An accurate distance measurement by calibration of doppler-shift for ultrasonic sonar sensing

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Ultrasonic distance measurement with the pulse-echo method is based on the determination of the time of flight (TOF) of ultrasonic waves. The pulse-compression technique, which involves the calculation of the cross-correlation operation between the transmitted and the reflected waves, is the conventional method for improving the resolution of the measurement. However, the calculation of a cross-correlation operation requires high-cost digital signal processing; furthermore, the distance of the moving objects cannot be accurately measured by the pulse compression.

This paper presents a low-calculation-cost method for the measurement for the moving objects using a linear-period-modulated (hyperbolic-frequency-modulated) signal. The proposed method consists of three parts: a recursive cross-correlation operation of single-bit signals, a smoothing operation accomplished by a moving average filter, and a Doppler-velocity-estimation operation by measurement of the length of the received signal. The Doppler-shifted TOF and the Doppler-shifted length of the received signal are determined from the cross-correlation function. Estimated Doppler velocity is used to calibrate the Doppler-shifted TOF, thus effectively improving the accuracy of the distance of the moving objects.

1 Introduction

Autonomous mobile robots require many kinds and relatively large numbers of sensors to measure the distance and the relative velocity of obstacles for environment recognition. Furthermore, the signal processing of each sensor requires enabling real-time environment recognition with high resolution, in spite of the limited computational ability for the sensor signal processing. Distance measurement using ultrasonic waves is widely used in industrial applications to measure the distance of objects, because ultrasonic waves can easily reflect from structures. The advantages of ultrasonic sensors include their low-purchase cost, small size, and simple hardware. Therefore, ultrasonic distance measurement has been used for environment recognition in autonomous mobile robots[1, 2, 3].

The method of ultrasonic distance measurement is based on the pulse-echo method, which determines the TOF of reflected waves. The distance of the object is calculated from the product of the TOF and the acoustic velocity. For effective improvement of the resolution of the pulse-echo method, the pulse-compression technique has been employed[4]. A linear-frequency-modulated (LFM) signal, which is an ultrasonic pulse, is transmitted in the typical pulse compression. The typical signal processing method for the pulse compression is a cross-correlation operation of a received signal that includes reflected waves and a reference signal, which is the transmitted wave. The TOF is determined from the time of the peak of cross-correlation function. Cross-correlation operations, consisting of huge iterations of multiplications and accumulations, require high-cost digital signal processing. Therefore, real-time distance measurement by the pulse compression is difficult given the computational ability of autonomous mobile robots. For reducing the calculation cost of the pulse compression, a sensor signal processing method using a delta-sigma modulated single-bit digital signal has been proposed[5]. Cross-correlation by single-bit signal processing of the proposed method reduces the calculation cost of digital signal processing.

When an object is moving, due to the Doppler effect introduced by the motion of the object, the received signal is Doppler-shifted. The Doppler-shift of the received signal is linear compression or expansion of the period of the signal in proportion to the Doppler velocity of the object. The Doppler-shifted received signal cannot be correlated with the reference signal, which is the LFM signal. Therefore, determination of the TOF is difficult with high resolution, and the distance of the moving object cannot be accurately measured by the proposed method. In this paper, a low-calculation-cost method for ultrasonic distance measurement of the moving object is proposed. A Doppler-shifted LPM signal can be correlated with a transmitted LPM signal[6, 7]. Therefore, when two linear-period-modulated (LPM) signals are continuously transmitted, the cross-correlation function has two peaks by the two LPF signals. The Doppler-shifted TOF is determined from the time of the first peak of the cross-correlation function. Furthermore, the Doppler velocity is estimated by the interval of the two peaks of the cross-correlation function. The estimated Doppler velocity is used to calibrate the Doppler-shifted TOF, thus effectively improving the accuracy of the distance of the moving object. The accuracy of Doppler velocity estimation was examined by computer simulation.

