廣東工業大學

本科毕业设计（论文）

高测量速率下具有串扰抑制的超声波测距方法

Ultrasonic Distance Measurement Method With Crosstalk Rejection at High Measurement Rate

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1.1　介绍

随着时间的推移，车辆、移动机器人和生产线逐渐采用了各种传感器。尤其是测量附近物体距离的传感器对智能系统至关重要。目前，激光传感器、超声波传感器、立体摄像头、雷达和光学测距系统广泛应用作为距离传感器。时间飞行（TOF）摄像头也被研究用于提供高帧率的 3D 成像 [1]。其中，超声波传感器非常便宜，传感器系统体积小且易于操作，但由于超声波的物理限制，性能、精度和测量速率通常低于其他传感器系统。因此，软件研究的重点是克服这些物理限制。

大多数超声波距离传感器的研究都集中在通过向超声波中添加附加信息来提高超声波传感器性能。有许多将信息存储在超声波信号中的方法：例如，频率调制、脉冲宽度调制信号编码、脉冲位置调制（PPM）和相位调制。

自上世纪 80 年代以来，已经进行了许多防止碰撞的研究。在避障领域，Borenstein 和 Koren [2]–[5] 进行了开创性的研究。此后，在多用户问题方面，为提高超声波传感器的精度做出了努力。研究了除简单阈值法以外的各种信号处理方法，用于精确的超声波脉冲检测。几位研究人员使用 Barker 码、Golay 码和 Kasami 码进行超声波局部定位系统 [6]–[10]。交叉相关法用于脉冲检测 [11]，[12]。Jörg 和 Berg [13]，[15]，[16] 以及 Jörg 等人 [14] 使用伪随机码来解决串扰问题。然而，这些用于准确的超声波脉冲检测的方法对于汽车应用来说并不足够，因为它们需要高性能微控制器的高计算负荷。

一些研究人员引入了二进制频率移位键控调制以产生发射信号 [17]–[20]。频率调制技术需要使用通常价格较高的宽频带压电换能器。

目前，信号编码方法的研究旨在解决移动机器人多超声波传感器系统中的串扰问题。在车辆应用中，当对向车辆在狭窄的单车道街道上使用超声波传感器，或者当城市道路上的车辆侧面有超声波传感器时，可能会发生外部串扰。串扰是超声波传感器实际应用中的一个重要问题。一篇综述性文章 [21] 介绍了截至 2005 年的串扰消除方法的研究。区分每个超声波传感器以拒绝串扰是至关重要的。当使用混沌 PPM（CPPM）生成一系列超声波脉冲序列时，每个超声波换能器可以变得独特，因此可以区分每个超声波传感器，这意味着消除串扰。

Borenstein 和 Koren [22]，[23] 提出了比较连续读数和比较交替延迟的错误消除快速超声波发射的思想。然后，随着计算机处理能力的增加，采用了交叉相关方法来比较序列。Fortuna 等人 [24]，[25] 将 CPPM 应用于声纳传感器发射，Yao 等人 [26] 使用混沌

脉冲位置宽度调制获得更好的结果。为增强实时性能，Meng 等人 [27] 提出了短优化的 PPM 序列。Alonge 等人 [28] 将雷达技术应用于超声波传感器系统。

与上述研究不同，本文的重点是在多用户环境中提高超声波传感器系统的测量速率。CPPM 信号克服了串扰和多用户问题，并通过使用信号编码方法在高测量速率下可稳健地测量物体距离，这与传统的简单 TOF 方法（单脉冲回波法）不同。此外，车辆应用还需要克服一些障碍。传感器系统必须对环境噪声具有鲁棒性，并能够测量移动目标。基本上，它应在多用户环境中可用，并且最重要的是具有成本竞争力。此外，一般的汽车控制应用要求均方根（rms）误差小于 50 毫米，并且测量速率超过 100 赫兹。

在传统的单脉冲回波方法中，当上一个脉冲仍在飞行中时，发射器无法发射附加的超声波脉冲，因为无法区分每个超声波脉冲。本文中，通过比较超声波脉冲序列而不是比较单个超声波脉冲，来获取 TOF。在计算 TOF 时，通过传输脉冲序列和接收到的脉冲信号之间的交叉相关计算时间延迟。然而，通常交叉相关需要高计算成本的长信号。因此，为了降低计算负载，本文采用 Hirata 等人 [29]，[30] 引入的单比特信号处理方法在交叉相关过程中降低计算负载并提高实时性能。通过在交叉相关中用单比特逻辑乘积替换多比特乘积，大大减少了计算量。在 [29] 和 [30] 中，应用了单比特信号处理来降低检测单个超声波脉冲的计算成本。然而，在本文中，将单比特信号处理应用于 CPPM 信号序列的交叉相关。

