Force Controlled Elastography with DaVinci Toolkit

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Introduction

Stiffness feature is a useful clinically relevant information. Traditionally, palpation is used to feel the stiffness of a patient's tissues qualitatively with the practitioner's hands. However, this kind of method is generally limited to superficial structures and cannot detect stiffer masses located deep in the body. Elastography is a medical imaging modality that maps the elastic properties of soft tissue. It is based on the hypothesis that soft tissues deform more than stiffer tissue, and these differences can be quantified in images of the tissue strain tensor or the Young's modulus. The advantage of elastography compared with palpation is it is quantitative and not limited to superficial structure. Elastography is very helpful in tumor recognition and intraoperative registration because compared with normal ultrasound images, the contrast of normal and abnormal tissues in elastography images is higher. In this project, we will integrate Ultrasound Elastography into the DaVinci Research Toolkit (DVRK) robot system to enable future research based on that.

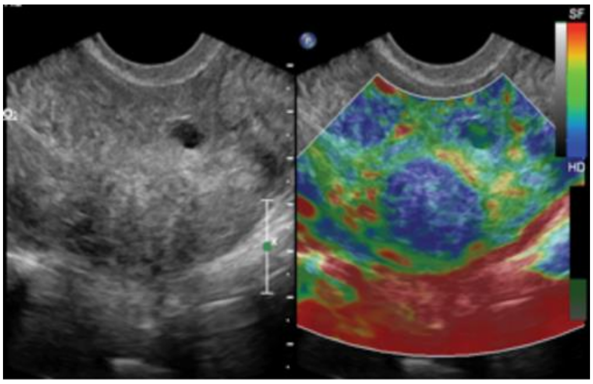

Figure 1. Comparison between ultrasound and elastography image

Technical Approach

Structure Diagram

Figure 2 is the proposed hardware structure diagram. The main hardware we will use is ultrasound machine, ultrasound probe which is compatible with DaVinci, DVRK hardware, force sensor, elasticity phantom and computer. Robot controlled probe is sweeping on the elasticity phantom, the force sensor will transmit contact force value to DVRK slave side and then further transmitted to computer. In the current setting, there's no place to attach the force sensor to the ultrasound probe, so it is placed underneath the elasticity phantom. The ultrasound signal is transmitted from probe to ultrasound machine and after processing, the RF data is transmitted to computer. The computer will adapt the control command based on received force value so that the ultrasound probe can move in the desired pattern. Combining force value and corresponding pre-compressed and post-compressed RF data, we can then generate elastography images.

