Using Optical Flow to Estimate Displacement Between 3D Navigators in Coronary Angiography

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Target Audience: MR physicists and engineers interested in motion correction and cardiac imagery.

Purpose: Motion estimated from navigators can be used to correct high resolution data retrospectively. The recent developments of image-based 3D navigators (iNAVs) [1,2] permit localized motion estimates throughout the imaged volume, which provide the opportunity to monitor beat-to-beat heart motion due to respiration. Previous work used optical flow [3] fields determined from 2D iNAVs for this purpose [4], and previous work in CT used 3D optical flow fields to estimate motion in reconstructed volumes of the heart [5]. In this work, we demonstrate the ability to estimate motion between 3D iNAVs using optical flow, which determines an individual velocity vector for each voxel. Unlike with 2D iNAVs and optical imagery, there are no occlusions in 3D iNAVs, thus optical flow is especially suitable to determine displacements from this data.

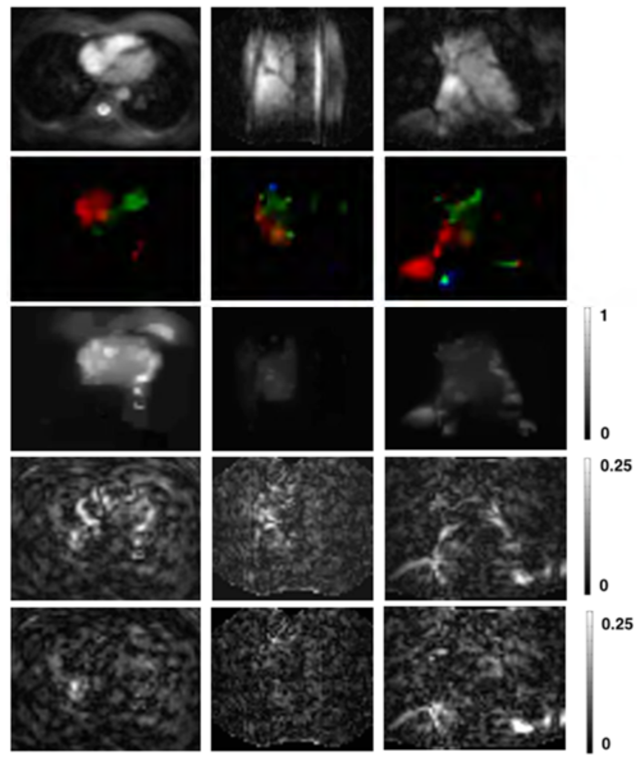

Figure 1. First / Second / Third column show axial / sagittal / coronal slices. Row 1: reconstructions. Row 2: optical flow velocity field. Red / Green / Blue indicate the horizontal / vertical / in-out velocities. Row 3: magnitude of optical flow velocity vectors in pixels per frame. Row 4 / 5: differences between un / aligned 3D iNAVs.

Methods: In a free-breathing whole-heart coronary MR angiography method, 3D iNAVs were acquired every heartbeat using an accelerated variable-density 3D cones trajectory with an acceleration factor of 9 [6]. 3D iNAVs covering a field of view of 28 x 28 x 14 cm^3 with 4.4mm isotropic resolution were collected in 176ms. Imaging was performed on a GE Signa 1.5T Excite scanner with an 8-channel cardiac coil. The assumption with optical flow is that if the tissue moves $[\Delta u\ \Delta v\ \Delta w]^T$ between frames, then its image intensity remains the same:

$$I(u,v,w,t) = I(u+\Delta u, v+\Delta v, w+\Delta w, t+\Delta t).$$

By linearizing this equation, the 3D optical flow constraint for a voxel is attained:

$$I_u(u,v,w,t)\Delta u + I_v(u,v,w,t)\Delta v + I_w(u,v,w,t)\Delta w + I_t(u,v,w,t)\Delta t = 0,$$

where I_u represents the partial derivative of the image I with respect to the u argument. Each voxel provides one linear equation with three unknowns. These equations from all voxels can be combined into a single underdetermined linear system $Ax = b$, where x is the concatenation of the variables Δu, Δv, and Δw. We made the assumption that the vector field is piecewise smooth, and determined the optical flow displacement vectors by minimizing $(1/2)\|Ax-b\|_2^2 + \eta \mathrm{TV}(x)$ with respect to x, where total variation (TV) regularization has been imposed. We minimized this cost function using the Alternating Direction Method of Multipliers (ADMM) [7], which in recent years has proved to be effective for this type of very large scale non-differentiable convex optimization problem. To convert the optimization problem into a form that ADMM could solve we introduced a splitting variable and solved

$$\text{minimize } (1/2)\|Ay-b\|_2^2 + \eta\|z_u\|_1 + \eta\|z_v\|_1 + \eta\|z_w\|_1$$
$$\text{subject to } y = x, z_v = Dx_v, z_u = Dx_u, \text{and } z_w = Dx_w,$$

where D is the discrete gradient operator. In each iteration of ADMM we used the 3D Discrete Cosine Transform (based on the FFT) to efficiently solve a large system of equations involving the discrete gradient operator. To account for large displacements, which may have led to violations of the optical flow constraint, we used a coarse-to-fine approach with a 3 level pyramid. Additionally, a median filter was applied at each level. The result was an estimate for the displacement of each voxel in the reconstructed volume. Once the displacement vectors were determined, velocity vectors could be attained by dividing the displacement vectors by Δt.

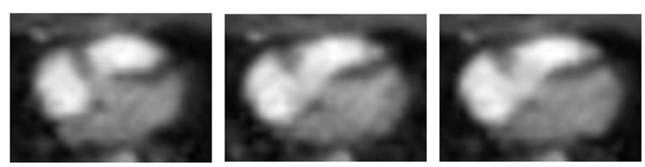

Figure 2. Axial slices of 3D iNAVs. (Left) and (Center) show adjacent iNAVs. (Right) shows the Left iNAV aligned to the Center iNAV using the Optical Flow field.

Results and Discussion: Figure 1 shows an example of the displacement estimates determined using optical flow. The fourth and fifth rows of Figure 1 show the magnitude of the differences between adjacent iNAVs before and after alignment with the optical flow field. The differences in the aligned imagery are significantly reduced. We calculated the difference images for 59 aligned and unaligned iNAVs. For a region encompassing the heart, the average RMS error of the unaligned differences was 7.6; the average error in the aligned difference images was 6.2; and the average improvement was 1.4. Figure 2 shows axial slices of two adjacent iNAVs before and after alignment. The left and center images show the unaligned iNAVs. Using the optical flow field, the right image shows excellent alignment of the left iNAV with the center image.

Conclusion: In this work, we have demonstrated that optical flow can be used to determine the displacement vectors between 3D iNAVs. These estimates can be used to correct for motion in free-breathing whole heart 3D cones MR angiography [8].

References: [1] Addy N, et al. J. Card. MR: 16(Suppl 1) P380: 2014. [2] Henningsson M, et al. MRM: 71(1): 173-181, 2014. [3] Sun D, et al. 2010 CVPR 2432-2439. [4] Hansen M, et al. MRM: 68(3): 741-750, 2012. [5] Gorce J, et al. Med Img Ana 1.3:245-261: 1997. [6] Addy N, et al., Proc 25th Intl. Workshop on MRA: 84, 2013. [7] Boyd S, et al., FaTML 3.1:1-122: 2011. [8] Odille F, et al. MRM 59:1401-1411, 2008.