第 II 节介绍了实验中使用的硬件系统，并解释了经典方法的物理限制。第 III 节介绍了实验中使用的硬件系统和混沌系统。第 IV 节介绍了用于实时距离测量的信号处理；噪声抵消采用了快速傅里叶变换（FFT）阈值，子采样和单比特信号处理用于降低计算负载。第 V 节展示了串扰抑制模拟的结果，并在第 VI 节给出了测量速率的距离测量实验结果。

1.2 测量方法

超声波距离传感器使用 TOF（Time of Flight）方法。在最简单的方式中，控制器测量从发射到回波到达的时间。更先进的方法是通过比较发送信号和接收信号来测量信号延迟。信号延迟可以通过交叉相关进行测量，该方法将在本文后面进行讨论。

$$d = C \cdot t_{\text{tof}}/2 \tag{1}$$

其中 d 为目标距离，C 为空气中的声速，ttof 表示通过该系统测量的声脉冲飞行时间。声速随温度和湿度而变化。线性模型如下：

$$C = 331.3 + 0.606 \cdot \theta + 0.0124 \cdot H \tag{2}$$

其中 θ 为摄氏度温度，H 为相对湿度。温度变化会导致声速发生较大变化，因此实时温度测量是超声波距离传感中基本且必要的。然而，湿度偏差被忽略，因为预计其对本文所需的精度影响非常小，不超过 0.2

1.2.1 单脉冲回波法

超声波距离传感器的传统方法称为单脉冲回波法。在超声波发射器发射声脉冲后，控制器等待回波脉冲以测量飞行时间 ttof。由于等待回波需要较长时间，测量速率与距离成反比关系。此外，如果回波由于噪声或环境原因消失，将会出现更严重的问题。传感器必须等待超时才能发射下一个声脉冲。

传统单脉冲回波法的最大测量速率如下：

$$\text{最大测量速率} = \frac{1}{t_{\text{tof}}} = \frac{C}{2 \cdot d}. \tag{3}$$

由于最大测量速率与距离成反比，对于 10 米的目标而言，仅为 17 赫兹。单脉冲方法测量速率受限的主要原因是它仅使用一个声脉冲进行测量。如果在先前的声脉冲飞行过程中超声波传感器发送额外的声脉冲，将在单脉冲回波法中计算错误的 TOF。为了包含更多信息，需要通过调制超声信号或超声脉冲序列，而不是一次发送相同的超声波脉冲。在之前的研究 [31] 中，每个声脉冲通过与上一个声脉冲之间的间隔进行特征化。然而，该方法的缺点是对噪声不够稳健。可以通过对发送和接收信号进行交叉相关来计算 TOF，而不是使用单个超声脉冲测量往返时间，从而解决这个问题。

1.3 测量系统

图 1 显示了所提出系统的硬件结构图。发射器和接收器均使用 40kHz 超声波换能器。微控制器用于运行超声波发射器操作和数据采集。微控制器包括一个 1MHz 的模拟数字转换器（ADC），对 40kHz 的超声波进行采样，并带有一个 1.33GHz 的双核 CPU 和可编程门阵列模块。微控制器计算 Chua 电路的微分方程以生成 CPPM 的混沌信号，并向超声波发射器提供数字脉冲序列。超声波脉冲按预定的混沌脉冲序列触发，收集的超声波数据传输到计算机，并在计算机上进行进一步的信号处理。模拟信号滤波器是一个简单的高通滤波器，用于去除直流分量。

为了消除串扰，采用了混沌系统。CPPM 方法被采用将混沌信息并入数字脉冲序列

以进行超声波脉冲输出。

1.3.1 Chua 电路

Chua 电路 [32] 是一个众所周知且最简单的自主电子电路，用于产生混沌信号。Chua 电路如图 2(a) 所示，产生双滚动吸引子 [33]。它由电阻、电感、电容和称为 Chua 二极管的非线性电阻组成，其静态特性如图 2(b) 所示。图 2 的状态方程为：

$$
\begin{aligned}
C_1\frac{dv_1}{dt} =& G(v_2 - v_1) - f(v_1) \\
C_2\frac{dv_2}{dt} =& G(v_1 - v_2) + i_L \\
L\frac{di_L}{dt} =& - v_2
\end{aligned} \tag{4}
$$

