Deformable image registration for pleural Photodynamic Therapy

Baochang Liu[1], Jun Li[2], and Timothy C. Zhu[1*]

[1]Department of Radiation Oncology, School of Medicine, University of Pennsylvania, Philadelphia, PA 19104
[2]Department of Radiation Oncology, Jefferson Medical College, Thomas Jefferson University, Philadelphia, PA, 19104

*Corresponding author: Radiation Oncology, University of Pennsylvania, 3400 Civic Blvd/TRC W4, Philadelphia, PA 19104, tzhu@mail.med.upenn.edu

Abstract: Deformable image registration is a medical image processing technique that can fuse images acquired by different modalities. It can provide insights into the development of phenomenon and variation in normal anatomical structures over time. During pleural photodynamic therapy treatment at the University of Pennsylvania, an infrared (IR) navigation system is used to contour the lung and chest cavity and to provide real-time treatment guidance. Before surgery, computed tomography (CT) scans of lungs are acquired for patients. This work studies the deformable image registration of the structure contours of the lungs obtained from two different modalities using the deformed mesh – moving mesh (ALE) model in COMSOL. The initial assessments of two-dimensional registration show good agreements .

Keywords: Deformable image registration, PDT, ALE, moving mesh.

1. Introduction

Photodynamic therapy (PDT) uses a light source and a light-activatable photosensitizer to treat target tissue with the presence of molecular oxygen. During PDT, molecular oxygen is excited to the singlet state becoming singlet oxygen ($^1O_2$), which produces biological effects. PDT has been used to treat both malignant and non-malignant diseases. At the University of Pennsylvania, intrapleural PDT is used as an adjuvant treatment with lung-sparing surgical treatment for mesothelioma. To improve the uniformity of the distribution of the delivered light dose, an infrared (IR) camera-based navigation system (known as the NDI system) is used to track the motion of the treatment light source. The structure contour for lung or chest cavity can also be obtained using the NDI system.

Prior to the surgical treatment for each patient, a series of computed tomography (CT) scans of the lungs are acquired. A deformable registration of the CT-scanned lung contour to that obtained using the NDI system will provide useful information about the movement of the organs during surgery.

This study aimed to develop a model based on the deformed mesh – moving mesh (ALE) using COMSOL Multiphysics to register two structure contours. First, the original lung CT images are processed and contoured in Matlab, and then the contours are imported as a geometry into COMSOL 4.3b. The preliminary results of the 2-dimensional registration are reported.

2. Materials and Method

The COMSOL ALE model is based on structure contours of the lung. A Matlab script was written to process the original CT images (DICOM format) in order to automatically generate lung contours. The whole process consists of image import, initial noise filtering, image segmentation, contouring, final filtering and smooth, and 3-D reconstruction.

The lung structure contour for the same patient acquired using the NDI system is reconstructed using our previously developed algorithm in Matlab.

In this study, the lung contour acquired from the NDI system is used as the reference contour, and the contour from CT is used as the target contour, which will be deformed. Before the deformation, two 2-D contours are registered with a rigid body transformation by overlaying their center of masses and orientations. Then, they are matched using a dynamic iterative contouring method as described by Li et al..[1] In short, a displacement vector is calculated between a vertex in the target contour and its nearest line segment in the reference contour. The map of all displacement vectors represents a force field, which pushes or pulls the target contour such that the difference between the reference contour and the deformed contour is minimized.

In the COMSOL ALE model, the domain of the reference contour is set to be fixed, and the target contour is set as a free domain. The boundaries of the free domain are given as the prescribed displacement vectors, which are calculated using this dynamic iterative method. These calculations are performed by calling the Matlab functions.

3. Results

First, all CT images were read into Matlab using the Image processing toolbox to create a 3-D matrix of the image intensities. Figure 1 shows a representative original lung image.

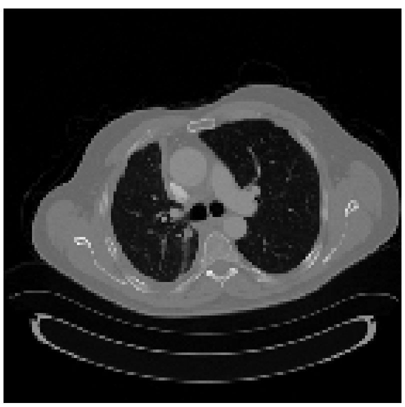

Figure 1. Original CT image of lung.

Second, after performing an initial filtering process to remove some random background noise, the CT image is segmented via partitioning the matrix of intensities into several clusters for further analysis. K-means approach was adopted for this purpose. The total number of clusters, k, is defined as 4 to represent four tissue types: bone, connective tissue, organs and air. Figure 2 shows the segmented CT image.

