33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

A Momentum-Based Constraint on Optical Flow Tracking of the Endocardial Surface

Ming Jack Po, Auranuch Lorsakul, and Andrew F. Laine, *Fellow, IEEE*

Abstract—**Echocardiography is the standard of care for the evaluation of cardiac function in a variety of clinical scenarios. Despite the increasing availability of RT3D imaging, its utility remains limited due to a lack of tools available to analyze 3D+t datasets. In previous work, we have proposed and validated optical flow as an effective correlation-based technique to track myocardial motion and deformation in RT3D datasets. However, OF's ability to track small regions of tissue (e.g. the endocardial surface) is diminished in less optimal acquisitions. Our goal, therefore, is to develop additional constraints on OF-estimated motion in order to increase the robustness of endocardial surface tracking. We present several modifications to OF-based tracking including motion field smoothing and momentum correction that results in improved OF tracking.**

I. Introduction

ECHOCARDIOGRAPHY is among the most prevalent imaging modalities in clinical cardiology. It offers the highest temporal resolution of any cardiac imaging technique, a critical advantage that allows ultrasound to detect functional diseases ranging from infarcts to bundle branch blocks to heart failure. However, despite the development of real-time 3D (RT3D) ultrasound since the early 1990s [1], 2D echocardiography remains the standard of care for assessment of cardiac function [2]. While effective for some diagnostic purposes, 2D visualizations of inherently complex 3D motion and deformation are subject to significant sources of error, including myocardial dropout, out-of-plane motion, and angle dependency (e.g. for Doppler studies) [3].

The lack of RT3D ultrasound integration into the clinical workflow is due in large part to the paucity of tools available for the analysis of the resulting 4D (3D-volume-in-time) data. Thus, while systems which use matrix phased array transducers to scan true 3D volumes, such as the SONOS 7500 and iE33 (Philips Medical Systems, Best, The Netherlands), are becoming more widely available, the interpretation of 4D sonograms remains largely confined to qualitative and structural aspects of heart function.

To aid the cardiologist in evaluating RT3D echocardiograms, several groups have proposed image-processing based techniques to quantify myocardial motion and strain in 3D. Meunier [4] showed that it is possible to use speckle tracking to characterize tissue dynamics in 3D using simulated ultrasound images. Elen et al [5] further showed the feasibility of using elastic registration in strain estimation. Our group has previously proposed [6] and validated the correlation-based optical flow technique in both simulated [7] and animal [8] models. In this study, our aim is further improve the accuracy of the endocardial surface tracking by 1) smoothing the displacement field at each time increment and 2) implementing a momentum-based constraint that spans multiple time increments to improve the accuracy of the cross-correlation optical flow tracking.

II. Methods

A. Data Acquisition

The data used in this analysis was acquired from two open-chest dogs. The experiments were performed under a research protocol approved by Columbia University's Institutional Animal Care and Use Committee. Anesthesia was induced with propofol (4–8 mg/kg i.v.) in both dogs and anesthesia was maintained using inhaled isoflurane (1.5–2.5%). A lateral thoracotomy was performed and the pericardium was opened and sutured to the chest wall to expose the left ventricle. Sutures were placed around the left anterior descending (LAD) and left circumflex (LCx) coronary arteries or their branches at proximal and distal sites. More details on the experimental setup are available in [9].

The apical RT3D echocardiograms were then acquired using a Philips iE33 ultrasound system (Philips Medical Systems, Andover, MA) at 10 – 12 frames per complete cardiac cycle. A silicone gel standoff (Aquaflex, Parker Laboratories, Fairfield, NJ) was placed between the ultrasound probe and the apex of the heart.

At the conclusion of the experiment, the dogs were euthanized by overdose injection of pentobarbital sodium (98–118 mg/kg) and phenytoin (12–15 mg/kg)

B. Manual Segmentation

After acquisition, three cardiologists manually traced the endocardial border in the ED and ES frames, using 3D visualization software provided by TomTec. Their tracings were averaged, and the resulting contour was regarded as the ground truth. The first tracing (at end diastole, ED) was used as the initial set of points, which were then tracked until end systole (ES) using the optical flow technique described

Manuscript received April 15, 2011.

V. Gamarnik, M. Po, A. Lorsakul and A.F. Laine are with the Department of Biomedical Engineering, Columbia University, ET-351, 1210 Amsterdam Avenue, New York, NY 10027, USA (212-854-5996; email: laine@columbia.edu)

Q. Duan is with NINDS, NIH, 10 Center Dr., Bethesda, MD 20892 (email: Qi.Duan@nih.gov)

below.