2 Cross-correlation by single-bit signal processing

The sensor signal processing of cross-correlation by single-bit signal processing consists of a recursive cross-correlation operation of single-bit signals and a smoothing operation accomplished by a moving average filter, as illustrated in Fig. 1. In the cross-correlation by single-bit signal processing, a transmitted wave, which is an LFM signal, is converted into a single-bit signal $h_1(i)$ by a digital comparator as the reference signal, and a received signal is converted into a single-bit signal $x_1(t)$ by a delta-sigma modulator. The cross-correlation function $C_1(t)$ is expressed as

$$C_1(t) = \frac{\pi}{4} \cdot \frac{1}{N} \Sigma_{i=0}^{N-1} h_1(N-i) \cdot x_1(t-i). \qquad (1)$$
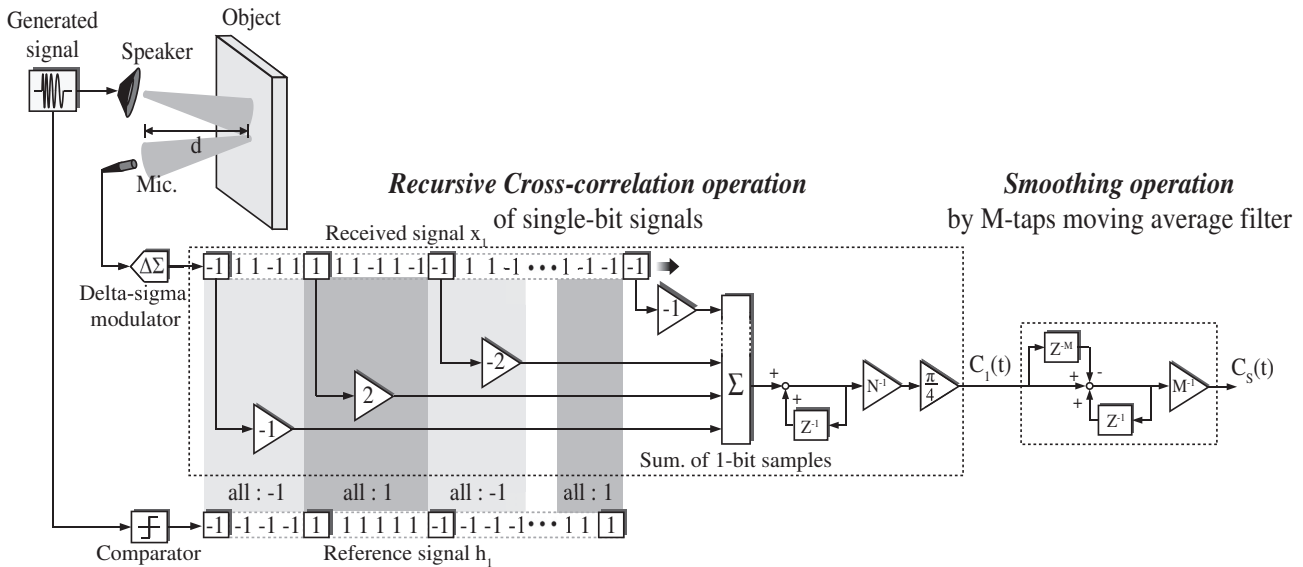
Figure 1: Design of the cross-correlation by single-bit signal processing, consisting of a recursive cross-correlation operation and a smoothing operation.

The calculation of the recursive cross-correlation operation of single-bit signals is performed by integrating the difference of the cross-correlation function. The difference of the cross-correlation function, $C_1(t) - C_1(t-1)$, is expressed as

$$C_1(t) - C_1(t-1) = \frac{\pi}{4} \cdot \frac{1}{N} \Sigma_{i=0}^{N-1} h_1(N-i)$$
$$\cdot \{x_1(t-i) - x_1(t-i-1)\}. \qquad (2)$$

$$C_1(t) - C_1(t-1) = \frac{\pi}{4} \cdot \frac{1}{N} [x_1(t) \cdot h_1(N)$$
$$+ x_1(t-N) \cdot h_1(1)$$
$$+ \Sigma_{i=1}^{N-1} \{h_1(N-i) - h_1(N-i+1)\}$$
$$\cdot x_1(t-i)] \qquad (3)$$

