# Level Set based Real-time Anatomy Tracking

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*Abstract*– **Real-time motion estimation is always challenging especially under MR imaging modality due to its low SNR. This study proposes a novel level set based method to estimate the anatomical boundary motion in real time. We construct a correspondence map on the spatial-temporal domain and advect it with the underlying dynamic level set function that delineates the organ of interest. In real-time, such correspondence map is estimated and moving trajectories for the anatomy boundaries are evolved. Unlike conventional level set-based registration, where velocity is assumed to be normal, we solve for the velocity with tangential component by minimizing an elasticity energy. The proposed method was tested with renal MR image sequences under both synthetic and physiological motion: the former generated by artificially translating a static reference MR image and the latter acquired with EPI pulse sequence under heavy breathing. With the new scheme to handle tangential velocity component, the proposed method is capable to estimate motion with good accuracy and/or physiological implication. In the synthetic motion test where ground-truth velocity is accessible, it significantly improved the accuracy of the motion estimation; in the real-time MR sequence test, the reconstructed motion field is smooth and exhibits periodic temporal behavior in accordance with respiratory motion and spatial variation in agreement with dynamics for renal physiology. In conclusion, the proposed scheme improves the estimation accuracy and provides insights about the spatial-temporal characteristics of anatomical and physiological motion. Such information will be incorporated into real-time motion adaptive radiotherapy to improve cancer target coverage and normal tissue sparing.**

## I. Introduction

Real time motion estimation plays an important role in adaptive radiation therapy. Accurate motion estimate can be used to guide the radiation beam to either follow or switch according to the instantaneous anatomy, improving the accuracy of radiation delivery [1]. However, an efficient real-time motion estimation method remains elusive, especially when performed under low SNR condition, as in the case of MR images. In this paper, we propose a novel level set based method for real time motion estimation by keeping track of the anatomical boundary movement(Fig.1). We define a correspondence function and evolve it along with the level set function to maintain the point correspondence on the moving interface. To circumvent the ill-conditionedness of level-set based motion estimation without assuming normal velocity, we regularize the smoothness of the velocity flow along local tangential directions.

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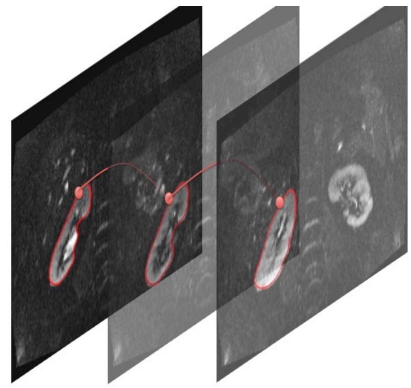


Fig. 1. Illustration of the proposed tracking method

## II. Method

Level set method [2,3] is a natural choice for representing moving interfaces. In this study, we use level set method to describe the temporal evolution of the anatomical boundaries at images are acquired in real-time. We define a point-wise correspondence map over the spatial temporal domain and keep record of the point wise correspondence during the level set evolution by evolving it along the level set function. In addition, we decompose the velocity field and solve for the tangential component to improve the correspondence accuracy. Our method mainly consists of four modules.

*i) Evolving Level Set Function:* We use distance regularized level set method [3] to obtain the boundary information. Gradient decent method is used to minimize the energy function defining as,

$$\varepsilon(\phi) = \mu\mathcal{R}_p(\phi) + \lambda\mathcal{L}_g(\phi) + \alpha\mathcal{A}_g(\phi) \tag{1}$$