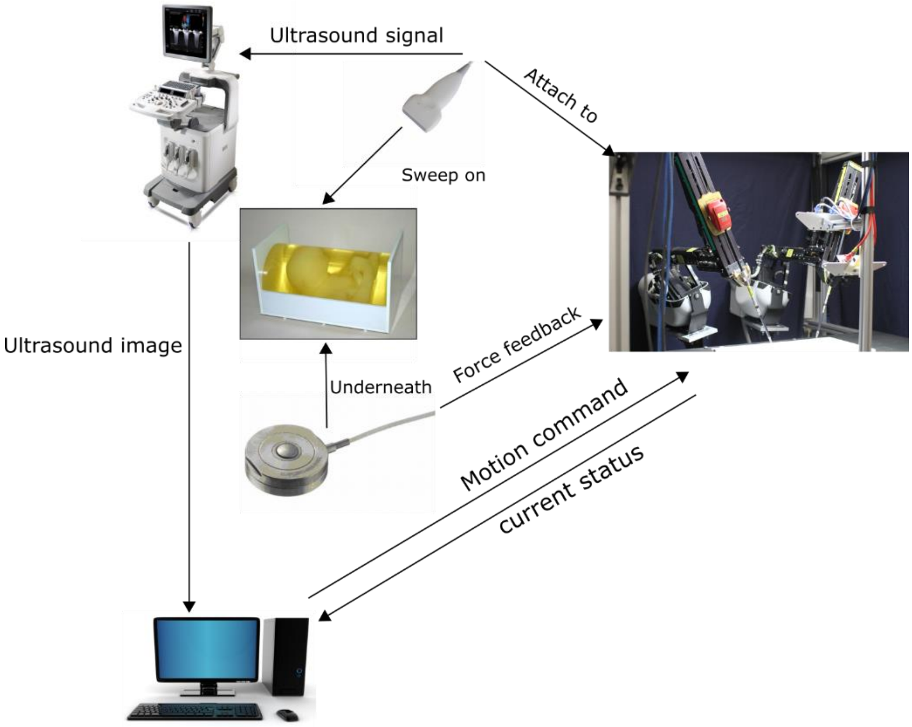

Figure 2 Hardware structure diagram

In this project, there will be basically two new modules integrated into the DVRK software system, which are Ultrasound imaging system and Elastography generating module. Ultrasound imaging system is used to communicate with the ultrasound machine so that DVRK can get access to the RF data. The Elastography generating module is to generate Ultrasound elastography images based on force value and RF data. The soft structure is in Figure 3.

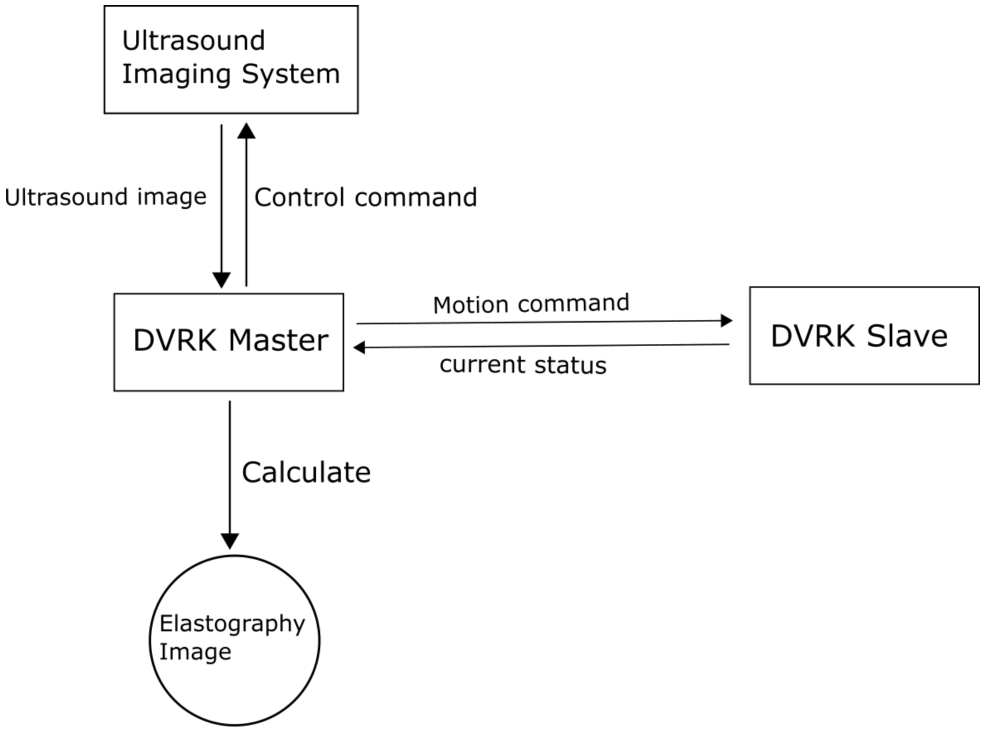

Figure 3 Software structure diagram

Key Techniques

There are several important techniques in this project. We will give a brief introduction to them.

