In Situ Needle Path Adjustment and Trajectory Optimization

Group 4

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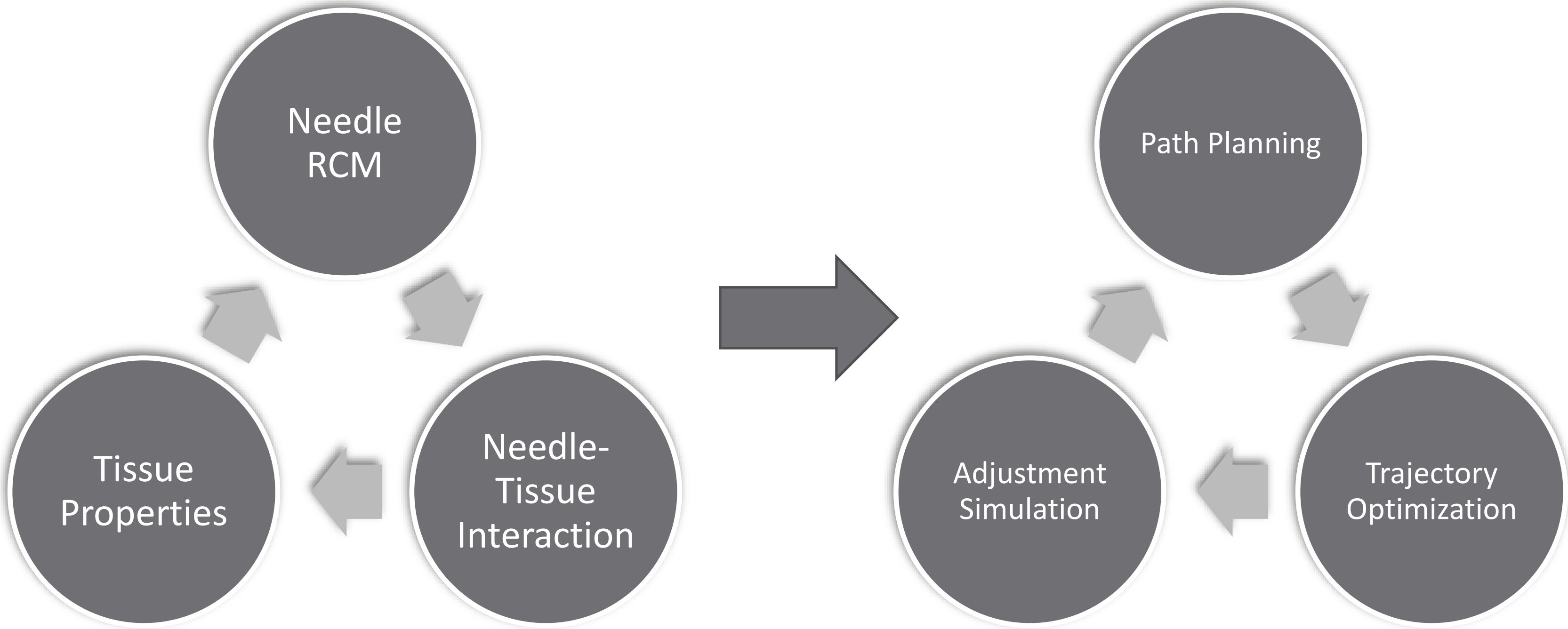
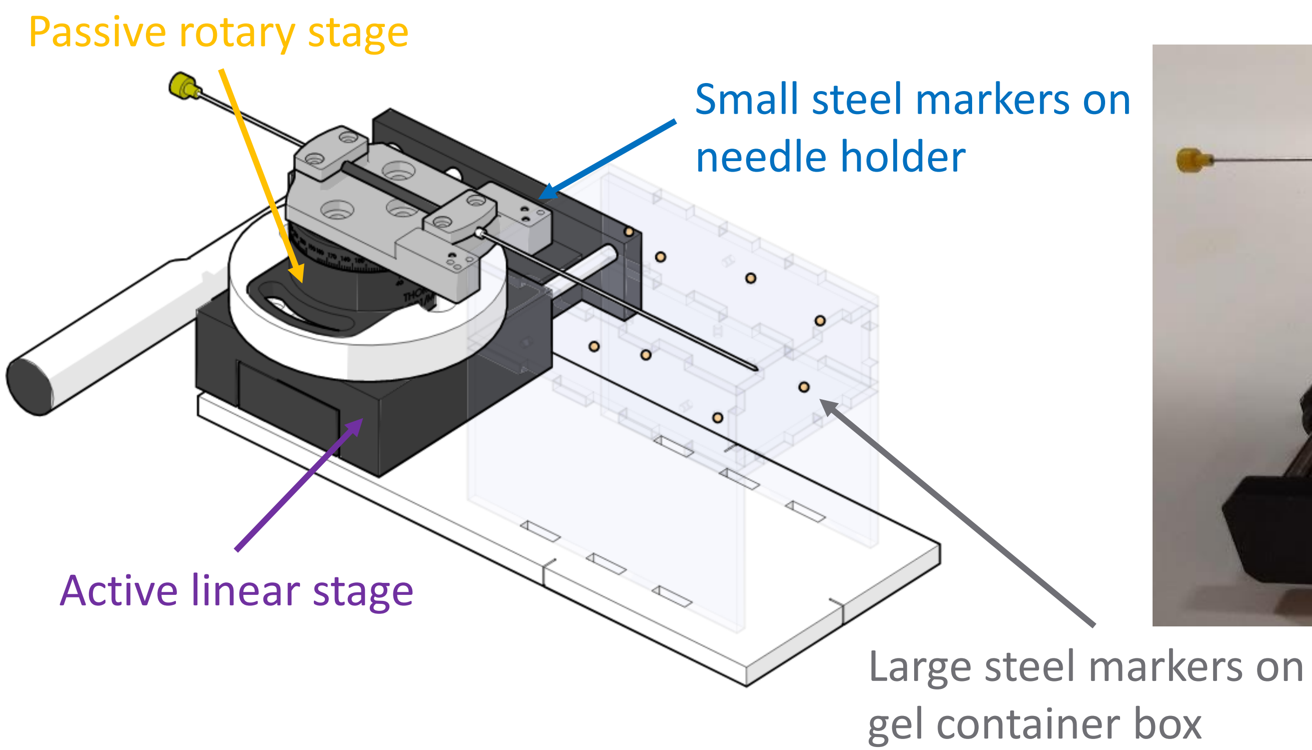
Project Summary and Goals

