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USING CODED SIGNALS TO BENEFIT FROM ULTRASONIC SENSOR CROSSTALK IN MOBILE ROBOT OBSTACLE AVOIDANCE

Shraga Shoval[1] and Johann Borenstein[2]

shovalcr@netvision.net.il and johannb@umich.edu

[1] Department of Industrial Engineering and Management, Academic College of J&S – Ariel, Israel.

[2] Mobile Robotics Laboratory, Dept. of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA

Abstract

Crosstalk is a common problem occurring with arrays of multiple ultrasonic sensors (sonars) in obstacle detection and avoidance systems. This paper presents a novel method that might allow the use of data generated by crosstalk to generate more reliable and accurate object detection. This is accomplished by assigning a unique code to the signals emitted by each sonar, so that the source sonar can be identified even if its signal's echo is received by another sonar. Using geometric interpolation between the various sonars increases the accuracy of the measurements, overcoming their limited resolution. Experimental results show the potential of our system for mobile robotics obstacle detection and avoidance, as well as for localization using map-matching techniques.

Key Words: Ultrasonic sensors, crosstalk, coded signals, positioning, range measurement, geometric interpolation.

1. Introduction

Ultrasonic sensors (sonars) are widely used for obstacle avoidance with mobile robots. The most common sonar sensor is the Polaroid 6500 Series Sonar Ranging Module together with the 600 Series Instrument Grade Electrostatic Transducer [Polaroid] (referred to as the "Polaroid sonar" in the remainder of this paper). The Polaroid sonar has a conical propagation profile (called a "lobe") with a beam angle of about 12°-15°. In order to provide a vehicle with a seamless panoramic "view" of the environment, Polaroid sonars are typically installed on the vehicle's periphery at 15-degree intervals. For a 360-degree panorama, 24 sensors are required [Moravec 1988].

One problem with multiple sonars operating in close proximity is a phenomenon known as *crosstalk,* where one sonar receives the echo of a signal emitted by adjacent sonars. The receiving sonar has no way of knowing that the echo was not created by its own signal, resulting in inaccurate time-of-flight measurement. Crosstalk occurs in almost all multiple sonar systems, especially in the vicinity of smooth surfaces. Moreover, if the firing sequence of the sonars is constant, then the same crosstalk error may occur repeatedly, until the geometry of the reflecting surfaces relative to the robot has changed sufficiently.

Several approaches have been developed to correct errors caused by crosstalk. Borenstein and Koren [1995] introduced the Error Eliminating Ultrasonic Firing (EERUF) method, in which the sonars' firing sequence is deliberately alternated. This way, if sonar A receives a crosstalk signal from sonar B as a result of one firing sequence, sonar A will not receive the same crosstalk reading from sonar B in the next sequence. Thus, if one compares any two consecutive readings of the same sonar and accepts only those readings that are near-equal to their predecessor, most erroneous readings due to crosstalk are effectively filtered out.

A different approach was demonstrated by Jörg and Berg [1998] who modulated the frequency of the sonar signals with pseudo-random sequences, thus giving each sonar a recognizable signature. A matched filter in the receiving circuit then identified the associated source sonar. This approach, "inspired by the work of [Audenaert et. al., 1992] and [Sabatini and Spinelli 1994]," allows for simultaneous firing of several sonars. The technique allows for superimposed echoes to be detected and identified, provided each wave is assigned with a unique, sharp autocorrelation function. The central element in this system is a fast Digital Signal Processor (DSP) board that acts as a function generator during the firing stage of each ultrasonic wave, and as a data analyzer using a Fast Fourier Transformation (FFT) during the receiving stage. This technique can be complex for a full array of 24 sonars. Furthermore, its performance depends heavily on the reflecting surface, as the reflector's geometry can produce large variations in the echo signal, possibly degrading the quality of the autocorrelation system.

This paper presents a simpler method for assigning unique identification codes to different sonars. Our method offers almost all of the advantages of the system by Jörg and Berg, but is much simpler to implement. The main advantage of both systems over all other conventional multi-sonar systems is that identifying the source of each echo alters crosstalk from being an undesirable side effect, to a source of additional, exploitable information. Specifically, echoes from other sonars can be used to calculate the relative position of the reflecting object with great accuracy (both radially and angularly) by means of triangulation. Section II describes our coding method in detail, as well as the method of triangulation. Section III shows results of preliminary tests and Section IV provides concluding remarks.