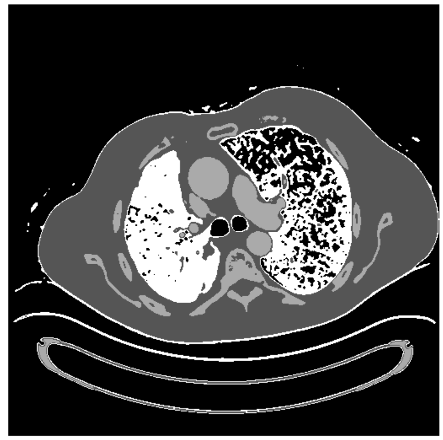

Figure 2. Segmentation of the CT image: bone, connective tissue, organ and air.

The next step is to identify object boundaries to create contours. Since the intensity matrices have been segmented into 4 clusters, a gradient edge-detection can be used to easily identify the boundaries of each clusters. Figure 3 shows the right lung contour.

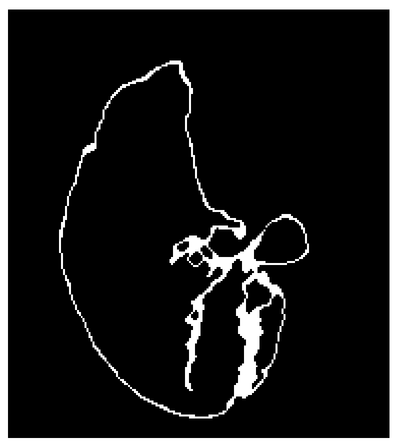

Figure 3. Contour of the lung using edge detection.

Once the lung contour is obtained, another filtering procedure is applied to remove the signals inside lung. Then, this contour is rigidly registered to the corresponding contour from the NDI system by overlaying the center of masses of the two contours and aligning their orientations. Figure 4 shows the rigidly registered two contours imported into COMSOL. The inner contour from CT as the target contour will be deformed to match the outer one from the NDI system.

Figure 4. Contours of lung obtained from NDI (outer) and CT (inner) scans.

Figure 5 shows the fine mesh of the target contour before the deformation.

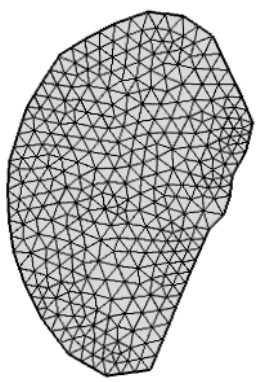

Figure 5. Mesh of CT lung image.

After applying the dynamic boundary matching, a deformed target contour is obtained. Figure 6 shows the color map of the mesh deformation volume ratio, which indicates that the greatest deformation volume ratio occurs around the bottom of the contour. The inner contour in the red line represents the original target contour from CT, and the outer red line is the reference contour from the NDI system.

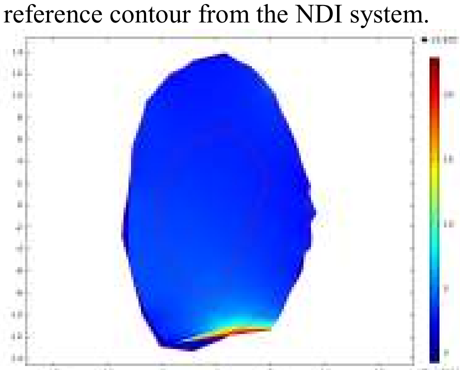

Figure 6. Mesh deformation volume ratio.

Figure 7 shows the displacement vector map on the deformed mesh, which illustrates the transformation of the target contour.

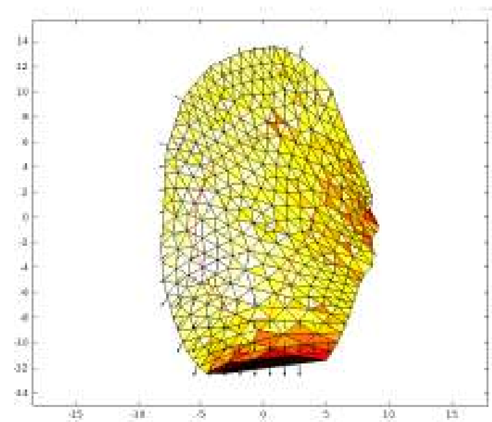

Figure 7. A displacement vector map.

To better visualize the movements of the target contour, a representative boundary match process is shown in Figure 8. The red dash-circle line is the initial target contour prior to the deformation. The magenta dashed lines demonstrate intermediate steps. The magenta dash-circle line is the final deformed target contour, which is to match the reference contour (blue solid line).