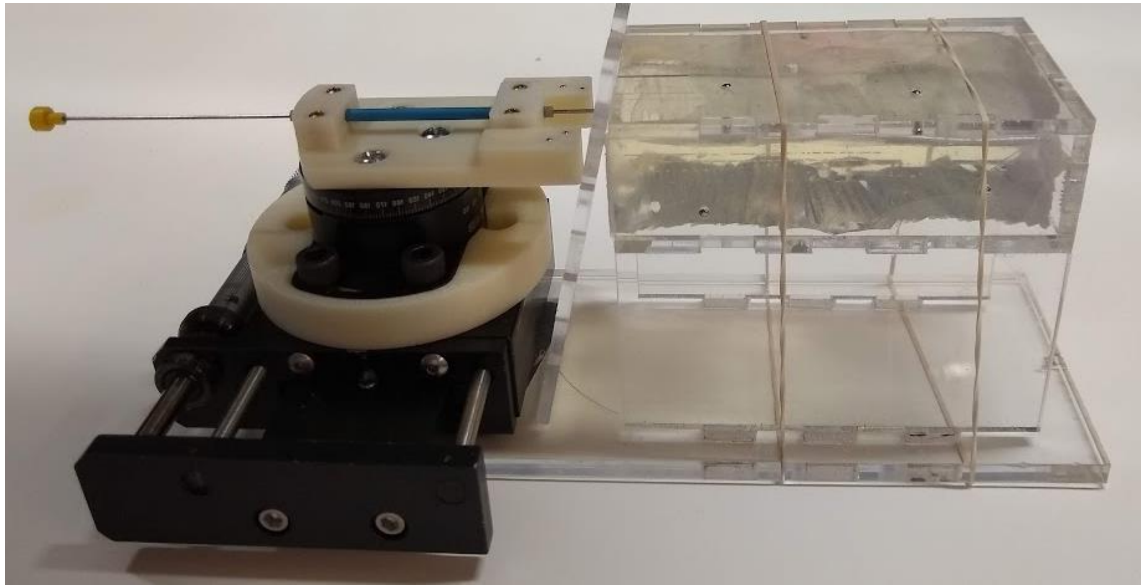
- Design and create experiment setup to mimic and capture needle natural remote center of motion (RCM)
- Evaluate the accuracy of proposed needle-tissue interaction model
- Implement path planning algorithms to generate optimal needle base motion



Experiment Setup to Mimic Needle RCM

- The setup include:
  1. *A manual linear stage to provide lateral needle base motion*
  2. *A passive rotary stage to allow natural needle rotation*
  3. *Two sets of steel markers on the needle holder and tissue phantom container*





