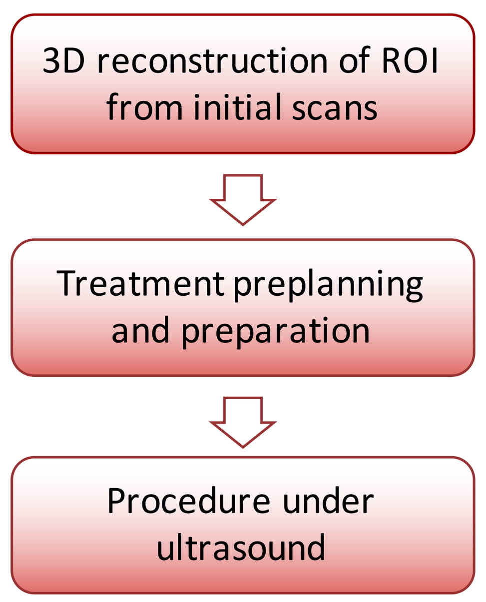
A Computational Framework to Optimize Fiducial Marker Placement to Account for Intraoperative Tissue Deformation

Ye Han, Yoed Rabin, Levent Burak Kara
Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213,USA

INTRODUCTION

Background

For the purpose of minimally invasive surgery, imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US) are utilized for procedure preplanning and intraoperative monitoring. In the preplanning phase, the geometry of the region of interest (ROI) is reconstructed, and is later registered with the observed ROI shape during surgery. Unfortunately, a notable difficulty with this two-phase approach is the potential mismatch of the ROI between these two phases, which diminishes the impact of preplanning.



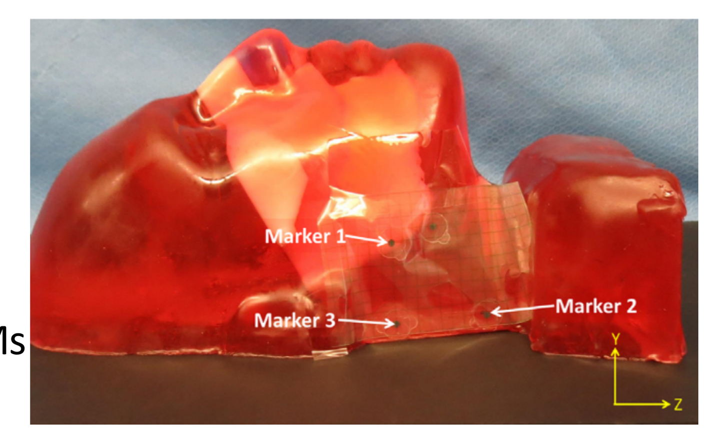
Framework of image guided surgery

Previous work

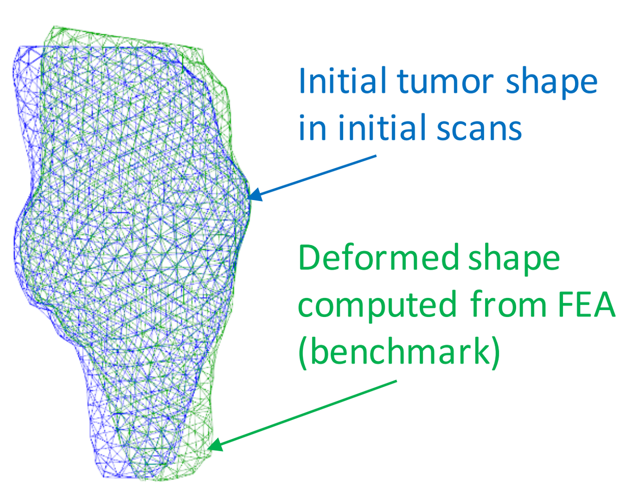
While it is technically difficult and computationally expensive to reconstruct the ROI in real time, using an intraoperative imaging modality, fiducial marker (FM) tracing can be used for predicting the treated and potentially deformed ROI. Our previous work[1] has demonstrated the feasibility of predicting tumor deformation based on traced FM locations in real time.