Equation (3) is a transformation of Eq. (2). The calculation of the recursive cross-correlation operation is also performed by integrating the difference of the cross-correlation function of Eq. (3). The reference signal $h_1(i)$ has several zero-cross points Z_k, and the same values, 1 or –1, exist between two zero-cross points. The difference of the reference signal, $h_1(N-i) - h_1(N-i+1)$, is expressed as

$$h_1(N-i) - h_1(N-i+1)$$
$$= \begin{cases} 2, -2 & \cdots & N-i = Z_k \\ 0 & \cdots & N-i \neq Z_k \end{cases}. \qquad (4)$$

The calculation cost of the recursive cross-correlation operation, integration and several hundred summations of single-bit samples, is constant and independent of the sampling frequency of the delta-sigma modulator. Therefore, the recursive cross-correlation operation reduces the calculation cost of digital signal processing compared with the cross-correlation operation of Eq. (1).

The received signal, which is a delta-sigma modulated single-bit signal, contains a quantized noise in a high-frequency band. The high-frequency noise decreases the accuracy of the cross-correlation function $C_1(t)$. To improve the accuracy of the cross-correlation function, a smoothing operation by a moving average filter, which is LPF, is required to cancel the high-frequency noise. The cross-correlation function $C_S(t)$ smoothed by moving average filter is expressed as

$$C_S(t) = \frac{1}{M} \Sigma_{i=0}^{M-1} C_1(t-i). \qquad (5)$$

3 Linear-period-modulated signal

3.1 Linear-period modulation

An LFM signal can be written as

$$u_F(t) = a \sin \left\{ 2\pi \cdot \left(f_0 + \frac{f_b}{2l} \cdot t \right) \cdot t \right\}, \qquad (6)$$

where a is the amplitude, l is the length, f_0 is the initial frequency, and f_b is the chirp rate of the frequency of the LFM signal. And an LPM signal can be written as

$$u_P(t) = a \sin \left\{ 2\pi \frac{l}{p_b} \ln \left(t + \frac{l}{p_b} p_0 \right) + \phi_0 \right\}, \qquad (7)$$

where a is the amplitude, l is the length, p_0 is the initial period, and p_b is the chirp rate of the period of the LPM signal. The frequency of the LFM signal linearly chirps with time, whereas the period of the LPM signal linearly chirps with time. The period of the Doppler-shifted signal is linearly compressed or expanded in proportion to Doppler velocity. Therefore, the received LPM signal, which is Doppler-shifted, can be correlated with the transmitted LPM signal, and the LPM signal is thus suitable for the cross-correlation of Doppler-shifted signals.
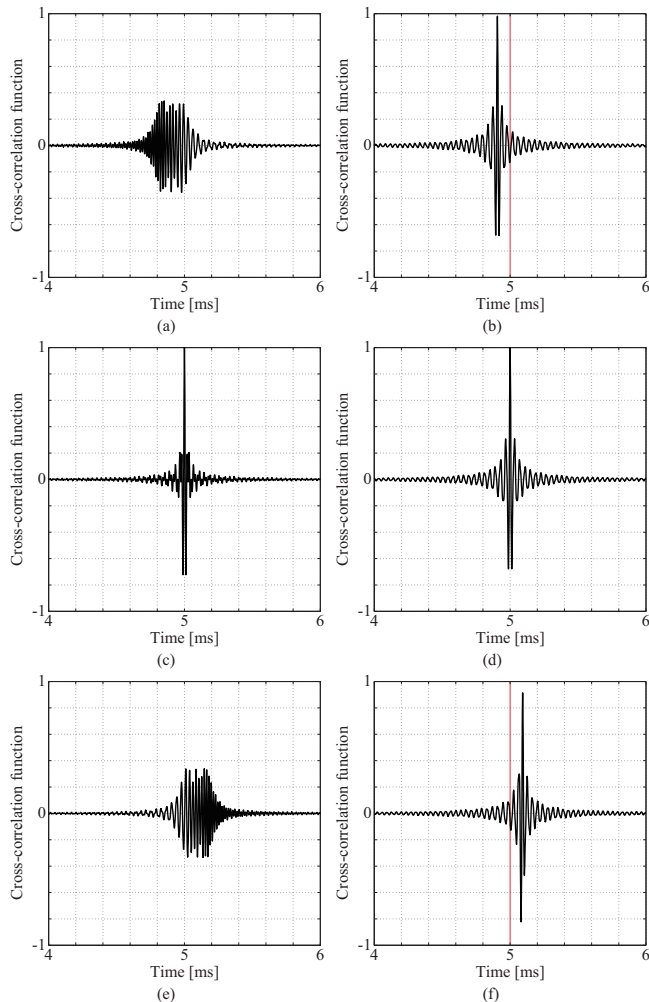
Figure 2: The influence of Doppler-shift on the cross-correlation. (a), (c), (e): the cross-correlation function of the Doppler-shifted LFM signal; (b), (d), (f): the cross-correlation function of the Doppler-shifted LPM signal; The Doppler velocity is -10 m/s for (a), (b), 0 m/s for (c), (d), 10 m/s for (e), (f).

