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Performance study of a new time-delay estimation algorithm in ultrasonic echo signals and ultrasound elastography

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ABSTRACT

Time-delay estimation has countless applications in ultrasound medical imaging. Previously, we proposed a new time-delay estimation algorithm, which was based on summation of the sign function to compute the time-delay estimate (Shaswary et al., 2015). We reported that the proposed algorithm performs similar to normalized cross-correlation (NCC) and sum squared differences (SSD) algorithms, even though it was significantly more computationally efficient. In this paper, we study the performance of the proposed algorithm using statistical analysis and image quality analysis in ultrasound elastography imaging. Field II simulation software was used for generation of ultrasound radio frequency (RF) echo signals for statistical analysis, and a clinical ultrasound scanner (Sonix® RP scanner, Ultrasonix Medical Corp., Richmond, BC, Canada) was used to scan a commercial ultrasound elastography tissue-mimicking phantom for image quality analysis. The statistical analysis results confirmed that, in overall, the proposed algorithm has similar performance compared to NCC and SSD algorithms. The image quality analysis results indicated that the proposed algorithm produces strain images with marginally higher signal-to-noise and contrast-to-noise ratios compared to NCC and SSD algorithms.

1. Introduction

Time-delay estimation is a commonly used signal processing task in various fields, including diagnostic ultrasound imaging. In the field of diagnostic ultrasound imaging, it has applications in areas such as tissue elasticity imaging [2–6], blood flow imaging [7–12], motion compensation for synthetic receive aperture imaging [13], phase-aberration correction [14–16], and non-invasive temperature estimation [17]. Time-delay estimation calculates the displacement between a sequence of ultrasound RF signals, where the displacement appears as time shift or phase shift. An accurate estimation of the time-delay is a key factor that determines the performance of many signal processing applications. To this end, time-delay estimation has been extensively studied and a number of methods and implementations have been reported in literature, where each offers trade-offs between accuracy, spatial resolution, and computational efficiency [18–21].

Typically, time-delay estimation between a reference and delayed echo signals is estimated in small overlapping windows. A pattern matching function is computed at each window to estimate the location where the two windows resemble each other the most. Common pattern matching functions includes correlation coefficient and squared difference. The length of the window and window overlap determines the axial resolution, which can be improved with decreasing window length or increasing window overlap [22].

The two commonly used time-delay estimation algorithms are the normalized cross-correlation (NCC) and the sum squared differences (SSD). The performance of the NCC and SSD has been extensively studied and generally, they yield optimal results in different criteria [18,19,23]. However, NCC suffers from high computational cost, which can be problematic for real-time implementations [18,19]. Many efficient implementations of the NCC and SSD have been reported in literature to reduce their high computational cost [20,24,25].

When dealing with ultrasound signals, many factors can deteriorate the performance of the time-delay estimation algorithms [18,19]. Practically, time-delay estimation is computed using discrete-time ultrasonic echo signals. When discrete-time signals are used to compute time-delay estimation the output is an integer multiple of the sampling period, which could be a potential source of error (i.e., high bias and variance) in time-delay estimation [18]. However, if the discrete-time signals are sampled beyond the Nyquist rate, then by using interpolation the time-delay estimates will be as precise and accurate as continuous-time signals. The reference and delayed signals can be interpolated before and/or after computing the pattern-matching function, as shown in Fig. 1.

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Interpolation of the signals before computing the pattern-matching function simply increases the sampling rate, which enables more accurate time-delay estimates [26]. Interpolation of the signals after computing the pattern-matching functions usually fits a predetermined type of curve or a polynomial to a number of samples points in the pattern-matching functions to describe the pattern-matching functions as if they are continuous-time functions [27]. This approach does not restrict the time-delay estimates to be an integer multiple of the sampling period. A number of interpolation techniques have been described in literature which include, but not limited to, cosine-curve fitting [28], parabolic-curve fitting [29,30], grid slope [31,32], and spline fitting [33].

In addition, the performance of the time-delay estimators are deteriorated when the finite length reference and delayed signals are contaminated by electronic and/or acoustic noises and decorrelated by physical processes [18,19]. These factors can cause two types of errors in the time-delay estimates, which are referred to as false peak and jitter errors [18,19].

In a recent publication, we proposed a new time-delay estimation algorithm, which used only the sign function to generate a zero-crossing curve (i.e., pattern-matching function) using the following equation [1]:

$$s(\tau) = \sum_{k=1}^{N} \operatorname{sign}(w_2(t_k - \tau) - w_1(t_k)) \times \operatorname{sign}(w_1'(t_k)) \qquad (1)$$

where $w_1(t)$ is the reference signal, $w_2(t)$ is the delayed signal, $w_1'(t)$ is the instantaneous time derivative of $w_1(t)$ that was computed by using the central approximation finite difference method, and whose sign is therefore the sign of $(w_1(t_{k+1}) - w_1(t_{k-1}))$, τ is the search lag (i.e., time shifting of $w_2(t)$ over $w_1(t)$ within a range), N is number of sample point within the window, and t_k is the current sample point. The location of the zero-crossing, in the zero-crossing curve, corresponds to the location where $w_1(t)$ and $w_2(t)$ are at their closest match. The location of zero-crossing also corresponds to the time-delay between them.

