Target Speed Sensing Technique using Dilation Correlation of Ultrasonic Signal for Vehicle

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***Abstract*—Direct measurement of the target speed ahead of the vehicle helps control the vehicle in many ways. Ultrasonic sensing is mostly used for distance measurement and differentiation is used for obtaining speed information. In most cases, the distance value differential is accompanied by a large speed error. This paper proposes direct target speed measurement in time domain, using the dilation correlation and the Doppler effect. Using the binarized ultrasonic signal in the correlation, it is possible to calculate the target speed even at a low sampling rate of 100 kHz, and the memory and computational load required for signal processing is low. Experimental results using two vehicles show acceptable RMS errors of 1.81 km/h that can be used for vehicle control, and have a better RMS error than the method of calculating the speed by differentiating the distance values obtained by the ultrasonic time-of-flight method.**

***Index Terms*—Vehicle control, ultrasonic sensor, target speed measurement, single-bit signal processing, the dilation correlation, Doppler effect, chaotic pulse position modulation, signal processing.**

I. Introduction

For vehicle control, there are a lot of cases where a target speed value as well as a target distance value is required. RADAR measures target velocity individually and simultaneously with distance, so it has a great advantage and is being used in vehicles much [1], [2]. When an ultrasonic sensor is used, the target speed value is generally obtained by measuring the distance and differentiating it. However, the differential process is not always desirable because it usually produces a large error. In the case of direct speed measurement using an ultrasonic sensor, the relative speed is calculated through frequency analysis using the Doppler effect, which requires a relatively high sampling frequency or requires a special electronic circuit. This paper proposes a method that can calculate target speed at low sampling rate using ultrasonic sensor.

Dilation may occur on the time-series ultrasonic signal due to the Doppler effect. When the ultrasonic sensor and the target are getting farther, the received signal will be stretched than the original signal and vice versa. The stretching of the signal on the time axis is called dilation of the signal. As time delay can be detected with cross-correlation function, the dilation can be detected as a dilation correlation function, which was introduces by M. Belmont [3]. The dilation correlation quantifies stretching or contraction between functions.

The proposed target speed measurement method can be used for various arrays. However, chaotic pulse position modulation (CPPM) method is used for ultrasonic pulse generation to exploit many advantages of CPPM in ultrasonic sensing. The CPPM method has been developed in the field of communication, which has the advantage that it can improve communication privacy even when there is a large amount of ambient noise [4]. The improved communication privacy of the CPPM method can be applied to improve the crosstalk problem of ultrasonic sensors. Crosstalk of an ultrasonic sensor is a phenomenon in which an undesired ultrasonic signal is received in an environment with a plurality of ultrasonic transmitters and receivers. The crosstalk problem is one of the biggest problems in vehicular ultrasonic sensing area. In many cases, when the vehicle is running, crosstalk ultrasonic signals from other vehicles are superimposed. Some pulse position modulation (PPM) based noncrosstalk sonar systems has been studied to solve the crosstalk problem [5]–[8].

After ultrasonic pulses are transmitted by the CPPM method, the dilation of the received signal is obtained by dilation correlation, and the target speed is calculated by using the Doppler effect. The two analog signals from the transmitter and receiver transducers can be used to correlation. However, to reduce the memory and computational complexity, analog signals are binarized into digital signals and subsampled to reduce the size and amount, as in [8]. Although the speed measurement resolution reduces due to binarization, but still desired resolution can be obtained.

II. Time Dilation Correlation

The speed of sound is usually considered to be fast, but if the vehicle speed is fast enough, the sound wave may be distorted by the Doppler effect. In the case of an analog ultrasonic signal, the frequency and the wavelength are deformed by the relative speed. In the case of a digital single bit signal, the interpulse interval of the digital pulse sequence is changed. In the situation of the sensor and the target are getting closer, the interpulse interval becomes smaller than that of the signal sent, and the entire signal is compressed.

