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Tracking Endocardium Using Optical Flow along Iso-Value Curve

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Abstract- **In cardiac image analysis, optical flow techniques are widely used to track ventricular borders as well as estimate myocardial motion fields. The optical flow computation is typically performed in Cartesian coordinates, and not constrained from *a priori* knowledge of normal myocardium deformation patterns. However, for cardiac motion analysis, displacements along specific directions and their derivatives are usually more interesting than 2D or 3D displacement fields themselves. In this context, we propose a general frame work on optical flow estimation along iso-value curves. We applied the proposed framework in a specific application: for endocardium tracking on cine cardiac MRI series. The endocardial surfaces tracked with the proposed algorithm were quantitatively compared with manual tracing at each frame. The proposed method was also compared to the regular Lucas-Kanade optical flow method directly applied to MRI image data in Cartesian coordinates. Quantitative comparison showed a positive improvement in average tracking errors, through the whole cardiac cycle.**

Keywords- **three-dimensional ultrasound, optical flow, cardiac wall motion analysis, echocardiography.**

I. INTRODUCTION

Cardiac imaging, including echocardiography, cardiac MRI, and cardiac PET/SPECT, is widely used in clinical screening and diagnostic examinations as well as in research for *in vivo* studies. These imaging techniques provide structural and functional information. In most clinical studies, quantitative evaluation of cardiac function requires endocardial border segmentation throughout the whole cardiac cycle.

Recent advancements in cardiac imaging technology have greatly improved the spatial and temporal resolution of acquired data, such as with real-time three-dimensional echocardiography [1] and high temporal resolution MRI [2]. However, as information content is more detailed, the amount of data needed to be analyzed for one cardiac cycle also increases dramatically, making manual analysis of these data sets prohibitively labor-intensive in clinical diagnostic centers. In this context, many computer-aided methods were developed to automate or semi-automate the endocardial segmentation or tracking tasks throughout the whole cardiac cycle. These computer-based techniques can be divided into two classes: segmentation methods and motion tracking methods.

Cardiac image segmentation is a very active research area. Many techniques have been proposed, including active contour [3, 4], level-set methods and deformable models [5-9], classification [10], active appearance models [11], and other methods [12]. Optical flow algorithms on tracking of the endocardial borders or other anatomical landmarks throughout the whole sequences were studied in several recent works [13-18]. Optical-flow based tracking techniques offer the possibility to compute motion fields of myocardium. Usually, these methods require initialization of the tracked points, either by manual tracing or with other segmentation techniques.

However, in cardiac motion analysis, displacements along specific directions are usually better indicators of wall motion abnormality. In this context, we propose a general frame work for optical flow estimation along iso-value curves. An additional constraint related to specific motion direction was incorporated in the original optical flow system of equations to properly constrain the problem. A least-square fitting method was applied to small neighborhoods for each point of interest to increase the robustness of the method. The proposed method was then applied for endocardium tracking and results were quantitatively compared with that obtained by manual tracing as well as tracking with the original Lucas-Kanade optical flow method [19].

II. METHODOLOGY

A. Optical Flow Constraint Equation

Optical flow (OF) tracking refers to the computation of the displacement field of objects in an image, based on the assumption that the intensity of the object remains constant. This notion was first proposed by [20] and drove the active area of motion analysis in the 1990s. Barron *et al.* [21] wrote an extensive survey of the major optical-flow techniques at that time and drew the conclusion that the Lucas-Kanade and the Fleet-Jepson methods were the most reliable among the nine techniques they implemented and tested on several image sequences.

Assuming the intensity at time frame t of the image point (x, y) is $I(x, y, t)$, with $u(x,y)$ and $v(x,y)$ being the corresponding x and y components of the optical flow

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vector at that point, it is assumed that the image intensity will remain constant at point $(x+dx, y+dy)$ at time $t+dt$, where $dx = udt$ and $dy = vdt$ are the actual motion of the point during time period dt, leading to the following equation:

$$I(x+dx, y+dy, t+dt) = I(x, y) \tag{1}$$

If the image intensity is smooth with respect to *x*, *y*, and *t*, the left-hand side of equation (1) can be expanded into a Taylor series [20]. Simplifications, as detailed in [20], performed by ignoring the higher order terms and taking limits as $dt \to 0$, lead to the following equation:

$$I_x u + I_y v + I_t = 0 \tag{2}$$

using the notations:

$$u = \frac{dx}{dt}, v = \frac{dy}{dt}, I_x = \frac{\partial I}{\partial x}, I_y = \frac{\partial I}{\partial y}, I_t = \frac{\partial I}{\partial t}, \tag{3}$$