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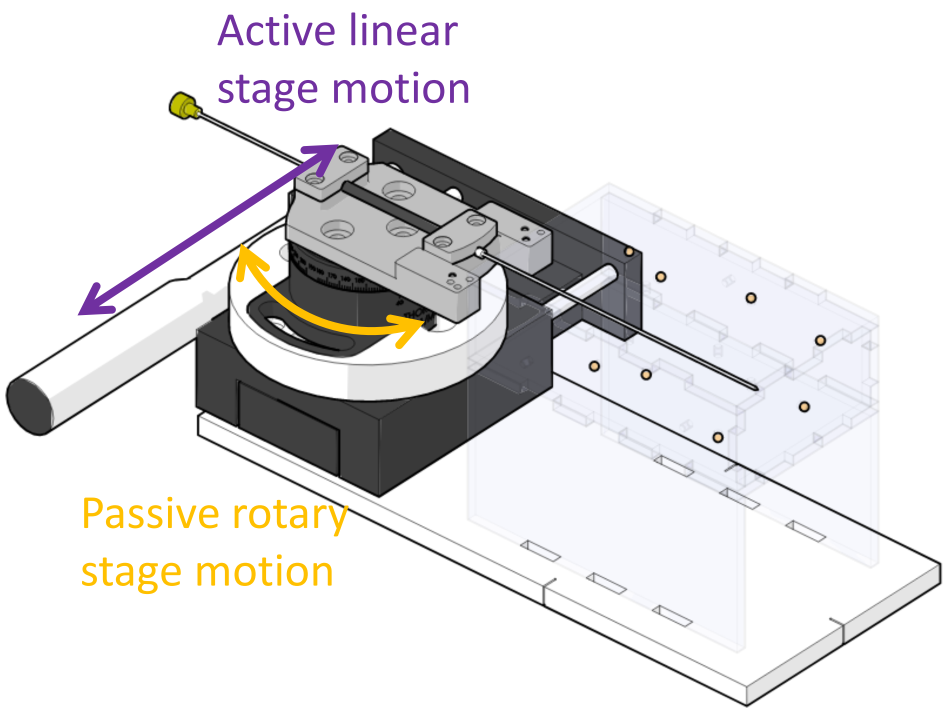
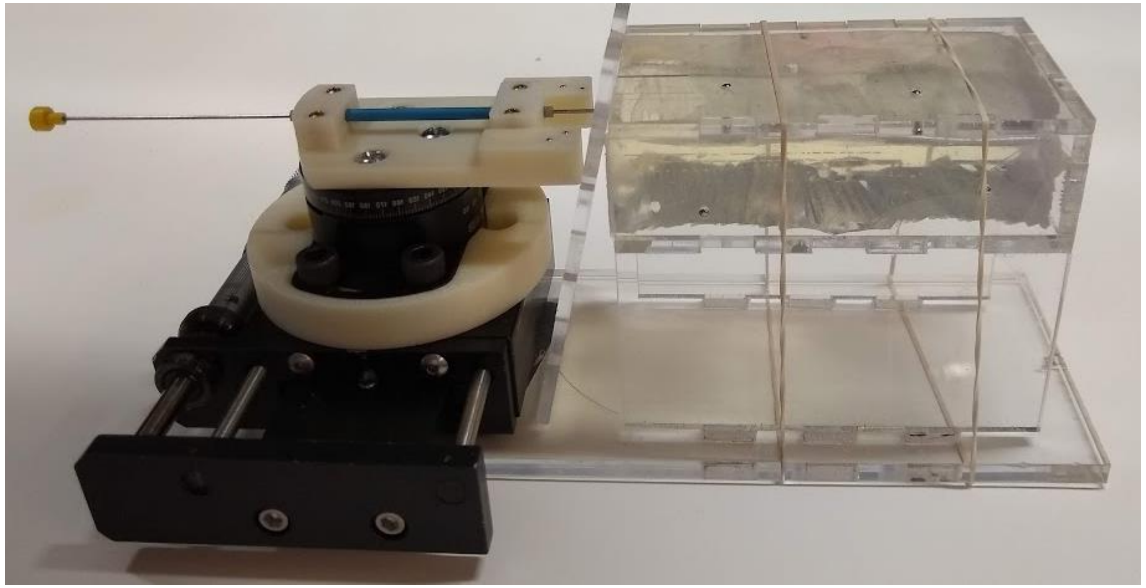
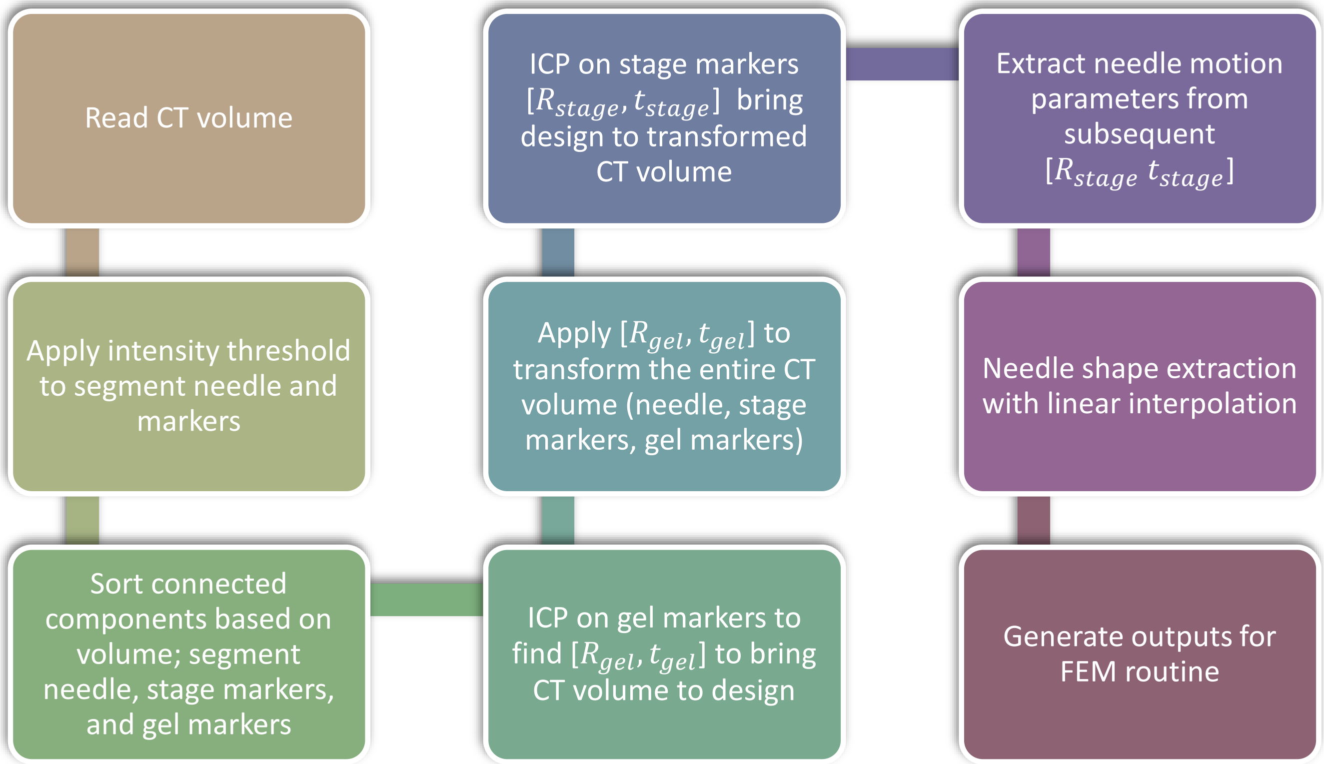


