Non-rigid MR-CT Image Registration for MR-Guided Liver Cancer Surgery

Y.-W. Chen[1,2], R. Xu[2], S.-Y. Tang[4], S. Morikawa[3], and Y. Kurumi[3]
[1]Electronics & Information Eng. School, Central South Univ. of Forestry and Technology, Changsha, Hunan, 410004, China
[2]College of Information and Science, Ristumeikan University, 525-8577, Japan
[3]Shiga University of Medical Science, Japan
[4]Beijing Institute of Technology, China

Abstract – Recently a growing interest has been seen in minimally invasive treatments with open configuration magnetic resonance (Open-MR) scanners. In this paper, we proposed a semi-automatic non-rigid MR-CT registration technique for MR-Guided Liver Cancer Surgery in which cancer tissues are coagulated by microwave ablation. Because of the lower magnetic field (0.5T) and various different surgical conditions, sometimes tumors can not be visualized clearly on Open-MR volumes. Combining of CT volumes acquired before surgery, it is possible to identify the tumor's location by application of registration techniques. Since such a registration problem belongs to a non-rigid one considering the easy deformation of livers, free-form deformation (FFD) based registration method is applied. Similarity measurement in registration is normalized mutual information (NMI). Experiments show that the registration is accurate enough (≈1.45mm) for liver cancer surgery given some proper processing steps.

Keywords – Non-rigid Image Registration, Free Form Deformation (FFD), Normalized Mutual Information (NMI), Open-MR Scanner Guided Liver Cancer Surgery, Computer Aided Surgery.

I. INTRODUCTION

Recently a growing interest has been seen in minimally invasive treatments with open configuration magnetic resonance (Open-MR) scanners, since it has many advantages for image navigation, such as good soft tissue contrast, free from ionizing radiation and multiplanar capabilities. Figure 1 is a typical picture of minimally invasive treatments with Open MR scanners. The doctor can do the treatment under the guidance of MR images.

Fig.1. Minimally invasive treatments with Open MR scanners.

In our previous works, an MR imaging guided microwave thermocoagulation therapy (at 2.45 GHz) of liver tumors has been successfully established [1]. In this treatment, liver tumors are percutaneously punctured by an MR-compatible needle under the guidance of continuously acquired real-time MR images. Because of low magnetic filed of Open-MR scanner (0.5T) and limited acquiring time (less than 2s), the real-time images are not always of satisfying contrast. So a 3D MR volume, collected by the Open-MR scanner after the determination of patient's position and just before the surgical procedure, is utilized to cooperate with the real-time images. This minimally intrusive therapy of liver tumors has been successfully performed for more than 200 cases; however it has a problem that sometimes tumors can not be visualized clearly from the 3D MR volume due to the low magnetic filed and various different surgical conditions. In such a case, a pre-surgery acquired CT volume with high-contrast tumor will be desirable for the assistance of determining tumor's locations on the MR volumes. In this paper, we propose a semi-automatic MR-CT non-rigid registration technique based on free-form deformation (FFD) with a similarity measure of normalized mutual information (NMI).

Recently medical image registration techniques have been applied to imaging guided therapy of liver cancer by several different groups [2-6]. A surface-based registration technique is adopted to map the triangulated CT liver surface to 3D physical space [2] and then the direct linear transformation is used to map physical space to the 2D laparoscopic video image space [3]. In [4] preoperative CT or MR images and the surgical plan are warped to the intraoperative ultrasound slice with a constraint of a patient-specific breathing and deformation model. A surface-based registration method that utilizes the salient anatomical features to ensure convergence to reasonable solutions under conditions of poor initial alignment is proposed for the image-guided liver surgery in [5]. We only find one research [6] which is somewhat similar to ours. In [6] a voxel-based rigid registration technique is applied to align the same patient's interventional MR images collected in different times together in order to facilitate interventional MR treatments of liver cancer. It differs from our research in two aspects. Firstly, our research is aimed to resolve a multi-modal registration problem, since the CT volumes should be registered to the Open-MR volumes. What's more we consider the rigid registration is not sufficient to deal with our problem. The collecting conditions of CT and Open-MR volumes are quite different. During CT scanning, patients are usually in a supine position; however for Open-MR scanning, in order to facilitate the surgery, cushions are inserted under patient's back to make a left oblique or left lateral position. Since livers are very soft, the insertion of cushions can easily result in the deformation of livers. If some other surgical tools, such as MR compatible laparoscope, are used in surgery, the liver will be deformed a lot. So a non-rigid registration should be considered to resolve this problem.

The paper is organized as follows. In Sec. 2, we describe the non-rigid registration method and the experimental results are shown in Sec. 3. The summary is given in Sec.4.

