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A linearization-based method of simultaneous position and velocity measurement using ultrasonic waves

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ABSTRACT

This paper proposes a novel system for three dimensional – position and velocity measurements with echolocation. It is improved from the former systems, based on low computational one-bit signal processing, to have wider detectability from one and two dimensions to three dimensions with the rearrangement of the ultrasonic receiver positions. The proposed method can measure the object location from nonlinear equations without using iterative methods. This method can concurrently measure position and velocity in three dimensional spaces with one-time measurement. The sound radiation and reflection studies using echolocation are also included in this paper. The additive noise: White Gaussian Noise, Colored Gaussian Noise, General Gaussian Noise, Laplacian Noise, and Gaussian Mixture Noise, is considered for the performance study. The system consists of one sound transmitter and three receivers. These devices are simple sound packages to support low-cost applications. In addition, to satisfy the requirement for a low-computation cost, an echo is converted into a one-bit signal by a three-channel delta–sigma-modulation board. Then, FPGA is used to determine recursive cross correlation based on one-bit computation. The object location is then defined with x–y–z coordinates. The object's velocity is computed using linear-period-modulated signals. The validity and repeatability of experimental results are evaluated using statistics.

1. Introduction

An echolocation concept is a simple technique of object navigations by determining time-of-flight (TOF), which is calculated using an echo from a target. This is a remarkable ability of bats and dolphins to identify objects, that are in front of them, by transmitting a sound wave and receiving an echoed reflection by sensory receptors. Bats and dolphins can sense the distance from their own position to obstacles. Accordingly, echolocation is widely used in many ranging measurements applications, such as radar, sonar, and other acoustic systems [1–3]. Acoustic systems have the benefits of being low in cost and, small in size, and using relatively simple hardware compared to other systems; they also tend to be the most up-to-date and reliable. Robotics studies using acoustic systems for localization problems have been proposed [4,5]. The most critical problem for robot navigation is to determine the location of obstacles. The determination of an obstacle's position must be as reliable as possible to satisfy the self-localization procedure. Currently, advanced devices based on laser ranging and a vision finder must scan in a single plain, and are relatively expensive; moreover, certain targets cannot be located accurately [6]. Three dimensional range finders are also available, but their measurement procedures are time consuming [7,8]. Thus, it is not appropriate to apply laser range finders for real-time robot navigation because the laser range finders have very narrow beam when relatively compared with ultrasound when we use a laser pointer in 3D space, it needs a long-time scanning of the position identification to cover 3D space. It is too slow if used for a moving object. When considering vision systems, a primary weak point is computationally expensive methods and high cost [9]. Three-dimensional-positioning methods based on echolocation have already been proposed [10,11]; however, these research papers have simply studied the vision of bats and require significant computational time. In the case of concurrently position and velocity measurement, the ambiguity function method, which is well known in radar technology [1], is used to

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detect the stationary and moving targets in various target detection scenarios. A delay and a Doppler shift of a chirp signal are computed by means of the cross ambiguity function. A peak can be located on both the delay axis and the Doppler shift axis. However, this method requires Fourier transform of lag products and consists of huge iterations of multiplications and accumulations when relatively compared with the general cross correlation [12]. In the field of acoustic, it can play a vital role in the positioning techniques in both two and three dimensions including sound-source localization, self-localization system, sensor networks, and robot navigation, for examples. Initially, 2-D simple measurement systems composing of two microphones mounted at the left and right ears for video conference and robotics have been realized [13,14]. 3-D sound source localization systems using four microphones have been developed [15,16]. Then, a 3-D localization system for simultaneous position and velocity measurements of a moving sound source has been described using four narrow-band ultrasonic receivers [17]. In the case of sensor networks, a system enabling both 2-D position and temperature measurements by means of speed difference between light and supersonic has been proposed [18] 2-D and 3-D communication architectures for under water acoustic sensor networks have been presented to support the robustness of the sensor network to node failures [19]. A grid-based method for the location of multiple sound sources in an acoustic sensor network containing a microphone array has also been proposed [20]. In addition, an acoustic ranging system for underwater localization of robotic fish involving simple hardware: a pair of monotone buzzer and microphone has been accomplished [21]. Several research groups as above papers are examples of noteworthy studies in acoustic positioning system. However, it seems that we lack a system-based echolocation for concurrent position and velocity measurements in three dimensional spaces. Therefore, it is of interest to explore a method to use echolocation for robot navigation with both simple computation and low-cost devices.

