A Novel Method of Distance Measurement Based on Pulse Position Modulation and Synchronization of Chaotic Signals Using Ultrasonic Radar Systems

Francesco Alonge, *Member, IEEE*, Marco Branciforte, and Francesco Motta

***Abstract*—This paper deals with a novel method of transmission and receipt of a signal based on both the property of two chaotic systems generating the same chaotic signal when they are synchronized and the property of pulse position modulation (PPM) to be insensitive to the distortions of the transmission channel. The method is discussed in the context of ultrasonic radar systems, in which the transmitter and receiver, which consist of ultrasonic sensors, are near each other, and the received signal consists of the transmitted signal reflected by an obstacle. A reference sinusoidal signal is superimposed to a chaotic signal generated by a master chaotic system, and the whole signal is modulated according to the PPM method and transmitted by the sensor. The received signal is demodulated, and the demodulated signal forces a slave chaotic system to generate the chaotic signal embedded in it, which allows recovery of the sinusoidal signal by subtracting this chaotic signal from the demodulated echo. The difference of the phases of the reference sinusoidal signal and the recovered sinusoidal signal allows computation of the *time of flight* of the signal and, consequently, the distance of the radar system from the obstacle. The novel method is illustrated and tested by both simulation and experiments. The interference problem between the considered radar system and other radar systems (*crosstalk*) is also addressed, and a solution is proposed to avoid it.**

***Index Terms*—Chaotic pulse position modulation (CPPM), chaotic system synchronization, crosstalk, distance measurement, multipath fading, ultrasonic sensors.**

I. Introduction

IN THE FIELD of the design and practical realization of mobile vehicles, the problem of avoiding impacts with either obstacles or other vehicles has to be considered to be of primary importance. In this paper, it is assumed that the vehicles in question are equipped with ultrasonic sensors, which, as is well known, emit a beam that returns back after the interception of an obstacle that is able to reflect it; the measurement of the time of flight (TOF) of the beam allows the measurement of the distance of the sensor emitting the beam from the obstacle.

Manuscript received August 5, 2007; revised May 28, 2008. First published September 12, 2008; current version published January 5, 2009.

F. Alonge is with the Department of Systems and Control Engineering, University of Palermo, 90128 Palermo, Italy (e-mail: alonge@unipa.it).

M. Branciforte is with the Automotive Product Group, ST Microelectronics, 95121 Catania, Italy (e-mail: marco.branciforte@st.com).

F. Motta is with Acheia s.r.l., 91018 Salemi, Italy (e-mail: motta.fra@libero.it).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIM.2008.2003309

As is well known, the mobile vehicles are usually equipped with several sensors that are placed as such, so that each of them emits a beam in a certain direction, which allows exploration of the whole neighboring space. In these cases, a problem arises due to the interference between the sensors, which causes the degradation of the quality of the information captured. Another problem that can cause the aforementioned degradation is the presence of closed vehicles that are equipped with sensors of the same type, some of which receive beams emitted by sensors placed on other vehicles.

It follows that the use of sensors that improve the navigational safety of mobile vehicles requires that the following two problems be addressed:

1) *crosstalk*, i.e., the problem of each sensor in distinguishing its echo from that due to signals produced by other sensors placed on either the same or other vehicles;
2) *multipath fading*, i.e., the problem of distinguishing the echo produced by direct reflection of the emitted beam that has an impact on the obstacle from that produced by multiple reflections due to impacts to walls or other obstacles. This generates uncertainty about the true distance of the obstacle itself.

The *multipath fading* problem has been addressed by several authors using data fusion techniques; in particular, good results have been obtained using methods based on fuzzy logic (cf., for example, [1]–[3]).

The *crosstalk* problem has also been treated in the literature for obstacle avoidance using mobile robots and as a guide cane for the blind (cf., for example, [4]–[7]). In [4], the authors illustrate a method (error-eliminating rapid ultrasonic firing) in which the firing sequence of the sensors is alternated, so that a sensor cannot receive the beam emitted by another sensor in two consecutive sequences; thus, the sensor compares two successive readings and accepts only the readings near each other. In [5], a different approach is considered based on the frequency modulation of the sensor signals, thus giving to each sensor an easily recognizable label. In [7], a method that uses the *crosstalk* to calculate the relative position of the reflecting surfaces by means of triangulation is presented.