3.2 Cross-correlation of Doppler-shifted signals

To show the influence of the Doppler effect on the cross-correlation, the cross-correlation functions of Doppler-shifted LFM and LPM signals were evaluated by a computer simulation using MATLAB. In the simulation, the transmitted signals were an LFM signal and an LPM signal from 65 kHz down to 25 kHz, and the duration of either signal was 5 ms. The acoustic velocity is 344 m/s at approximately 20 degrees C. The sampling frequency of the delta-sigma modulator was 12.5 MHz; hence, the calculation cost of the recursive cross-correlation operation was integration and 451 (the number of zero-cross points of the LFM signal) or 390 (the number of zero-cross points of the LPM signal) summations of single-bit samples. The length of the moving average filter for the smoothing operation was 51 taps.

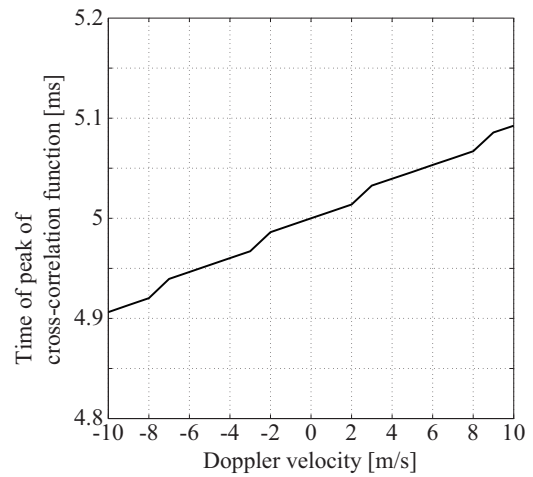Figure 2 shows the cross-correlation functions of the

Figure 3: The time at the peak of the cross-correlation function of the Doppler-shifted LPM signal.

Doppler-shifted LFM and LPM signals. The abscissa of Fig. 2 is the time, and the ordinate of Fig. 2 is the cross-correlation function normalized by an autocorrelation function. The Doppler-shifted LFM signal cannot be correlated with the transmitted LFM signal. It is difficult to determine the TOFs of the received signal by the cross-correlation functions of (a), (e) in Fig. 2. The Doppler-shifted LPM signal can be correlated with the transmitted LPM signal. The cross-correlation functions of (b), (f) in Fig. 2 have peaks, and thus the TOF of the received signal can be determined in these cases. However, the time of the peaks of the cross-correlation functions of (b), (f) in Fig. 2 are different from 5 ms, the time of the peak of the cross-correlation function of (d) in Fig. 2. The Doppler-shift of the TOF is proportional to Doppler velocity of the object, as illustrated in Fig. 3. The abscissa of Fig. 3 is the Doppler velocity, and the ordinate of Fig. 3 is the time at the peak of the cross-correlation function of the Doppler-shifted LPM signal.

4 Doppler velocity estimation

Doppler velocity estimation is required to calibrate the Doppler-shifted TOF of Fig. 3. However, Doppler velocity estimation for autonomous mobile robots must be processed with low calculation cost. When the object is moving at relatively velocity v_d, and the acoustic velocity is v, the Doppler velocity $\frac{v}{v+vd}$ can be typically estimated from the Doppler-shifted frequency of the received signal. Like the frequency, the period and the length of the received signal are also Doppler-shifted.