其中，G=1/R。Chua 二极管表现出一个只有一个变量的非线性函数，这与具有两个非线性的 Lorenz 方程不同，每个非线性都是两个变量的标量函数。Chua 二极管的非线性函数是一个由三条直线段组成的奇对称分段线性函数：

$$
f(v_1) = m_0 v_1 + \frac{1}{2}(m_1 - m_0)(|v_1 + B_p| - |v_1 - B_p|). \tag{5}
$$

应用以下无量纲变量：

$$
\begin{aligned}
x =& \frac{v_1}{B_p} \quad y = \frac{v_2}{B_p}\ z = \frac{i_L}{B_p G} \\
a =& \frac{m_1}{G} \quad b = \frac{m_0}{G} \\
\alpha =& \frac{C_2}{C_1} \quad \beta = \frac{C_2}{LG^2}
\end{aligned} \tag{6}
$$

当时间缩放为 τ=tG/C2 时，得到无量纲形式的方程组：

$$
\begin{aligned}
\frac{x}{\tau} =& \alpha(y - x - f(x)) \\
\frac{y}{\tau} =& x - y - z \\
\frac{z}{\tau} =& - \beta y
\end{aligned} \tag{7}
$$

其中，

$$f(x) = bx + \frac{1}{2}(a-b)(|x+1| - |x-1|). \tag{8}$$

所使用的变量、初始值和时间缩放因子如下：

$$\alpha = 9, \quad \beta = \frac{100}{7}\, a = -\frac{8}{7}\, b = -\frac{5}{7}$$
$$x(0) = 0.09 \quad y(0) = 0\; x(0) = 0\; \frac{G}{C_2} = 1000.$$

(7) 式的状态变量 x 的图形如图 3 所示。

1.3.2　混沌脉冲位置调制

为了创建具有混沌间距的数字信号，混沌模拟信号经过一种称为脉冲位置调制（PPM）的过程，即 CPPM。调制机制如图 4 所示。这种方法在 Fortuna 等人的超声波距离传感器系统中引入。连续的脉冲位置调制器由采样保持电路和斜坡发生器组成。混沌信号是 PPM 电路的输入，并进行采样和保持。当保持值减去递增的斜坡信号等于零时，电路生成一个数字脉冲，重置斜坡信号，并再次进行采样和保持。模拟电压的混沌信息转换为数字脉冲之间的间隔。

1.3.3　信号处理

图 5 显示了所提出的测量方法的信号处理过程。图中的发射器部分包括 Chua 电路和 PPM 调制器。接收器部分包括超声波接收器、用于噪声过滤的正弦波相关器和用于二值化的阈值。发射器根据 CPPM 序列生成超声波脉冲。当从发射器发射的超声波反射到目标并被接收器收集时，会发生传输延迟。传输延迟对应于 TOF（飞行时间），可以通过两个信号的互相关测量来测量。每个发射器和接收器部分向处理单元提供单比特信号以计算距离。在本文中，接收器部分被配置为采样系统以进行进一步研究，但可以根据需要配置为模拟电路。

FFT 用于确定超声波接收器收集到的电压信号中是否存在超声波信号。本文中使用的超声波频率为 40 kHz（准确为 39.4 kHz）。由于在接收到的电压信号中只需要 40 kHz 的频域，如果仅计算 40 kHz 分量，则计算量非常小，可以快速计算。本文中，超声波信号的 ADC 速度为 1 MHz，40 kHz 超声波的周期为 25 μs。因此，每 1 μs 获得一个新的电压值，然后，对一个 25 μs 长的电压信号的 40 kHz 分量值进行计算。也就是说，每 1 μs 添加一个新值，并将包括新值在内的前 25 个值与 40 kHz 正弦波进行卷积。25 个值

的卷积积分非常小，可以每 1μs 计算一次。因此，这是实时的 40 kHz FFT 值

$$X_{40\ \text{kHz}} = \left|\sum n = 1^{N-1} xn \cdot \left(\cos\left(-2\pi k\frac{n}{N}\right) + i\sin\left(-2\pi k\frac{n}{N}\right)\right)\right| \tag{9}$$