In this paper, a novel measurement method of the distance of a vehicle from an obstacle is proposed based on the property of chaotic systems [8] to generate the same chaotic signal when they are synchronized and the insensitivity property of the pulse position modulation (PPM) technique to the distortions of the transmission channel. Practically, the proposed idea is conceptually similar to that shown in [5] since both ideas attempt to assign a label to a sensor.

In this paper, the aforementioned idea is developed, with the aim of obtaining an efficient low-cost transducer based on an ultrasonic sensor that is useful for increasing the navigation safety of a vehicle. The proposed method for solving the problem consists of the following steps: A reference sinusoidal signal of suitable frequency is added to a chaotic signal generated by a master chaotic system, and the whole signal (hereinafter called information signal) is modulated according to the PPM method; since the information signal contains a chaotic component, the aforementioned method is called the chaotic PPM (CPPM) method [9]. The modulated signal is transmitted by the transmitter of the sonar sensor, and the received echo is first demodulated to obtain the original information signal shifted by the TOF and then applied to a slave chaotic system synchronized with the master; this allows the generation of a chaotic signal that is equal to that embedded into the information signal [10], [11] shifted in time by the TOF, due to the insensitivity of CPPM to the distortions introduced by the transmission channel. This allows extraction of the sinusoidal signal embedded into the demodulated signal by simply subtracting the chaotic signal generated by the slave system from the demodulated signal itself. From the difference of the phases of the reference and recovered sinusoidal signals, the TOF is computed, and the distance of the given vehicle from the obstacle is obtained.

Simulation results are shown, with the aim of verifying the validity of the aforementioned idea. Experimental results are also shown, with the aim of proving that the aforementioned idea can be implemented on analog electronic circuits.

The use of chaotic signals is inherent in the method proposed in this paper. In fact, as already stated, it is necessary to recover the chaotic signal embedded into the information signal from the received echo, which can easily be done using the synchronization property of two identical chaotic systems. A similar property does not exist for either random or pseudorandom signal generators.

However, the use of chaos does not allow avoidance of *crosstalk* due to the other radar systems present in the same environment. To cope with *crosstalk*, two simple approaches are proposed, which can be implemented either via hardware or software based on the *cleaning* of the spurious pulses, which are caused by the other radar systems eventually present in the environment, from the recovered information signal. The mechanism of *crosstalk* interference and the approach to avoid it are studied by simulation.

This paper is organized as follows: Section II describes the blocks that compose the measurement system and the measurement procedures. Section III illustrates the master and slave chaotic systems, their realization by means of Chua's circuit, the chaotic pulse position modulator, the chaotic pulse position demodulator (CPPD), and the sensor driver. The aim of this section is to verify the validity of the proposed method on the theoretic point of view; consequently, the displayed results will not be compared with the experimental results discussed in Section V. Section IV deals with the *crosstalk* problem and discusses two approaches to cope with it. Section V shows some experimental results. Section VI deals with the conclusions.

II. Measurement Method

As already stated, this paper deals with the problem of measuring the distance of an obstacle from a given vehicle, in unstructured and multivehicle environments, by computing the TOF of a signal emitted by an ultrasonic sensor that reaches the obstacle that is reflected and whose echo is received by the receiver of the sensor itself. The basic idea is connected to the peculiarity of two chaotic systems to produce the same signal when they are synchronized in a suitable manner and the property of CPPM to be insensitive to the distortions of the transmission channel. This suggests measuring the aforementioned TOF as follows: A reference sinusoidal signal of frequency f_r generated by an oscillator is added to a chaotic signal produced by a master chaotic system, and the whole signal is the useful information to be transmitted, i.e., the information signal. Assuming that the transmitted information can be recovered from the echo of the transmitted signal reflected by the obstacle, the sinusoidal signal can be extracted from this signal by subtracting the aforementioned recovered information and the chaotic signal produced by a slave chaotic system inserted into the receiver of the sensor synchronized with the master chaotic system. The difference of the phases of the reference and recovered sinusoidal signals allows the computation of the TOF.