II. Non-rigid Registration Method

The flowchart of our registration method is shown in Fig.1. Given two volumes of image data that are to be registered as the reference volume and the test volume. A voxel of the reference volume is denoted $f_1(\mathbf{x})$, where $\mathbf{x}$ are the coordinates of the voxel. A voxel of the test volume is denoted similarly as $f_2(\mathbf{x})$. Given that $\mathbf{T}$ is a transformation from the coordinate frame of the reference volume to the test volume, $f_2(\mathbf{T}(\mathbf{x}))$ is the test volume voxel associated with reference volume voxel $f_1(\mathbf{x})$. Note that in order to simplify some of the subsequent equations we will use $\mathbf{T}$ both to denote the transformation and its parameterization. We seek an estimate of the transformation that registers the reference volume and test volume by maximizing their metric function (similarity measure) as shown in Eq.(1).

$$\hat{\mathbf{T}} = \arg\max_{\mathbf{T}} Mtric[f_1(\mathbf{x}),\ f_2(\mathbf{T}(\mathbf{x}))] \tag{1}$$

where $\mathbf{x}$ is the coordinate of a 3D point.

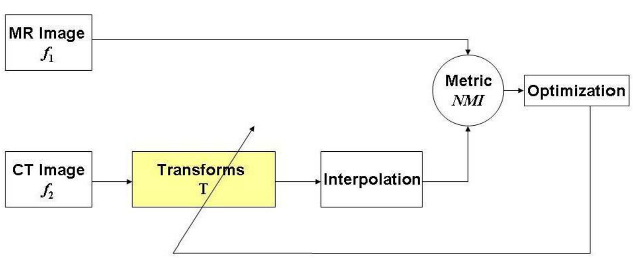

Fig.2. The flowchart of our non-rigid registration methid.

A. Transformation

In our registration algorithm, the transformation is comprised by a global and a local transformation. It can be expressed by Eq. (2).

$$\mathbf{T}(\mathbf{x}) = \mathbf{T}_{Global}(\mathbf{x}) + \mathbf{T}_{Local}(\mathbf{x}) \tag{2}$$

The global transform is a rigid one which deals with 6 degrees of freedom, i.e., translation and rotation. It can be expressed by Eq. (3). It is used to describe the global motion of the objects.

$$\mathbf{T}_{Global}(\mathbf{x}) = \mathbf{R}\mathbf{x} + \mathbf{t}$$
$$= \begin{pmatrix} \cos\beta\cos\gamma & \cos\alpha\sin\gamma + \sin\alpha\sin\beta\cos\gamma & \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma \\ -\cos\beta\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & \sin\alpha\cos\gamma - \cos\alpha\sin\beta\sin\gamma \\ \sin\beta & -\sin\alpha\cos\beta & \cos\alpha\cos\beta \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} \tag{3}$$

where α, β, γ are rotation angles around each axis and t_x, t_y, t_z are translations around each axis, respectively.

The local transformation is a free-form deformation model based on the cubic B-spline kernels [12]. It is used to describe the local motion of the objects. The FFD model is parameterized by the coefficients of a set of sparse, uniformly-spaced control points. Let $\boldsymbol{\rho} = [\rho_x, \rho_y, \rho_z]^T$ be the spacing of the control points along each axis, the coordinate of a control point can be expressed by $\boldsymbol{\varphi}_{ijk} = [\varphi_{ijk,x}, \varphi_{ijk,y}, \varphi_{ijk,z}]^T = [i\rho_x, j\rho_y, k\rho_z]^T$, where i, j, k are the sequence number of the control points. Given the coefficients of the control point denoted as $\boldsymbol{\lambda}_{ijk} = [\lambda_{ijk,x}, \lambda_{ijk,y}, \lambda_{ijk,z}]^T$, the deformation of each point can be calculated from these coefficients by cubic B-spline interpolation, according to Eq. (4).

$$\mathbf{T}_{Local}(\mathbf{x}) = \sum_{ijk} \boldsymbol{\lambda}_{ijk} \beta^{(3)}\left(\frac{x - \varphi_{ijk,x}}{\rho_x}\right) \beta^{(3)}\left(\frac{y - \varphi_{ijk,y}}{\rho_y}\right) \beta^{(3)}\left(\frac{z - \varphi_{ijk,z}}{\rho_z}\right) \tag{4}$$

where $\beta^{(3)}(x)$ is the third order B-spline kernel and its definition is showed by Eq.(5).

$$\beta^{(3)}(x) = \begin{cases} (1/2)|x|^3 - |x|^2 + 2/3, & 0 \le |x| < 1 \\ -(1/6)|x|^3 + |x|^2 - 2|x| + 4/3, & 1 \le |x| \le 2 \\ 0, & elsewhere \end{cases} \tag{5}$$

From Eq.(5), it can be seen that the third order B-spline kernel has the width of four, so in Eq.(4) the deformation of each point is only determined by the coefficients of its nearest 64 control points. This makes the FFD model can control the localized motion of the tissues. The coefficients $\boldsymbol{\lambda}_{ijk}$ are the parameters of the FFD model.

