BIMODAL ULTRASOUND MOTION RECOVERY FROM INCOMPLETE DATA

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OVERVIEW: We propose a novel method for motion recovery from ultrasound data using both B-mode and tissue Doppler images. Both modalities provide partial information of the motion: B-mode images yield relative motion along the intensity gradient (also known as optical flow constraint) and the tissue Doppler images give relative motion along the beam direction. The proposed method attempts to exploit both kinds of partial information to recover the true motion. We propose to use Doppler measurements from all pixel locations whereas we choose optical flow constraints only in the high-gradient regions. This corresponds to an irregular sampling problem, where the samples are these relative motion data. We formulate the reconstruction problem in the continuous domain; in particular, we search for a solution in a cubic spline space that minimizes the error at sampling locations subject to some regularization constraint. We demonstrate that our method is more robust than the approaches of the literature which estimate motion from optical flow alone (unimodal formulation). Part of the robustness of our algorithm is imposed globally via the regularization constraint; another important local component is due to the elimination of pixel locations where the optical-flow constraint is unreliable (irregular sampling). In addition, our continuous-domain formulation in the spline spaces leads to a very fast and numerically efficient algorithm.

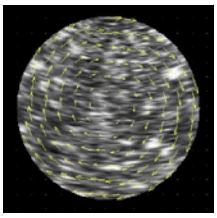
THE MEASUREMENT MODEL: From an ultrasound acquisition, we typically get two sequence of images: (1) the B-mode (intensity) images $I(\mathbf{r},t)$; and (2) the tissue Doppler velocity images $v_D(\mathbf{r},t)$. The latter gives the relative velocity of a point along the direction of the beam and is given by $v_D=\cos(\beta)u+\sin(\beta)v$, where u and v are true velocity components and β is the beam angle. $I(\mathbf{r},t)$ contains the motion information in the form of the so called optical flow constraint: $-I_t=I_xu+I_yv$, where I_x, I_y, and I_t are spatial and temporal derivatives. One can easily verify that both types of constraints or measurement equations can be written as $s=\mathbf{p}^T\mathbf{V}$, where $\mathbf{V} = [u, v]^T$. In the case of Doppler, $s=v_D$ and $\mathbf{p}=[\cos(\beta),\sin(\beta)]^T$, whereas in the case of optical flow, $s = -I_t$ and $\mathbf{p}=[I_x, I_y]^T$. Hence the measurement set will be a list of triplets $\{\mathbf{r}_i,\mathbf{p}_i,s_i\}$, where $\mathbf{r}_i$ is the measurement location, $\mathbf{p}_i$ is the direction, and s_i is the relative velocity along $\mathbf{p}_i$. We choose Doppler measurements from all pixel locations and optical flow measurements from locations of high gradient magnitude. Hence a location can have either Doppler measurement alone or both Doppler and optical flow measurements, which means that in the list of triplets two entries can have the same $\mathbf{r}_i$.

THE RECONSTRUCTION METHOD: Given the list $\{\mathbf{r}_i,\mathbf{p}_i,s_i\}$, we reconstruct the velocity field $\mathbf{V}(\mathbf{r})$ such that $J=\sum_i\left(\mathbf{p}_i^T\mathbf{V}(\mathbf{r}_i)-s_i\right)^2+M(\mathbf{V})$ is minimized, where

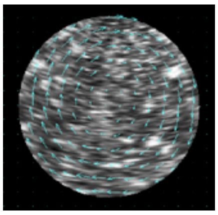
$$M(\mathbf{V})=\lambda_1\int|\nabla\cdot\mathbf{V}|^2\mathbf{dr}+\lambda_2\int\|\nabla(\nabla\cdot\mathbf{V})\|^2\mathbf{dr}+\lambda_3\int\|\nabla(\nabla\times\mathbf{V})\|^2\mathbf{dr}.$$

It can be shown that $M(\mathbf{V})$ quantifies the deformation of the medium that undergoes motion. If we restrict $\mathbf{V}(\mathbf{r})$ to be of the form $\mathbf{V}(\mathbf{r})=\sum_{\mathbf{k}}\mathbf{c}_{\mathbf{k}}\beta(\mathbf{r}/h-\mathbf{k})$, where β is the tensor product B-spline, then the solution $\mathbf{c}=\left[\cdots\ \mathbf{c}_{\mathbf{k}}\ \cdots\right]^T$ is given by a very large linear system of equations $\mathbf{Ac}=\mathbf{b}$. We have developed a very fast multi-grid algorithm to solve this system.

RESULTS—CONTROLLED PHANTOM EXPERIMENT : We applied our reconstruction method to real ultrasound data obtained from a phantom rotating with a known speed. The results are given below.



Phantom with true velocity field.



Reconstructed velocity field.

Average angular error: 4.9 degrees.

CONCLUSION: We have proposed a computationally efficient and robust method for ultrasound motion reconstruction from bimodal measurements where the robustness is achieved by a physically meaningful regularization.