C. Anisotropic Diffusion Filtering

To suppress the speckle noise in the data, all data sets were pre-processed with anisotropic diffusion filtering. As presented in [10], anisotropic diffusion does not blur edges, capable of preserving high spatial accuracy, while de-noising the data for further analysis.

D. Correlation-Based Optical Flow

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 [11]. As described in Duan et al [12], in the field of RT3D ultrasound, optical flow may be implemented as a region-based matching technique to compute displacements between sequential image frames by maximizing the cross-correlation coefficient, defined as

$$corr = \frac{\sum_{\mathbf{x}\in\Omega}\left(I(\mathbf{x},t)\cdot I(\mathbf{x}+\Delta\mathbf{x},t+\Delta t)\right)}{\sqrt{\sum_{\mathbf{x}\in\Omega}I^2(\mathbf{x},t)\sum_{\mathbf{x}\in\Omega}I^2(\mathbf{x}+\Delta\mathbf{x},t+\Delta t)}} \quad (1)$$

where $I(\mathbf{x}, t)$ and $I(\mathbf{x}, t + \Delta t)$ represent the data from consecutive time frames, and the displacement vector $\Delta\mathbf{x}$ is defined in the small neighborhood Ω around each pixel. In this study, a 3D window of 5×5×5 pixels was used to compute the cross-correlation in a 7×7×7 pixel area around each pixel.

Unlike OF computations within the myocardial wall, motion estimation at the endocardial border may be considerably less stable. This is due to the presence of the low-SNR blood cavity in the immediate neighborhood of any given target pixel. Combined with the small search region around each pixel, this makes it easier for a pixel to "jump off" the true endocardial border, and be unable to find it again in subsequent frames. Two techniques were implemented to improve the robustness of OF when the tracking of only a border region was desired.

First, to capture more of the myocardial tissue without performing OF on the full volume, the initial voxel space was expanded by adding each voxel's neighbors to the list of tracked points. Three neighboring points in both directions along the x and y axes were added (e.g. $x\pm3$, $y\pm3$), thereby expanding a single pixel to 13. The initial 3D vector field estimated from OF was then median-filtered in 3D using a 5×5×5 window, and the resulting displacement values were used to update the pixel coordinates.

In addition, we implemented a momentum-based constraint on the motion of individual pixels. As formulated in (1), OF does not take into account the momentum of physical tissue, which makes sudden changes in direction or magnitude of displacement less likely. We therefore modified the displacement calculation by updating the OF-estimated displacement as the average of the current displacement and the previous frame's value. This procedure favors continuous motion while limiting erroneous large jumps in values between consecutive frames.

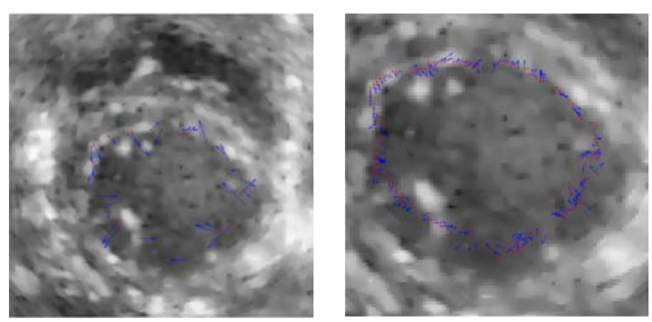
E. Evaluation

Typically, myocardial motion tracking results are compared on the basis of global measurements such as end-systolic/end-diastolic volume, ejection fraction, or mean-squared errors. However, the localized nature of the OF method of motion estimation warrants a more specific approach to evaluate accuracy. To measure the correspondence between OF-tracked points and the expert tracings, we computed the difference in the convex hull areas encompassed by the endocardial border points. At each C-scan level, the area of the non-overlapping regions was divided by the total area from the expert tracing, to give an estimate of the error for that slice. Consequently we determined the average error for the ED and ES frames; because ground-truth data was not available for the intermediate frames in the sequence, error estimation was not possible on these frames.

III. Results

A. Median Filtering

In our published cross-correlation optical flow framework [6], an endocardial border traced by experts at end diastole is needed to seed the algorithm. The manually-traced border is interpolated and resulting points are then propagated to the other cardiac temporal volumes via optical flow tracking. In our published framework, only the interpolated endocardial pixels are tracked. In noisier ultrasound volumes, this sometimes resulted in displacement fields that rapidly fluctuated among neighboring pixels (Fig 1a). For the improved framework, we increased the number of points tracked roughly 10-fold, as described in the methods. Furthermore, the resultant optical flow displacement field is median-filtered, resulting in much smoother and denser displacement fields, as shown (Fig 1b).



(a) (b)

Fig. 1 (a) Optical flow displacement field using the unrestrained optical flow algorithm and (b) Optical flow displacement field after median filtering and increased tracking window.

