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Ultrasound elastography using multiple images

Hassan Rivaz *, Emad M. Boctor, Michael A. Choti, Gregory D. Hager

Department of Computer Science, Johns Hopkins University, Baltimore, MD, USA

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A B S T R A C T

Displacement estimation is an essential step for ultrasound elastography and numerous techniques have been proposed to improve its quality using *two* frames of ultrasound RF data. This paper introduces a technique for calculating a displacement field from *three (or multiple)* frames of ultrasound RF data. To calculate a displacement field using three images, we first derive constraints on variations of the displacement field with time using mechanics of materials. These constraints are then used to generate a regularized cost function that incorporates amplitude similarity of three ultrasound images and displacement continuity. We optimize the cost function in an expectation maximization (EM) framework. Iteratively reweighted least squares (IRLS) is used to minimize the effect of outliers. An alternative approach for utilizing multiple images is to only consider two frames at any time and sequentially calculate the strains, which are then accumulated. We formally show that, compared to using two images or accumulating strains, the new algorithm reduces the noise and eliminates ambiguities in displacement estimation. The displacement field is used to generate strain images for quasi-static elastography. Simulation, phantom experiments and *in vivo* patient trials of imaging liver tumors and monitoring ablation therapy of liver cancer are presented for validation. We show that even with the challenging patient data, where it is likely to have one frame among the three that is not optimal for strain estimation, the introduction of physics-based prior as well as the simultaneous consideration of three images significantly improves the quality of strain images. Average values for strain images of two frames versus ElastMI are: 43 versus 73 for SNR (signal to noise ratio) in simulation data, 11 versus 15 for CNR (contrast to noise ratio) in phantom data, and 5.7 versus 7.3 for CNR in patient data. In addition, the improvement of ElastMI over both utilizing two images and accumulating strains is statistically significant in the patient data, with *p*-values of respectively 0.006 and 0.012.

1. Introduction

Displacement or time delay estimation in ultrasound images is an essential step in numerous medical imaging tasks including the rapidly growing field of imaging the mechanical properties of tissue (Ophir et al., 1999; Greenleaf et al., 2003; Parker et al., 2005). In this work, we perform displacement estimation for quasi-static ultrasound elastography (Ophir et al., 1999), which involves deforming the tissue slowly with an external mechanical force and imaging the tissue during the deformation. More specifically, we focus on real-time freehand palpation elastography (Hall et al., 2003; Hiltawsky et al., 2001; Doyley et al., 2001; Yamakawa et al., 2003; Zahiri and Salcudean, 2006; Deprez et al., 2009; Goenezen et al., 2012) where the external force is applied by simply pressing the ultrasound probe against the tissue. Ease of use, real-time performance and providing invaluable elasticity images for diagnosis and guidance/monitoring of surgical operations are invaluable features of freehand palpation elastography.

A typical ultrasound frame rate is 20–60 fps. As a result, an entire series of ultrasound images are freely available during the tissue deformation. Multiple ultrasound images have been used before to obtain strain images of highly compressed tissue by accumulating the intermediate strain images (O'Donnell et al., 1994; Varghese et al., 1996; Lubinski et al., 1999) and to obtain persistently high quality strain images by performing weighted averaging of the strain images (Hiltawsky et al., 2001; Jiang et al., 2007, 2006; Chen et al., 2010; Foroughi et al., 2010). Accumulating and averaging strain images increases their signal to noise ratio (SNR) and contrast to noise ratio (CNR) (calculated according to Eq. (35)). However, these techniques are susceptible to drift, a problem with any sequential tracking system. We show that considering three images simultaneously to solve for displacement field significantly improves the quality of the elasticity images compared to sequentially accumulating them. Multiple images have also been used to obtain tissue non-linear parameters (Krouskop et al., 1998; Erkamp et al., 2004a; Oberai et al., 2009; Goenezen et al., 2012).

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* Corresponding author. Tel.: +1 5143981573.
E-mail addresses: rivaz@jhu.edu (H. Rivaz), eboctor1@jhmi.edu (E.M. Boctor), michael.choti@utsouthwestern.edu (M.A. Choti), hager@cs.jhu.edu (G.D. Hager).
URL: http://cs.jhu.edu/~rivaz/ (H. Rivaz).

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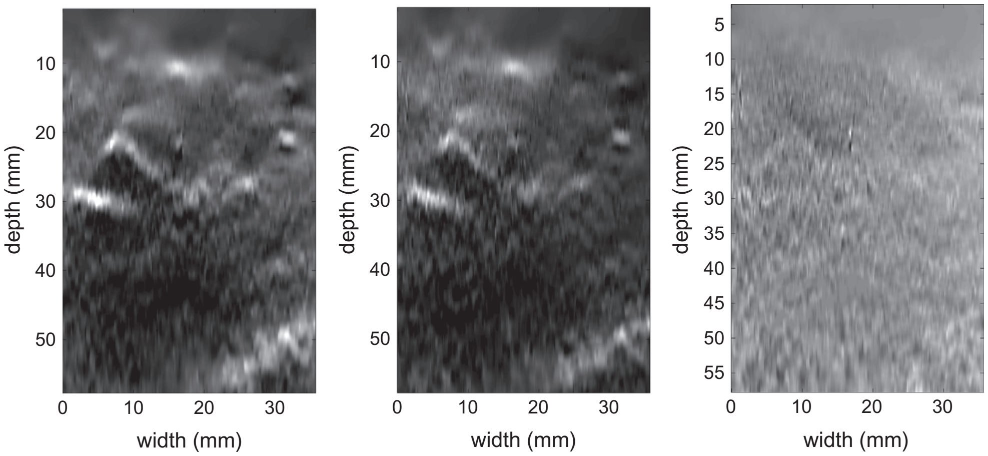

Fig. 1. Consecutive strain images are "similar" up to a scale factor. First and second (S_1 and S_2 from left) are two strain fields calculated from I_1 and I_2, and from I_2 and I_3 respectively (I_1, I_2 and I_3 not shown here). S_1 & S_2 look similar. Third image is $S_1 - \eta S_2$ for $\eta = 1.1$. The strain range in the first two images is 0–0.6%, and in the third image is $\pm 0.3\%$. Images are acquired freehand and *in vivo* during liver surgery.