2. Coded Ultrasonic Chirps

To add clarity to the discussion throughout this paper we define the following terms (see also Fig. 1):

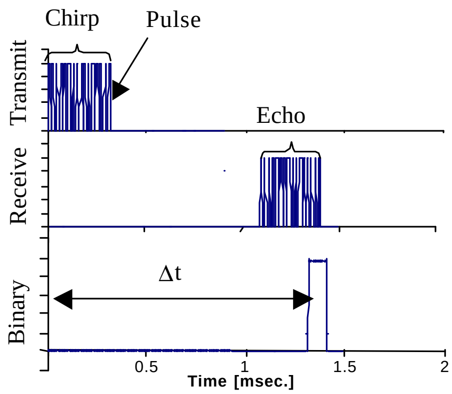


Figure 1: Typical signal cycle

Pulse – The discrete electrical excitation of the transducer membrane that results in one period of an ultrasound wave.

Chirp – A group of pulses fired in sequence (also called a burst). In standard Polaroid sonars a chirp consists of 16 pulses 20 ìs apart. In our system chirps have variable length.

Wave - A pulse or a chirp traveling from the transmitter to the reflector and back to the receiver.

Reflector – An object that reflects the ultrasonic chirp.

Echo – An ultrasonic pulse or chirp after being reflected off an object.

The Polaroid sonar is designed to emit one complete chirp every time the circuit board receives a single, discrete firing signal. The transducer element has two functions: during the chirp the transducer acts as a loudspeaker. Then, after a waiting period of a few milliseconds (needed to allow the membrane vibration to abate) the transducer is ready to receive the echo, acting as an electrostatic microphone.

The method we are proposing applies a unique code to the transmitted chirp. With the help of this code, the sonar receiving an echo can unambiguously identify the transmitting sonar (similar to the idea presented in [Jörg and Berg, 1998]). However, our implementation is different as shown in Figure 2. Each sonar transmits a chirp that consists of a number of pulses, the exact number of which is determined by the unique code assigned to that sonar. Once the signal is emitted, the sonar is switched to receiving mode, receiving its own, as well as echoes transmitted by other sonars. The received signal is continuously digitized by means of a comparator and stored in a First-In-First-Out (FIFO) chip. The sonars remain in receiving mode for the maximal duration allowed by the system (proportional to the maximum detection range) enabling several echoes to be recorded in the FIFO. Once the receiving cycle is completed, the control system analyzes the content of the FIFO to determine the number of pulses returned by each echo. The implementation of the system is fast and simple, making it suitable for mobile platforms where size, weight and on-the-fly operation is required. Only echoes that overlap upon detection by a specific sonar cannot be used for range measurements. However, overlapping of echoes occurs only if reflectors are positioned in close proximity to each other (less than 5 cm) or when two adjacent sonars emit their chirps at the exact same time (which can be avoided by implementing a predetermined firing schedule as with EERUF). Figure 3a shows a short chirp (consisting of 6 pulses) and its corresponding echo after being reflected from a wall 70 cm away from the sonar, while Figure 3b shows a long chirp (16 pulses) and its echo. All signals were recorded using a digital oscilloscope.

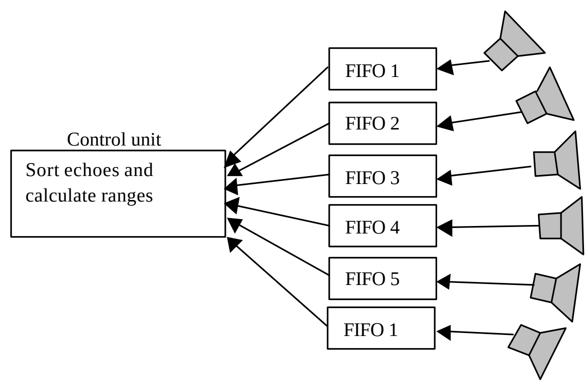
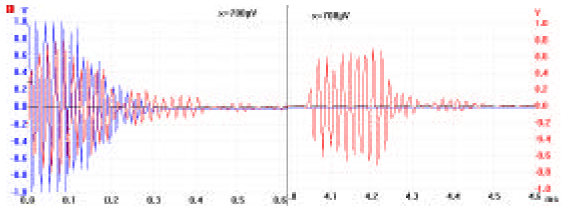
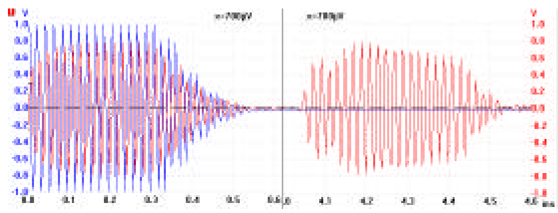


