[POSTER] Deformation Estimation of Elastic Bodies Using Multiple Silhouette Images for Endoscopic Image Augmentation

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Abstract

This study proposes a method to estimate elastic deformation using silhouettes obtained from multiple endoscopic images. Our method can estimate the intraoperative deformation of organs using a volumetric mesh model reconstructed from preoperative CT data. We use this elastic body silhouette information of elastic bodies not to model the shape but to estimate the local displacements. The model shape is updated to satisfy the silhouette constraint while preserving the shape as much as possible. The result of the experiments showed that the proposed methods could estimate the deformation with root mean square (RMS) errors of 5.0–10 mm.

Keywords: Deformation estimation, Shape matching, Computer-assisted surgery

Index Terms: [Computing methodologies]: Artificial Intelligence - Computer vision, [Computing methodologies]: Modeling and simulation

1 Introduction

Recent advances in medical devices now enable a variety of minimally invasive procedures over a wide range of surgery types. Although recently developed surgical navigation systems can display tool position and three-dimensional (3D) organ shapes as volumetrically rendered (VR) or augmented reality (AR) images generated from preoperative CT data, handling intraoperative deformation is still a technical issue [1, 2]. Because the positional relationship between the tumor and vascular structures is an essential factor during surgery, the accurate and robust estimation of elastic bodies has gained attention for intraoperative navigation. Although an optical tracking approach using feature descriptors [3] has been recently investigated for AR-based navigation, the stable acquisition of feature values from the intraoperative states of organs is a problem caused by time-varying illumination in laparoscopic surgery.

This study proposes a method to estimate elastic deformation using silhouettes obtained from multiple endoscopic images. Silhouette information can be stably obtained from organs in an intraoperative state when illuminated during laparoscopic surgery. Additionally, our method is able to estimate the local deformation of organs with internal structures using a volumetric mesh model reconstructed from preoperative CT data. The model shape is updated to satisfy the constraint of the silhouettes while preserving the shape of the model as much as possible. We have conducted some experiments and confirmed the performance of the proposed techniques using various cameras and their possible arrangements in laparoscopic surgery.

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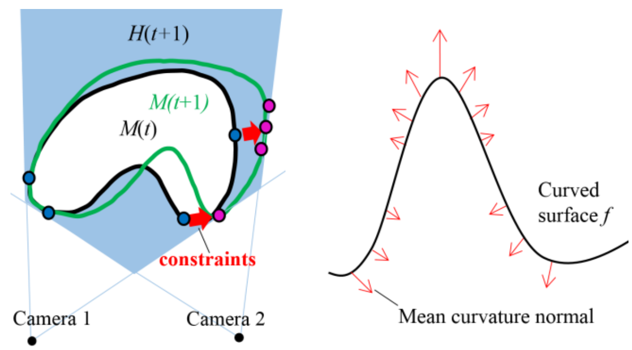

(a) (b)

Figure 1: (a) Conceptual diagram of the algorithm. Candidates for contact points of $H(t+1)$ are first searched for locality, and the corresponding vertices of $M(t)$ are determined to set positional constraints. (b) Mean curvature normal of a curved surface. Our algorithm updates the shape of the model while preserving the mean curvature normal of the previous shape as much as possible.

2 Silhouette-based Deformation Estimation

Figure 1(a) shows a conceptual diagram of the proposed algorithm. We assume that the initial shape of the target organ is obtained from preoperative CT images. In the figure, $M(t)$ represents the current shape (or initial shape) of the organ. A tetrahedral mesh is used as a volumetric shape representation of $M(t)$, and local deformation is represented by displacement of the vertices. A visual hull $H(t+1)$ of the next deformed state is computed from multiple silhouettes captured from endoscopic cameras. Marching cubes is applied to the view volume of the target shape, and a set of vertices with normal vectors are used to represent $H(t+1)$.

In our algorithm, we use silhouette information of the organ not to model the shape but to estimate the local displacements. The next shape $M(t+1)$ is estimated from $M(\mathrm{t})$ and $H(t+1)$ while preserving the shape of $M(t)$ as much as possible. To do this, we focus on the geometrical constraints at each contact point between the obtained visual hull and the target deformed shape. If the elastic body forms a smooth surface, the normal vector at a contact point of $M(\mathrm{t}+1)$ should be similar to the normal vector at the corresponding contact point of $H(t+1)$. Based on this observation, we first search for candidates for contact points of $H(t+1)$ within a certain distance d_{th} from the surface of $M(t)$. The candidates of the corresponding vertex of $M(t)$ are then evaluated to select the optimal set using

$$C^* = \underset{C}{\operatorname{argmin}}(|\boldsymbol{v}_s - \boldsymbol{v}_d| + w|\boldsymbol{n}_s - \boldsymbol{n}_d|) \quad (1)$$

where v_d and v_s are candidates of contact points on $H(t+1)$ and $M(t)$ respectively, n_d and n_s are their respective normal vectors, and w is

