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SHORT COMMUNICATION

Three-dimensional-positioning based on echolocation using a simple iterative method

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ABSTRACT

This paper describes a method for determining the position of an object in three dimensions using time-of-flight (TOF) echolocation. The position is computed using a one-bit cross correlation and requires less computation time than a general cross correlation. A delta-sigma modulation board is introduced to convert the echo signal into one-bit signals. This solution uses an iterative method, i.e., Newton–Raphson, to obtain a position estimate. Additionally, an initial value for the solution is obtained by averaging TOFs, and no guess is required. Three hand-held communication devices are adapted as acoustical receivers. The validity of the proposed method is verified by the repeatability of the experimental results.

1. Introduction

Echolocation is a method for object navigation that functions by determining the time required for a reflected echo to return from an object. This system is used by bats and dolphins to detect and locate obstacles by transmitting high-pitched sound that reflect back to the animal's ears or sensory receptors. Thus, bats and dolphins can determine the distance from their position to targets around them. There are several studies on the methods that bats use [1–3]. Moreover, echolocation is exploited by many ranging measurements applications, such as radar, sonar, and acoustic systems. Acoustic systems have the advantage of a variety of acoustic transducers, small size and simple hardware. Because of these benefits, many robotics studies use acoustic echolocation for localization problems [4,5]. Additionally, ultrasonic distance measurement, which uses an acoustic system, is a relatively flexible approach for environmental recognition in robotic systems [6,7]. Ultrasonic distance measurements can be determined simply by using the time-of-flight (TOF) method, which is a measurement of the time for sound waves to travel between the sound source and the object, multiplied by the sound velocity. TOF can typically be computed by performing a cross-correlation between the transmitted and received signals [8]. As a result, TOF is a measurement of the maximum peak during a sample time.

Chirp signals are an ingenious method of handling a practical problem in ultrasonic distance measurement because they give the accuracy and resolution of TOF measurements [9]. A linear-period-modulated (LPM) signal, which is a type of chirp signal, has a period that is swept linearly with time and, is presented first [10]. This signal allows the cross-correlation function to determine the TOF via the Doppler effect [11]. Although this signal solves the problem, it requires a long computation. Therefore, to yield fast signal processing, a low-calculation-cost method for ultrasonic distance measurement is proposed using the LPM signal [12]. This goal is accomplished by using one-bit signal processing. One-bit cross correlation can reduce the number of computations compared with the general cross-correlation [9].

Ultrasonic distance measurement in one dimension has already been accomplished using one acoustical receiver [9]. In the case of a two dimensional ultrasonic measurement, a solution has been presented by exploiting acoustical microphones [6,13]. An idea for three dimensions has been proposed via a numerical method; the Newton–Raphson method [14]. This method has not been verified in real experiments, but the simulation results are encouraging. In the previous ultrasonic measurements in both one and two dimensions [9,12,13], the acoustical receiver is a very expensive microphone, which is inconvenient for three dimensions because the system requires more than one acoustical receiver. Instead, a hand held telecommunication receiver is adapted for this experiment. Thus, this paper presents an ultrasonic three-dimensional measurement using a simple algorithm to provide fast signal processing, which is accomplished via one-bit signal processing. Additionally, it uses hand held telecommunication receivers, which

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are viable for low-cost applications. The validity of the system can be confirmed by the experimental results.

2. Three-dimensional-position estimation

Based on the fundamental Cartesian coordinates, the model of an object with an unknown position in three dimensions can be arranged according to Fig. 1. We consider a three-dimensional scenario where the acoustic sensors, $\boldsymbol{m}_i = [x_i, y_i, z_i]^T$, where $i = 1, 2$, and 3, are used to determine the object position $\boldsymbol{u} = [x, y, z]^T$. The position of the sound source is set as the origin [0, 0, 0]. The relationship of the distance between the sound source, object, and receivers, can be expressed as in Eq. (1). This equation uses the TOF to be the input of the function. The three unknown variable, x, y, and z, in Eq. (1) are not available to determine in a linear form. The optimal method for solving this problem is estimation using numerical methods. This paper uses the Newton–Raphson method, which is an iterative method.

$$f_i = \sqrt{(\boldsymbol{u} - \boldsymbol{m}_i)^T(\boldsymbol{u} - \boldsymbol{m}_i)} + \sqrt{\boldsymbol{u}^T\boldsymbol{u}} - v_{\text{sound}} \cdot \text{TOF}_i = 0 \tag{1}$$

TOF_1, TOF_2, and, TOF_3 are the time-of-flight at receivers on x, y, and z axes, respectively. v_{sound} is sound propagation. The Newton–Raphson algorithm for unknown-parameters estimation, $\boldsymbol{u} = [x, y, z]^T$ can be summarized in the following steps:

Step 1: Make an initial guess for the parameter vector $\boldsymbol{u}^0$ and $k = 0$ (an upper case is iterative number).
Step 2: Model $\boldsymbol{F} = [f_1, f_2, f_3]^T$. A quadratic approximation $\boldsymbol{F}$ can be obtained using the given twice continuously differentiable object function. The Taylor series expansion plays a vital role of $\boldsymbol{F}$ approximation about the current point $\boldsymbol{u}^k$, neglecting terms of order three and higher [15]. We obtain $f_i(x^0 + \Delta x, y^0 + \Delta y, z^0 + \Delta z) \cong f_i(x^0, y^0, z^0) + \frac{\partial f_i}{\partial x}(x^1 - x^0) + \frac{\partial f_i}{\partial y}(y^1 - y^0) + \frac{\partial f_i}{\partial z}(z^1 - z^0)$. Thus, a root of f_i can be estimated by using the iteration of $\boldsymbol{u^k} = [x^k, y^k, z^k]^T$.
Step 3: Iterate the parameter vector $\boldsymbol{u}^{k+1} = \boldsymbol{u}^k - [\boldsymbol{H}(\boldsymbol{u}^k)]^{-1} \cdot \boldsymbol{F}(\boldsymbol{u}^k)$, where $\boldsymbol{H}(\boldsymbol{u}^k)$ is the Hessian matrix and

$$\boldsymbol{H}(\boldsymbol{u}^k) = \begin{bmatrix} \dfrac{\partial f_1}{\partial x} & \dfrac{\partial f_1}{\partial y} & \dfrac{\partial f_1}{\partial z} \\ \dfrac{\partial f_2}{\partial x} & \dfrac{\partial f_2}{\partial y} & \dfrac{\partial f_2}{\partial z} \\ \dfrac{\partial f_3}{\partial x} & \dfrac{\partial f_3}{\partial y} & \dfrac{\partial f_3}{\partial z} \end{bmatrix}$$

Step 4: Check convergence criterion $\left\|\boldsymbol{u}^{k+1} - \boldsymbol{u}^k\right\| <$ tolerance, then stop.
Step 5: Set $k + 1$ and go to step 2.

However, this method is iterative and has significant disadvantages, i.e., requires an initial guess [16]. Thus, the initial guess can be supplied by averaging the TOF, incident on every receiver and assuming that $\boldsymbol{u}^0 = [x_0, y_0, z_0]^T$ is the initial position of the object. When carefully considering all TOFs measured from receivers, we enable them to be used as a starting point of routines. To do so, a primary distance (d_0) is averaged by the TOFs, for obtaining only one way from the sound source to the object, and thereafter it is multiplied with sound velocity. This procedure can be expressed as Eq. (2).

$$d_0 = \frac{(\text{TOF}_1 + \text{TOF}_2 + \text{TOF}_3) \cdot v_{\text{sound}}}{2 \times 3}. \tag{2}$$

We know that this distance, which is connected to a co-ordinate x, y, and z, is

$$d_0 = \sqrt{x_0^2 + y_0^2 + z_0^2} \tag{3}$$

Next, we assume that, $x_0 = y_0 = z_0$ is a same value at the starting point. Thus, the starting point is obtained with $x_0 = y_0 = z_0 = d_0/\sqrt{3}$ relied on an averaging TOF measurement. The cross-correlation function can be defined as Eq. (4), where s_i is the received signal from the object. It is incident on microphones and converted to a digital signal by three delta-sigma modulators. On the other hand, a reference signal h, which is the original LPM signal, uses a digital comparator for conversion. Then, both one-bit signals from those devices are processed together to compute TOFs by means of the cross-correlation function. This process can be pictured in Fig. 1

$$c_i(t) = \sum_{l=0}^{N-1} h(N - l) \cdot s_i(t - l). \tag{4}$$

For Eq. (4), when N is a total sample number, the computational-time cost of the cross-correlation operation of Eq. (4) requires many numbers N of multiplications and summations of single-bit signals. The computational load can be reduced by taking a difference in the cross-correlation function. It can be defined as

$$c_i(t) - c_i(t-1) = \sum_{l=0}^{N-1} h(N-l) \cdot s_i(t-l) - \sum_{l=0}^{N-1} h(N-l) \cdot s_i(t-l-1) \tag{5}$$

and reform Eq. (5)

$$c_i(t) - c_i(t-1) = h(N) \cdot s_i(t) - h(1) \cdot s_i(t-N) + \sum_{l=1}^{N-1} (h(N-l) - h(N-l+1)) \cdot s_i(t-l). \tag{6}$$

The value of $h(1)$ and $h(N)$ are 1 and −1, respectively, because $h(l)$ is the reference LPM signal. It has many hundred zero-cross points Z_l of the same values, 1 or −1, between two zero-cross points Z_l and Z_{l+1} in $h(l)$. Thus, a term of $h(N - l) - h(N - l + 1)$ can be defined as

$$h(N-l) - h(N-l+1) = \begin{cases} 2, \ldots, N - l = \mathcal{Z}_{2m-1} \\ -2, \ldots, N - 1 = \mathcal{Z}_{2m} \\ 0, \ldots, N - 1 \neq \mathcal{Z}_l \end{cases} \tag{7}$$

where m is a natural number. The computational number of the recursive cross-correlation operation, which is performed by integrating the difference in the cross correlation, is expressed as

$$c_i(t) = c_i(t-1) - s_i(t-N) + 2s_i(t - N + \mathcal{Z}_1) - 2s_i(t - N + \mathcal{Z}_2) + 2s_i(t - N + \mathcal{Z}_3) - \cdots - s_i(t). \tag{8}$$

The calculation cost of the recursive cross-correlation operation is the integration and summations of one-bit samples. Therefore, the calculation costs are constant and independent on the sampling frequency of one-bit signal processing. The recursive cross-correlation operation of the one-bit signal thus decreases the computation costs of the cross-correlation function [9].

To improve the SNR of $c_i(t)$, a moving average filter is used as a smoothing operation and required to eliminate the high-frequency noise in $c_i(t)$. M is the length of the moving average filter.

$$c_{s,i}(t) = \sum_{l=0}^{M-1} c_i(t - l) \tag{9}$$