Figure 2: Schematic description of the system

The control system then relates each echo to the relevant transmitting sonar and calculates the range to the reflector (explained below). This procedure is repeated for all sonars, producing a large number of measurements. Theoretically, a system that includes *n* sonars operating in ideal conditions (where each echo is received and analyzed by all other sonars) can provide n^2 measurements for each chirp transmitted by each sonar. For example, a system consisting of eight (mostly) forward-looking sonars each transmitting signals at a rate of 100 Hz can provide $8^2 \times 100 = 6{,}400$ measurements/sec., compared to 800 measurements/sec. provided by conventional methods operating under the same ideal conditions.



(a)

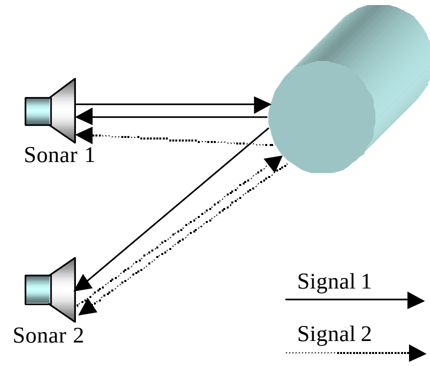


(b)

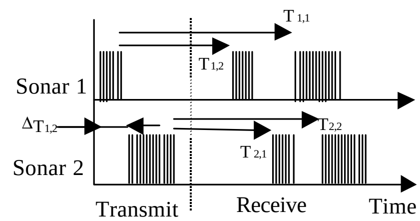
Figure 3: Oscilloscope view of the outgoing chirp (left wave form) and the amplified echo (right wave form) a) Short chirp b) Long chirp

To illustrate the operation of the proposed system, consider the configuration shown in Fig. 4a. This system consists of two sonars (sonar 1 and sonar 2) and a single reflector in front of them. Each sonar transmits a coded chirp (chirp 1 consists of eight pulses and chirp 2 of 16 pulses). Figure 4b shows the transmitted and received signals of each sonar. Let $T_{i,j}$ be the time elapsed between transmitting a chirp by sonar j and receiving an echo by sonar i, measured by sonar i (using its own time frame). Let $\Delta T_{i,j}$ be the delay in transmitting the chirps between sonar i and j. Accordingly, $\Delta T_{i,i} = 0$, and $T_{i,j} = -DT_{j,i}$. Finally, let the total time of flight of the signal be denoted by $TOF_{i,j} = T_{i,j} + \Delta T_{i,j}$. For example, the total time of flight of signal 1 (transmitted by sonar 1) while traveling from sonar 1 to the reflector and back to sonar 1 is $TOF_{1,1} = T_{1,1}$. The time of flight of signal 1 from sonar 1 to the reflector and back to sonar 2 is given by $TOF_{2,1} = T_{2,1} + DT_{2,1}$.

To illustrate the operation of the proposed system, consider the configuration shown in Fig. 4a. This system consists of two sonars (sonar 1 and sonar 2) and a single reflector in front of them. Each sonar transmits a coded chirp (chirp 1 consists of eight pulses and chirp 2 of 16 pulses). Figure 4b shows the transmitted and received signals on each sonar. Let $T_{i,j}$ be the time elapsed between transmitting a chirp by sonar j and receiving an echo by sonar i, measured by sonar i (using its own time frame). Let $\Delta T_{i,j}$ be the delay in transmitting the chirps between sonar i and j. Accordingly, $\Delta T_{i,i} = 0$, and $T_{i,j} = -DT_{j,i}$. Finally, let the total time of flight of the signal be denoted by $TOF_{i,j} = T_{i,j} + DT_{i,j}$. For example, the total time of flight of signal 1 (transmitted by sonar 1) while traveling from sonar 1 to the reflector and back to sonar 1 is $TOF_{1,1} = T_{1,1}$. The time of flight of signal 1 from sonar 1 to the



(a)



(b)

Figure 4: A typical signal sequence of the system

reflector and back to sonar 2 is given by $TOF_{2,1} = T_{2,1} + DT_{2,1}$.