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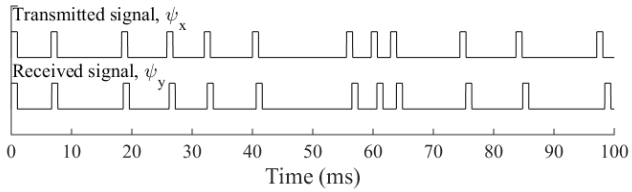


Fig. 1. The time dilation of ultrasonic single-bit signal.

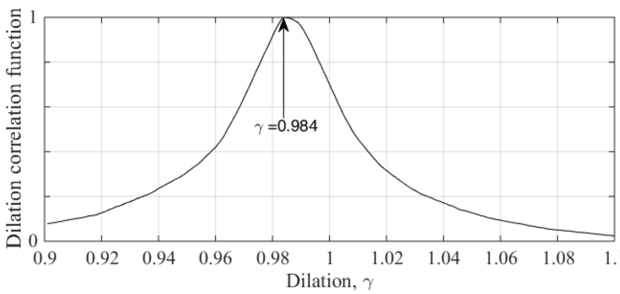


Fig. 2. Time dilation correlation result.

Fig. 1 shows the transmission reference signal for ultrasonic pulse generation and its echo signal. When the distance between the sensor and the target is gradually getting farther away, the echo signal expands in the time domain than the transmitted signal. Let T be the time from the first pulse to the last pulse of the transmitted signal and T' for the received signal. Defining a variable, time dilation γ, we can define the following relationship:

$$\gamma T' = T \tag{1}$$

Cross-correlation, a well-known signal analysis method, is usually the analysis of the convolution product of two signals, giving a delay.

$$C_{xy}(\tau) = \int_{-\infty}^{\infty} \psi_x^*(t)\psi_y(t+\tau)dt \tag{2}$$

where ψ_x^* means complex conjugate of ψ_x

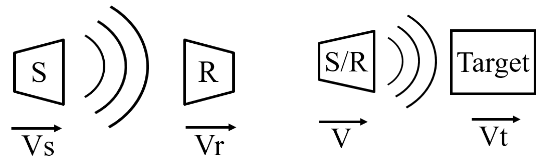
Time dilation correlation is defined as time-compressing a signal and analyzing the convolution product of the two signals [3].

$$D_{xy}(\gamma) = \int_{-\infty}^{\infty} \psi_x(t)\psi_y(\gamma t)dt \tag{3}$$

As shown in Fig. 1, the received signal is time-dilated. The time dilation coefficient γ should be less than 1, so that the length of the received signal becomes the same as the transmitted signal. The dilation correlation is shown in Fig. 2. The peak indicates a value of 0.984, which is smaller than 1, and which is the value of the time dilation coefficient γ of the received signal.

III. Doppler Effect

The situation studied in this paper differs from the general case of the Doppler effect. Fig. 3 (a) shows the situation for a commonly known Doppler effect. The source generating the



(a) General case. (b) Special case.

Fig. 3. Situations where the Doppler effect may occur. S and R represent the sound source and receiver, respectively.

ultrasound wave is labeled S and the sound receiver is labeled R. The source and receiver are separated from each other and have speeds of V_s and V_r, respectively. The situation that arises in this study is Fig. 3 (b). The sound source and receiver are identical and analyze the echo. The speeds of the sensor user and the target are V and V_t, respectively. Because of this difference, the frequency and wavelength of the received sound waves are expressed differently in the two situations. Equation (4) is for a general situation of Fig. 3 (a), and the measurement conditions in this study are shown in Fig. 3 (b), and (5) is applied.

$$\begin{aligned} f_r &= \frac{C - V_r}{C - V_s} f \\ T_r &= \frac{C - V_s}{C - V_r} T_s \end{aligned} \tag{4}$$

where f and T are frequency and wavelength of transmitted sound, f_r and T_r are frequency and wavelength of received sound and C is the speed of sound.

$$\begin{aligned} f' &= \frac{(C+V)(C-V_t)}{(C-V)(C+V_t)} f \\ T' &= \frac{(C-V)(C+V_t)}{(C+V)(C-V_t)} T \end{aligned} \tag{5}$$

where f and T are frequency and wavelength of transmitted sound as in (4), f' and T' are frequency and wavelength of received sound.