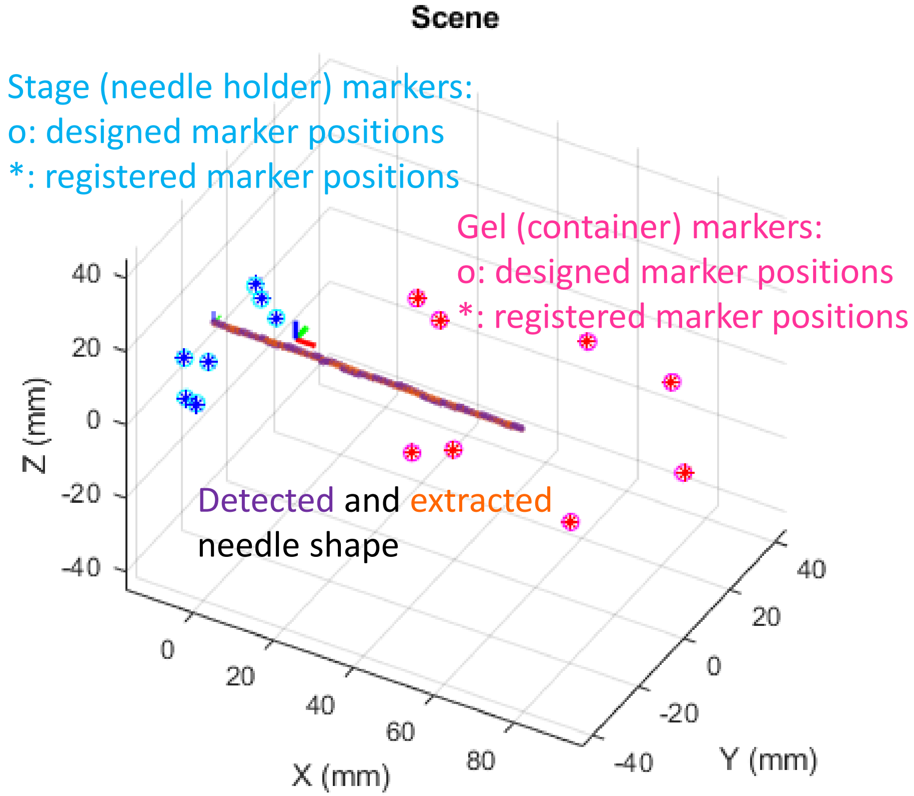


Needle Motion and Shape Detection with CT

- The current segmentation and registration method:
  1. *Segment groups of steel markers and the needle from CT volume*
  2. *Detect needle base motion parameters from steel markers*