B. Momentum Constrained Optical Flow

Though median filtering can improve the smoothness of the displacement fields generated from optical flow, it is also useful to impose constraints on the optical flow itself. A momentum constraint was implemented on the optical flow algorithm as described in the methods in shown in Fig 2. On the left are short axis views of one representative 2D slice of the mid-left ventricle processed using the original optical flow analysis framework with median filtering. On the right are the same six slices processed using the modified analysis framework with both median filtering on a denser vector field and momentum constraints. Median filtering was performed on both sets of results for figure 2 to demonstrate the effects of the momentum constraint alone. The averaged contours of three cardiologists' tracings are also super-imposed on each figure and used as ground truth for evaluation as described in the methods.

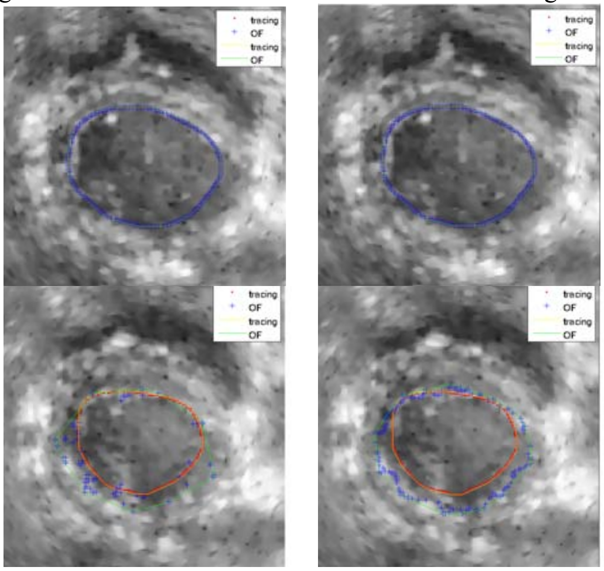


Fig. 2. On the left are results from the original optical flow framework and on the right are results from the new optical flow framework with median filtering and momentum based constraints. The top row shows the tracings at ED, which are used to seed the OF algorithm. The bottom row shows the expert and OF-based contours at ES, after tracking for 6 consecutive frames. For clarity, only a single representative short-axis slice of the LV is shown.

In the second row, one can observe that the momentum constraints have eliminated unrealistic sharp corners in the contours of the endocardial border at ES. Furthermore, one can observe that the top portion of the endocardial border is much better tracked. Overall, the average non-overlap error for all six temporal slices is 43.24% for the left and 33.06% on the right.

IV. Discussion

In traditional cross-correlation based optical flow, each pixel undergoes template matching by itself, utilizing no physical constraints that are inherent in even pathological hearts. These physical constraints can consist of zeroth order smoothness conditions on the endocardium border or even higher order conditions on the velocity and acceleration fields. In this paper, we have chosen to focus our physical constraints on 1) the zeroth order continuity condition of the displacement field and 2) smoothness constraints on the first order velocity field through a momentum-based constraint.

A. *Median Filtering*

Due to the technical constraints of RT3DE ultrasound acquisition, the acoustic signal and its associated speckle originating from the endocardial border is sometimes difficult to localize in every pixel of every temporal volume [13]. This creates difficulties for algorithms such as traditional cross-correlation optical flow when the template volume can be reasonably matched with a number of different candidate volumes in the search window. This is especially problematic when optical flow is used iteratively, as it is in our analysis framework. Since the result of optical flow tracking in our analysis framework from time point N-1 to time point N is used to seed the input for time point N+1, early errors in the displacement field can compound and propagate into later temporal volumes, leaving the final contour at end systole unusable.

In this paper, we have chosen to address the problem by implementing a continuity constraint on the displacement field. Specifically, we expect that within a voxel of 3 × 3 × 3 pixels (~0.8 mm in dimensions), the displacement vectors should not drastically change in either direction or magnitude. We implemented this constraint by using a non-linear median filter on the displacement field. To save on processing time, in our original framework, we only tracked the pixels that were directly on the endocardial border. To implement the linear median filter properly, we would need to track at least the endocardial border plus the bandwidth of the median filter. After some empirical experimentation, we have found that ($x\pm3$, $y\pm3$) offered the best results, resulting in only a 3× increase in processing time.

In Fig 1a, one can observe that optical flow tracked the upper border of the left ventricle short axis view acceptably, but was unable to properly localize the bottom border, resulting in displacement vectors that randomly shift in direction from pixel to pixel. In Fig 1b, we can see that our new framework is able to significantly smooth the displacement field without affecting its ability to still change direction and magnitude from region to region. The non-linear median filter is particularly useful in correcting random errors from optical flow tracking, but is not able to correct systemic errors that could result when optical flow incorrect tracks blocks of pixels into an incorrect region, though this situation is relatively rare.