Equation (1) and (5) can be summarized as follows.

$$\gamma = \frac{T}{T'} = \frac{(C+V)(C-V_t)}{(C-V)(C+V_t)} \tag{6}$$

Our goal is to find the target speed V_t when we know C, V and γ. For V_t, (6) becomes:

$$V_t = \frac{C(1-\gamma) + V(1+\gamma)}{C(1+\gamma) + V(1-\gamma)} C \tag{7}$$

The second term of the denominator can be approximated to zero because it is very small compared to the first term of the denominator. In short,

$$V_t = V + \frac{1-\gamma}{1+\gamma} C \tag{8a}$$

$$V_r = V_t - V = \frac{1-\gamma}{1+\gamma} C \tag{8b}$$

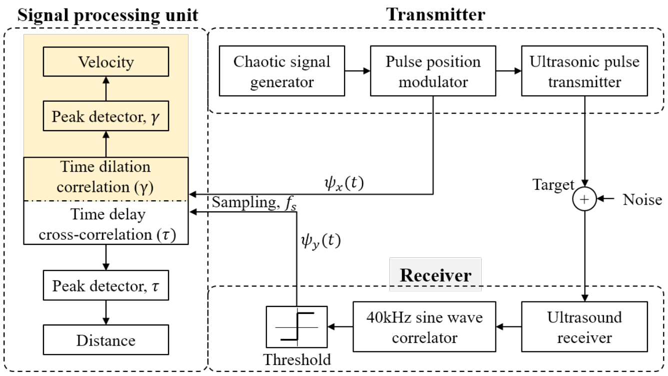


Fig. 4. The block diagram of the proposed measurement system. The highlighted part is the dilation correlation and target speed measurement part.

Sensor user's speed V is separated, and the target speed or relative speed can be calculated immediately by calculating the time dilation γ through the time dilation correlation.

IV. Experimentation

A. Signal Processing

Fig. 4 shows the target speed measurement signal processing, and Fig. 5 shows the signal graphs at each part in the transmitter and receiver.

At the transmitter, Chua's circuit [9], the well-known and the simplest chaotic signal generator provides a chaotic signal. The chaotic signal is input to the pulse position modulator (PPM) to generate a CPPM reference signal: Fig. 5 (a), for ultrasonic pulse transmission [5], [8].

The ultrasound receiver collects echoes that are returned to the target: Fig. 5 (c). Though thresholds can be applied to the collected analog signals to convert them to digital signals, a threshold is applied to the 40 kHz component of the FFT to further enhance noise rejection. The threshold is determined experimentally and is set slightly higher than the road noise collected during driving at 90 km/h. Fig. 5 (d) shows the FFT 40 kHz components and Fig. 5 (e) shows its binary digital signal.

Both binary signals ψ_x and ψ_y were sampled at a sampling rate of 100 kHz. The sampling rate of 100 kHz has a target speed resolution of 0.062 km/h, which is sufficient for vehicle control applications. If the sampling rate is 10 kHz, the speed resolution would be 0.62 km/h. After sampling the binary signals, the dilation correlation was performed. As can be seen in Fig. 2, the peak position can be considered as the time dilation γ of the echo signal, due to the Doppler effect. Once the time dilation γ is obtained, the target speed or relative speed can be calculated according to (8a, 8b).