Depth calculation from a trinocular-stereo system (Ayache and Lustman, 1991; Mulligan et al., 2002; Brown et al., 2003) is a similar problem where more than two images are used to increase the accuracy and robustness of the stereo system. The third image is used to introduce additional geometric constraints and to reduce the noise in the depth estimates. Unfortunately, these geometric constraints do not hold in the elastography paradigm, and therefore these methods cannot be applied to elastography.

Fig. 1 shows *two consecutive strain images* calculated from *three ultrasound images* using the 2D analytic minimization (AM) method (Rivaz et al., 2011a).[1] Our motivation is to utilize the similarity of these two images to calculate a low variance displacement field from three images. We derive physical constraints based on the mechanical properties of soft tissue, and incorporate them into a novel algorithm that we call ElastMI (Elastography using Multiple Images). ElastMI minimizes a cost function that incorporates data obtained from three images and exploits the mechanical constraints. Like Pellot-Barakat et al. (2004); Jiang and Hall (2006); Sumi (2008); Sumi and Sato (2008); Brusseau et al. (2008); Rivaz et al., 2008a, 2009, 2011a; McCormick et al. (2011), we use a regularized cost function that exploits tissue motion continuity to reduce the variance of the displacement estimates caused by ultrasound signal decorrelations. The cost function is optimized using an iterative algorithm based on expectation maximization (EM) (Moon, 1996). Compared to our previous work (Rivaz et al., 2011b), we present significantly more details and in-depth analysis of ElastMI. We also provide extensive results for validation and more analysis of the results.

To formally study the advantage of using three images, we assume ultrasound noise is additive Gaussian and prove that exploiting three images not only reduces the noise in the displacement estimation, but also eliminates false matches due to possible periodic patterns in the tissue. We assume an additive Gaussian noise model in ultrasound images for two main reasons. First, most real-time motion estimation techniques use different forms of sum of squared differences (SSD) as a similarity metric. This includes window-based methods[2] and the sample based methods of 2D AM and ElastMI. The fact that these similarity metrics have been shown to give low noise displacement estimates suggests that additive Gaussian noise model is a good approximation for the true ultrasonic noise for small deformations. Second, using the additive Gaussian noise model in ultrasound images allows us to analytically obtain the noise in the estimated displacement field as a function of the image noise for three different algorithms: AM (Rivaz et al., 2011a), ElastMI, and a third method that we propose in the AppendixA.

We use simulation, phantom and *in vivo* patient trials to validate our results. The *in vivo* patient trials that we present in this work are related to imaging liver tumors and also imaging ablation lesions generated by thermal ablation. Thermal ablation is a less invasive alternative for tumor resection where the cancer tumor is coagulated at temperatures above 60 °C. To eliminate cancer recurrence, the necrosis should cover the entire tumor in addition to some safety margin around it. Currently, both guidance and monitoring of ablation are performed under ultrasound visualization. Unfortunately, many cancer tumors in liver have similar echogenicity to normal tissue and are not discernible in ultrasound images. Regarding ablation monitoring, the hyperechoic region in the ultrasound image caused by formation of gas bubbles during ablation does not represent tissue ablation and usually disappears within 1 h of ablation (Goldberg et al., 2000). To minimize the misclassification of these hyperechoic regions with ablated lesion, ultrasound elastography has been proposed for monitoring ablation: HIFU probes (high intensity focused ultrasound) (Righetti et al., 1999), radio-frequency Cool-tip probes (Valleylab/Tyco Healthcare Group, Boulder, CO) (Fahey et al., 2006; Jiang and Varghese, 2009; Jiang et al., 2010) and radio-frequency RITA probes (Rita Medical Systems, Fremont, CA) (Varghese et al., 2003, 2004; Boctor et al., 2004; Rivaz et al., 2008b) have been investigated. Electrode vibration elastography (Bharat et al., 2008; DeWall et al., 2012a) and shear wave imaging (Arnal et al., 2011) have also been used to monitor ablation. Elastography in the presence of gas bubbles is challenging because they are a major source of noise in the ultrasound signal and degrade the quality of both B-mode and strain images.The noise associated to them is also not simply additive Gaussian and depends strongly on both the spatial location and time. We show that ElastMI generates high quality strain images in such high noise environment in three patient trials.

The contributions of this work are: (1) introducing constraints on variation of the motion fields based on similarities of strain images through *time*; (2) proposing ElastMI, an EM-based algorithm to solve for motion fields using three images; (3) formally proving that the ElastMI algorithm reduces displacement estimation variance, and further illustrating that with simulation, phantom and patient data, and (4) reporting clinical studies of ablation guidance/monitoring, with data collection corresponding

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[1] The 2D AM code is available online at www.cs.jhu.edu/~rivaz.

[2] Real-time window based methods generally use SSD, cross correlation or normalized cross correlation as the similarity metric. Under certain normality conditions, it can be shown that all of these methods are maximum likelihood estimators if the ultrasound noise model can be assumed to be additive Gaussian.