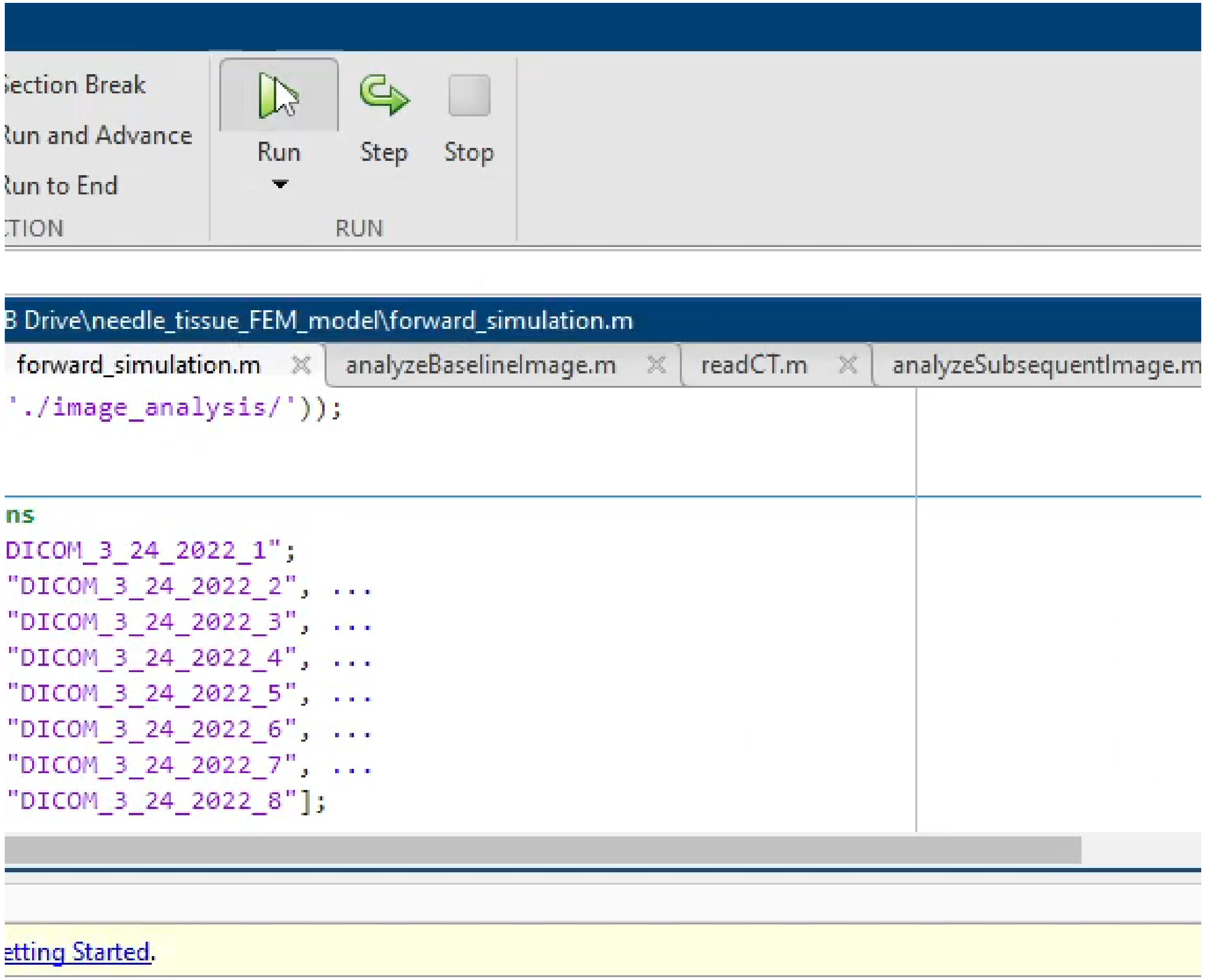
Needle motion and shape detection workflow