A. Ultrasound Probe Calibration

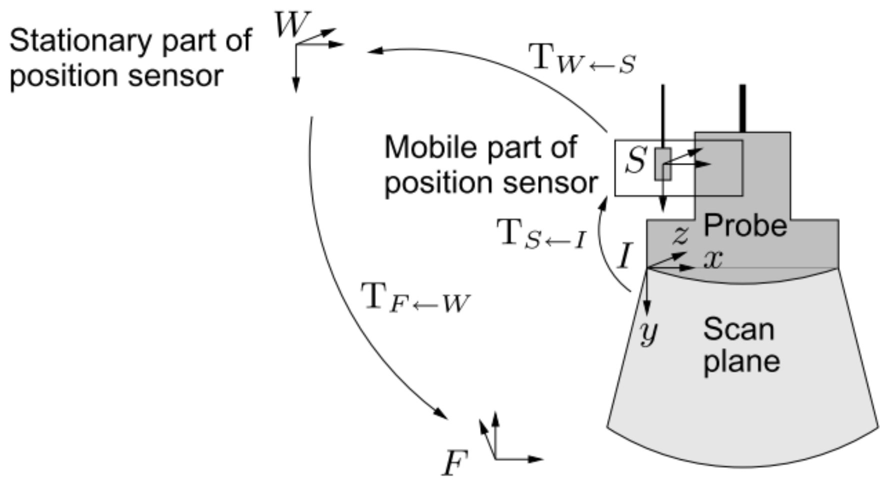

Figure 4 relevant coordinates of Ultrasound probe calibration procedure

The goal for ultrasound probe calibration is to know the transform $T_{S,I}$, which is the transform between the scan plane coordinate I and the coordinate of the position sensor which is fixed on the probe. Also, when the pixel scale factor T_S is not known, we also need to determine it at the same time during the calibration procedure.

There are two kinds of basic formula for scanning plane calibration. The first one is used when the scale factor is not known and the second one is used when it is known. For the first formula, there are no closed form solution and there are 8 unknowns in total, two scale factors and six calibration parameters. So it needs to be optimized with iterative optimization algorithm like Levenberg-Marquardt algorithm. And in the second formula, there are 6 unknowns, which can be derived with singular value decomposition based closed-form solution proposed by Umeyama.

In this project, the technique is similar, but we need to estimate the transform between scan plane and end effector of the robot arm so that we can know the scan plane location with respect to robot base and apply axial motion on the phantom to generate elastography images.

$$f_{\text{point2}} = \sum_{i=1}^{N} \left| p^W - \mathrm{T}_{W\leftarrow S_i} \mathrm{T}_{S\leftarrow I} \mathrm{T}_s p^{I_i'} \right|$$

$$f_{\text{point3}} = \sum_{i=1}^{N} \left| \mathrm{T}_{W\leftarrow S_i}^{-1} p^W - \mathrm{T}_{S\leftarrow I} \mathrm{T}_s p^{I_i'} \right|$$

B. Hybrid Force Feedback Control

To generate pre-compressed and post-compressed RF data and calculate elastography quantitatively. It is very important to control the contact force between the elasticity phantom and ultrasound probe to the desired value. There are two kinds of hybrid force feedback control laws that can help us achieve this goal.

Primitive I

$$\delta v = (I - M)\dot{\delta x} + M.\delta v_f$$

Primitive II

$$\begin{aligned} \delta v &= \dot{\delta x}^{*} + M\delta v_f, \\ &= \delta x + \hat{n} z_a Sin(2\pi\omega t) + M\delta v_f \end{aligned}$$

where,

$$\delta v_f = \mathcal{G}(F_c - F_d)$$

δx is a constant incremental step along the surface of the model and δv_f is the incremental velocity calculated based on contact force F_c and some desired bias force F_d. M is a projection matrix decomposing the forces in the normal direction of the surface.