其中 X40 kHz 是信号中的 40 kHz 分量的大小，xn 是要检查的接收到的电压信号。

本文中使用的参数为

$$k = f \times \frac{N}{f_s};\quad f = 40\ \text{kHz};\ f_s = 1\ \text{MHz};\ N = 25.$$

该值仅表示 40 kHz 分量的强度，因此仅显示了除去其他噪声的超声波强度，充当噪声滤波器。

1.3.4 噪声消除

图 6 和图 7 展示了超声波信号与各种噪声之间的差异。超声波信号是从墙壁反射而来的回波信号，距离为 5 米。环境噪声是在车辆以 90 km/h 的速度行驶时在道路表面附近收集到的。超声波信号和噪声在不同的实验中收集并进行比较。对于实际应用，超声波传感器系统应能够在车辆高速行驶时拒绝任何噪声。

图 6 显示了从 30 kHz 到 50 kHz 的两个信号的 FFT 结果。超声波信号和噪声信号都包含在 30 kHz 到 50 kHz 范围内。在 40 kHz 频率附近，噪声比超声波信号强得多。在本文中，从 40 kHz FFT 值中删除了噪声。

我们每 10 微秒计算一次 40kHz 的 FFT 值，以减少数据量。这在图 5 中表示为 fss，相当于 100kHz 的子采样或降采样。子采样直接与距离测量分辨率相关，100kHz 的子采样具有 1.7 毫米的测量分辨率。子采样是使用单比特信号的主要优势，而模拟信号分析则需要更高的采样率。子采样频率可以根据所需的距离测量分辨率进行决定，例如每 100 微秒计算一次，以获得 17 毫米的距离测量分辨率。如果 40kHz 的值大于一个阈值，我们确定接收到了超声波，并将其转换为以下的单比特信号。

1）高：存在超声波信号的状态。

2）低：没有超声波信号。

对于汽车超声波传感器而言，传感器中最大的噪声来自于轮胎和路面的噪声。阈值值越低，由于对低水平信号进行二值化而导致的信息损失越小。因此，阈值被设置为略高于实验获得的噪声值。

图 8 显示了整体的信号处理过程。图 8(a) 显示了参考信号，超声波发射器在上升沿时振荡并发射超声脉冲 [见图 8(b)]。发射的超声脉冲被目标物反射并回波到接收器 [见

图 8(c)]，微控制器计算 40kHz 的 FFT 值 [见图 8(d)]。同时进行 40kHz 值的计算，通过阈值产生单比特信号 [见图 8(e)]。

单比特信号处理和子采样压缩了数据大小。模拟的 32 位数字可以被压缩为单比特数字。在本文中，以 1MHz 进行采样的 32 位模拟信号被转换为 100kHz 的单比特信号，从而节省了 320 倍的存储空间。

在以前的研究 [31] 中，只比较接收信号与之前接收到的信号之间的间隔，并给出脉冲的唯一性以找到 TOF。然而，在本文中，TOF 是通过 CPPM 发射信号与接收信号之间的互相关得到的。两个信号的互相关的最高点的延迟就是 TOF。

图 8(a) 和 (e) 显示了单比特的发射参考信号和接收信号，它们的互相关显示在图 9 中。峰值延迟为 19.25 毫秒，这意味着当接收信号延迟该时间时，接收信号与参考信号最相似。因此，TOF 为 19.25 毫秒，即峰值的延迟，根据公式（1）和（2），距离为 3.215 米。我们进行了温度校正，激光传感器测得的实际值为 3.218 米。

图 8 显示了整体的信号处理过程。图 8(a) 显示了参考信号，超声波发射器在上升沿时振荡并发射超声脉冲 [见图 8(b)]。发射的超声脉冲被目标物反射并回波到接收器 [见图 8(c)]，微控制器计算 40kHz 的 FFT 值 [见图 8(d)]。同时进行 40kHz 值的计算，通过阈值产生单比特信号 [见图 8(e)]。

由于这两个信号都是二进制的单比特信号，可以缩短处理时间以实现实时互相关计算。与多比特乘法相比，单比特乘法可以显著减少总计算成本，因为互相关涉及大量乘法。单比特乘法可以通过逻辑操作轻松实现。因此，图 8(a) 和 (e) 的互相关比图 8(b) 和 (c) 创建了更好的实时性能。

2 外文文献原文

2.1 Introduction

Over time, vehicles, mobile robots, and production lines have been acquiring various sensors. In particular, sensors that measure distance to nearby objects are essential to smart systems. Currently, laser sensors, ultrasonic sensors, stereo cameras, and radio detection and ranging (RADAR) and light detection and ranging systems are widely used as distance sensors. Time-of-flight (TOF) cameras are also being studied to provide 3-D imaging at high frame rates [1]. Among them, ultrasonic sensors are very cheap, and the sensor system is small in size and easy to handle, but due to the physical limitations of ultrasound, the performance, accuracy, and measurement rate are usually lower than with other sensor systems. Accordingly, software research has focused on overcoming the physical limitations.