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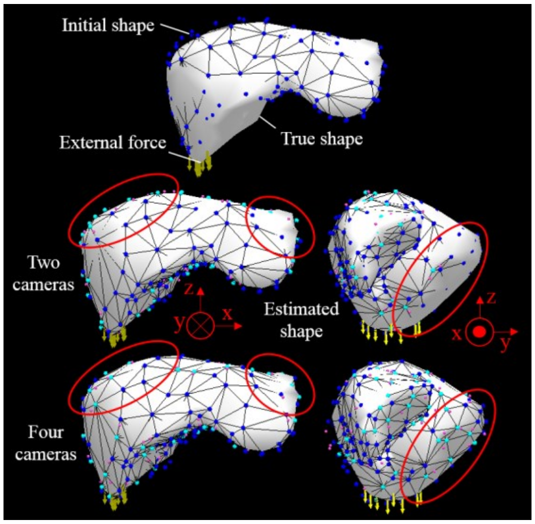

Figure 2: The result of deformation estimation. The estimation error (red circled area) shown in the two-camera case was reduced in the four-camera case.

a weight parameter determined experimentally. We use the relationship C: v_s - v_d as the positional constraints that should be satisfied by the next shape.

To achieve shape preservation, we focus on the mean curvature normal of a curved surface (Figure 1(b)), and employ a discrete Laplacian [4] as a shape descriptor of the mesh. Finally, the next shape $M(t+1)$ is obtained by minimizing the evaluation function, described as follows

$$\underset{V}{\operatorname{argmin}}\left(\sum_{i}\|L(\boldsymbol{v}'_i)-L(\boldsymbol{v}_i)\|^2+\sum_{i\in P}\|\boldsymbol{v}_i-\boldsymbol{u}_i\|^2\right) \qquad (2)$$

where v'_i denotes the modified vertices, $L(v_i)$ is the discrete Laplacian at vertex v_i, u_i is the positional constraint, V is the set of all vertices, and P is a set of vertices with constraints. In the estimation process, both a local search of the corresponding vertices based on Eq. (1) and mesh editing using Eq. (2) are iteratively performed until the displacement of all vertices becomes small.

3 Experiments and Results

We conducted simulation experiments to confirm the performance of the proposed algorithm. In the experiments, we first prepared an initial liver mesh with 288 vertices and 1,015 tetrahedral elements from clinical CT data, and generated the true deformed state with small displacements (5.6–33.8 mm) based on a linear finite element model. Next, the silhouette of the deformed state was captured from the rendered image, and the visual hull $H(1)$ was created, for which we assumed either a two-camera or a four-camera configurations for the observations. We then tried to estimate the deformed state $M(1)$ from the initial state $M(0)$ using $H(1)$. The estimation results were evaluated using the root mean square (RMS) error of the corresponding vertices. We investigated the influence of parameter d_{th}, which is used for local search of the contact points.

Figure 2 shows the result of deformation estimation. A displacement of 11.3 mm was applied to generate the true deformed state, and d_{th} = 10mm was used for a local search of the contact points. In the figure, the wire-frame model represents the volumetric mesh M and the surface is the true deformed state. The light-blue vertices represent v_s and the magenta points represent v_d. Estimation error on the upper and back side were visually confirmed in the two-camera case, but reduced in the four-camera case. Figure 3 shows the RMS error on the corresponding vertices of the true and estimated shape. The graph shows that the proposed algorithm can estimate elastic deformation within 5.0-10mm RMS error. The estimation result using d_{th} =10mm results in a relatively small RMS error and this error can be reduced by the number of cameras.

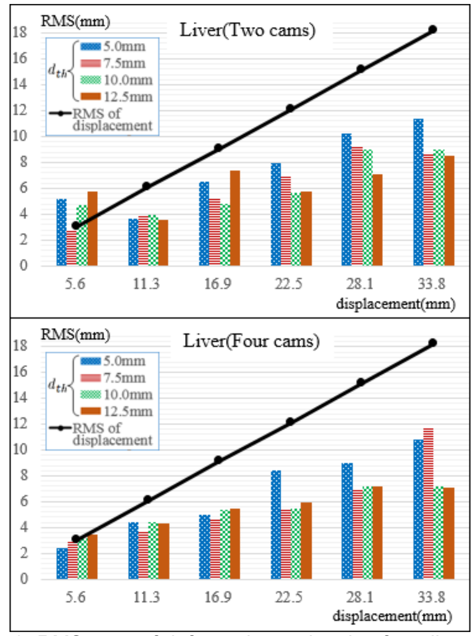

Figure 3: RMS error of deformation estimation for a liver model in case of two or four cameras.

4 Conclusion

This study proposed a method to estimate elastic deformation using silhouettes obtained from multiple endoscopic images for endoscopic surgery. The result of the experiments showed that the proposed methods could estimate the deformation with RMS errors of 5.0-10mm.

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