In this work, we compare the performance of the new-time delay estimation algorithm with other established algorithms both numerically and experimentally using statistical and image quality analysis methods in ultrasound elastography imaging.

2. Methodology

2.1. Simulation methods

A series of simulation was carried out to investigate the performance of the proposed algorithm. The performance of the proposed algorithm was investigated in terms of standard deviation of the jitter error (i.e., standard deviation of time-delay estimate error) as a function of sub-sample delay, signal-to-noise-ratio (SNR), and kernel window length. The performance of the proposed algorithm was compared with the NCC, and SSD with and without cosine curve fitting algorithms. The NCC and SSD expressions are defined as [26]:

$$\mathrm{NCC}(\tau) = \frac{\sum_{i=r}^{r+N-1} (s_1(i) \times s_2(i+\tau))}{\sqrt{\sum_{i=r}^{r+N-1} s_1^2(i) \times \sum_{i=r}^{r+N-1} s_2^2(i+\tau)}} \qquad (2)$$

$$\mathrm{SSD}(\tau) = \sum_{i=r}^{r+N-1} (s_1(i) - s_2(i+\tau))^2 \qquad (3)$$

where s_1 is the reference signal, s_2 is the shifted signal, r is the origin of the reference window, N is the length of the windows, τ is the search lag.

Field II ultrasound simulation software [34,35] was used to generate a series of ultrasound RF echo signals. Field II can accurately simulate a typical ultrasound scanner to generate RF signals. To this end, it generates RF echo signals from a collection of point scatterers, which are distributed uniformly in the region of interest and with a normal scattering strength distribution [36]. Thus, different types of B-mode images can be constructed by adjusting the scatterers spatial distribution and strength.

In order to simulate time-delay in ultrasound RF signal, first a reference signal was generated by uniformly distributing a number of scatterers within a volume and then Field II was used to construct the corresponding RF echo signal. A delayed version of the reference signal was generated by shifting the positions of the same scatterers, which was used for the generation of the reference echo signal, in the axial direction. A linear array transducer with 192 elements, utilizing 64 active elements with a Hanning apodization in transmit and receive, was simulated to scan the 160,000 scatterers within a 40 × 40 × 10 mm^3 (axial, lateral, elevation) volume. Main simulation parameters and their values that were used in Field II are listed in Table 1. The scatterers were displaced by sub-sample amount (i.e., displacement which corresponds to a fraction of the sampling period) and the displacement of the scatterers was varied from 0 to 1 samples, in increment of 0.05 samples, to generate a total of 21 sets of delayed signals. A set of 200 reference and delayed echo signal lines were generated for statistical analysis, where each line included about 5000 sample points (equivalent to 50 μs). In addition, a narrow-band noise (i.e., noise which had the same bandwidth as the signals) was added to the reference and delayed signals to generate

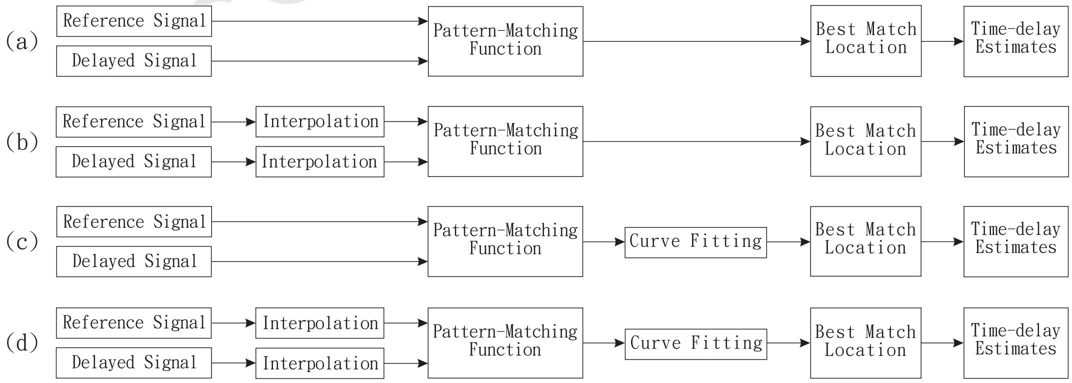

Fig. 1. Most common time-delay estimation schemes. (a) Time-delay estimation without interpolation. (b) Time-delay estimation with interpolation of the reference and delayed signals before computing a pattern-matching function. (c) Time-delay estimation with interpolation of the pattern-matching function. (d) Time-delay estimation with interpolation of the reference and delayed signals, and interpolation of the pattern-matching function. Figure adopted and modified from [26].

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