Modally Controlled Free Form Deformation for Non-rigid Registration in Image-Guided Liver Surgery

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1. Introduction

One of the difficulties in surgical navigation based on preoperative image information is intra-operative deformation of the organs consisting of soft tissues. In liver surgery, liver shape is deformed dynamically due to patient respiration, posture change and surgical operations. Such intra-operative liver deformation includes so-called large displacement, which requires much computation cost for numerical simulation based on non-linear FEM. Herline [Herline99] reported rigid liver surface registration for such purpose. In this study, we propose a new method of modal representation of liver deformation applied for intra-operative non-rigid registration in image-guided liver surgery. Several experiments with synthetic range data were performed based on error factor analysis.

2. Materials and Methods

We developed a new method for deformation description, *modally-controlled free form deformation*, based on a combination of modal representation and free form deformation (FFD). The FFD [Sederberg86] is a technique for shape manipulation in computer-aided design. By moving control points interactively, object shape is edited. In our method, the, the grid control points surrounding liver shape model are moved in several modes to provide volumetric deformation so that the inner structures such as blood vessels are also deformed. For non-rigid object tracking, Pentland and Scraroff [Sclaroff96] developed a technique of a modal representation of deformation for non-rigid object tracking, based on modal analysis of shape models. In the method, displacement of each vertex is represented by linear combinations of orthogonal eigen-modes. In our study, instead of physically based analysis, artificial and reusable modes, called *generalized geometric modes*, were designed by using several non-linear functions, including bending and twisting of shapes [Barr84]. The modes are: (1) rigid motion (rotation and translation), (2) bending, and (3) twisting (Fig.1) [Masutani01]. The number of parameters is 21, which consists of 6 for rigid motion, 6 for bending 3 axes in 2 directions, and 9 for twisting along 3 axes.

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We assume that the partial surface of the liver is obtained intra-operatively as range data of unstructured surface point coordinates. For the deformable liver surface matching, the optimization process of the parameter set is performed to minimize the root mean square (RMS) of the distances between range data points and model vertex points. A simple iterative search algorithm in the maximum gradient direction was employed. Based on our preliminary experiments, after a rigid registration with only 6 rigid parameters, registration by using all parameters was performed for faster convergence. The depth information of the range data was employed for the registration for two reasons.

3. Results, Discussion, and Summary

In this study, we performed preliminary experiments for registration with modal parameter optimization. The 9 types range data (3 types of deformation and 3 view directions) were synthesized by using deformed models and their depth-cueing images. Gaussian noise (σ=2.0mm) was added to the synthetic range data in the depth direction for simulation of the range sensor errors. The registration errors were evaluated by using root mean square (RMS) of the vertex distances of the two liver models (target and registered). Table 1 shows the RMS errors for the entire liver surface. The errors were generally larger for the larger displacement and non-rigid deformation. As shown in Figure 2, however, the surface matching errors were not uniform on the entire surface. Obviously, the errors were larger outside the range data acquisition area. The RMS errors inside the area were about 4-7 mm. These results naturally showed that the registration is guaranteed only around the range data acquisition area. The registration was about 30 seconds by using a PC workstation with a Pentium III 800 MHz processor.

One of the important properties of our method is that not only the surface but also the inner structures are also deformed according to the same deformation patterns. Though the patterns are based on an approximation of modal deformation theory, we must investigate the errors inside the registered surface before clinical study. Studies by using phantoms made of silicon rubber are currently in progress. For the purpose of analyzing the errors based on the limitation of deformation description, measurement of intra-operative liver deformation and statistical analysis are in progress. Based on the results of the analysis, it might be possible to remove redundant parameters without increasing errors.

Our final purposes of development for intra-operative registration include guidance of surgical robots. One of the potential advantages of such robotic surgery is that surgical operations can be performed with minimal deformation of organs. Therefore, robotic surgery with navigational information based on our registration method is expected to realize more precise and minimally invasive surgeries.

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RMS (mm)	Rest Shape	Registered in View (A)	Registered in View (B)	Registered in View (C)
Deformed #1	24.5	4.3	4.1	5.2
Deformed #2	21.0	5.9	9.7	8.5
Deformed #3	38.8	12.3	12.7	14.5

Table 1. RMS errors of the overall liver surface in registration results

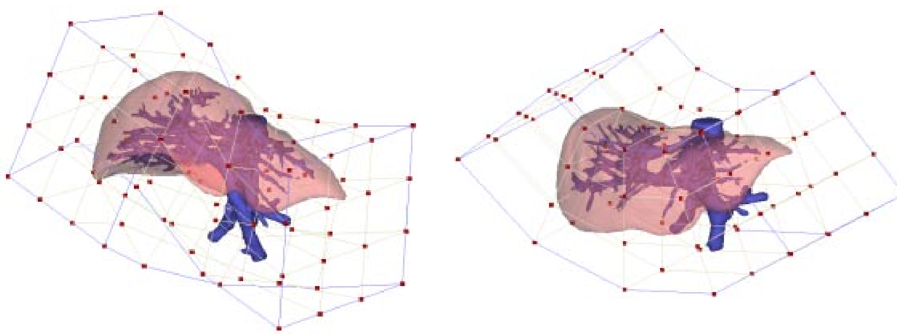

Fig. 1 Liver model deformation by modally controlled FFD
generalized geometric modes of twisting (left), and bending (right)

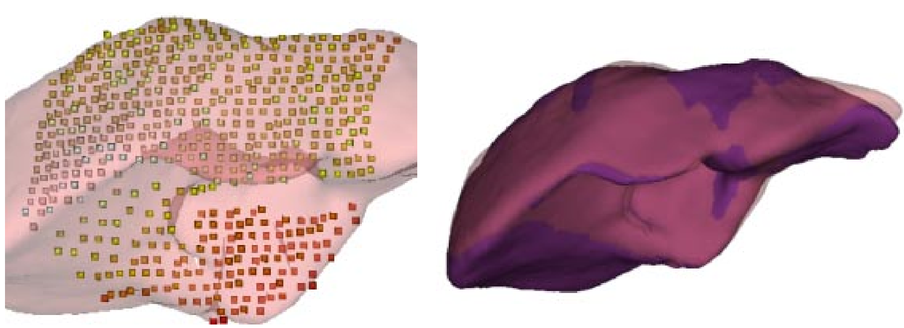

Fig. 2 Registration error analysis by using synthetic range data
synthetic range data (left), and registration result in the view (right)
The given deformed shape is semi-transparent and the registered are opaque.

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