B. Measurement System

Fig. 6 shows a diagram of the hardware system. It contains an ultrasonic transmitter, an ultrasonic receiver, a signal conditioner and a microcontroller. Both the transmitter and the

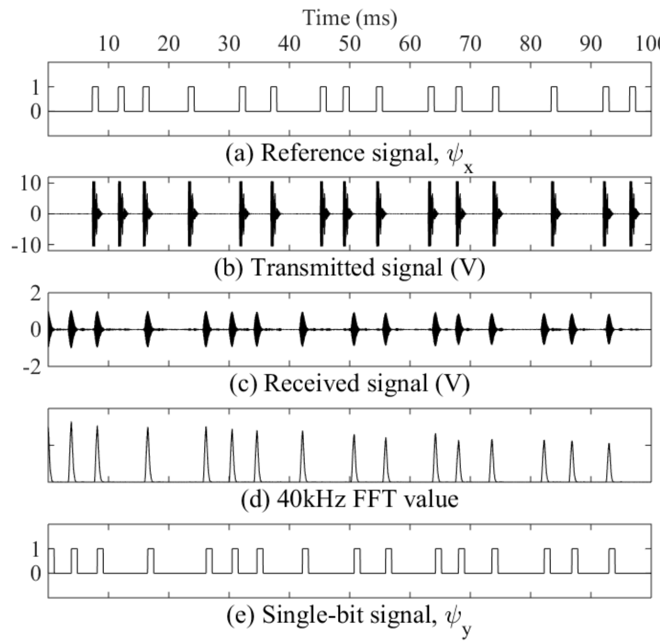


Fig. 5. Signal processing procedure.

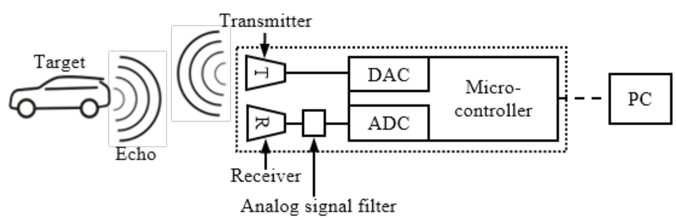


Fig. 6. Diagram of the ultrasonic distance sensor system.

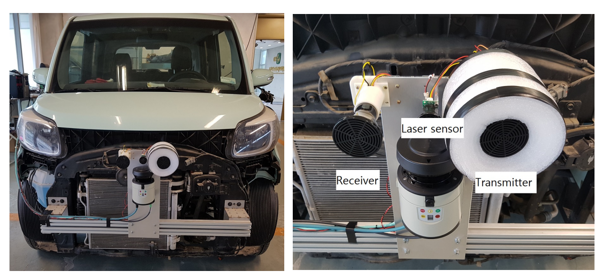


Fig. 7. An experimental vehicle with sensors.

Fig. 8. Target speed measurement experiment.