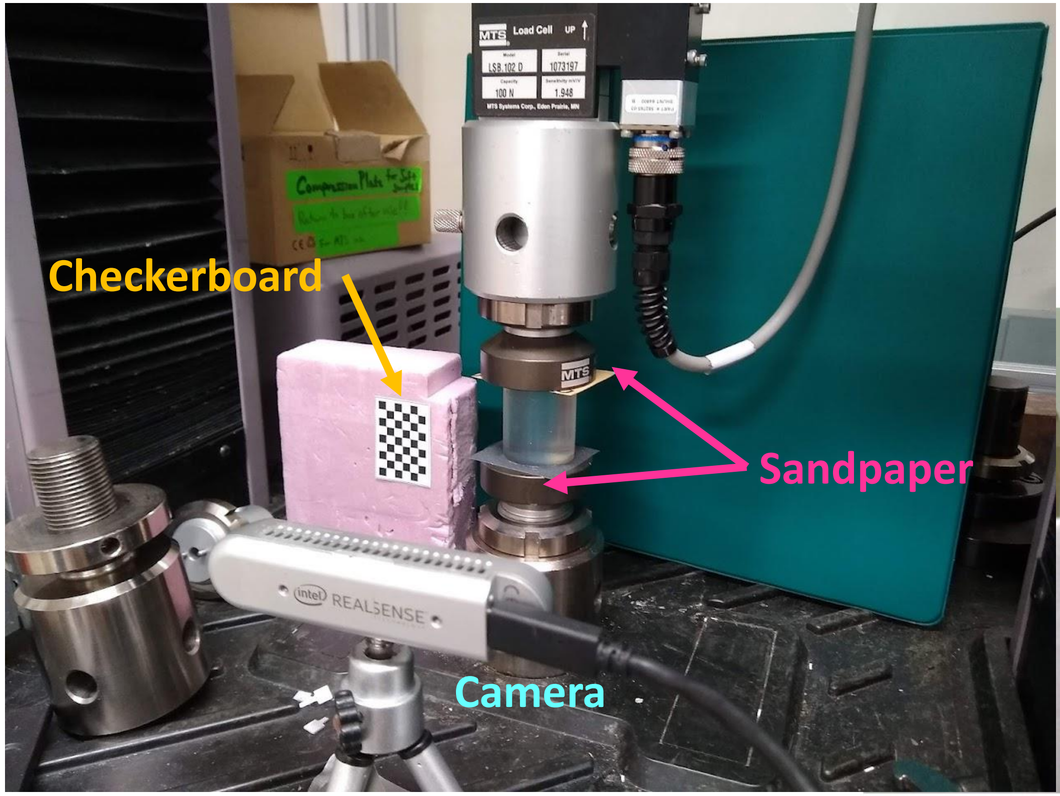
Needle Motion and Shape Detection with CT -- Outcome

- Gel markers avg. registration error: 0.356 mm
- Stage markers avg. registration error: 0.137 mm
- Number of elements: 153
- Size of each element: 0.5 mm
- Origin x-axis separation (~-16.8): -16.857 mm
- Baseline rotation axis (~z): [0.442, 0.051, 0.895]
- Baseline rotation angle (~0): 0.494 degrees

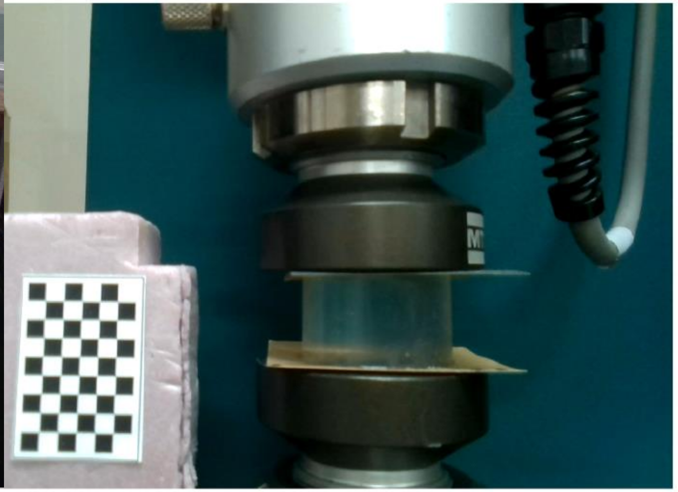


Tissue-mimicking Phantom Fabrication and Testing

- Phantom fabrication and testing:
  1. *Custom mold to create samples that (roughly) satisfy the ASTM testing standards for rubber (D575-91)*
  2. *Perform unconstrained compression testing on samples*
  3. *Evaluate goodness of fit of different hyperelastic models*



