CPS: Medium: Collaborative Research: Human-on-the-loop Control for Small Ultrasound Imaging

Michael M. Zavlanos, Wilkins Aquino, Miroslav Pajic, Mostafa Fatemi, and Azra Alizad

Duke PRATT SCHOOL of ENGINEERING

DUKE ROBOTICS

Project Overview

Ultrasound Medical Imaging

- Low operating cost
- High patient safety
- Variability in image quality

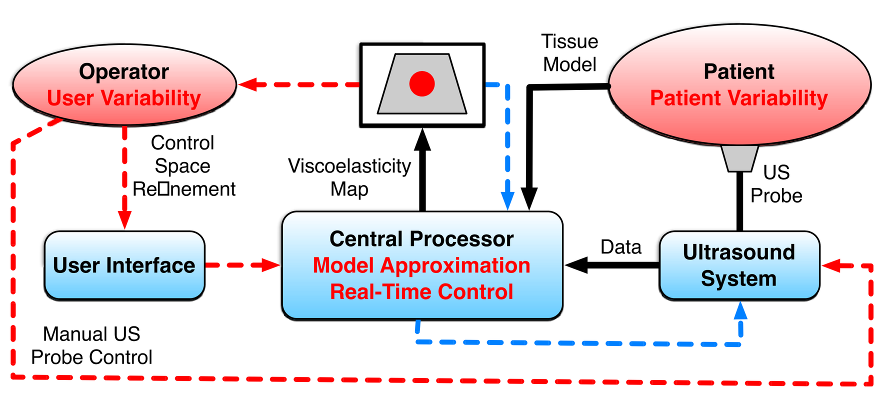
Goal: The goal of this project is to develop a new active ultrasound system where expert users with varying levels of training interact with a smart ultrasound device to improve medical imaging and facilitate diagnosis

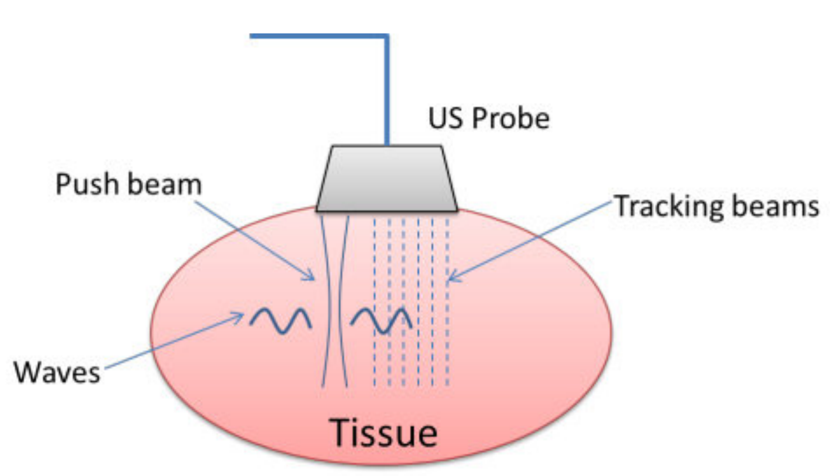
Impact

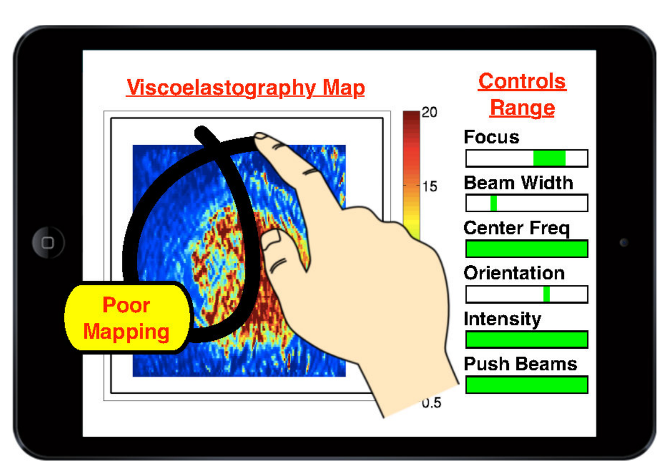
- Reduce the number of unnecessary biopsies
- Application of the novel closed-loop MCPS techniques in other medical devices and systems
- Application beyond medicine and healthcare
- K-12, undergraduate, and graduate education
- Diversity

Focus

- Develop an Active Viscoelastography (AVE) system
- Viscoelasticity Mapping
- Closing the Loop with Autonomous Parameter Optimization
- User-Machine Interaction







Research Description

The Elastography Inverse Problem:

- Motion in tissue described in the frequency-domain:

$$\nabla\cdot\boldsymbol{\sigma} + \boldsymbol{b} + \rho\omega^2\boldsymbol{u} = \boldsymbol{0}, \quad \boldsymbol{\epsilon}[\boldsymbol{u}] = \frac{1}{2}(\nabla\boldsymbol{u} + \nabla\boldsymbol{u}^T), \quad \boldsymbol{\sigma} = 2G\boldsymbol{\epsilon}_d[\boldsymbol{u}] + Be[\boldsymbol{u}]\boldsymbol{I} \qquad \text{in } \Omega$$

$$e[\boldsymbol{u}] = \sum_i \epsilon_{ii}[u], \quad \boldsymbol{\epsilon}_d[\boldsymbol{u}] = \boldsymbol{\epsilon}[\boldsymbol{u}] - \frac{1}{3}e[u]\boldsymbol{I}$$

Elastography as an Inverse Problem:

$$\{\boldsymbol{u}^*, G^*\} := \underset{\boldsymbol{u}\in\mathcal{U}, G\in\mathcal{G}}{\operatorname{argmin}} \; J(\boldsymbol{u}, G; \tilde{\boldsymbol{d}}) \text{ subject to } \mathcal{M}(\boldsymbol{u}, G, \boldsymbol{c}) = \boldsymbol{0}.$$

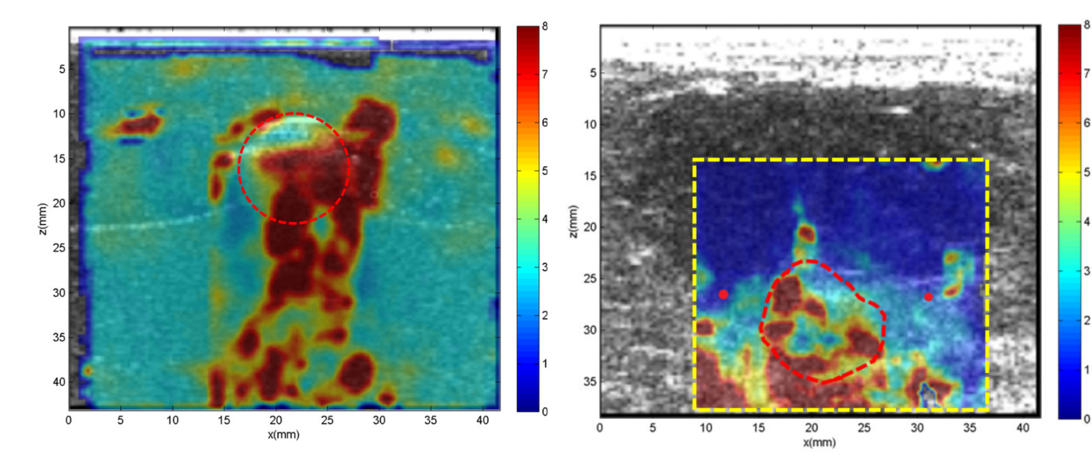
where

$$J(\boldsymbol{u}, G; \tilde{\boldsymbol{d}}) := \frac{1}{2}\|D(\boldsymbol{u} - \tilde{\boldsymbol{d}})\|^2 + \mathcal{R}(G)$$

Research Description (Cont.)

Objective 1: Data Fusion for Ultrasound Elastography:

- **Autonomously eliminating image artifacts**



- **The data fusion problem:**

$$\{\{\boldsymbol{u}_i\}^*, G_n^*\} := \underset{\boldsymbol{u}_i\in\mathcal{U}, G_n\in\mathcal{G}}{\operatorname{argmin}} \; \hat{J}(\{\boldsymbol{u}_i\}, G_n; \{\tilde{\boldsymbol{d}}_i\}) \text{ subject to } \mathcal{M}(\{\boldsymbol{u}_i\}, G_n, \{\boldsymbol{c}_i\}) = \boldsymbol{0}, \quad i = 1...n.$$

Challenges
- The constraints are comprised of n systems of PDEs
- The domain of each PDE may change

Trade off between implementation speed and accuracy
- Every iteration requires the solution of a forward and an adjoint problem that are decoupled across the control variables
- Parallel implementation
- Rapid Optimization Library (ROL)

Objective 2: Control and Human interaction for Smart Ultrasound Elastography:

- **Autonomous control and parameter optimization:**

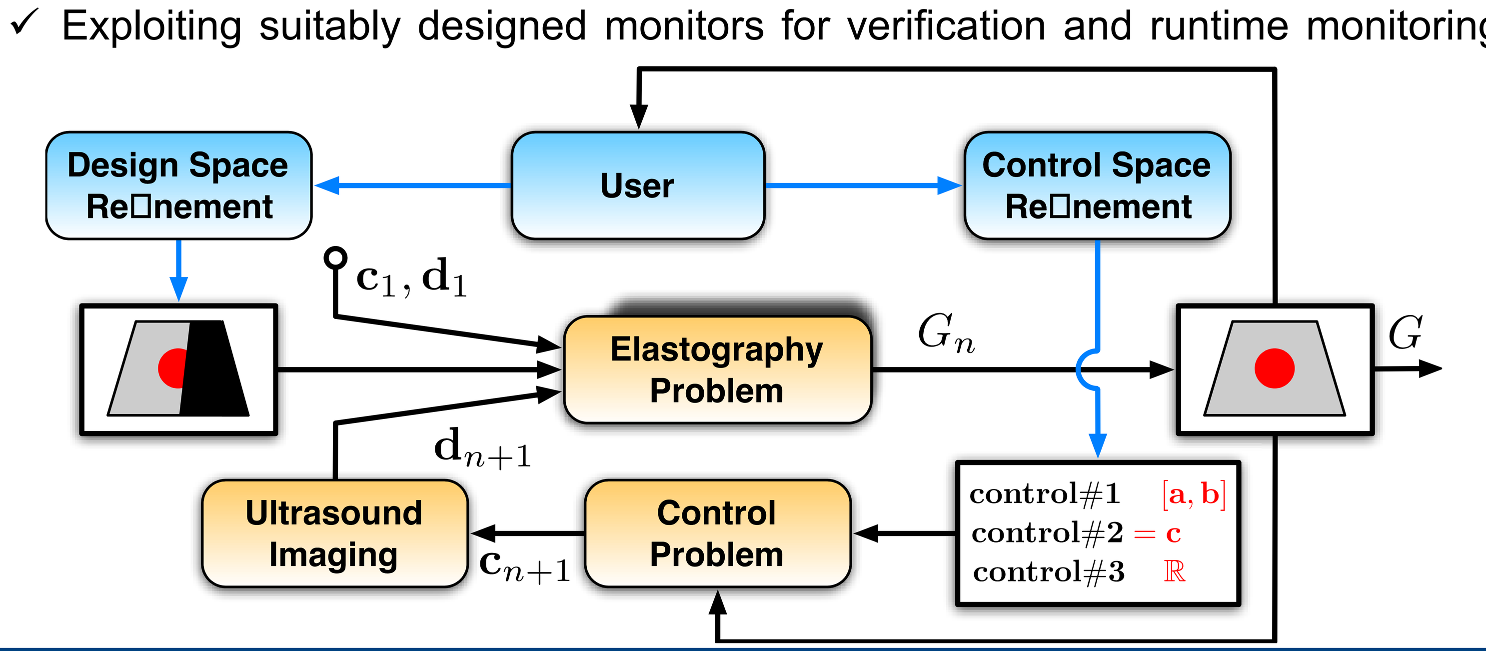
  Defining an optimality index
  - ✓ Fisher Information,
  - ✓ Hessian of the objective function:

$$\boldsymbol{c}_{n+1} = \underset{\boldsymbol{c}, G}{\operatorname{argmin}} \; J(\boldsymbol{u}, G; \tilde{\boldsymbol{d}}) - \sum_{i=1}^{n} w_i \|G - G_i\|, \;\; \text{s.t. } \mathcal{M}(\boldsymbol{u}, G, \boldsymbol{c}_i) = \boldsymbol{0}, \; \forall i, \;\; \mathcal{M}(\boldsymbol{u}, G, \boldsymbol{c}) = \boldsymbol{0}.$$

- **Operator-Machine Interaction.**

Objective 3: Safe and Efficient Design of Active Ultrasound Elastography:

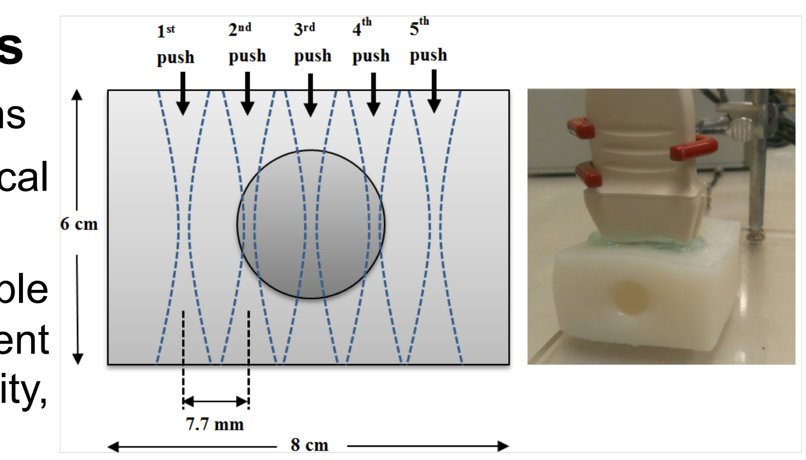
- Efficient real-time implementation of ultrasound Elastography (FPGA or GPU)
- Ensuring patient safety:
  - ✓ Exploiting the architectural modeling of the system as a design process part
  - ✓ Exploiting suitably designed monitors for verification and runtime monitoring



Experimental Plans

Laboratory phantoms

- Tissue mimicking phantoms
- Determination of mechanical parameters independently
- Construction of multiple phantoms with different values of elasticity, viscosity, and sizes



Ultrasound System

- Verasonics, Vantage with a linear probe (L7-4 or L11-4v)

Validation:

- ❑ Testing various phantoms,
- ❑ Comparing the estimated properties
- ❑ Evaluating the consistency of solutions across different operators

Preliminary Results

- Single ARF push at different locations for the first five experiments
- Five simultaneous pushes for the sixth experiment