$$x_{pred} = A(D)d$$

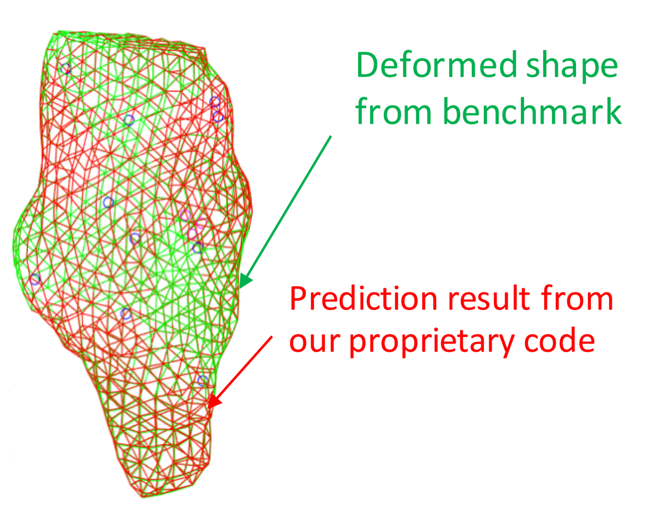
x_{pred}: predicted displacements of all nodes
D: a binary indicator matrix which specifies the choice of FMs
$A(D)$: a mapping matrix depending on the choice of FMs
d: displacements of chosen FMs



FMs in gel phantom model[2]



Benchmark deformation



Our prediction

Objectives

- To develop a geometric modeling tool of a deformed tumor based on its predeformed shape and displacement of fiducial markers.
- To develop an optimization method for the fiducial marker layout.

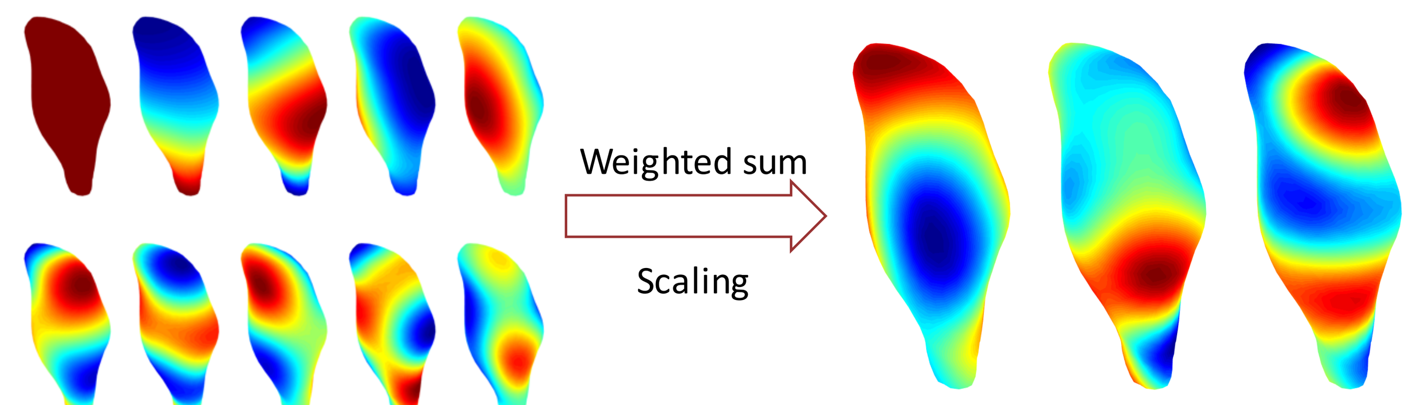
METHODS

Creation of benchmarks

Simulated ground truth deformations (benchmarks) are created by applying random smooth force fields on the tumor surface. For every benchmark, each component of the force field on tumor surface is obtained as:

$$F_j = s\sum_{i=1}^{n_f} w_i f_i$$

F_j: the j^{th} (x, y or z) component of a benchmark force field
s: scale factor
w_i: weights sampled uniformly from [-1, 1]
n_f: number of template force fields
f_i: force field template obtained from the i^{th} eigenvector of the discretized Laplace-Beltrami operator