A fundamental issue in the described procedure is the recovery of the information signal. Observing that an analog signal attenuates during flight, it needs to employ suitable procedures. In this paper, the chosen procedure consists of the modulation of the information to be transmitted using the CPPM method. According to this method, the modulating signal is translated into variations of the positions of the pulses of a train of pulses at a suitable frequency f_p generated by a pulse generator. The use of the CPPM method is justified, observing that it is practically insensitive to the distortions of the transmission channel; in fact, these distortions modify the form of the pulses but do not change the distance between them. Moreover, CPPM requires low power for the transmission, choosing the duty cycle of the pulse train that is relatively small. In [12], it is shown that CPPM preserves the chaotic characteristics of the chaotic signal.

As is well known, sonar sensors are able to produce oscillations at a frequency f_o, which, in turn, generate ultrasonic waves that propagate in the space. Consequently, the modulated train of pulses of frequency $f_p \ll f_o$ cannot be transmitted. In this paper, to obtain a signal that can be transmitted, a method consisting of the generation of a train of pulses of frequency f_o, which is of time duration d_p, inside each pulse of the modulated signal is proposed.

The preceding discussion shows that the echo of the transmitted signal is a train of oscillating waveforms at a frequency f_o of time duration d_p. From this train of oscillating waveforms, a train of pulses is recovered, in which the variations of the positions of the single pulses are practically the same as those of the modulated signal generated in the transmitter.

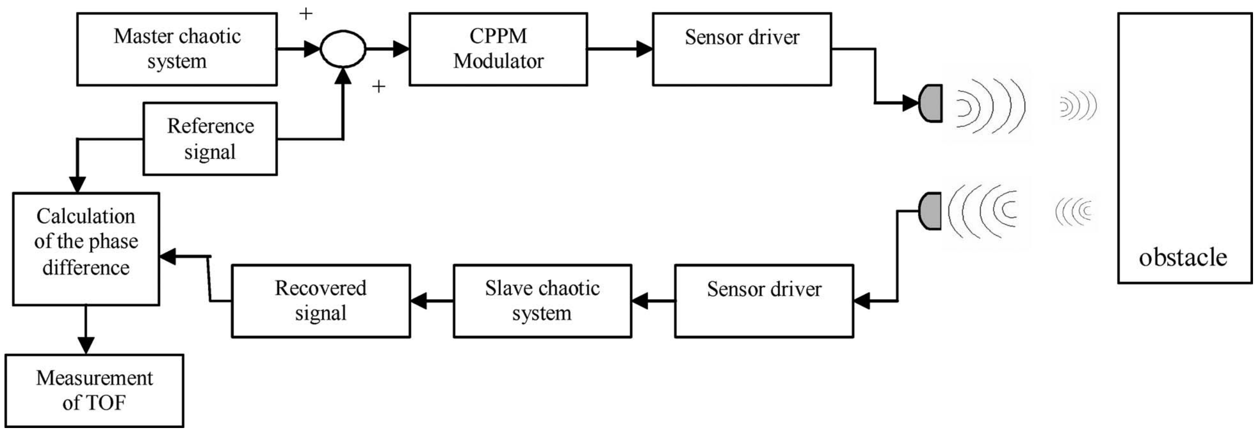


Fig. 1. Basic scheme of the measurement system.

Starting from the preceding train of pulses, a demodulator allows recovery of the information signal shifted by the TOF. This allows the recovery of the sinusoidal signal embedded into the information signal by simply subtracting the chaotic signal generated by the slave chaotic system from the recovered information signal itself. The difference of the phases of the reference sinusoidal signal and the recovered sinusoidal signal $\Delta\phi$ allows the computation of the TOF of the transmitted signal as follows:

$$\mathrm{TOF} = \frac{\Delta\phi}{2\pi f_r}. \tag{1}$$

The distance d of the sensor and the obstacle is computed as follows:

$$d = \frac{\mathrm{TOF}}{2} v_s \tag{2}$$

where v_s is the speed of the sound. The basic scheme of the system, which allows the implementation of the proposed method for measurements of distances from obstacles, is shown in Fig. 1.

