \left\{ \frac{C_j(\delta_a, \delta_l, i-1) + C_{j-1}(\delta_a, \delta_l, i)}{2} + wS(d_a, d_l, \delta_a, \delta_l) \right\} + \Delta(d_a, d_l, i)$$

The difference between pre and post-compressed corresponding signals:

$$\Delta(i, j, d_a, d_l) = \left| g_j(i) - g'_{j+d_l}(i + d_a) \right|$$

The smoothness of the displacements for adjacent locations in strain images:

$$S(d_a, d_l, \delta_a, \delta_l) = (d_a - \delta_a)^2 + (d_l - \delta_l)^2$$

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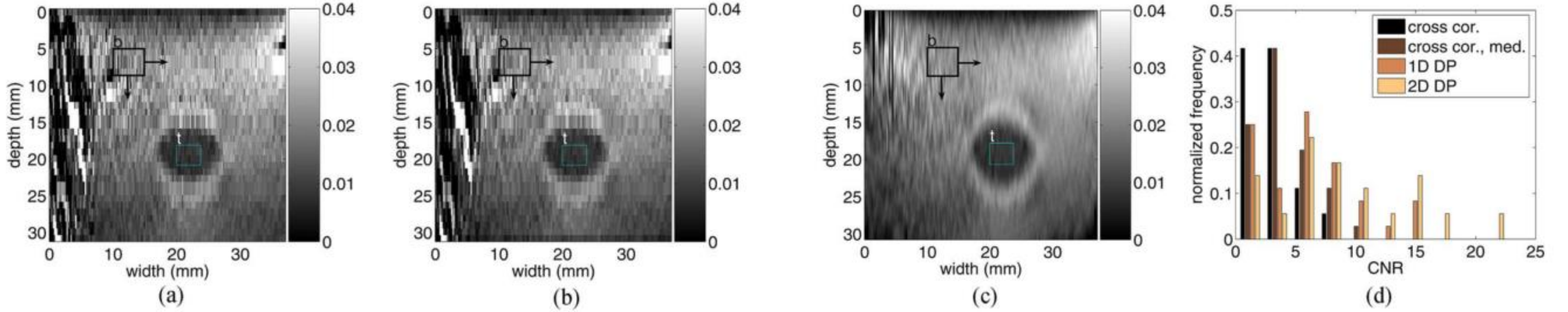
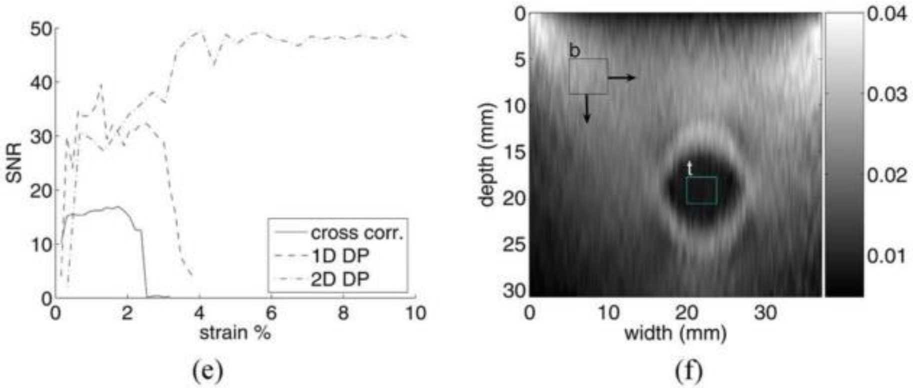
Results

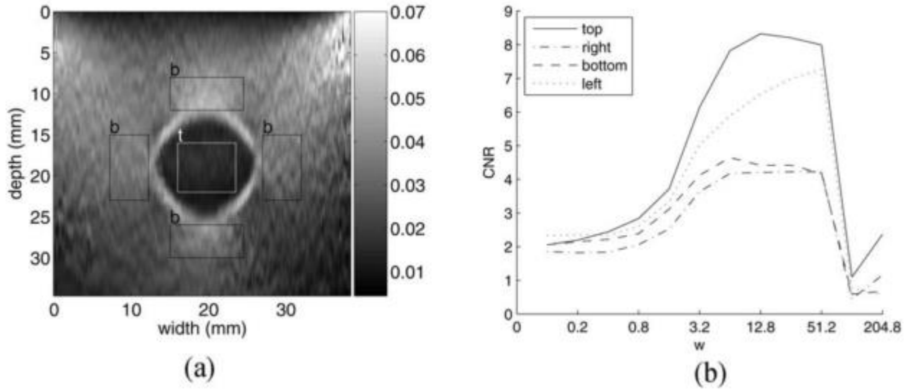
$$\mathrm{CNR} = \frac{C}{N} = \sqrt{\frac{2(\bar{s}_b - \bar{s}_t)^2}{\sigma_b^2 + \sigma_t^2}}, \quad \mathrm{SNR} = \frac{\bar{s}}{\sigma}$$



(a) (b) (c) (d)



(e) (f)



(a) (b)

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Assessment

Pros:

- More robust to the signal decorrelation (caused by scatterer motion in high axial compression, and lateral and out of plane motions of the probe) than standard cross correlation techniques.
- Able to generate low-noise elastograms using almost any two frames in free-hand palpation, given that they both belong to the same compression or relaxation cycle of the palpation excitation.
- No post-processing step such as median filtering needed.
- 1 second processing time per frame, potential real-time elastography with further optimization.

Cons:

- Need to tune the smoothness parameters to control the degree of smoothness in generated elastograms.
- Lateral search is only to decrease the noise and increase robustness of the axial strain, not suitable for calculating lateral strain.
- Intrinsic difficulty of static elastography – unknown stress distribution inside tissue, which leads to only qualitative results.

How to use it in my project?

- Combining force value from the force sensor underneath the elasticity phantom, we can get an inaccurate estimate of young’s modulus for everywhere inside the tissue – ultrasound elastography imaging.

References

[1] York, G., & Kim, Y. (1999). Ultrasound processing and computing: review and future directions. *Annual Review of Biomedical Engineering*, *1*, 559–588. https://doi.org/10.1146/annurev.bioeng.1.1.559

[2] Gennisson, J. L., Deffieux, T., Fink, M., & Tanter, M. (2013). Ultrasound elastography: Principles and techniques. *Diagnostic and Interventional Imaging*, *94*(5), 487–495. https://doi.org/10.1016/j.diii.2013.01.022

[3] Rivaz, H., Boctor, E., Foroughi, P., Zellars, R., Fichtinger, G., & Hager, G. (2008). Ultrasound elastography: A dynamic programming approach. *IEEE Transactions on Medical Imaging*, *27*(10), 1373–1377. https://doi.org/10.1109/TMI.2008.917243