Where $\mathcal{R}_p(\phi)$ penalizes deviation of levelset energy $\phi$ from a distance function, $\mathcal{L}_g(\phi)$ attracts zero level set to the image edges and $\mathcal{A}_g(\phi)$ regularizes the encompassed area by the curve. The relative tradeoff is controlled by the coefficients $\mu$, $\lambda$ and $\alpha$. More specifically, for image $I$ defined on $\Omega$, $g$ is an edge indicator function taking small values at image locations with large gradient values:

$$g = \frac{1}{1+|\nabla G_\sigma * I|^2} \tag{2}$$

,where $G_\sigma$ is the Gaussian kernel with standard deviation $\sigma$. The distance regularization term $\mathcal{R}_p(\phi)$ is defined by

$$\mathcal{R}_p(\phi) = \int_\Omega p(|\nabla\phi|)\,dx, \tag{3}$$

where $p$ is a double-well potential function.

$$p(s) = \begin{cases} \frac{1}{(2\pi)^2}(1-\cos(2\pi s)), if\ s \le 1 \\ \frac{1}{2}(s-1)^2, \qquad\qquad if\ s \ge 1 \end{cases} \quad (4)$$

It encourages the signed distance property $(|\nabla\phi| = 1)$ near the zero level set and strongly smoothes the locations far away from it.

The edge regularization term $\mathcal{L}_g(\phi)$ drives the zero level set to anatomical interface with high image gradient indicated by small $g$ function values

$$\mathcal{L}_g(\phi) = \int_\Omega g\delta(\phi)|\nabla\phi|dx \quad (5)$$

The area term $\mathcal{A}_g(\phi)$ is used to speed up initial evolution of the zero level set.

$$\mathcal{A}_g(\phi) = \int_\Omega gH(-\phi)dx\ , \quad (6)$$

where $H$ is the Heaviside function.

The descending flow of the energy function (1) is obtained by taking the Gâteaux derivative [4]

$$\frac{\partial\phi}{\partial t} = \mu div\left(d_p(|\nabla\phi|)\nabla\phi\right) + \lambda\delta(\phi)div\left(g\frac{\nabla\phi}{|\nabla\phi|}\right) + \alpha g\delta(\phi) \quad (7)$$

*ii) Calculating Velocity:* We calculate the velocity field that drives the $\phi$ function to evolve in step (i). Since interface geometry only depends on the normal component of the velocity, conventional level-set based shape tracking often assumes zero-tangential component and evolve the interface along normal direction to solve the underdetermined equation

$$\phi_t + \vec{V}\cdot\nabla\phi = 0 \quad (8)$$

Such practice, however, ignores the underlying physical motion and produces erroneous results when the velocity field, in addition to the evolved interface geometry, is of interest. To address this limitation, we adopt a regularization approach and seek a smooth velocity field that satisfies (8). More specifically, we minimize the following energy with respect to velocity $\vec{V} = (V_x, V_y)$ [5]

$$\int\left[\left(\frac{\partial V_x}{\partial s}\right)^2 + \left(\frac{\partial V_y}{\partial s}\right)^2\right]ds \quad s.t.\ \ \phi_t + \vec{V}\cdot\nabla\phi = 0 \quad (9)$$

*iii) Evolving Correspondence Function*: Inspired by [6], we define the correspondence function $\mathbb{R}^n\times\mathbb{R}^+ \to \mathbb{R}^n$ as

$$\psi(x_0, t) = x_t, \quad (10)$$

where $x_o$ are the initial coordinates of the interface and $x_t$ are the coordinates at time $t$. We evolve the $\psi$ function along with the level set function $\phi$ under the velocity calculated from step (*ii*) based on the equation