III. Measurement System

This section describes all the blocks of the basic scheme, their possible realization, and some theoretic results. In Sections III-A and E, the realization of the master and slave chaotic circuits and their synchronization are discussed. Sections III-B and D show the chaotic pulse position modulator and demodulator, respectively, and finally, Section III-C describes the sensor driver.

A. Master Chaotic System

The master and slave chaotic systems are realized by means of Chua's circuit, which, as is well known, is the simplest electronic circuit that is able to generate chaotic signals. This circuit, as shown in Fig. 2(a), consists of a linear part realized with resistors, inductors, and capacitors interconnected with a nonlinear part given by Chua's diode NL, whose static characteristic i_R versus v_{c1} is displayed in Fig. 2(b), where m_0 and m_1 are the slopes of the two lines of the aforementioned characteristics [13]. The mathematical model of the system of Fig. 2 is given by

$$\begin{aligned} C_1\frac{dv_{c1}}{dt} &= G(v_{c2}-v_{c1}) - f(v_{c1}) \\ C_2\frac{dv_{c2}}{dt} &= -G(v_{c2}-v_{c1}) + i_L \\ L\frac{di_L}{dt} &= -v_{c2} \end{aligned} \tag{3}$$

where $G = 1/R$, and

$$f(v_{c1}) = m_0 v_{c1} + 0.5(m_1 - m_0)\left(|v_{c1}+B_p| - |v_{c1}-B_p|\right). \tag{4}$$

By changing the time scale according to the equation $\tau = tG/C_2$ and putting

$$x=\frac{v_{c1}}{B_p} \quad y=\frac{v_{c2}}{B_p} \quad z=\frac{i_L}{B_pG} \quad a=\frac{m_1}{G}$$
$$b=\frac{m_0}{G} \quad \alpha=\frac{C_2}{C_1} \quad \beta=\frac{C_2}{LG^2}$$

the following model is obtained:

$$\begin{aligned} \frac{dx}{d\tau} &= \alpha\left(y-x-f(x)\right) \\ \frac{dy}{d\tau} &= x-y-z \\ \frac{dz}{d\tau} &= -\beta y \end{aligned} \tag{5}$$

where

$$f(x) = bx + 0.5(a-b)\left(|x+1| - |x-1|\right). \tag{6}$$

The implementation of model (5), taking into account the time scale factor G/C_2, can easily be performed using Matlab–Simulink software. The block scheme of the master

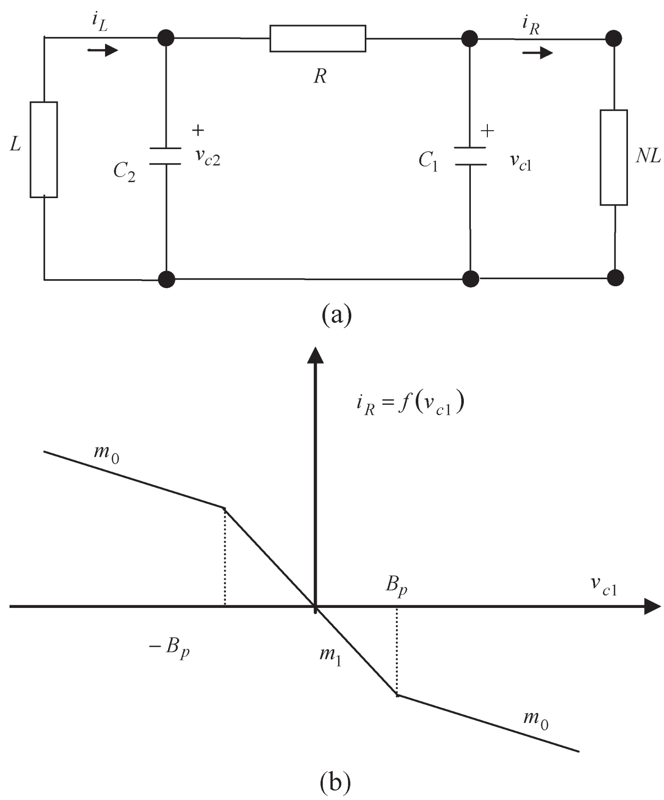


Fig. 2. Chua's circuit. (a) Electric scheme. (b) Characteristic of the Chua's diode NL.

