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Improvement of three-dimensional position and velocity measurement using a pair of linear-period-modulated ultrasonic signals

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1. Introduction

Ultrasonic system is well known for sensing in many applications. The key reason why this is relatively famous because it has many adventages of ultrasonic sensors, low cost, small size, and simple hardware. The pulse echolocation is a general idea of the distance measurements. This method is dependent on the time-of-flight (TOF) determination beetween a sound source and an obstacle.

A linear-frequency-modulated (LFM) signal, which is one of the pulse-compression technique, is given for an object detection. It has a good point for improvement of signal-to-noise ratio (SNR) from the reflect echo. In general, the frequency of LFM linearly sweeps with time. TOF can readily be computed by cross-correlation method of referent and received signal. However, the LFM signal still has a significant problem when it is considered under the moving-object case. The frequency of the LFM signal is effectively modulated due to the doppler-shift velocity. TOF is unable to directly be solved because the received signal cannot perfectly correlate with the referent signal according to the doppler affect. To accomplish this problem, a liner-period-modulated (LPM) signal is employed instead of LFM, the period of which is linear with time.

The two-demensional ultrasonic position and velocity has been proposed by using LPM signal [1]. This paper used two microphones for echo detection of a moving object under X-Y coordinate. It satisfied the experimental results. Moreover, to make the ultrasonic position and velocity system more applicable, a paper proposed such a system on the three dimensions [2]. This idea was thougth of utillizing three microphones under +X,+Y, and +Z quadrant of the object location. It is viewed only on an angle of elevation but not including on an angle of depression under +X,+Y, and –Z quadrant. This paper is to improve the vision ability to cover an object location on angles of both evaluation and depression in **Fig. 1**. It proposes using foure microphones for receiving echoes.

In additional, the key ideal of ultrasonic position system almost uses TOF cosideration by cross-correlation technique. This method consists of a huge of iterations of multiplications and accumulations. For reducing the computation cost, this paper selects to apply a method of a delta-sigma modulated signal in the form of one-bit digital signal for processing [3].

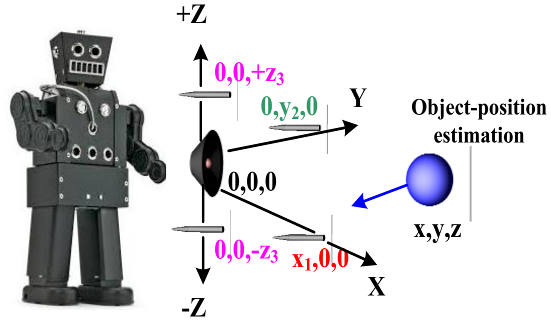

Fig.1Microphone location on each axis.

2. Object-position measurement

In **Fig. 1**, an unknown-position object can appear on both up and down sides. Firstly, the location is tested that an object is on +Z or –Z. It is easily notifiable by TOF beetween the object and microphones on those axes. If which one is quicker, that means the object on its own side. We will only use a magnitude of the microphone-location value on Z axis and do not care about sign. After that, an algorithm for the object localization uses TOFs of three michrophones on X,Y, and Z. Based on the Cartesian coordinate fundamental, the mathematical equation, which directly relates on the object, sound source, and microphone positions, can be expressed in equation (1) – (4).

$$f_1 = \sqrt{(x^2 + y^2 + z^2} - D = 0 \quad (1)$$

$$f_2 = \sqrt{(x - x_1)^2 + y^2 + z^2} + D - c.TOF_X = 0 \quad (2)$$

$$f_3 = \sqrt{x^2 + (y - y_2)^2 + z^2} + D - c.TOF_Y = 0 \quad (3)$$

$$f_4 = \sqrt{x^2 + y^2 + (z - z_3)^2} + D - c.TOF_Z = 0 \quad (4)$$

Where D is a distance during a sound source and an object and TOF_X, TOF_Y, and TOF_Z are Time-of-Flight at receivers on X, Y, and Z axes.