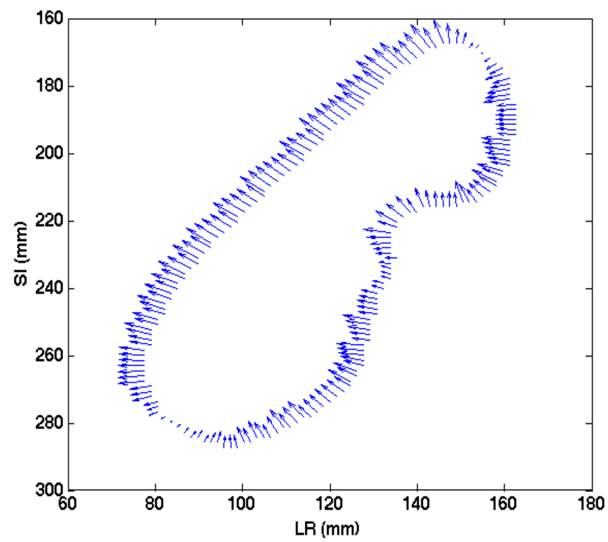
$$\frac{\partial\psi}{\partial t} + \vec{V}\cdot\nabla\psi = 0. \quad (11)$$

The backward correspondence maps are naturally built during the evolution. At each time $t$, $\psi(x_t, t)$ indicates the position where each current point was occupying at time *t = 0.*

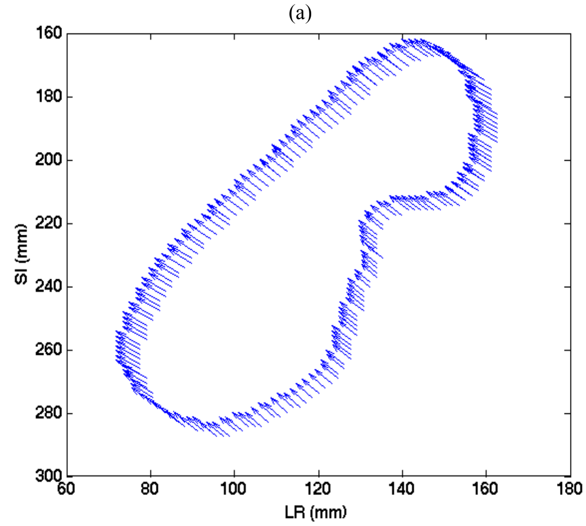
*iv) Reconstructing the Moving trajectory*: We concatenate the obtained correspondence maps to estimate the trajectory of the moving boundary. Under backward correspondence scheme, we can concatenate all such maps recursively from the interface at the end of the time horizon to the initial one via telescoping.

## III. Experiments and Results

Two experiments were conducted in the study. First, we used proposed method to estimate the tangential component of the velocity from synthetic MR images. We manually generated one translational image by shifting the initial image in the superior-left direction by 2.15 mm. The calculated velocity fields with and without tangential component are shown in Fig. 2(a)(b). Table.1 reports the comparison of the error statistics. Considerable improvement can be observed as the result of introducing the tangential component of velocity estimate.



(a)



(b)

Fig. 2. Estimated velocity field without and with tangential component, (a) estimated velocity field without tangential part, (b) estimated velocity field with tangential component.