One-bit stream signal processing is well known as a digital decoder of Super Audio CD (SACD) with Direct Stream Digital (DSD) Technology. This processing allows SACD to achieve high audio quality that is better than any other digital or analog technology [22] because quantization noise of Analog to Digital conversion (ADC) can be relatively reduced inside a signal band by delta–sigma modulation. When considering an oversampling technique, cross correlation with accuracy and resolution based on one-bit signal processing has been proposed for ultrasonic distance measurement [23]. This method can compute TOF with low computational costs using one-bit signal processing-based a linear-frequency-modulated (LFM) signal. However, the important problem of LFM signals cannot not exactly correlate with an echo of a moving object due to the Doppler effect. To solve this issue, a linear-period-modulated (LPM) signal, a period of which is linearly swept with time, has been proposed for ultrasonic systems identifying moving objects [24,25]. Although these methods can provide cross-correlation functionality to calculate the TOF from the reflected echo, they require significant computation time due to envelope-signal computations. Therefore, a low cost and high-resolution method of ultrasonic distance measurement using pulse compression with two cycles of LPM signals and Doppler-shift compensation has been presented [26].

In the case of an ultrasonic two-dimensional system relied on one-bit signal processing, a solution for position and velocity measurements using two ultrasonic receivers has also been proposed [27]. However, this system uses expensive acoustical receivers from the B&K Company, which are often used in calibration applications; this is inconvenient for the development of larger systems. Instead, to support low-cost applications, a system using a silicon MEMS microphone as an acoustical receiver, which is much cheaper than the acoustical microphone in the previous version,

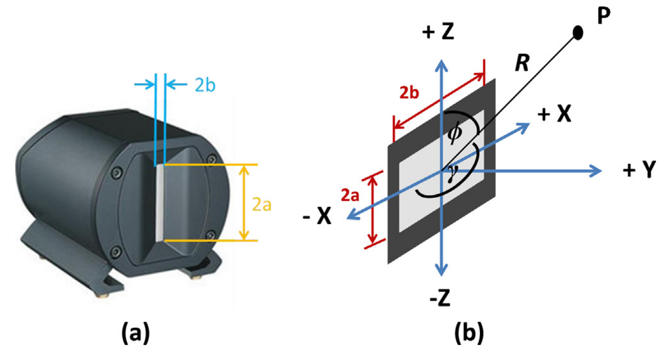

Fig. 1. Sound source used in the proposed system: (a) loudspeaker model PT-R4; and (b) radiation of a rectangular surface source.

is used in the proposed three-dimensional ultrasonic positioning system [28]. These systems can estimate an object's position as a distance from the sound source, the azimuth angle, and the elevation angle; however, they cannot measure the object's velocity. Therefore, this paper has been developed from the earlier works for a new three dimensional ultrasonic position and velocity measurement by reducing the number of the acoustical receivers and uses a general home stereo as a sound source to support low-cost application. As claimed, recursive cross correlation based on one-bit signal processing and Doppler-shift compensation is applied to achieve low computational times. The object position is calculated as x–y–z coordinates. Then, a delta–sigma modulation board and FPGA are adapted to support one-bit signal processing. The validity of the proposed system is confirmed by the repeatability of the experimental results.

2. Sound source and acoustic receiver

2.1. Sound source

In the proposed system, a home stereo is used as a sound source that radiates sound directly into the air. The loudspeaker used is a direct-radiator Pioneer PT-R4. This speaker is often used in small public address system. The principle advantage of a direct-radiator speaker is a satisfactory response across a comparatively wide frequency range. However, the primary disadvantages of this type are low efficiency, narrow directivity pattern and frequently irregular response at high frequencies. To fully describe the loudspeaker, we need to know the intensity levels it produces at all frequencies of interest. The loudspeaker used has a rectangular plane diaphragm [29], which is shown in Fig. 1(a). The sound-pressure direction of the rectangular plane surface at a point P, which is placed far from the diaphragm at a distance R in Fig. 1(b), can be expressed by the directivity index $D\varphi{,}g$ [30,31] as:

$$D_{\phi,\gamma}(\mathrm{dB}) = 10\log_{10}|p_T| \quad (1)$$

where p_T is the total sound pressure. Thus, on the Z–Y plane;

$$D_{Z-Y}(\mathrm{dB}) = 10\log_{10}\left|\frac{i\omega\rho_0 u_T}{2\pi R}4ab\,\mathrm{sinc}(ka\cos\phi)\right| \quad (2)$$

and on the X–Y plane

$$D_{X-Y}(\mathrm{dB}) = 10\log_{10}\left|\frac{i\omega\rho_0 u_T}{2\pi R}4ab\,\mathrm{sinc}(kb\cos\gamma)\right|. \quad (3)$$

Fig. 2(a) and (b) shows the directivity intensity of the loudspeaker used for a rectangular plane with a = 25 mm. and b = 3 mm. In this state, u_T is the total amplitude of small elements on the diaphragm area $4ab$, the frequency ω is 50 kHz, the density of the air ρ_0 is 1.20 kg/m^3, the amplitude of vibration on the plane is 2 μm, and the wave number k is ω/v, where the speed of sound propaga-