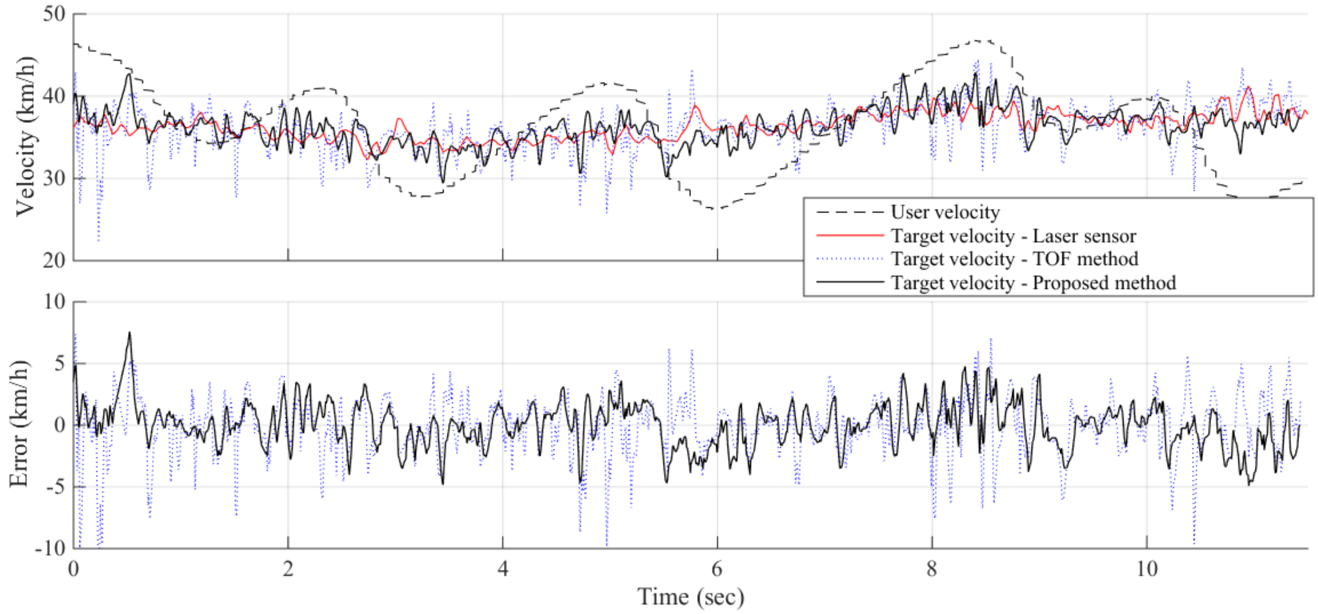


Fig. 9. Target vehicle speed sensing result and its error.

receiver used a 40 kHz ultrasonic transducer. A microcontroller 'National Instrument CompactRIO-9036' was used to run ultrasonic transmitter operation and data acquisition. The microcontroller included a 1 MHz analog to digital converter (ADC) that samples 40 kHz ultrasound wave and a 1.33 GHz dual core CPU with a field programmable gate array (FPGA) module. The microcontroller collected ultrasound data and transferred to a computer. After collecting the data, signal processing was performed on the computer. The analog signal filter is a simple high-pass filter to remove DC components.

Fig. 7 shows the sensor part used in the experiment. An ultrasonic transmitter and a receiver are arranged side by side and a laser sensor is installed as a reference sensor to be compared with the ultrasonic measurement result.

C. Experimental Results

As shown in Fig. 8, two vehicles were moving. The preceding vehicle kept the speed constant for safety. The following vehicle speeds were varied to produce a relative speed. Both vehicles travel in the same direction and a sensor is installed on the following vehicle to measure the distance to the preceding vehicle and the speed of the preceding vehicle. Fig. 9 shows the following four speed values:

- Sensor user speed (dashed black line).
- The speed value obtained by differentiating the distance values measured by laser sensor (solid red line).
- The speed value obtained by differentiating the distance values obtained by the ultrasonic sensor time-of-flight (TOF) method [8] (dotted blue line).
- The speed value obtained using the proposed method in this paper (solid black line).

All target speed values were calculated by determining the relative speed and adding the user vehicle speed. The two error graphs show the error of the last two of the above values. Each error was calculated based on the value of laser sensor. The RMS errors are 2.39 km/h and 1.81 km/h, respectively. The proposed method, which can directly measure the target speed, shows that there is acceptably small error, while the distance value differential has a lot of error.

V. Conclusion

The proposed target speed measurement method using the time dilation correlation enables the Doppler effect to be analyzed in the time domain rather than frequency domain. This method has great advantages in a sampled signal processing such as the system of this paper. In general, the Doppler effect is analyzed in the frequency domain, and the sampling frequency should be several to several tens of times higher than the wave to be analyzed, to achieve the desired speed resolution. However, when analyzed in the time domain, the speed analysis can be performed at much lower sampling frequencies with the proposed method. Moreover, time scaling of analog signals could be difficult, but is relatively easy for digital single bit signals.

Experimental results show that it has less RMS error to obtain the target speed directly by the Doppler effect and the time dilation correlation, than to differentiate the distance obtained by time-of-flight (TOF) method. It allows to calculate the target speed with a simple and small calculation.

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