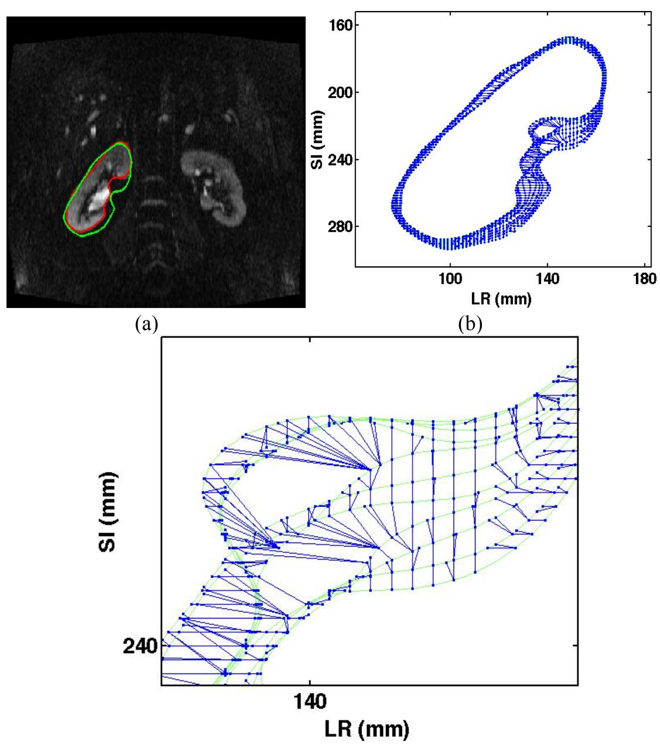
TABLE I. COMPARISON OF ERROR STATISTICS

| | M.E. w/o T.*(mm) | M.E. w/ T.(mm) | S.D. w/o T.**(mm) | S.D. w/T.(mm) |
|---|---|---|---|---|
| SI | 0.801 | -0.0003 | 0.997 | 0.226 |
| LR | 0.151 | -0.118 | 1.062 | 0.34 |
| 2D | 1.830 | 0.119 | 1.982 | 0.095 |

* Mean Error without Tangential component

**Standard Deviation without Tangential component

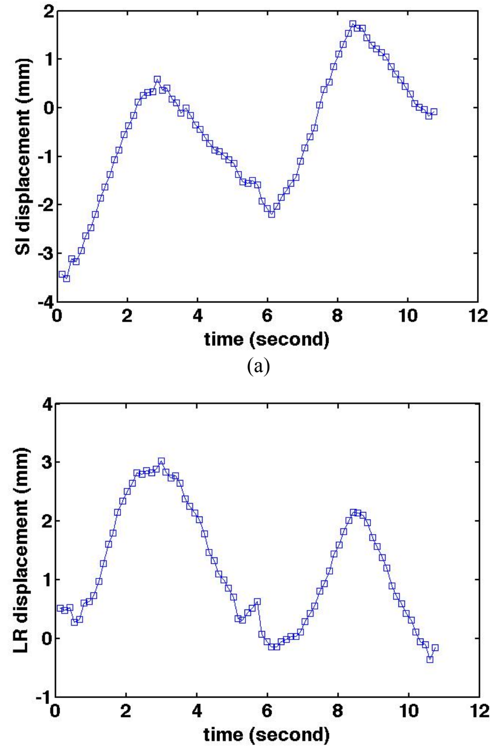
In the second experiment, we applied the proposed method to estimate the kidney motion on real-time EPI MR images (TR = 137ms, FOV = 390*390mm$^2$) under heavy-breathing conditions. The dataset consists of 80 consecutive images spanning about 10 seconds (137ms/TR*80). Two breathing cycles can be easily identified by visually examining the raw image sequence. Smooth moving trajectories among the first 20 frames were produced as shown Fig. 3(b)(c). The mean motion trajectory on the interface approximately exhibits two cycles as shown in Fig. 4(a)(b), which agrees visual inspection of the raw image sequence and the knowledge that typical respiratory cycles take approximately 4-6 seconds. The motion magnitude of 5-6 mm in SI direction and 3-4mm in LR direction also agrees with published results from magnetic resonance angiography of renal artery [7] and 4DCT studies on abdominal organ motion [8].




(a) (b)

(c)

Fig. 3.Motion estimation results from real-time MR sequences: (a) Overlay of renal contour from different time, (b) reconstructed forward moving trajectory with green curves indicating the various renal boundaries, (c) enlarged view of (b).




(a)

(b)

Fig. 4.Mean contour motion as a function of time: (a) mean displacement in superior-inferior direction, (b) mean displacement in left-right direction.

## IV. CONCLUSIONS

We have proposed a novel method of estimating the organ motion by advecting a correspondence function along with the level set method. We further extended the approach to account for tangential component of the velocity and greatly improve the estimation accuracy. The results provide important knowledge about the underlying physiological and anatomical motion and have great potential to guide the image-based radiotherapy in real time. Future works include further investigation of various regularization approaches [10-13] on solving velocity from equation (8), improvement of the algorithm efficiency and extending the implementation and validation tests to 3D.

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