Most studies on ultrasonic distance sensors have focused on increasing the performance of ultrasonic sensors by adding additional information to the ultrasonic wave. There are many ways to store information in ultrasound signals: for example, frequency modulation, signal coding by pulsewidth modulation, pulse-position modulation (PPM), and phase modulation.

Since the 1980s, many studies have been conducted to prevent collisions. In the field of obstacle avoidance, pioneering studies have been made by Borenstein and Koren [2]–[5]. After that, efforts were made to improve the accuracy of ultrasonic sensors in the field of robotics considering the multiuser problem. Precise ultrasonic pulse detection methods using various signal processing methods, other than the simple threshold method, have been studied. Barker codes, Golay codes, and Kasami codes were used by several researchers for an ultrasonic local positioning system [6]–[10]. The cross correlation method was used for pulse detection [11], [12]. Jörg and Berg [13], [15], [16] and Jörg et al. [14] used a pseudorandom code to solve the crosstalk problem. However, these methods for accurate ultrasonic pulse detection are inadequate for automotive applications because of their high computational load, which requires a high-performance microcontroller.

Several researchers introduced binary frequency shift keying modulation to produce emission signals [17]–[20]. The frequency modulation technique requires wide frequency band piezoelectric transducers, which are usually high priced.

Currently, research on signal coding methods aims to solve the crosstalk problem in the mobile robot multiultrasonic sensor system. In vehicle applications, external crosstalk may occur when the opposite vehicle is using ultrasonic sensors on a narrow one-lane street or when there is an ultrasonic sensor on the side of a vehicle in the other lane on an urban road. Crosstalk is a big problem in practical applications of ultrasonic sensors. A review journal [21] introduced research up to 2005 on crosstalk elimination methods. It is essential to distinguish each ultrasonic sensor to reject crosstalk. When a series of ultrasonic pulse sequences is generated using the chaotic PPM (CPPM), each ultrasonic transducer can be made unique, so it was possible to distinguish each ultrasonic sensor, which means the crosstalk elimination.

Borenstein and Koren [22], [23] introduced the idea of comparison of consecutive readings and comparison with alternating delays called error eliminating rapid ultrasonic firing. Then, as the computer processing capability increased, a cross-correlation method was used to compare the sequences. Fortuna et al. [24], [25] applied CPPM to fire the sonar sensor, and chaotic pulse position-width modulation was used by Yao et al. [26] to obtain better results. To enhance the real-time performance, Meng et al. [27] proposed short optimized PPM sequences. Alonge et al. [28] applied RADAR technology to the ultrasonic sensor system.

Unlike the above-described studies, the focus of this paper was to increase the measurement rate of the ultrasonic sensor system in a multiuser environment. CPPM signals overcome the crosstalk and multiuser problem, and by using the signal coding method, the distance to the object can be measured robustly at a high measurement rate, which is different from the conventional simple TOF method (single pulse echo method). In addition, there are obstacles to overcome for vehicular application. The sensor system must be robust to environmental noise and able to measure moving targets. Basically, it should be available in a multiuser situation and, above all, be cost competitive. In addition, general automotive control applications require a root mean square (rms) error of less than 50 mm and a measurement rate of over 100 Hz.

In a conventional single pulse echo method, the transmitter cannot emit additional ultrasonic pulses while the last pulses are still in flight because each ultrasonic pulse cannot be distinguished. In this paper, the TOF is obtained by comparing ultrasonic pulse sequences rather than comparing single ultrasonic pulses. When calculating the TOF, the time delay was calculated by cross correlation between the transmitted pulse sequence and the received pulse signal. However, cross correlation of a long signal typically requires high computing costs. Therefore, in order to reduce the computational load, single-bit signal processing, introduced by Hirata et al. [29], [30], was used in the cross-correlation process to reduce the computational load and improve the real-time performance. By replacing the multibit products with single-bit logical products in cross correlation, the amount of computation was greatly reduced. In [29] and [30], single-bit signal processing was applied to reduce the computing cost of detecting single ultrasonic pulses. However, in this paper, single-bit signal processing was applied to the cross correlation of CPPM signal sequences.