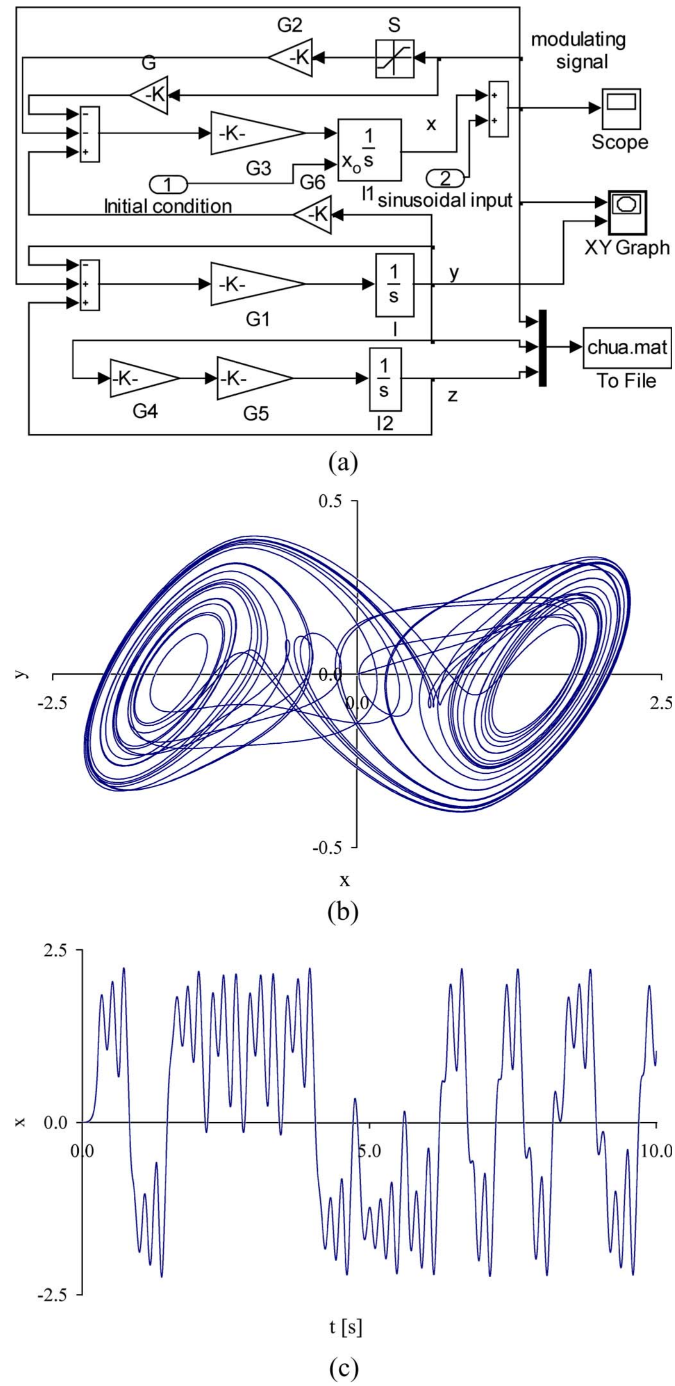


Fig. 3. Simulink block scheme and simulation results of the model (3) and (4). (a) Master block scheme. G1, G3, and G5: G/C_2, G4: $-\beta$, G: $\alpha(1+b)$, G2: $\alpha(a-b)$, S: $0.5(|x+1|) - |x-1|)$. (b) Double scroll projection on the $x-y$ plane. (c) x versus time.

chaotic system is shown in Fig. 3(a), and the results obtained, assuming

$$\alpha = 9, \quad \beta = 14.286, \quad a = -1.1429, \quad b = -0.7143$$
$$x(0) = 0.09, \quad y(0) = 0, \quad z(0) = 0, \quad \frac{G}{C_2} = 11$$

are given in Fig. 3(b) and (c), where the projection of the double-scroll attractor on the $x-y$ plane and the waveform of x versus time are shown.