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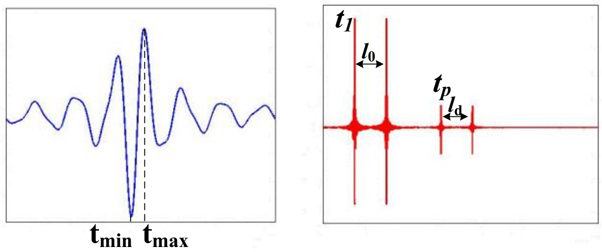

Fig.2 Doppler shift Time of Flight compensation.

Newton-Raphson algorithm for unknown parameter estimation $\Theta = [x\ y\ z\ D]^T$ can be summarized in the following computational steps.

Step 1. Make initial values for the parameter vector $\Theta^{(0)}$ and $k = 0$ (iteration number).

Step 2. Compute the gradients $H(\Theta^{(k)})$ and the model $F(\Theta^{(k)}) = [f_1\ f_2\ f_3\ f_4]^T$.

Step 3. Iterate the parameter vector:

$$\Theta^{(k+1)} = \Theta^{(k)} - [H(\Theta^{(k)})]^{-1}.F(\Theta^{(k)})$$

Step 4. Check convergence criterion.

If $\|\Theta^{(k+1)} - \Theta^{(k)}\| <$ tolerance, then stop.

Step 5. Set $k \longrightarrow k+1$ and go to Step 2.

It can be noted that the results from estimation are only positive but since, in the first step, the object position is set up on + Z or − Z sides, thus it, especially on z result, must response to that one.

2. Object-velocity measurement

In previous chapter, TOF is obtained to calculate the object position. This variable is directly computed by means of the cross correlation between the reflected echoes and referent signal. However, in the case of the moving object, TOF is shifted due to the Doppler affect between $\mathbf{t_{max}}$ and $\mathbf{t_{min}}$ in **Fig.2**. A method, proposed in [4], has been proposed to achieve compensation. Doppler velocity is dependent on the echo length because when LPM signal is reflected from a moving object, its own length is changed according to velocity. Therefore, Doppler velocity (vd) incident on each microphone can be known by measuring the interval echo length (l_d).

As for object-velocity measurement, Suppose that the object-velocity vector is an unknown vector $U = [u_x\ u_y\ u_z]^T$ and the receiver vectors, which are the direction of moving object to microphone position, are $V = [v_x\ v_y\ v_z]^T$. Then, the relative velocity on each axis is $V_d = [v_{dx}\ v_{dy}\ v_{dz}]^T$. This is equivalent to the vector projection between the vector U onto the unit vector of the

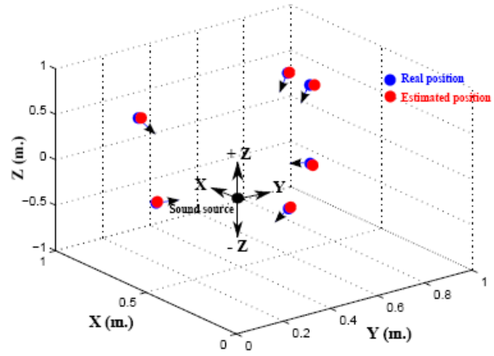

Fig.3 Simulation results.

vector V. When already measuring the Doppler velocity V_d, we can readily express the object - velocity vector as:

$$U = V_d \cdot \left(\frac{V}{|V|} \right)^{-1} \tag{5}$$

3. Simulation and results

This system is evaluated by MATLAB. For environment setup, the period of LPM signal was linearly swept from 20 μs to 50 μs, and the signal length was equal to 6.548 ms. Propagation velocity of ultrasonic wave was 331.5 m/s. Signal-to-noise ratio was 0 dB, and attenuation factor was 0.1 times degraded from amplitude of the original signal. In this simulation, we used delta-sigma modulator for one-bit signal processing. Oversampling frequency was 50 MHz. The distance from a speaker to each microphone was 10 cm. Results at various positions are pictured in **Fig. 3**.

4. Conclusion

This paper is to present the improvement of the object localization on three-dimension space to satisfy up and down sides of Z direction. The fourth microphone was added up on − Z axis. Moreover, Newton-Raphson and vector concept was used for object-location and velocity estimation, respectively. Simulation results can confirm accuracy.

References

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