First 10 force field templates

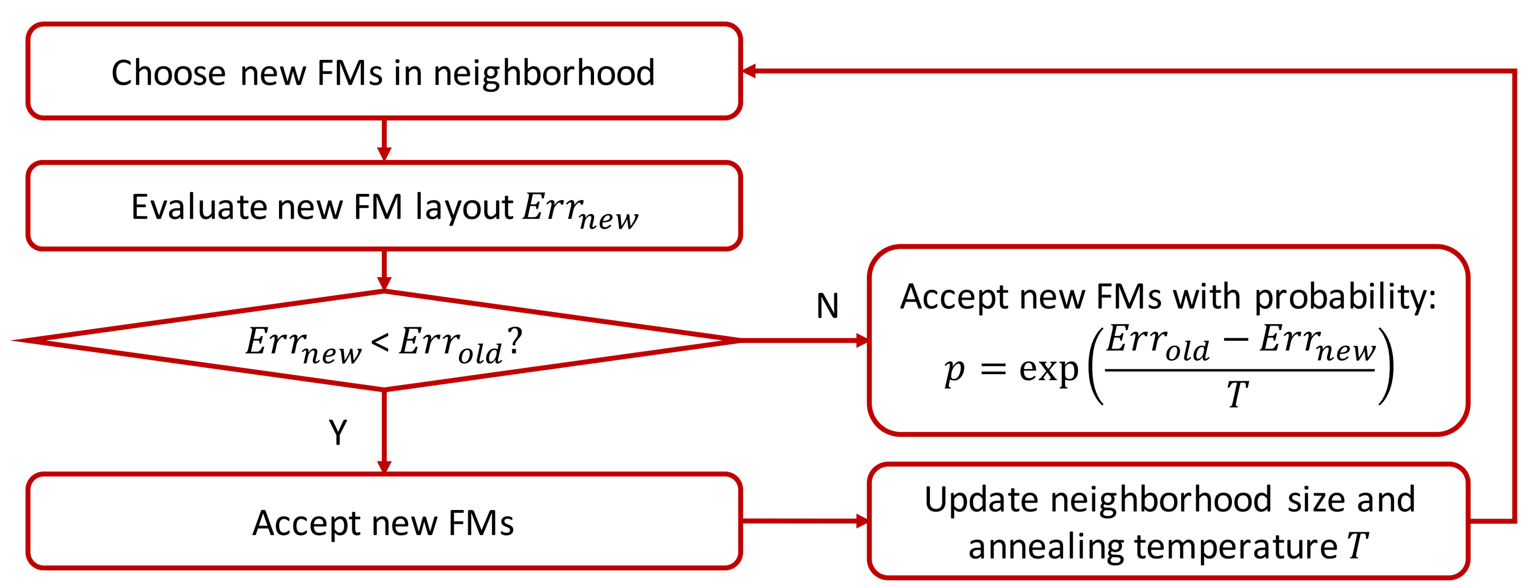
x, y and z component of an example benchmark force field

Optimization of fiducial marker layout

1. Initial Prediction: choose n random FMs, compute the difference between the benchmarks x_{bench} and the initial predictions x_{pred}.