B. Chaotic Pulse Position Modulator

The chaotic pulse position modulator is a voltage-to-time converter. A constant signal is first added to the information signal, which consists of the sum of the chaotic signal x generated by the master chaotic system and a reference sinusoidal signal, to obtain an always-positive modulating signal. This signal is compared with a ramp of suitable slope; when the ramp reaches this signal, a pulse is generated, which is fed back to reset and restart the ramp according to Fig. 4. Examination of Fig. 4 shows that the distance between two successive pulses $t_j - t_{j-1}$ is proportional to the value of the signal at instant t_j; obviously, the aforementioned distance depends on the slope of the ramp and the harmonic content of the signal itself. The resulting train of pulses represents the modulated signal.

C. Sensor Driver

As already stated, the aforementioned modulated signal is not suitable to drive the sonar sensor; consequently, it cannot be transmitted. To overcome this problem, inside of each pulse of the modulated signal, a train of pulses is generated, whose frequency $f_o \gg f_p$ belongs to the range of operation of the sonar sensor. The sensor driver of the transmitter generates these pulses at a frequency f_o. Fig. 5 shows the CPPM signal transmitted by the sensor driver transmitter obtained by simulation of the system of Fig. 1, assuming a reference sinusoidal signal of amplitude and frequency of 0.5 V and 10 Hz, respectively. Note the train of pulses at a frequency f_o (41 kHz in this simulation) generated inside each pulse of the signal at a mean frequency f_p (1 kHz in this simulation).

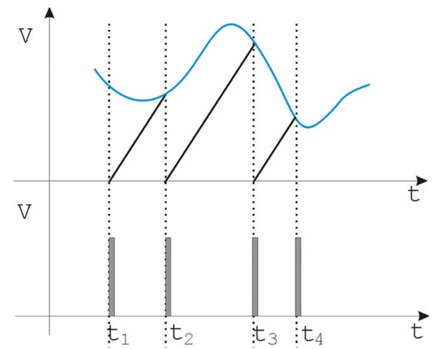


Fig. 4. CPPM. Modulation mechanism.

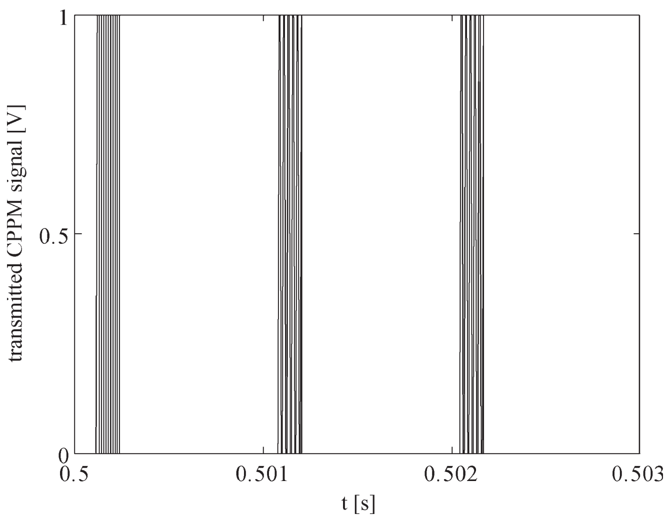


Fig. 5. Transmitted CPPM signal.

The preceding discussion shows that the echo of the transmitted signal is a train of oscillating waveforms at a frequency f_o of duration d_p. The sensor driver of the receiver generates a train of pulses whose distance between two successive pulses is the same as that of the modulated signal. To this end, the received signal is first rectified, filtered, and squared by means of a comparator, which gives a high output when the signal exceeds a chosen threshold and a low output in the other situations.

D. CPPD

From the train of pulses recovered by the sensor driver of the receiver, the CPPD recovers the modulating signal generated by the transmitter. To this end, the train of pulses is compared with a ramp of the same slope as that generated in the modulator, which starts at the beginning of the each pulse; this ramp is reset and restarts at the beginning of the successive pulse, and its value that was immediately reached before the reset is equal to the value of the modulating signal. By subtracting the constant previous added from this signal, the information signal is recovered. As an example, Fig. 6 shows the original signal applied to the CPPM and the signal recovered from the CPPD corresponding to a TOF equal to zero, which is obtained by simulation of the system of Fig. 1.