Equation (2) is called the *optical flow constraint equation*, as it expresses a constraint on the components *u* and *v* of the optical flow. This system is under-constrained and with this equation alone, the optical flow problem can not be uniquely solved. All gradient-based optical flow methods try to add additional constraints to make the system sufficiently constrained or even over-constrained. For example, the Lucas-Kanade method [19] tries to solve equation (2) through a weighted least-squares fitting in each small spatial neighborhood Ω by minimizing the following equation, assuming a constant motion within the neighborhood:

$$\sum_{(x,y)\in\Omega} W^2(x,y)\left[I_x u + I_y v + I_t\right]^2 \tag{4}$$

where $W(x,y)$ denotes a window function applied to the neighborhood. The solution to equation (4) is given by the following linear system:

$$A^T W^2 A \begin{bmatrix} u \\ v \end{bmatrix} = A^T W^2 \mathbf{b} \tag{5}$$

where for *n* points in the neighborhood Ω at single time *t*,

$$A = \begin{bmatrix} I_{x_1} & \cdots & I_{x_n} \\ I_{y_1} & \cdots & I_{y_n} \end{bmatrix}^T,$$
$$W = diag\left[W(x_1, y_1), \quad \cdots, \quad W(x_n, y_n)\right], \tag{6}$$
$$\mathbf{b} = -\begin{bmatrix} I_t(x_1, y_1) \\ \vdots \\ I_t(x_n, y_n) \end{bmatrix}$$

The system described in (5) can be solved by matrix inversion when the 2x2 matrix $A^T W^2 A$ is non-singular. The intrinsic least-square fitting property increases the robustness of the optical flow estimation for Lucas-Kanade method.

B. Optical Flow along Iso-Value Curves

In cardiac motion analysis, motion along some iso-value curves is usually more interesting than the full 2D or 3D displacement itself. In both cardiac biomechanics [22], and cardiac imaging analysis, such as [23], 2D or 3D displacement vectors are usually decomposed into radial and circumferential displacement components. These components and their derivatives (strains) are usually good indicators of ventricular abnormalities. For example, myocardium thickening, computed via radial derivatives of radial displacements, is the best indicator for ischemia according to a recent biomechanics study [24]. With the correct use of a coordinate system, such as polar coordinates [25] in 2D and cylindrical coordinates [23] in 3D, displacements along some directions (e.g. along radial directions) can be mathematically formulated as motion along some iso-value curves (e.g. $\theta = const$). In this context, investigating optical flow along iso-value curves becomes important.

Assuming the optical flow estimation is performed along iso-value curves $g(x, y, u, v) = const$, by letting $f(x, y, u, v) = g(x, y, u, v) - const$, the problem can be converted into an optical flow estimation along the zero-value curve $f(x, y, u, v) = 0$. Thus, for a point (*x*, *y*), two constraints are imposed on the optical flow vector (*u*, *v*):

$$\begin{cases} I_x u + I_y v + I_t = 0 \\ f(x, y, u, v) = 0 \end{cases} \tag{7}$$

To increase the robustness of optical flow estimation, following the rationale of the Lucas-Kanade method, for each point (x_c, y_c), the final optical flow estimation is solved via energy minimization, in the least square fitting sense, in an *n*-point neighborhood Ω, assuming a constant motion within the neighborhood:

$$\sum_{(x,y)\in\Omega} W^2(x,y)\left[I_x u + I_y v + I_t\right]^2 + f^2(x_c, y_c, u, v) \tag{8}$$

Generally solving the energy minimization problem in (8) is not trivial depending upon the nonlinearity of the function $f(x, y, u, v)$.

C. Example: Tracking Radial Displacements of the Endocardium

A direct application of the proposed framework was tested to track the endocardium motion along radial displacements. Previous work involving tracking endocardial borders using optical flow, such as [26], usually applied the optical flow algorithm directly on the Cartesian image data without additional constraints on motion direction. Since radial displacements and its derivatives are the most interesting components of endocardial motion, we focused on OF radial displacement computation only. Usually in 2D cardiac images, a polar coordinate system is used to decompose the endocardium displacement field in radial and circumferential directions. We followed the same coordinate system convention. The selection of the center of the polar coordinate system can not simply be the centroid of the blood pool because of the well known “floating centroid” problem in cardiac biomechanics [27]. Following the proper ventricle axis selection protocol described in [27], the long axis of left ventricle was first selected and then the center of the polar coordinate system was set as the intersection of LV long axis and the imaging plane. In this coordinate system, radial displacements can be defined as displacements along iso-value lines $\theta = const$. The corresponding zero-value function $f(x_c, y_c, u, v) = 0$, expressing the fact that the point (x_c, y_c) and its motion vector (u, v) are along the line $\theta = const$, is given by:

$$\begin{cases} x_c \sin\theta - y_c \cos\theta = 0 \\ u \sin\theta - v \cos\theta = 0 \end{cases} \tag{9}$$

which can be simplified into

$$f(x_c, y_c, u, v) = y_c u - x_c v = 0 \tag{10}$$

The energy minimization problem described by (8) can be solved by least-square fitting of the following equivalent over-constrained system:

$$\left[\begin{array}{cc} \sum W^2 I_x^2 & \sum W^2 I_x I_y \\ \sum W^2 I_x I_y & \sum W^2 I_y^2 \\ \hline y_c & -x_c \end{array}\right] \begin{bmatrix} u \\ v \end{bmatrix} = \left[\begin{array}{c} A^T W^2 \mathbf{b} \\ \hline 0 \end{array}\right] \tag{11}$$

where W, A, and $\mathbf{b}$ are defined in (6).