$$Err_{old} = \left|\left|x_{pred} - x_{bench}\right|\right|_{fro}^2$$

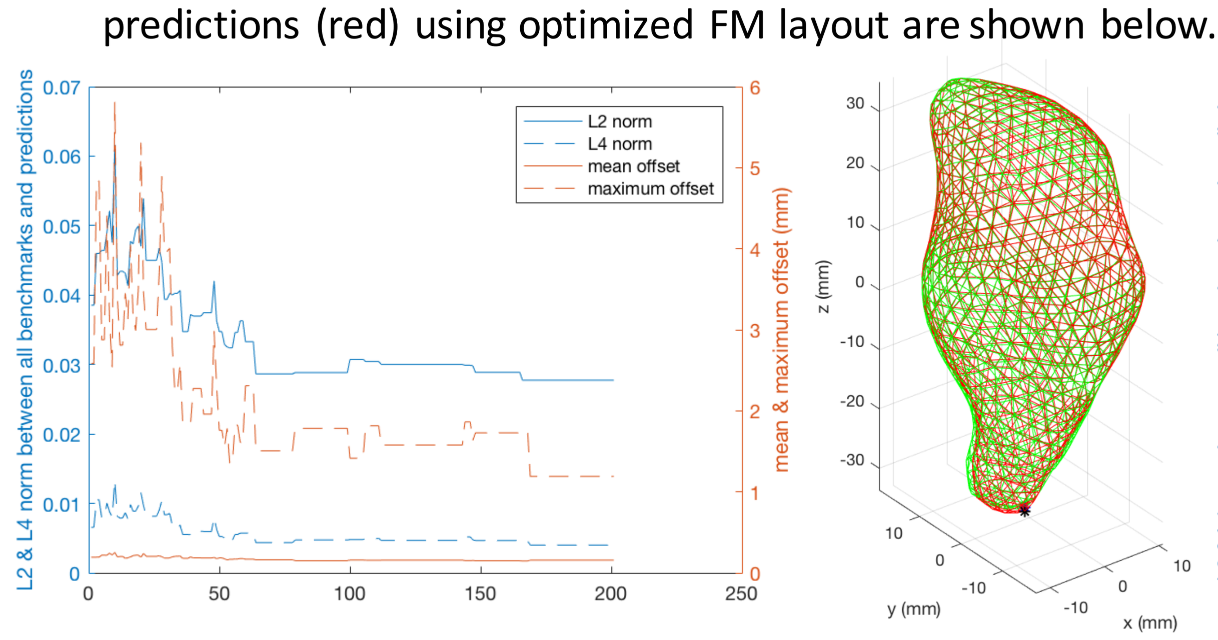
2. In analogy with the annealing process, an iterative optimization scheme is developed. The flow chart of each iteration is shown below:



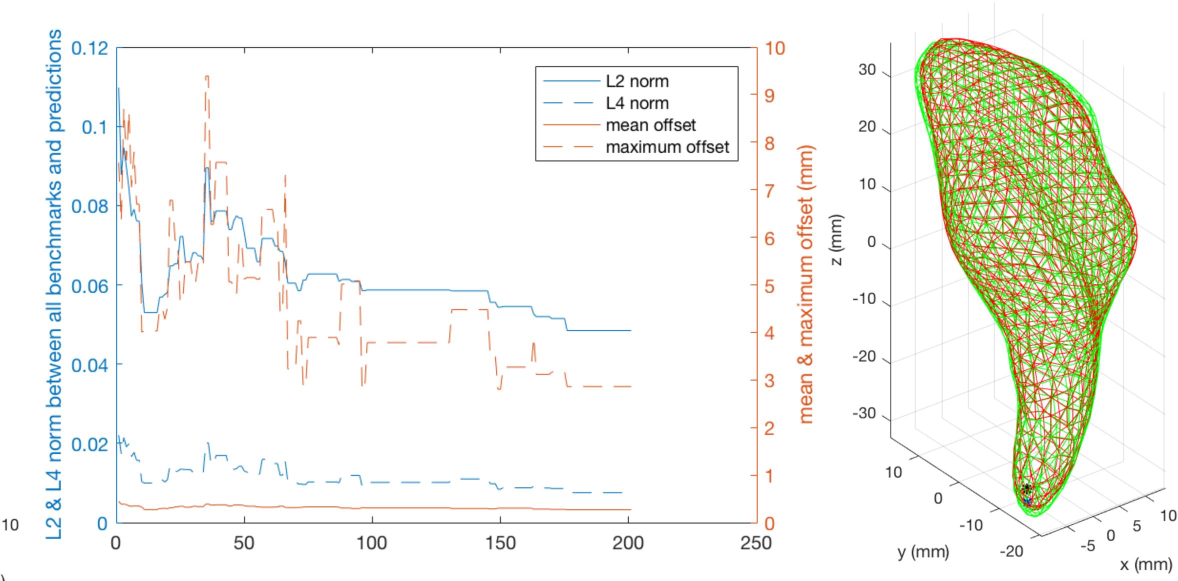
RESULTS

Optimization results

The changes in prediction errors over optimization iterations and the visual comparison between benchmarks (green) and predictions (red) using optimized FM layout are shown below.