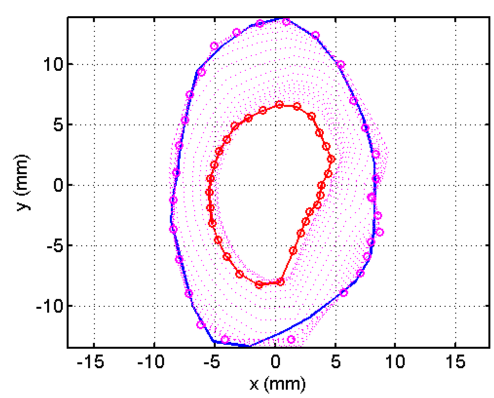

Figure 8. Boundary matching of the CT contour (inner: red dash-circle line and outer: magenta dash-circle line) and the NDI contour (outer: blue solid line). The dished lines are the deformed contours during the intermediate steps.

Figure 9 shows the final deformation results of the ALE model. As seen, the deformed target contour (black dash-star line) has reasonably good matches with the reference contour (red dash-circle line).

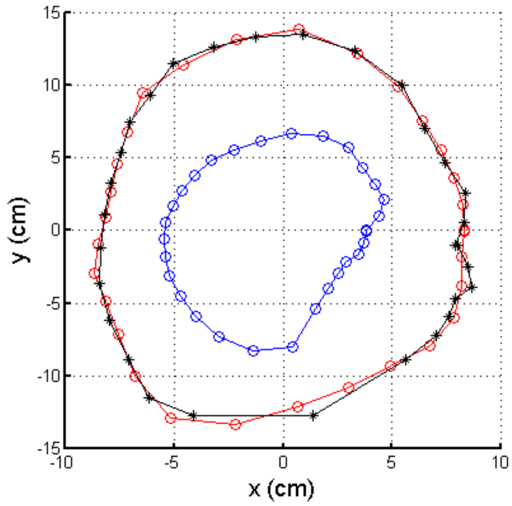

Figure 9. Final boundary matches. The inner blue dash-circle line: CT contour (target). The outer red dash-circle line: deformed CT contour. The outer black dash-star line: NDI contour (reference).

4. Discussions and Future work

Two 2-D structure contours can be registered using the COMSOL ALE moving mesh model. The deformed contour has good matches to the reference contour after the dynamic matching process. This model will be further developed into a 3-D model, which takes into account the deformation along the z-axis.

The current Matlab algorithm is capable of processing all the CT images as described. A 3-D lung structure can be reconstructed, as shown in Figure 10.

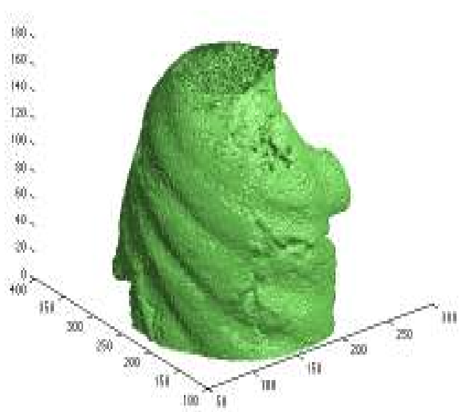

Figure 10. The reconstruction of the three-dimensional lung.

The reconstructed 3-D contours from both CT and NDI can be converted to COMSOL geometries so that a 3-D ALE model can be developed. Figure 11 demonstrates the fine mesh of the contours. In future work, the current dynamic iterative boundary matching process will be expanded to 3-D coordinates, which can be directly implemented for 3-D deformation.

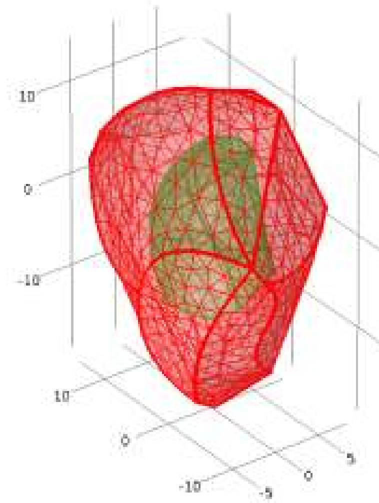

Figure 11. Three-dimensional mesh of NDI and CT contours. (unit: cm)

5. References

1. J. Li *et al.*, "Deformable medical image registration using finite-element method," Proceedings of the COMSOL, (2006).

6. Acknowledgements

This work is supported by grants from National Institute of Health (NIH P01 CA 87971 and NIH R01 CA154562).