D. *Evaluation*

The endocardial border tracking scheme developed in the previous section was tested on a 2D cardiac MRI series with ECG gating acquired by GE 1.5T system using protocol FIESTA for 2D short axis stacks from an IRB approved experiment of LAD occlusion in sheep hearts. Endocardial border points for each time frame were traced by an experienced expert. The optical flow algorithm was initialized with manual tracing points on the first frame (end-diastole) and then automatically run to track those points throughout the whole cardiac cycle (20 frames in total). Two error measurements were used to evaluate the performance of the optical flow: (1) the Tanimoto index (TI) [28], which is widely used in comparison of segmentation results; (2) relative errors in radial coordinates. A 24 finite element model was used to fit manually traced points or optical flow tracked points for each time frame. The relative errors in radial coordinates of each element were then computed, with its mean served as a performance indicator for each frame. The original Lucas-Kanade optical flow method was also implemented and applied to the same data as a comparison method for endocardium tracking, without iso-value curve constraint.

III. RESULTS AND DISCUSSION

Radial lengths for the endocardial border points tracked by our method at end-diastole (ED) and end-systole (ES) were plotted in Fig. 1(a). When compared to endocardium obtained by manual tracing, our proposed method has TI value 74.62%±8.54%, compared with that obtained by original Lucas-Kanade method as 72.06%±9.13%. These results showed that our proposed method has more accurate and robust performance than the original Lucas-Kanade method. Example tracking results at frame 10 were shown in Fig. 1(b), showing that our method is less likely to fail compared with original method. Similar conclusion can be drawn from the comparison of the relative errors in radial coordinates plotted in Fig. 1(c,d), for which the proposed method has lower average errors as well as lower standard deviations in the relative errors in radial coordinates. The additional constraint of the OF motion along iso-value curves improved the robustness and accuracy for tracking of the endocardium.

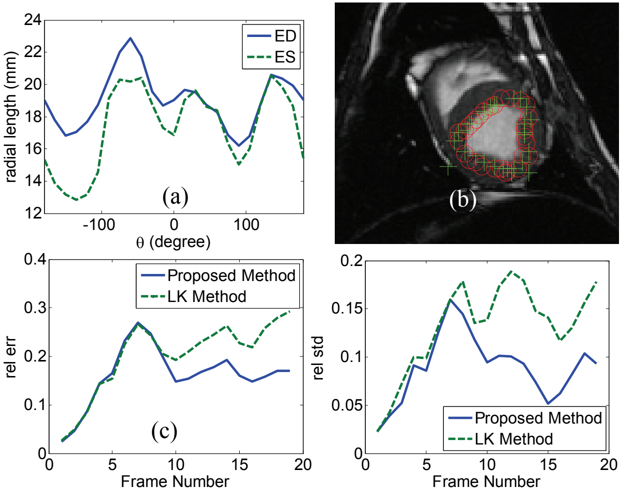

Fig. 1. (a) Radial length of endocardium points at ED (solid line) and ES (dashed line); (b) Tracking result at frame 10 with proposed method (red circle) and Lucas-Kanade method (green cross) ; (c-d) Relative radial coordinates errors: (c) relative error (%) and (d) standard deviation. (b-d) solid line: proposed method; dashed line: Lucas-Kanade method.

Error accumulation of consecutive frames in the OF estimation can be noticed from the plots, which suggests that applying forward and backward tracking or adding more reference points may improve the performance of OF estimation.

Our proposed framework is generic and can be easily extended to higher dimensions without much effort: (1) In the energy function described by (8), the image intensity gradients and optical flow components along additional dimensions need to be added; (2) the zero-value function f should become a function of n-D coordinates and optical flow components in all directions; (3) and multiple zero-value functions $f_1, \dots f_m$ may be needed in order to define the iso-value curves completely. The energy minimization problem may become non-linear depending on the non-linearities of zero-value functions and iterative methods may be required to solve the least-square fitting problem. This framework could be merge with variational optical flow approaches, such as works in [29] and [30].

IV. CONCLUSION

A generic framework for optical flow along iso-value curves was proposed as an energy minimization problem with local constraints related to iso-value curves. One application of this framework was presented for tracking of the endocardium on 2D MRI data series. The endocardium borders tracked by the proposed method as well as the Lucas-Kanade method were quantitatively compared to manual tracing at each frame through the Tanimoto Index and relative errors in radial coordinates after FEM fitting. The results showed superior performance for the proposed method in tracking the endocardium. Although illustrated in 2D+Time only, the framework is generic and can be readily extended to n-dimensional spaces with little effort to properly define the iso-value curves and solve as a non-linear energy minimization problem.

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