B. *Momentum Constrained Optical Flow*

We have chosen to implement the first order physical constraint by averaging the current calculated displacement vector with the previous frame's displacement vector and using the resulting vector to update the displacement field. Together with median filtering, these two physical constraints leverage both spatial and temporal smoothness constraints to help improve optical flow tracking results.

From figure 2, one can see that the momentum constrained optical flow can clearly help correct for large tracking errors stemming from a few contiguous pixels being tracked improperly. However, it is not able to leverage unobserved anatomical knowledge that cardiologists are using to help draw their contours of the endocardial border. Large sections of their tracings on the bottom left sections of the left ventricles do not coincide with any discernible changes in either pixel values or speckle patterns. This suggests that simultaneous tracking of both endocardial and epicardial borders might be necessary to help further constrain the endocardial contours. This work is currently in progress and results are expected by time of conference.

V. CONCLUSION

Using a published 4D correlation-based optical flow speckle tracking algorithm as a starting point, we investigated the effect of imposing zeroth order and first order continuity and smoothness constraints on the optical flow displacement fields. It was found that the physical constraints significantly improved the ability of optical flow to track the endocardial border when the ultrasound data was able to localize the endocardial border junction without too many gaps. When the junction is hard to detect, optical flow can makes mistakes and track portions of the epicardial border as endocardial border. We are currently experimenting with simultaneous tracking of both the endocardial and epicardial borders with the additional non-trivial constraint of limiting the endocardial border from crossing past the epicardial border. Though this result is not ready for this abstract, preliminary results are encouraging.

REFERENCES

[1] O. T. Ramm and S. W. Smith, "Real time volumetric ultrasound imaging system," *Journal of Digital Imaging*, vol. 3, no. 4, p. 261-266, Nov. 1990.

[2] P. S. Douglas et al., "ACCF/ASE/AHA/ASNC/HFSA/HRS/SCAI/SCCM/SCCT/SCMR 2011 Appropriate Use Criteria for Echocardiography," *Journal Of The American College Of Cardiology*, vol. 57, no. 9, p. 1126-1166, Mar. 2011.

[3] M. Uematsu et al., "Myocardial velocity gradient as a new indicator of regional left ventricular contraction: Detection by a two-dimensional tissue doppler imaging technique," *Journal Of The American College Of Cardiology*, vol. 26, no. 1, p. 217-223, Jul. 1995.

[4] J. Meunier, "Tissue motion assessment from 3D echographic speckle tracking.," *Physics in medicine and biology*, vol. 43, no. 5, p. 1241-1254, May. 1998.

[5] A. Elen et al., "Three-Dimensional Cardiac Strain Estimation Using Spatio–Temporal Elastic Registration of Ultrasound Images: A Feasibility Study," *IEEE transactions on medical imaging*, vol. 27, no. 11, p. 1580-1591.

[6] Q. Duan et al., "Tracking of LV endocardial surface on real-time three-dimensional ultrasound with optical flow," *Functional Imaging And Modeling Of Heart, Proceedings*, vol. 3504, p. 434-445, 2005.

[7] Q. Duan, E. Angelini, and S. Homma, "Validation of optical-flow for quantification of myocardial deformations on simulated RT3D ultrasound," *Biomedical Imaging: From …*, Apr. 2007.

[8] Q. Duan, E. Angelini, A. Lorsakul, S. Homma, J. Holmes, and A. Laine, "Coronary Occlusion Detection with 4D Optical Flow Based Strain Estimation on 4D Ultrasound," *Functional Imaging and Modeling of the Heart*, p. 211-219.

[9] S. L. Herz et al., "Quantitative three-dimensional wall motion analysis predicts ischemic region size and location.," *Annals of Biomedical Engineering*, vol. 38, no. 4, p. 1367-1376, Apr. 2010.

[10] Q. Duan, "Proceedings of SPIE," in *Medical Imaging 2004: Ultrasonic Imaging and Signal Processing*, vol. 5373, p. 331-342.

[11] B. Horn and B. Schunck, "Determining optical flow," *Artificial intelligence*, 1981.

[12] Q. Duan et al., "Dynamic Cardiac Information From Optical Flow Using Four Dimensional Ultrasound," *Engineering in Medicine and Biology Society, 2005. IEEE-EMBS 2005. 27th Annual International Conference of the*, p. 4465-4468, 2005.

[13] D. Qi, "Real-time four-dimensional cardiac image analysis for left ventricular function," *csa.com*, 2008.