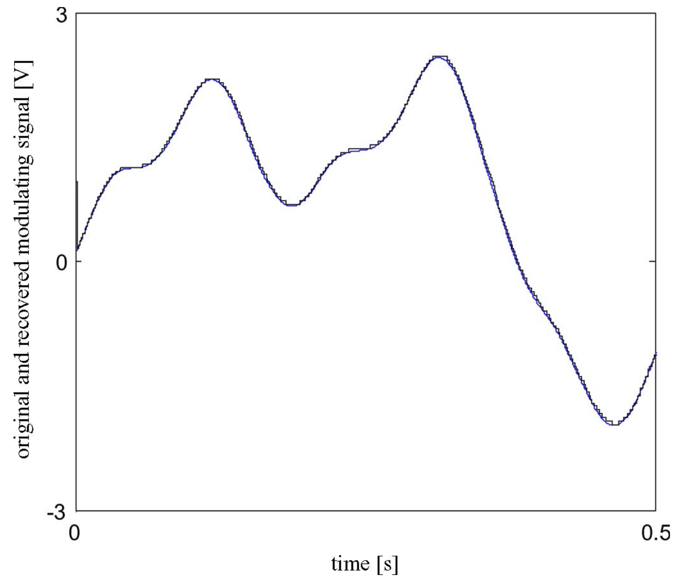


Fig. 6. Original and recovered modulating signals for TOF $= 0$.

E. Slave Chaotic System

As already stated, the chaotic signal embedded into the information signal has to be reconstructed to recover the reference signal. This can be done by applying the information signal to a slave chaotic system having the same parameters as the master chaotic system but not necessarily the same initial conditions, as shown in Fig. 7, where the recovered information signal supplies both integrators relative to variables y and z of the slave chaotic system. In this case, the recovered output x of the slave chaotic system exactly reproduces the chaotic signal embedded into the recovered information signal shifted by the TOF. If the master and slave chaotic systems have different parameters, synchronization does not take place, and the chaotic signal embedded into the information signal cannot be reconstructed. This is shown in Fig. 8(a) and (b).

IV. Crosstalk

Fig. 9 shows the sinusoids recovered as the output of a third-order passband Butterworth filter centered on the frequency of the reference sinusoid, which is supplied by the difference of the recovered information signal and the chaotic signal generated by the slave system when the master and slave chaotic systems are either synchronized or not synchronized; the initial transients were removed. The examination of the two signals represented in Fig. 9 shows that the recovered signal in the absence of synchronization is no longer a sinusoid; in addition, in this case, no errors occur, because the measure is discarded.

Fig. 10 shows the reference and recovered sinusoidal signals when the distance to be measured is zero in the presence of synchronization. The recovered signal requires about 750 ms to reach the steady-state operation conditions. After this time, the difference of the phases of the reference and recovered sinusoidal signals allows computation of the TOF and the distance from the obstacle. Note that, at steady state, the recovered sinusoid has almost the same amplitude as the reference sinusoid.

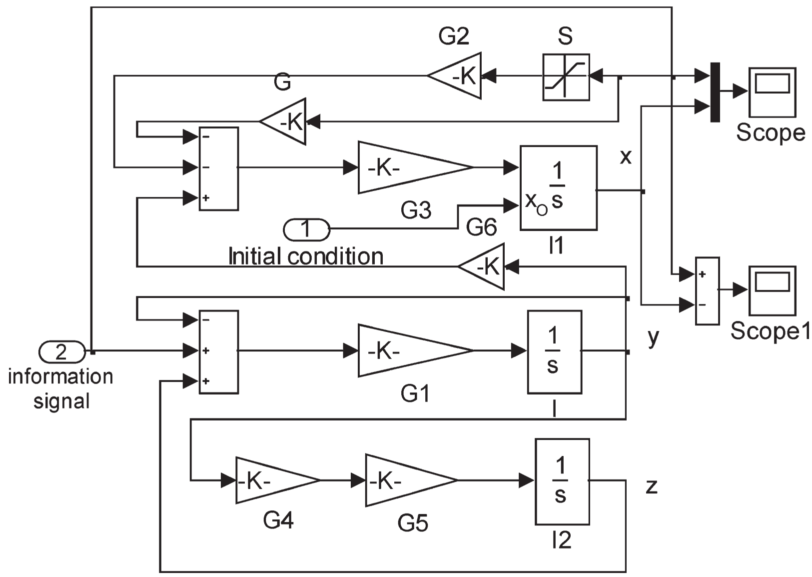


Fig. 7. Block scheme of the slave chaotic system.