According to Eq.(3) and Eq.(4) the set of parameter for the transformation is $\boldsymbol{\mu} = \{\boldsymbol{\theta}, \mathbf{t}, \boldsymbol{\lambda}_{ijk}\}$. $\boldsymbol{\theta}=[\alpha, \beta, \gamma]^T$ and $\mathbf{t}$ have three parameters respectively. The number of the coefficients $\boldsymbol{\lambda}_{ijk}$ is determined according to the spacing of the control points. In our application, the spacing on each axis is equal to 15-voxel-width, so the number of the control points is about 2000 and the number of the coefficients is about 6000.

B. Metric function (similarity measure)

Since the CT volumes should be registered to the Open-MR volumes, mutual information is usually used as a similarity measure. Mutual information (MI) is an intensity-based similarity measure and quantifies the distance between the joint distribution of f_1 and f_2. In this paper, we adopt a normalized mutual information (NMI) in stead of mutual information (MI) [8, 9], since it is less sensitive to the overlapping part and more robust than MI [10,11]. NMI can be expressed by Eq.(6).

$$I(F,M) = \frac{H(F) + H(M)}{H(F,M)} \quad (6)$$

where *H()* is the Shannon's entropy. *F* and *M* are the fixed volumes and moving volumes respectively.

It can be seen that NMI is determined by three entropies which are the joint entropy *H(F,M)* and two marginal entropies *H(F)* and *H(M)*. Based on some easy mathematical derivations, all of the three entropies are determined by the joint probability density function (PDF) [10]. Usually, a discrete joint histogram is adopted to estimate the joint PDF for the calculation of NMI [11, 12]; however this will result in the discontinuous derivatives. Parzen-window estimation method is able to estimate a continuous joint PDF and widely adopted for the calculation of mutual information [10, 13-14], But we did not find a paper to use the Parzen-window method for the calculation of NMI. Additionally, we did not find a paper that gives the explicit expression of the 1st order derivatives of NMI, although there are some papers giving the derivatives of MI [14, 13]. Details about the Parzen-window estimation method based on two 3rd order B-spline kernels and the detailed derivations for the 1st order derivatives of NMI have been presented in [15].

C. Optimization

Multiresolution strategy is adopted to overcome the local minimum in optimization. Before registration, Gaussian filter and downsampling are first applied on both CT and Open-MR volumes to halve the resolution and to form Gaussian pyramids. Registration is then carried from low-resolution volumes to high-resolution volumes and the results on low-level will be used as an initial value for the following higher level.

The parameters of global and local transformation are optimized separately. Firstly, the local transformation is set to be an identity transformation and only the parameters of rigid transformation are adjusted by gradient descent optimization method. When this process is finished, the parameters of rigid transformation are set to be fixed and L-BFGS-B [16] optimization method is applied to find the optimal parameters of FFD. Multiresolution is used in optimization of parameters of both rigid transformation and FFD.

III. EXPERIMENTAL RESULTS

Six pairs of CT and Open-MR volumes are used to evaluate the registration accuracy. The Open-MR volumes are taken at the beginning of the Open-MR guided surgery. The Open-MR scanner is 0.5T GE Signa SP/i. Volume data is acquired with 3D fast gradient echo sequence with 2.7 ms TE, 17 ms TR and 30 degree flip angle. Both of them have 28 slices with 5mm thickness and their in-plane dimensions are 1.17mm x 1.17mm with a 300x300 mm^2 FOV. CT volumes are usually obtained from several days to a week before surgery. They are collected on a SIEMENS SOMATOM Sensation Cardiac/16 CT scanner. For three patients, the CT data has 25 slices with 7mm thickness and its in-plane dimension is 0.684mm x 0.684mm with a 350x350 mm^2 FOV; while the data for the other three patients has 60 slices with 3mm thickness and its in-plane dimension is 0.582mm x 0.582mm with a 300x300 mm^2 FOV. Two typical image pairs are shown in Fig.2 and Fig.3, respectively. As a preprocessing, 3D liver volumes are first manually segmented from the open MR volume images and the CT volume images. Figure 2(a) and 3(a) are Open MR images and its segmented liver images. Figure 2(b) and 3(b) are CT images and its segmented liver images. The segmented Open MR liver images and CT liver images are used for registration.