Figure 4 shows a method of Doppler velocity estimation by transmitting two continuous LPM signals. When two LPM signals are continuously transmitted, the cross-correlation function of two continuous LPM signals and an LPM signal has two peaks, as illustrated in Fig. 4. The interval of the first peak and second
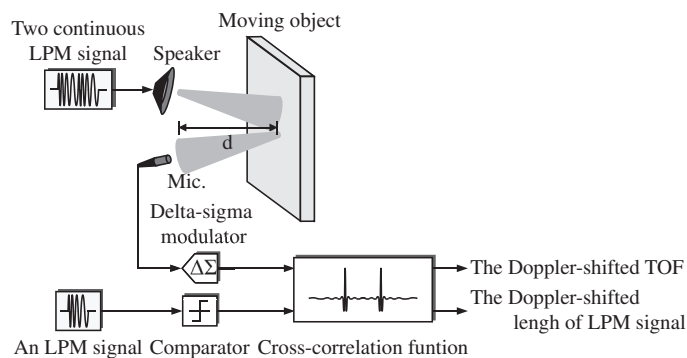
Figure 4: Design of the proposed method of Doppler velocity estimation by transmitting two continuous LPM signals.

peak of the cross-correlation function shows the length of the LPM signal. Therefore, by measurement of the two peaks of the cross-correlation function, the Doppler-shifted length of the LPM signal can be measured from the interval of two peaks. The proposed method for Doppler velocity estimation, the cross-correlation by single-bit signal processing, can measure the time with high resolution. Furthermore, the proposed method does not require any calculation cost beyond that of distance measurement.

For Doppler velocity estimation, the cross-correlation function of Doppler-shifted LPM signals was evaluated by a computer simulation using MATLAB. In the simulation, the reference signal was an LPM signal from 65 kHz down to 25 kHz, and the duration of the signal was 5 ms; hence, the transmitted signal was two continuous LPM signals, and the duration of the signals was 10 ms. The acoustic velocity is 344 m/s at approximately 20 degrees C. The sampling frequency of the delta-sigma modulator was 12.5 MHz; hence, the calculation cost of the recursive cross-correlation was integration and 390 summations of single-bit samples. The length of the moving average filter for the smoothing operation was 51 taps.

Figure 5 shows the two peaks of the cross-correlation functions of two continuous LPM signals, which are Doppler-shifted. The abscissa of Fig. 5 is the time, and the ordinate of Fig. 5 is the cross-correlation function normalized by an autocorrelation function. The intervals of the first peaks and the second peaks of the cross-correlation functions of Fig. 5 are the Doppler-shifted lengths of the LPM signal in proportion to the Doppler velocity.