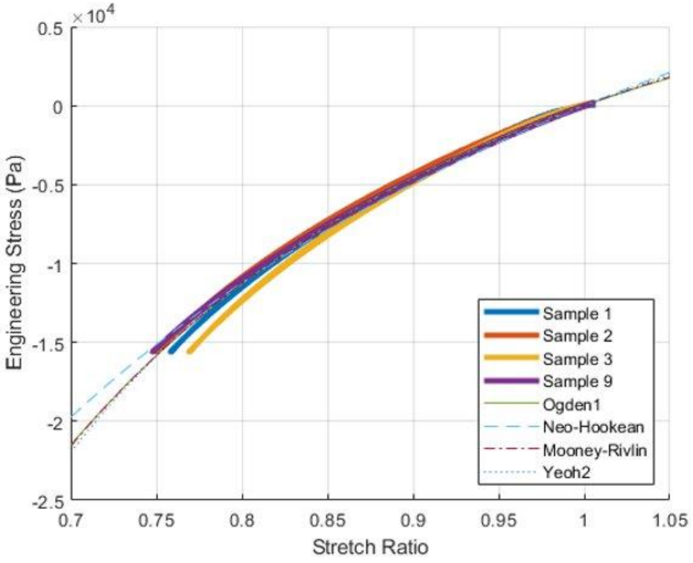
Tested samples



Hyperelastic Model Selection and Integration to FEM Routine

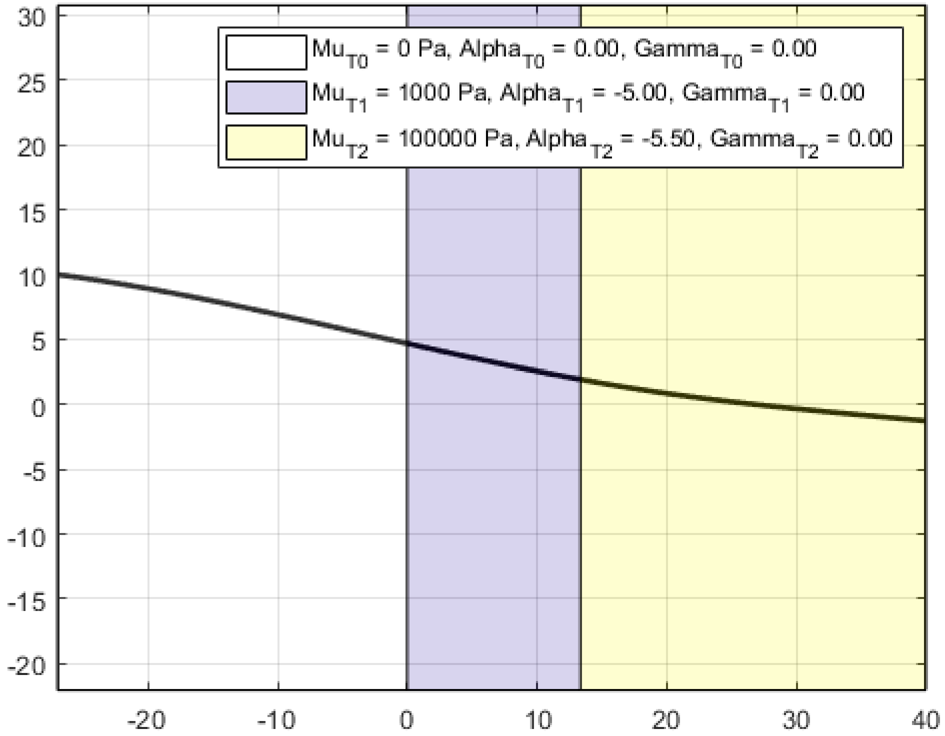
- Goodness of fit R^2:
  - **One-term Ogden: 0.9943**
  - Neo-Hookean: 0.9911
  - Mooney-Rivlin: 0.9942
  - Two-term Yeoh: 0.9939

Stress-Stretch curves of selected samples



- Model integration and forward FEM:
  - Versions available:
    - unconstrained compression + engineering strain,
    - constrained compression + true strain

Nonlinear FEM with one-term Ogden model



Needle-Tissue Interaction Model Evaluation using Forward FEM

- Estimated material property:
  - **Ogden1: 12.715 kPa**
  - Mooney-Rivlin: 13.008 kPa
  - Yeoh2: 13.667 kPa
- Estimated model parameter:
  - $\boldsymbol{\alpha = -1}$ in Ogden1

- Forward simulation:
  - Three insertion depths: 20, 40, 60mm
- Simulated vs detected needle shape:
  - Total error: cumulative error of each element node over all elements
  - Tip error: error at the needle tip

20mm

Linear Motion d_b	Total Error [mm]	Tip Error [mm]
0.91	**1.40**	**0.34**
2.05	**1.32**	**0.13**
3.07	**1.54**	**0.39**
4.06	**1.58**	**0.14**
3.10	**1.24**	**0.32**
2.05	**1.29**	**0.02**
1.07	**1.61**	**0.21**

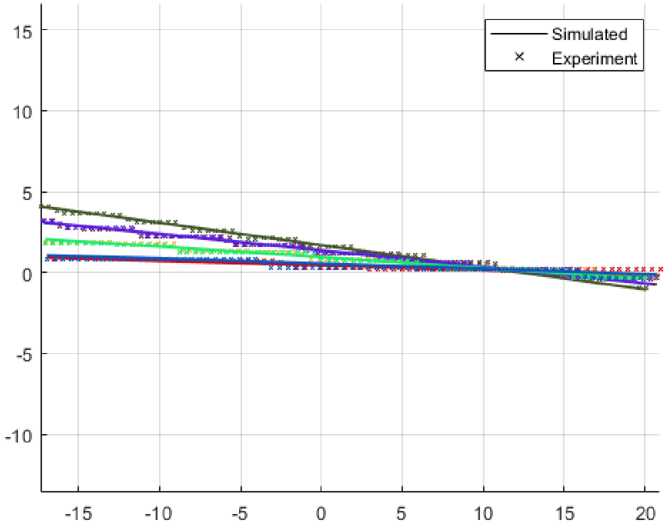
40mm

Linear Motion d_b	Total Error [mm]	Tip Error [mm]
0.94	**3.29**	**0.54**
2.08	**4.17**	**0.40**
3.07	**4.16**	**0.68**
4.12	**5.25**	**1.01**
3.10	**4.74**	**0.74**
2.11	**3.36**	**0.41**
1.07	**2.92**	**0.59**