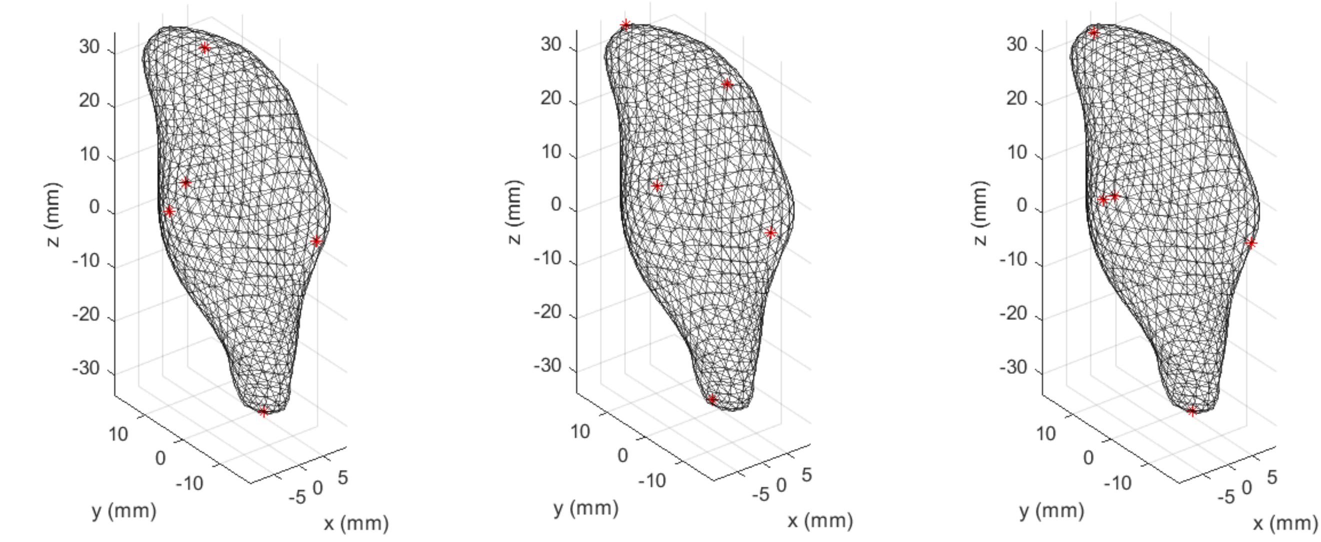
10 mm maximum displacement case



20 mm maximum displacement case

RESULTS (Cont.)

Comparison with empirical selections of FM layout



Axis-aligned extrema

High curvature points

Metric k-centers

Selection for FMs	10 mm maximum displacement		20 mm maximum displacement	
	Average offset (mm)	Maximum offset (mm)	Average offset (mm)	Maximum offset (mm)
Axis aligned extrema	0.18	2.53	0.38	6.71
High curvature region	0.18	1.94	0.39	6.87
Metric k-center	0.18	2.29	0.38	7.23
Random	0.31	9.36	0.50	11.00
Optimized	0.13	1.30	0.28	3.21

CONCLUSIONS

- A computational framework to optimize FM layout for tracking tumor deformation is developed as a proof of concept.
- The prediction performance using the optimized FM layout is superior to using empirical selections.
- The maximum difference between benchmarks and our FM-optimized predictions is 1.3 mm, where 1mm to 2mm is the typical resolution of ultrasound (US) imaging.
- Applications of FMs and the presented algorithm can bridge the gap between preplanning and intraoperative US imaging for the purpose of tumor destruction.

REFERENCES

[1] Han, Y, *et al.*, “Reconstruction of a Deformed Tumor Based on Fiducial Marker Registration: A Computational Feasibility Study,” *Technol. Cancer Res. Treat.*, 2018, vol. 17.
[2] Oakley, E, *et al.*, “Surface markers for guiding cylindrical diffuser fiber insertion in interstitial photodynamic therapy of head and neck cancer,” *Lasers Surg. Med.*, 2017, vol. 49, no. 6, pp. 599–608.

ACKNOWLEDGEMENTS

This study has been supported by seeds funds from the Department of Mechanical Engineering at Carnegie Mellon University to Y. Rabin and L.B. Kara. Authors would like to thank Prof. Gal Shafirstein and Roswell Park Comprehensive Cancer Center for providing anatomical geometries from CT scanning.