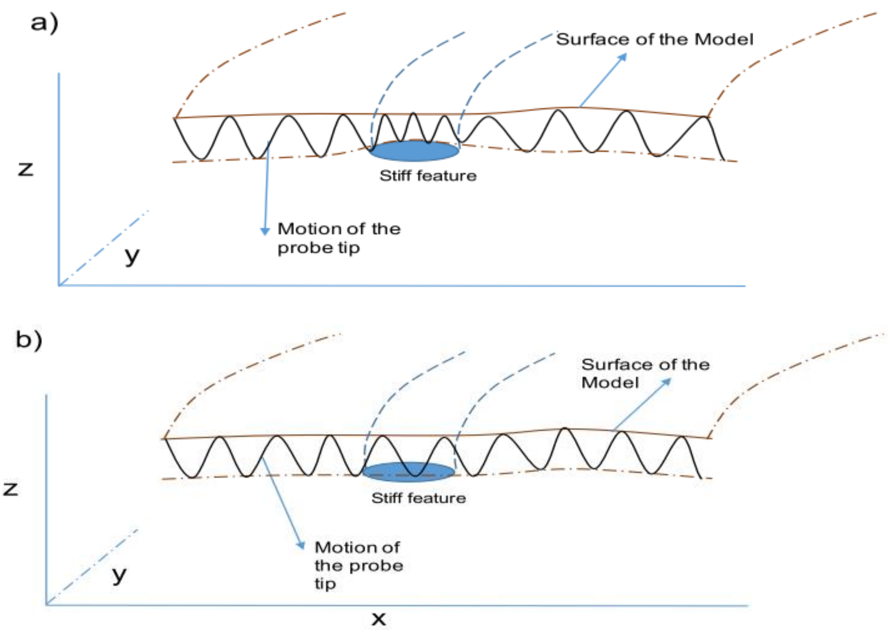

Figure 5 Trajectories of end effector under different hybrid force feedback control law ((a) is Primitive I, (b) is Primitive II)

C. Ultrasound Elastography

We plan to apply static elastography in this project. Static elastography is a technique that applies quasi-static compression on tissue and simultaneously images it with ultrasound. Through analysis of the ultrasound images, a tissue displacement map can be obtained. We plan to use dynamic programming proposed by Hassan et al. to solve this optimization problem.

Below is the cost function,

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

where,

$$S(d_{a_i}, d_{l_i}, d_{a_{i-1}}, d_{l_{i-1}}) = (d_{a_i} - d_{a_{i-1}})^2 + (d_{l_i} - d_{l_{i-1}})^2$$

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

S is the smoothness constraints term that encourages the displacements of adjacent locations are similar and don't tend to change dramatically.

Δ is the data similarity term that encourages pre-compressed RF data to find the corresponding one which is similar to itself in terms of RF value in the post-compressed RF data. To treat the whole B-mode image as a tree structure where the root node is located at upper left pixel, we can use dynamic programming to solve this global optimization problem.

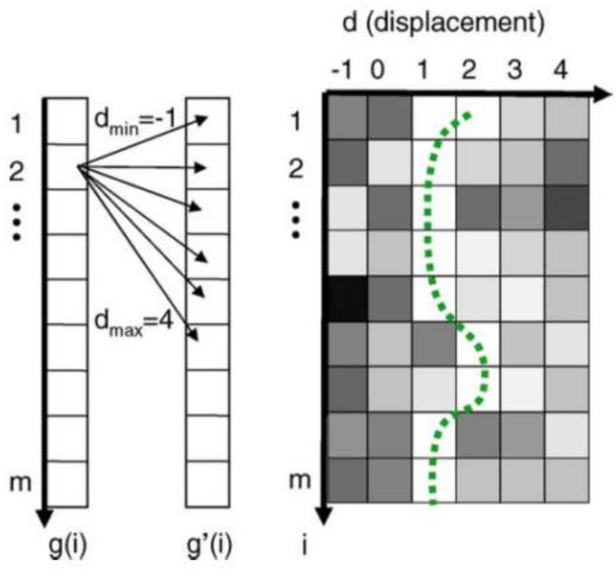

Figure 6 Diagrammatic sketch of dynamic programming algorithm for elastography generating