60mm

Linear Motion d_b	Total Error [mm]	Tip Error [mm]
0.96	**3.66**	**0.46**
1.59	**3.50**	**0.58**
2.00	**2.92**	**0.23**
2.96	**2.98**	**0.36**
4.02	**4.34**	**0.60**
3.02	**3.15**	**0.27**
2.06	**2.89**	**0.50**

Simulated vs. Experiment Comparison For 20mm insertion



Updated Project Deliverables

- Minimum: (Expected by 3/7/2022) **[FINISHED]**

1. Hardware setup to mimic freehand needle adjustment motion
2. Algorithm to extract needle shape and base motion from CT
3. Evaluation of hyperelastic models in compression range of tissue phantoms

- Expected: (Expected by 4/11/2022) **[FINISHED]**

1. Integration of chosen hyperelastic material model with needle-tissue interaction model
2. Verification/Evaluation of proposed needle-tissue interaction model

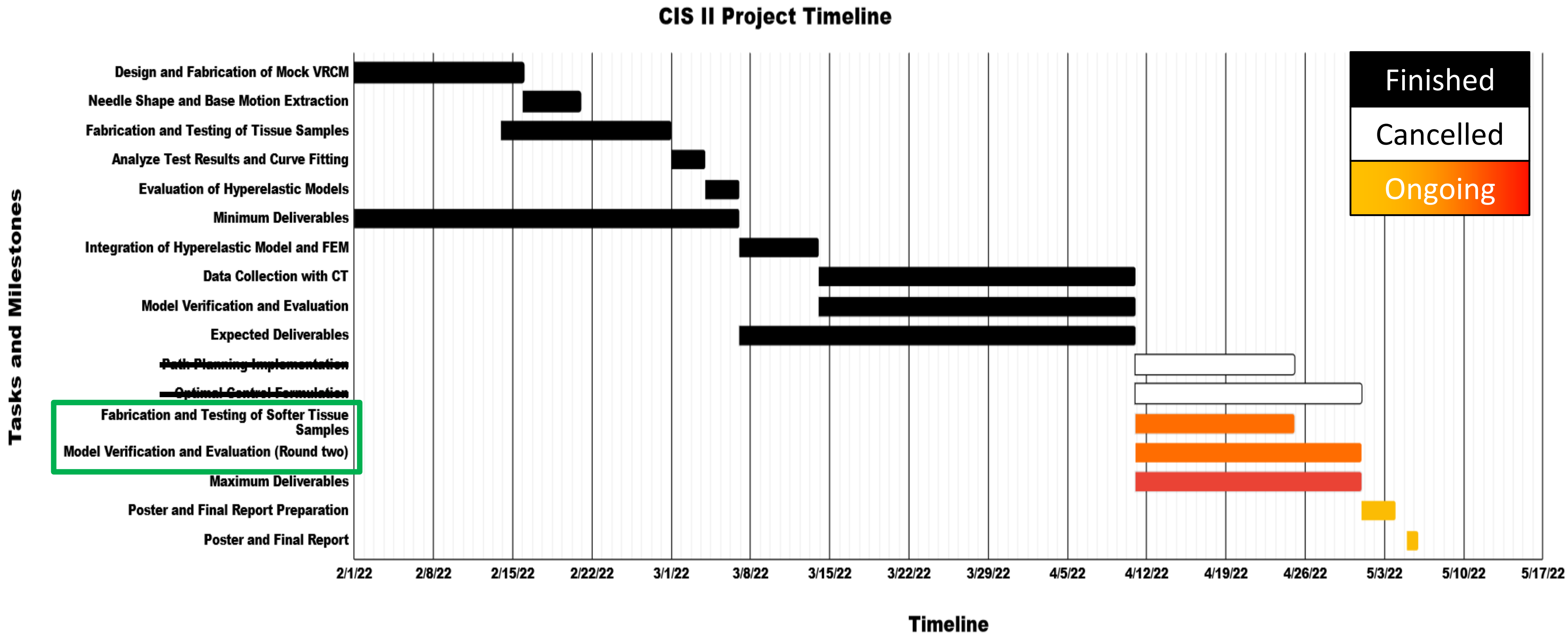
- Maximum: (Expected by 5/1/2022) **[ON GOING]**

~~Path planning simulation of needle retraction and adjustment~~

~~Optimal control formulation to minimize tissue displacement~~

1. Further verification of proposed needle-tissue interaction model with softer tissue phantoms

Updated Project Timeline



Updated Dependencies

Item	Solution	Delay in Schedule	Effect on Outcome	Status
Equipment availability: LCSR Machine shop, 3D printer	Use equipment in Wyman Park building	3~5 days (Long queue, training)	N/A	**Resolved**
Equipment availability: MSE MTS tensile tester	Use equipment in Wyman Park building	3~7 days (Training)	Difference in resolution of stress-stretch data	**Resolved**
Equipment availability: Mock OR C-arm	Contact Prof. Mehran Armand for CT access	2~3 days	Cannot complete model verification	**Resolved**

Thank you