The lengths of the LPM signal and their errors measured from the interval of the two peaks of the cross-correlation functions are illustrated in (a) of Fig. 6. The Doppler velocities and their errors estimated from the lengths of the LPM signal are illustrated in (b) of Fig. 6. The errors of the lengths are smaller than twice the minimum time resolution of 0.08 μs, when the sam-
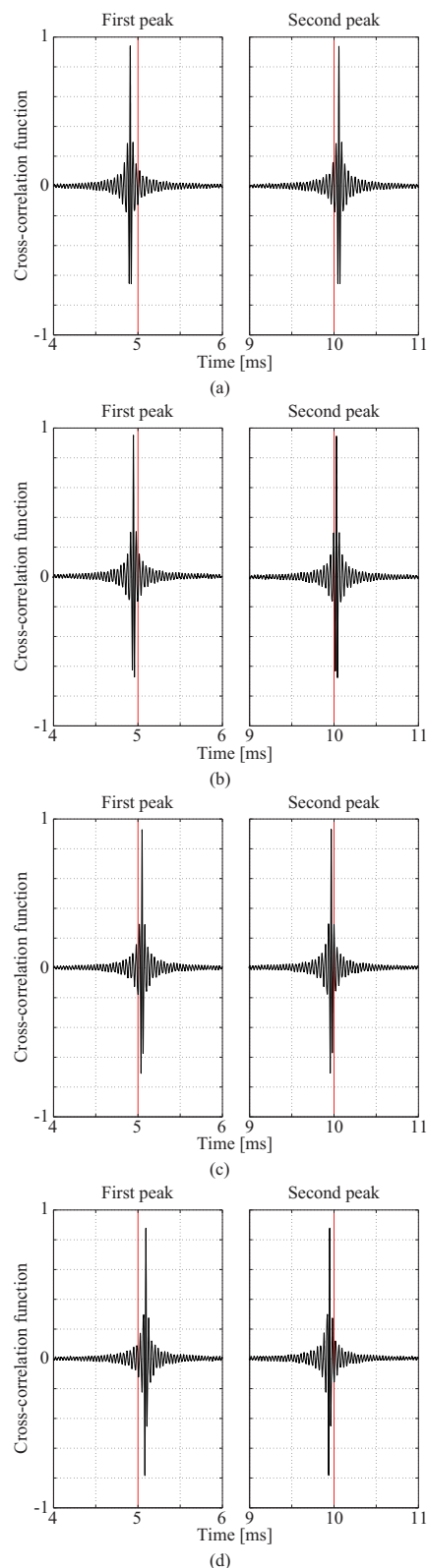

Figure 5: Two peaks of the cross-correlation function of the Doppler-shifted LPM signal. The Doppler velocity is -10 m/s for (a), -5 m/s for (b), 5 m/s for (c), 10 m/s for (d).

pling period of the delta-sigma modulator is 12.5 MHz. To calibrate the Doppler-shifted TOFs of Fig. 3 by the Doppler velocities of Fig. 6, the distance of the moving object is accurately measured.
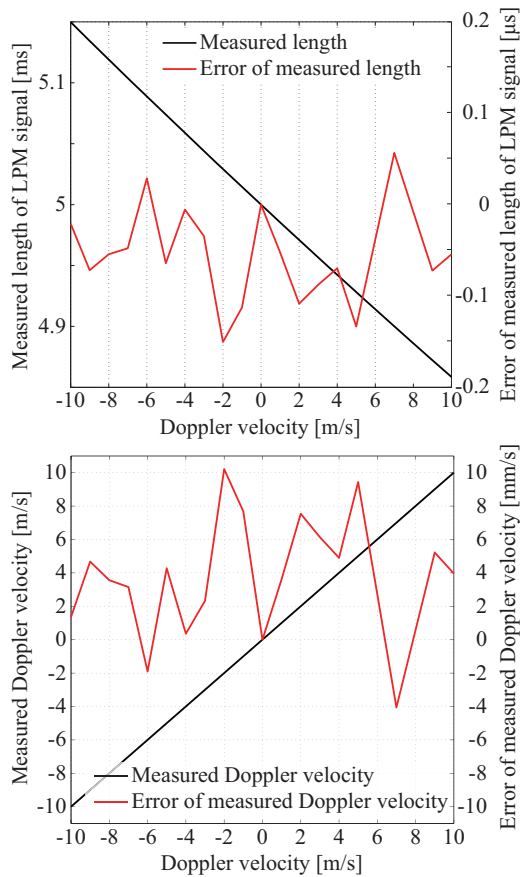
Figure 6: The intervals and their errors measured from the two peaks of the cross-correlation functions of the Doppler-shifted LPM signals (a), the Doppler velocities and their errors estimated from the intervals (b).

5 Conclusion

A low-calculation-cost method for ultrasonic distance measurement of moving objects, transmitting two continuous LPM signals, is proposed. The sensor signal processing consists of a recursive cross-correlation operation of single-bit samples, a smoothing operation accomplished by a moving average filter, and an estimation operation of the Doppler velocity. The proposed method, which is Doppler velocity estimation from the intervals of two continuous LPM signals, can measure the Doppler-shifted TOF and estimate the Doppler velocity of the object with high resolution, and does not require additional calculation cost beyond the pulse compression. By calibrating the Doppler-shifted TOF with the Doppler velocity, the distance of the moving object can be accurately measured.

Acknowledgments

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