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Adaptive time-delay estimation based on normalized maximum correntropy criterion for near-field electromagnetic ranging☆

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ABSTRACT

Indoor location systems can track objects using near-field electromagnetic ranging technology (NFER). However, the ranging error can be large because the phase difference between the electronic and magnetic fields cannot be measured directly. This study proposes a method that adopts an adaptive time-delay estimation algorithm based on a normalized maximum correntropy criterion (NMCC-ATDE) instead of exploiting the phase behavior of the electromagnetic signal for near-field ranging. In the NMCC-ATDE algorithm, the input signal is normalized to mitigate any sudden increase in the input signal. As our simulation results reveal, compared to the algorithms based on maximum correntropy criterion and normalized least mean square, the NMCC-ATDE algorithm can estimate the time delay in real time with a fast convergence rate and small steady-state error.

1. Introduction

In recent years, real-time location systems are currently the subject of intensive research since they have extensive application prospects. The main purpose of a real-time location system is to provide an accurate position of a mobile object. As a favored solution for a real-time indoor location system, near-field electromagnetic ranging (NFER) technology, operating at low frequencies, can provide preferable obstacle penetration and multipath resistance [1]. This technology is inspired by some simple physics discovered a century ago. NFER implements ranging and location through the relationship between the phase behavior of the electromagnetic signal and the distance between the transmitter and receiver [2]. In general, the phase difference between the electronic and magnetic fields can be detected by a phase discriminator, which requires a priori spectrum knowledge of the objective signal and synchronization between the electronic and magnetic channels. However, synchronization over both channels is so complex that it affects the accuracy of the phase discriminator and consequently interferes with ranging accuracy. In addition, as the signal-to-noise ratio (SNR) decreases, this system becomes unusable [3]. Thus, implementing indoor near-field ranging with a phase discriminator in an actual environment is difficult.

For a low-frequency narrowband signal, the phase difference between the electronic and magnetic fields can be transformed into a time-delay issue [4], which can be solved using a parameter estimation method that has been researched

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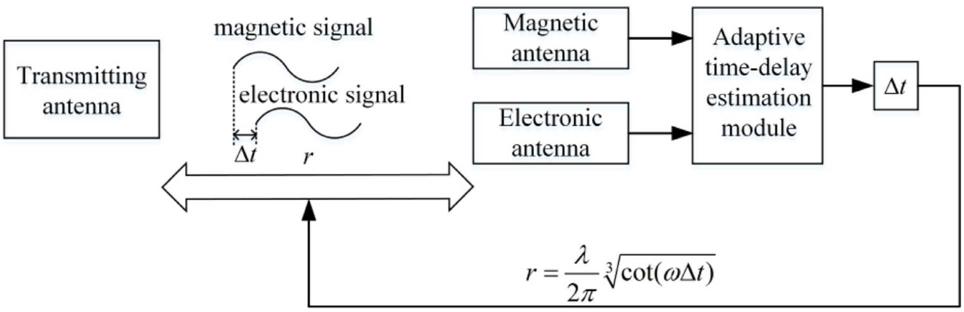

Fig. 1. System framework for near-field ranging by time delay estimation.

based on different aspects and applications [5]. However, the time delay between the electronic and magnetic components is different from the time difference of arrival (TDOA): with distance, one decreases whereas the other increases [6]. Therefore, indoor near-field electromagnetic ranging can be realized by the adaptive time-delay estimation (ATDE) between the electronic and magnetic components of low-frequency signals [7]. Generally speaking, in an adaptive filter, the mean square error (MSE) algorithm usually performs very well under the interference of Gaussian noises. However, in an indoor environment, the outliers have an impulsive characteristic with a long tail and thus no longer conform to Gaussian distribution [8]. The outliers, which mostly come from power lines, may severely interfere with the performance of radio systems [9]. For a narrowband receiving system, the impulsive noise can be modeled by symmetric α-stable (SαS) [10]. Under these non-Gaussian situations, the MSE algorithm may degrade considerably. In addition, in [11], different adaptive algorithms such as least mean fourth (LMF), least mean p-power (LMP), and the sign algorithm (SA) have been examined. In recent years, the maximum correntropy criterion (MCC) has been successfully used in robust adaptive filtering, and several gradient-based robust adaptive filtering algorithms have been developed [12,13]. As a measurement of the similarity of two random variables, correntropy is a popular cost function for training an adaptive system. The convergence performance against non-Gaussian noise has been studied in [14,15].

A sudden increase in input power can momentarily cause divergence for a gradient-based algorithm, which is catastrophic for an adaptive algorithm [16]. If the weights of an adaptive system diverge, then all past input data would be discarded and the adaptive algorithm would restart. Thus, divergence is deleterious for the convergence rate of the algorithm and affects the capability of real-time indoor ranging. The most widely used method to overcome this issue is the normalized least mean square (NLMS) algorithm, which has been proven to be immune to the fluctuations of input power [17]. By imitating the derivational process of the normalized LMS algorithm, a normalized minimum entropy error stochastic algorithm was proposed in [18]. It showed that normalizing the input signal is beneficial to improving the convergence rate.

In this study, for the purpose of indoor near-field ranging, we propose an adaptive time delay estimation algorithm based on normalized maximum correntropy criterion (NMCC-ATDE). As the cost function, correntropy is adopted to train the adaptive filter. Comparisons of the NMCC-ATDE, MCC-ATDE, and NLMS-ATDE methods were also conducted in this study. The comparisons revealed that the NMCCC-ATDE algorithm can achieve a fast convergence rate and small steady-state error, thus realizing indoor ranging in real time.

The remainder of this paper is organized as follows. Section 2 introduces the time-delay estimation model. In Section 3, we derive the time-delay estimation algorithm based on NMCC. Simulation experiments and analysis are provided in Section 4. We present a conclusion to the study in Section 5.

2. Time-delay estimation model

Fig. 1 shows the system framework, including one transmitting and two receiving antennas. In the transmitting terminal, a loop antenna is applied to transmit an electromagnetic signal. In the receiving terminal, a loop antenna is used for the magnetic component and a monopole is used for the electronic component. In the near field, the relationship between the phase difference $\Delta\phi$and the range r is given by [1,2]:

$$r = \frac{\lambda}{2\pi}\sqrt[3]{\cot(\Delta\phi)} \tag{1}$$

where λ is the wavelength of the electromagnetic wave and cot(.) denotes the cotangent function. If we replace the phase difference $\Delta\phi$ with the time delay Δt, we then obtain:

$$r = \frac{\lambda}{2\pi}\sqrt[3]{\cot(\omega\Delta t)} \tag{2}$$

where ω is the signal frequency.

Fig. 2 shows the time delay between the electronic and magnetic components within approximately half of a wavelength of a small electromagnetic antenna. The max time delay ($T_D = T_s\omega_s/4\omega$) is related to the sampling time (T_s), sampling