Section II introduces the hardware system used in the experiment and explains the physical limitations of the classical method. Section III introduces the hardware system used in the experiment and the chaotic system. Section IV deals with signal processing for real-time distance measurement; the fast Fourier transform (FFT) threshold was used for noise cancellation, and subsampling and single-bit signal processing were used to reduce the computational load. The results of the crosstalk rejection simulation are shown in Section V, and the results of the distance measurement experiment showing the measurement rate are given in Section VI.

2.2 Measurement Method

Ultrasonic distance sensors use a TOF method. In the simplest way, the controller measures the time from departure to echo arrival. The more advanced methods measure the signal delay by comparing the transmitted signal with the received signal. The signal delay can be measured by cross correlation, which is discussed later in this paper

$$d = C \cdot t_{\mathrm{tof}}/2 \tag{1}$$

where d is the target distance, C is the speed of sound in the air, and ttof indicates the flight time of the sound pulse measured through this system. The speed of sound varies with temperature and humidity. The linear model is

$$C = 331.3 + 0.606 \cdot \theta + 0.0124 \cdot H \tag{2}$$

where θ is the temperature in degrees Celsius and H is the relative humidity. Temperature changes can cause large changes in the speed of sound, so real-time temperature measurement is basic and is necessary for ultrasonic distance sensing. However, humidity deviations were ignored because they were expected to have a very small impact of less than 0.2

2.2.1 Single Pulse Echo Method

The traditional method of ultrasonic distance sensors is called the single pulse echo method. After an ultrasonic transmitter shoots a sound pulse, the controller waits for the echo pulse to measure the flight time ttof . Wasting much time waiting for an echo is inevitable. Since the flight time increases proportionally to the distance, the measurement rate decreases inversely with the distance. Moreover, if the echo disappears due to noise or environmental reasons, more serious problems arise. The sensor cannot shoot the next sound pulses until a timeout.

The maximum measurement rate of the conventional single pulse echo method is as follows:

$$\text{Maximum measurement rate} = \frac{1}{t_{\text{tof}}} = \frac{C}{2 \cdot d}. \tag{3}$$

Since the maximum measurement rate is inversely proportional to the distance, it is only 17 Hz for a 10-m target. The main reason for the limitation of the measurement rate of the single pulse method is that it measures with only one sound pulse. If the ultrasonic sensor transmits additional sound pulses while the previous sound pulses are in flight, a wrong TOF will be calculated in the single pulse echo method. Instead of sending the same ultrasound pulse one at a time, it is necessary to modulate the ultrasound signal or the ultrasound pulse sequence to include more information. In a previous study [31], each sound pulse was characterized by its interval to the last pulse. However, this method has the disadvantage of not being robust to noise. This problem can be solved by calculating the TOF by cross correlation of the transmitted and received signals, instead of measuring the round trip time using one ultrasonic pulse.

2.3 Measurement System

Fig. 1 shows a diagram of the hardware of the proposed system. Both the transmitter and the receiver used a 40-kHz ultrasonic transducer. A microcontroller was used to run ultrasonic transmitter operation and data acquisition. The microcontroller included a 1-MHz analog-to-digital converter (ADC) that samples a 40-kHz ultrasound wave and a 1.33-GHz dual-core CPU with a field-programmable gate array module. The microcontroller computed the differential equations of Chua’s circuit to generate the chaotic signal for the CPPM and provided a digital pulse sequence to the ultrasonic transmitter. The ultrasound pulses was fired in the predetermined chaotic pulse sequence, the collected ultrasound data were transferred to a computer, and further signal processing was performed on the computer. The analog signal filter is a simple high-pass filter to remove dc components.

A chaotic system was applied to remove crosstalk. The CPPM method was adopted to incorporate chaotic information into a digital pulse sequence for the ultrasound pulse output.