Once the TOF of signals from all sonars to all other sonars (in the case of 2 sonars there are 4 measurements-2 per signal), the position of reflector O can be calculated according to geometric interpolation between sonar 1 and sonar 2. Many researchers have investigated the use of geometric triangulation in multi-sonar systems [LeMay and Lamancusa 1992; Kleeman and Kuc, 1995]. Typically these systems consist of an array of several sonars, but only one sonar transmits a signal at a time while all other sonars receive the echo. In addition to the range measurement, the geometric interpolation procedure provides an estimate of the bearing of the reflector [Nagashima and Yuta 1992], differentiating edges, corners and walls [Barshan and Kuc 1990; Sabatini 1992], and radius of curvature [Peremans et al., 1993]. However, due to their limited transmission rate, these systems are unsuitable for fast moving vehicles.

Figure 5 illustrates the geometric triangulation procedure. A coordinate system C_1 is attached to sonar 1, which is located at the origin of this system and transmits its coded chirps in the V_1 direction (along the Y-axis). Sonar 2 is located at position P_2 and transmits its coded chirps in the direction V_2 - creating angle θ with the X-axis. Reflector O is positioned at P_3 (to be determined) within the lobe of the chirp transmitted by sonar 2. Assuming the echo transmitted by sonar 2 is received by both sonars, the location of reflector O is calculated by both sonars: The calculation for Sonar 2 is based on $TOF_{2,2}$ and that for sonar 2 is based on $TOF_{1,2}$.

The uncertainty of the reflector position as measured by sonar 2 is within the circular arc (±15° for conventional sonar) as shown in Fig. 5. The uncertainty of the reflector position as measured by sonar 1 is within an elliptic arc defined by the geometric relation between the two. The actual position of the object is accurately determined based on the intersection between the circular arc and the elliptical arc, as shown in Fig. 5.

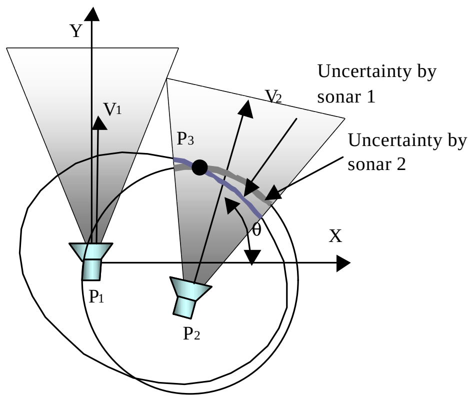


Figure 5: Positioning of the reflector based on measurements of sonar 1 and sonar 2.

In addition to the accurate location of the reflector, the intersection between the two arcs provides information required for sorting the echoes detected by the sonars. When several echoes are perceived by a particular sonar, it is essential to relate each echo to echoes perceived by other sonars. However, some of the measurements can be erroneous due to reflection from several reflecting surfaces, sensor inaccuracies, or external noise. The intersection method rejects this erroneous data, as only arcs that intersect within the lobe of the transmitted chirp represent acceptable echoes. Arcs that either do not intersect at all, or intersect outside the lobe pattern of the transmitted signal represent erroneous echoes. This solution provides a unique method for localizing reflectors ensures the rejection of most erroneous data. This phenomenon is demonstrated in experiment #2 of the next section.

3. Experimental Results

This section provides results of basic experiments designed to test the feasibility of the proposed technique. First, consider the system shown in Fig. 5, in which sonar 1 is positioned at (0, 0) and sonar 2 at (50, -5), with $\theta = 85^{o}$. The reflector is at (50, 100) close to the left edge of the lobe. In this experiment each sonar transmits one coded chirp. The measurements obtained by the two sonars are $TOF_{1,2} = 216.8$ cm and $TOF_{2,2} = 105.13$ cm (no echoes are perceived from the chirp transmitted by sonar 1). Assuming a conical propagation profile for the emitted chirp, the measurement of sonar 1 constructs an elliptical arc and sonar 2 a circular arc. The intersection of the two arcs establishes the position of the object to be (49.71, 100.13), an offset of 0.32 cm from the actual position, as shown in Fig. 6.