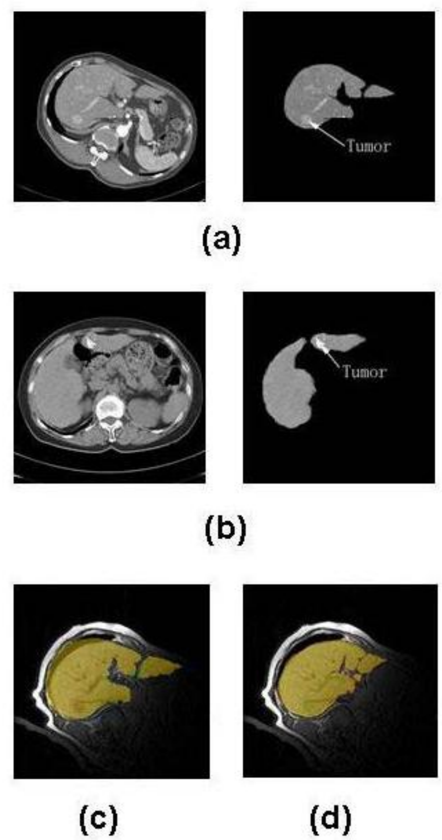

Fig.3. Example 1. (a) Open MR image and its segmented liver image; (b) CT image and its segmented liver image; (c) rigid registration result; (d) FFD-based non-rigid registration result.

The registration results are also shown in Fig.2 and Fig.3, respectively. The segmented liver on CT volumes is transformed back to the coordinate system of Open-MR volumes according to different registration results, and then overlaid on Open-MR volumes. Figure 2(c) and 3(c) are the results based on conventional rigid registration and Fig. 2(d) and 3(d) are the results based on the proposed FFD-based non-rigid registration. It can be seen that the liver transformed by FFD-based non-rigid registration result looks more similar to the one on Open-MR volumes. Especially, for the 2nd case shown in Fig. 3(c) and 3(d), liver transformed by a rigid registration result differs a lot from its counterpart in Open-MR volume. So it can be concluded that the FFD-based non-rigid registration is necessary for the Open-MR based liver cancer surgery and only a rigid registration is not sufficient. The average registration errors for FFD-based and rigid registrations are estimated as 1.5mm and 3.5 mm respectively [16]. This demonstrates the FFD-based non-rigid registration is more efficient than the rigid registration.

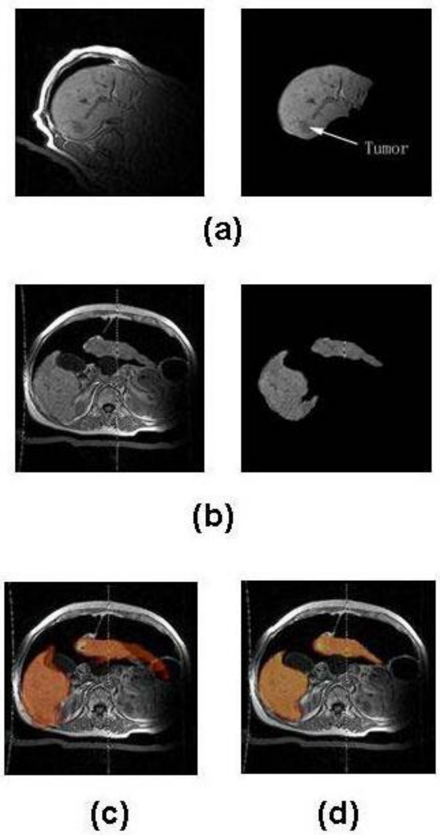

Fig.4. Example 2. (a) Open MR image and its segmented liver image; (b) CT image and its segmented liver image; (c) rigid registration result; (d) FFD-based non-rigid registration resul.t

IV. Experimental Results

A semi-automatic non-rigid registration technique is applied to assist and improve the open configuration magnetic resonance (Open-MR) imaging guided liver cancer surgery in which cancer tissues are coagulated by microwave ablation. Since the Open-MR volumes are obtained in a lower magnetic field (0.5T) and there are various kinds of surgical conditions, sometimes it is difficult to visualize tumors on them. Therefore, a possible solution to identify tumors is to apply a proper registration algorithm aligning the pre-surgery collected CT volumes with contrast tumors and Open-MR volumes together. Considering the easy deformation of livers, a FFD-based non-rigid registration is applied. Similarity measurement is normalized mutual information (NMI). Registration accuracy is evaluated by both objective and subjective evaluated methods. Experiments show that the average registration accuracy is about 1.45 mm and the average processing time is about 30 minutes. So the proposed non-rigid registration algorithm is suitable to the Open-MR based liver cancer surgery.

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