2.3.1 Chua’s Circuit

Chua’s circuit [32] is a well-known and the simplest autonomous electronic circuit that generates chaotic signals. Chua’s circuit is shown in Fig. 2(a) and generates a double scroll attractor [33]. It consists of resistors, inductors, capacitors, and a nonlinear resistor called Chua’s diode, whose static characteristic is plotted in 2(b). The state equations of Fig. 2 are

$$\begin{aligned} C_1\frac{dv_1}{dt} &= G(v_2 - v_1) - f(v_1) \\ C_2\frac{dv_2}{dt} &= G(v_1 - v_2) + i_L \\ L\frac{di_L}{dt} &= -v_2 \end{aligned} \tag{4}$$

where G=1/R . Chua’s diode exhibits a nonlinear function of only one variable, which is different from the Lorenz equation with two nonlinearities, each one being a scalar function of two variables. The nonlinearity function of Chua’s diode is an odd-symmetric piecewise linear function made of three straight line segments

$$f(v_1) = m_0 v_1 + \frac{1}{2}(m_1 - m_0)(|v_1 + B_p| - |v_1 - B_p|). \tag{5}$$

Applying the following dimensionless variables:

$$\begin{aligned} x &= \frac{v_1}{B_p} \quad y = \frac{v_2}{B_p} \; z = \frac{i_L}{B_p G} \\ a &= \frac{m_1}{G} \quad b = \frac{m_0}{G} \\ \alpha &= \frac{C_2}{C_1} \quad \beta = \frac{C_2}{LG^2} \end{aligned} \tag{6}$$

when time scaling is τ=tG/C2 , the dimensionless form is obtained

$$\begin{aligned} \frac{x}{\tau} &= \alpha(y - x - f(x)) \\ \frac{y}{\tau} &= x - y - z \\ \frac{z}{\tau} &= -\beta y \end{aligned} \tag{7}$$

where

$$f(x) = bx + \frac{1}{2}(a - b)(|x + 1| - |x - 1|). \tag{8}$$

The variables, initial values, and time-scaling factor we used are as follows:

$$\begin{gathered} \alpha = 9, \quad \beta = \frac{100}{7} \; a = -\frac{8}{7} \; b = -\frac{5}{7} \\ x(0) = 0.09 \quad y(0) = 0 \; x(0) = 0 \; \frac{G}{C_2} = 1000. \end{gathered}$$

The graph of state variable x of (7) is drawn in Fig. 3.

2.3.2 Chaotic Pulse-Position Modulation

To create a digital signal having a chaotic interpulse interval, the chaotic analog signal goes through a process called PPM, which is called CPPM. The modulation mechanism is shown in Fig. 4. This method was introduced in the ultrasonic distance sensor system by Fortuna et al. [24]. The continuous pulse-position modulator consists of a sample-and-hold circuit and a ramp generator. The chaotic signal is an input to the PPM circuit, and the signal is sampled and held. When the held value minus the increasing ramp signal goes to zero, the circuit generates a digital pulse, resets the ramp signal, and performs sample-and-hold again. The chaotic information of the analog voltage is transferred into the intervals between digital pulses.

2.3.3 Signal Processing

Fig. 5 shows the signal processing of the proposed measurement method. The transmitter section of the diagram includes Chua’s circuit and a PPM modulator. The receiver part consists of an ultrasound receiver, a sine wave correlator for noise filtering and threshold for binarization. The transmitter generates ultrasonic pulses according to the CPPM sequence. A transport delay occurs while the ultrasound emitted from the transmitter is reflected on the target and collected by the receiver. The transport delay corresponds to TOF and can be measured by cross correlation of the two signals. Each transmitter and receiver part provides a single-bit signal to the processing unit to calculate the distance. In this paper, the receiver part is configured as a sampled system for further study but can be configured as an analog circuitry as needed.

The FFT was used to determine whether there is an ultrasonic signal in the voltage signal collected by the ultrasonic receiver. The ultrasound used in this paper was 40 kHz (39.4 kHz for exactly). Since another frequency domain of the full FFT is not needed in the incoming voltage signal, if only the 40-kHz component is calculated, the calculation amount is very small and can be calculated quickly. In this paper, the ultrasonic signal ADC speed is 1 MHz, and the period of the 40-kHz ultrasonic wave is 25 µs . Therefore, a new voltage value is obtained every 1 µs , and then, the 40-kHz component value of a 25-µs -long voltage signal is calculated. That is, a new value is added every 1 µs , and the previous 25 values, including the new value, are convoluted with the 40-kHz sine wave. The convolution integral of 25 values is very small and can be calculated every 1µs . Therefore, this is the real-time 40-kHz FFT value

$$X_{40\text{ kHz}} = \left| \sum_{n=1}^{N-1} x_n \cdot \left(\cos\left(-2\pi k \frac{n}{N}\right) + i \sin\left(-2\pi k \frac{n}{N}\right) \right) \right| \tag{9}$$

where X40 kHz is the amount of 40 kHz in the signal and xn is the received voltage signal to be examined.