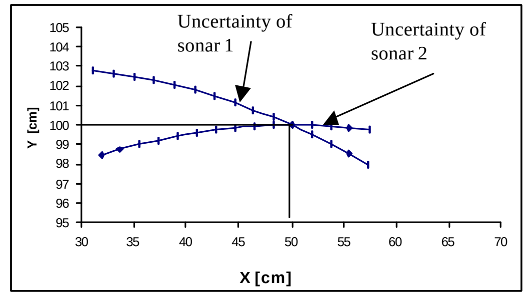


Figure 6: Experimental results for the configuration shown in Fig. 5.

Next, the more complex configuration shown in Fig. 7a is tested. The sonars are positioned at the same locations as in the previous experiment, with three vertical cylindrical reflectors (5 cm diameter), positioned at (-14, 100), (40, 300), and (95, 200). The sonars are firing one coded chirp each, 5 ms apart (sonar 2 after sonar 1). The timing diagram in Fig. 7b shows when each echo was received by each sonar. As shown, sonar 1 receives its own echoes reflected from reflectors 1 and 2, as well as the echoes transmitted by sonar 2 and reflected from reflector 2. Sonar 2 receives its own echoes reflected from reflectors 2 and 3 and the echo transmitted by sonar 1 and reflected by reflector 2.

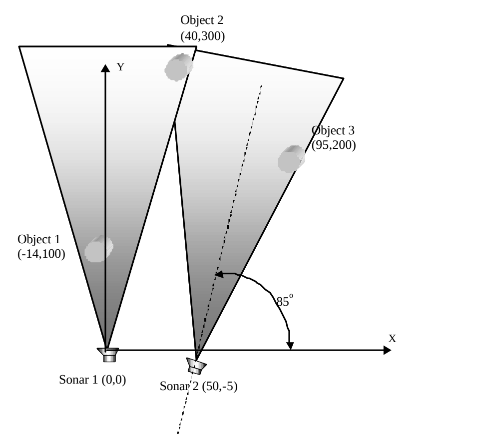


Figure 7a: Set up for experiment #2.

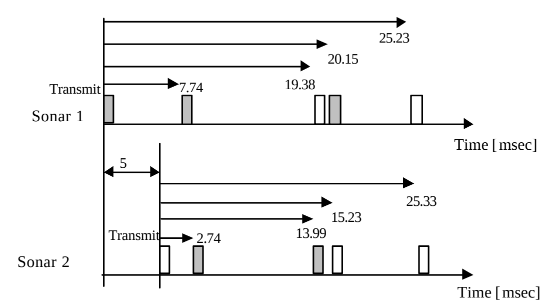


Figure 7b: Signals transmit/receive schedule for the set up of experiment #2.

Table I summarizes the results of this experiment. The first column provides a serial number to each echo and the second column (R, T) indicates the sonar that transmitted the chirp (R) and the sonar that received that echo (T). The other columns provide time data on receipt of the echo by each sonar and the total time of flight from transmission, through reflection and perception ($TOF_{i,j}$). Finally, the translation of TOF to distance is shown, based on $V_{air,}$ the speed of sound in air at 20°C (V_{air} = 343.2 m/s). It should be noted that for echoes received by the transmitting sonar the distance to the reflector is half TOF×V_{air}, while for other echoes the distance is the sum of the distances transmitter-reflector-receiver.

Based on the data shown in Table I, a series of circular and elliptical arcs is constructed. These arcs are shown in Fig. 8. It should be noted that at this stage the echoes are not related to a specific reflector. However, all possible intersections between arcs show that there are only four intersections that fall within the chirps' conical propagation patterns and all other intersections do not represent real reflectors. The actual intersections are between arcs 1+2 (reflector 1), 3+4 and 5+7 (reflector 2) and 7+8 (reflector 3). Reflector 2 is represented by two sets of intersections because there are two sets of echoes perceived by the two sonars. This occurs only for objects that are positioned on the overlapping conical propagation patterns of the two chirps.

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Table II provides the position estimate of the three reflectors based on the geometric interpolation of the arcs. As shown, most intersections provide an accurate position estimate (within ±2 cm). The arc # in the left column referes to the measurements of Table I.

Finally, experiment #3 involves a wall and a cylindrical reflector in front of it, as shown in Fig. 9 (experiment #3). In this experiment, sonar 1 transmits a short chirp of 5 pulses while sonar 2 transmits a long chirp of 16 pulses. The two sonars are 50 cm apart, the wall is 345 cm from the line connecting the two sonars, and the cylinder is at (120, -40) in a coordinate system attached to sonar 1.