Deliverables

Minimum deliverable

Integration of DaVinci ultrasound tool and ultrasound system into DVRK system

Expected deliverable

Ultrasound imaging with force feedback control

Maximum deliverable

Integration of Ultrasound elastography into DVRK system

Dependencies

Dependency	Status	Fallback
Collaboration		
Ultrasound probe kinematics calibration with Preetham	Solved	
Ultrasound probe scan plane calibration with Alexis	Solved	
Hardware		
DVRK hardware	Solved	
Compatible ultrasound probe	Solved	
Ultrasound machine	Solved	
Elasticity ultrasound phantom with stiff features and proper weight from MUSIIC group	Pending	Build a proper one with gel by myself
Software		
DVRK software	Solved	
Ultrasound data acquisition API	Solved	
Robot operating system (ROS)	Solved	
Proper visualization library	Solved	
Elastography code from MUSIIC group	Solved	

Timeline

Task Name	Start Date	End Date	Duration	Status
Milestone 1 - Ultrasound data acquisition integration	02/28/17	03/14/17	11d	In Progress
Learn DVRK software framework	02/28/17	03/06/17	5d	In Progress
Learn ultrasound data acquisition API	03/07/17	03/08/17	2d	Not Started
Integrate API into DVRK framework	03/09/17	03/10/17	2d	Not Started
Ultrasound image display in DVRK framework	03/13/17	03/14/17	2d	Not Started
Milestone 2 - Ultrasound probe calibration	03/15/17	03/28/17	10d	Not Started
Ultrasound probe install	03/15/17	03/15/17	1d	Not Started
Ultrasound kinematics calibration	03/16/17	03/20/17	3d	Not Started
Ultrasound scan plane calibration	03/21/17	03/24/17	4d	Not Started
Calibration results verification	03/27/17	03/28/17	2d	Not Started
Milestone 3 - Hybrid force feedback control with ultrasound probe	03/29/17	04/07/17	8d	Not Started
Learn force sensor data acquisition API and force control in DVRK	03/29/17	03/30/17	2d	Not Started
Get a ready-to-use elasticity phantom or make a proper one	03/31/17	04/03/17	2d	Not Started
Install force sensor underneath phantom and test force sensor data acquisition	04/04/17	04/04/17	1d	Not Started
Move ultrasound probe on phantom surface with constant force	04/05/17	04/07/17	3d	Not Started
Milestone 4 - Ultrasound Elastography integration	04/10/17	04/25/17	12d	Not Started
Obtain Ultrasound Elastography source code or implement one	04/10/17	04/14/17	5d	Not Started
Integrate Ultrasound Elastography into DVRK software framework	04/17/17	04/20/17	4d	Not Started
Test Ultrasound Elastography on phantom	04/21/17	04/25/17	3d	Not Started
Project refinement and further verification	04/26/17	05/12/17	13d	Not Started
Seminar presentation	03/06/17	03/08/17	3d	Not Started
Checkpoint presentation	04/03/17	04/05/17	3d	Not Started
Final presentation	05/13/17	05/17/17	4d	Not Started

Management

Weekly meeting with Dr. Taylor on Model and Registration Meeting.
Weekly meeting with Preetham on pre-scheduled time.
Regular meeting with Dr. Boctor.

Reading List

[1] Chalasani, P., Wang, L., Roy, R., Simaan, N., Taylor, R. H., & Kobilarov, M. (n.d.). Concurrent Nonparametric Estimation of Organ Geometry and Tissue Stiffness Using Continuous Adaptive Palpation.

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[6] Krupa, A., & Chaumette, F. (2005). Control of an ultrasound probe by adaptive visual servoing. *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS*, 2007–2012.
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[8] 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.
[9] Chalasani, P., Wilkening, P., Chen, Z., & Taylor, R. (2014). CSA NRI Research Environment.
[10] Mueller, K. (1990). Introduction to Medical Imaging Ultrasound Imaging Milestone applications : Non-linearity.