The parameters used in this paper were

$$k = f \times \frac{N}{f_s}; \quad f = 40\text{ kHz}; \; f_s = 1\text{ MHz}; \; N = 25.$$

This value only represents the intensity of the 40-kHz component, so it only displays the intensity of the ultrasonic wave with other noise removed, acting as a noise filter.

2.3.4 Noise Elimination

Figs. 6 and 7 show the difference between the ultrasound signals and an ambient noise in various ways. The ultrasonic signal is an echo signal reflected from a wall 5 m away. The ambient noise was collected near the road surface while the vehicle was running at 90 km/h. The ultrasonic signal and the noise were collected in separate experiments and compared. For practical applications, the ultrasonic sensor system should be able to reject any noise while the vehicle is running at high speed. Fig. 6 shows the FFT result of two signals from 30 to 50 kHz. The ultrasonic signal has a much higher peak value than the noise signal. When the 40-kHz component is analyzed in real time [see Fig. 7(b)], it is easier to distinguish an ultrasonic component from noise than when only the voltage value is analyzed [see Fig. 7(a)]. This allows external noise, such as noise from the road surface, to be filtered.

We calculated the 40-kHz FFT value per 10 μs to reduce the amount of data. This is fss in Fig. 5 and is 100-kHz subsampling or downsampling. The subsampling is directly related to the distance measurement resolution, and the subsampling of 100 kHz has a measurement resolution of 1.7 mm. Subsampling is a main advantage of using single-bit signals, while analog signal analysis requires much high sampling rates. Subsampling frequency can be decided according to the desired distance measurement resolution, such as calculating every 100 μs to get 17-mm distance measurement resolution. If the value of 40 kHz was larger than a threshold, we determined that the ultrasonic wave was received and converted into the single-bit signal as follows.

1)High: A state in which an ultrasonic signal exists.

2)Low: No ultrasonic signal.

In the case of ultrasonic sensors for automobiles, the largest noise coming into the sensor is the tire-road noise. The lower the threshold value is, the less information loss due to the binarization of the low-level signal can be minimized. Therefore, the threshold was set to a value that was just above the noise obtained from the experiment.

Fig. 8 shows the overall signal processing process. Fig. 8(a) shows the reference signal, and the ultrasonic transmitter oscillates at the rising edge and emits an ultrasonic pulse [see Fig. 8(b)]. The transmitted ultrasonic pulses are reflected back to the target and echoed into the receiver [see Fig. 8(c)], and the microcontroller calculates the 40-kHz FFT value [see Fig. 8(d)]. Simultaneously with the 40-kHz value calculation, a single-bit signal was generated by a threshold [see Fig. 8(e)].

Single-bit signal processing and subsampling compress the data size. Analog 32-bit numbers can be compressed into single-bit number. In this paper, a 32-bit analog signal measured at 1 MHz was converted to a 100-kHz single-bit signal, resulting in 320 times memory savings.

In a previous study [31], only the interval between the received signal and the previously received signal was compared, and the uniqueness of the pulse was given to find the TOF. However, in this paper, the TOF was obtained by the cross correlation between the CPPM transmitted signal and the received signal. The delay, at the highest point of the cross correlation of the two signals, is the TOF.

Fig. 8(a) and (e) shows the single-bitted transmitted reference signal and the received signal, and their cross correlation is shown in Fig. 9. The peak delay is 19.25 ms, which means that the received signal is the most similar to the reference signal when it is delayed by that amount. Therefore, the TOF is 19.25 ms, which is the delay of the peak, and the distance is 3.215 m according to (1) and (2). We computed a temperature correction, and the actual value measured by the laser sensor was 3.218 m.

Since both the signals are binary single-bit signals, the processing time can be shortened to enable real-time cross-correlation calculations. Single-bit multiplication can significantly reduce the total calculation cost compared with multibit multiplication [29], because cross correlation involves a large number of multiplications. Single-bit multiplication can be easily done by logical operations. Therefore, cross correlation of Fig. 8(a) and (e) created a better real-time performance than Fig. 8(b) and (c).