Table I: Results summary of experiment #1.

#	R,T	$T_{i,j}$	$\Delta T_{i,j}$	$TOF_{i,j}$ [ms]	Dist. [cm]
1	1,1	7.33	0	7.33	125.8
2	2,1	2.74	5	7.24	248.5
3	1,1	20.15	0	20.15	345.8
4	2,1	15.23	5	20.23	694.3
5	2,2	20.33	0	20.33	348.9
6	1,2	25.23	-5	20.23	694.2
7	2,2	13.99	0	13.99	240.0
8	1,2	19.38	-5	14.38	493.5

Table II: Position estimate for three reflectors.

Arc #	Estimated position	Actual position	Error [cm]
1+2	(-13.59,59.99)	(-13,100)	0.59
3+4	(50,77,298.41)	(50,300)	1.76
5+7	(50.25,301.0)	(50,300)	1.03
7+8	(95.23,200.07)	(95,200)	0.24

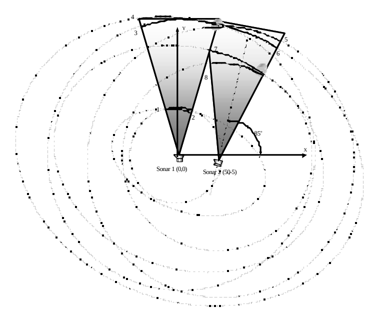

Figure 8: Intersections of all circular and elliptical arcs.

Table III summarizes the results of this experiment and provides the position estimate of the wall and cylinder as measured by the two sonars.

Table III: Location errors for a wall with a cylinder in front.

TOF [sec]		TOF [sec]		Location [cm]	Error [cm]
1,1	131.4	2,1	253.9	(122.4, -45.8)	6.27
1,2	247.4	2,2	122.7	(120.9, -30.5)	9.5
1,1	348.7	2,1	-	(348.7,0)	3.7
1,2	681.4	2,2	351.5	(348.3, -36.3)	3.3

In this experiment the cylinder position is estimated within ±9.5 cm (less than 8%) and the wall's position is estimated within ±4 cm (less than 1.2%). It should be noted that the short echo (transmitted by sonar 1) is not received by sonar 2 after being reflected from the wall (however it is received after being reflected from the cylinder). This is due to the low energy of that signal which disipates faster than the longer echo that is received by the two sonars after being reflected by the cylinder and the wall. However, the short echo provides more accurate data for the position estimate of reflectors in close proximity. This leads to the conclusion that a variety of echoes are required to cover a wide range of measurement. This can be achieved by constructing a mixture of coded chirps either by alternating the codes tranmitted by each sonar, or by assigning various codes to neighbouring sonars.

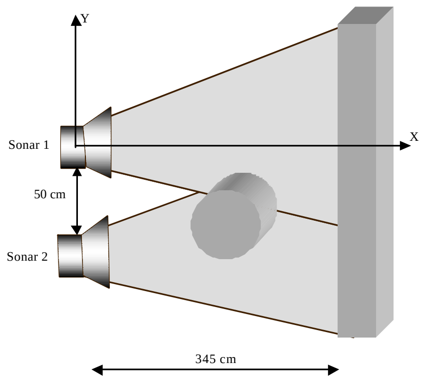

Figure 9: Set-up of experiment #3.

5. Conclusions

A method for simple coding of ultrasonic signals was presented. Each signal consists of a different number of ultrasonic pulses, creating uniquely coded chirps. Attaching codes to ultrasonic signals in a multi sensor system provides several advantages in obstacle detection. First, the number of usable measurements is significantly increased, which improves the reliability of reflector position estimation using statistical analysis. Furthermore, using geometric interpolation based on the relative position of all sonars provides sufficient data for accurate positioning of reflectors. This improved accuracy is essential for fast moving vehicles in highly congested environments or when moving through narrow passageways. Attaching a unique code to the chirps provides an efficient tool for detecting various reflector surfaces and ranges. The method relies on the crosstalk phenomenon, which is traditionally considered to be undesirable in multi ultrasonic sensor systems. This method proposes that information generated by crosstalk provides meaningful data for determining accurate and reliable obstacle position. As a result, the amount of useful data increases significantly, providing a more reliable and accurate sensing system.

Acknowledgements

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