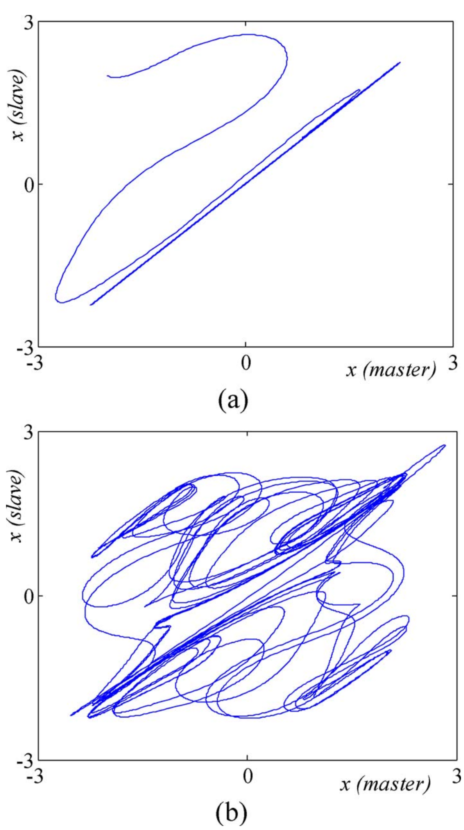


Fig. 8. Synchronization of chaotic systems. (a) Synchronization of two identical chaotic systems independent of initial conditions. (b) No-synchronization of two chaotic systems with the same initial conditions but different parameters: $\beta_{\text{slave}} = 0.9\,\beta_{\text{master}}$.

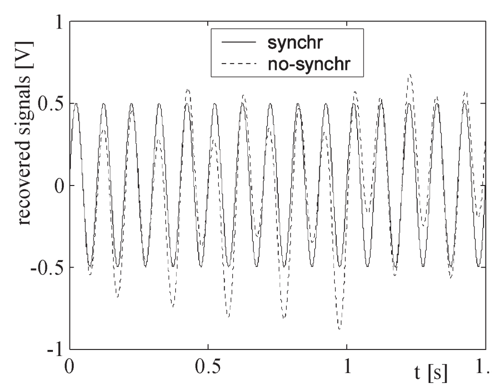


Fig. 9. Recovered signals in the presence and absence of synchronization of the master and slave.

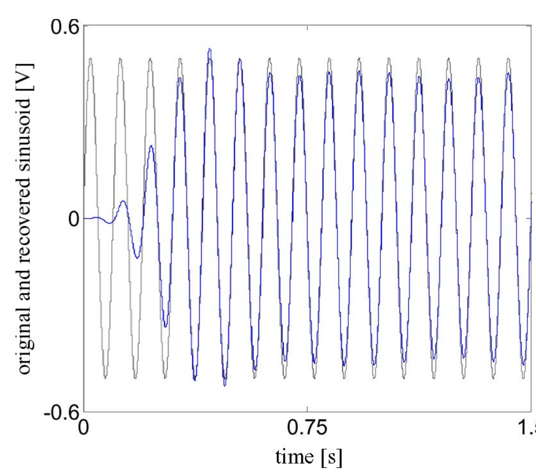


Fig. 10. Reference and recovered sinusoidal signals for a distance equal to zero.

However, the receiver of the sensor can receive spurious signals transmitted by other sensors. In this case, the sensor driver of the receiver generates a train of pulses consisting of the train of pulses generated by the transmitter, to which a new train of pulses is superimposed due to the aforementioned spurious signals. Consequently, the CPPD recovers a chaotic signal different from that generated in the transmitter, and the measurement method fails.

To cope with this problem, it is convenient to analyze the waveforms generated by the receiver of the system in the presence of a received signal consisting of pulses generated by

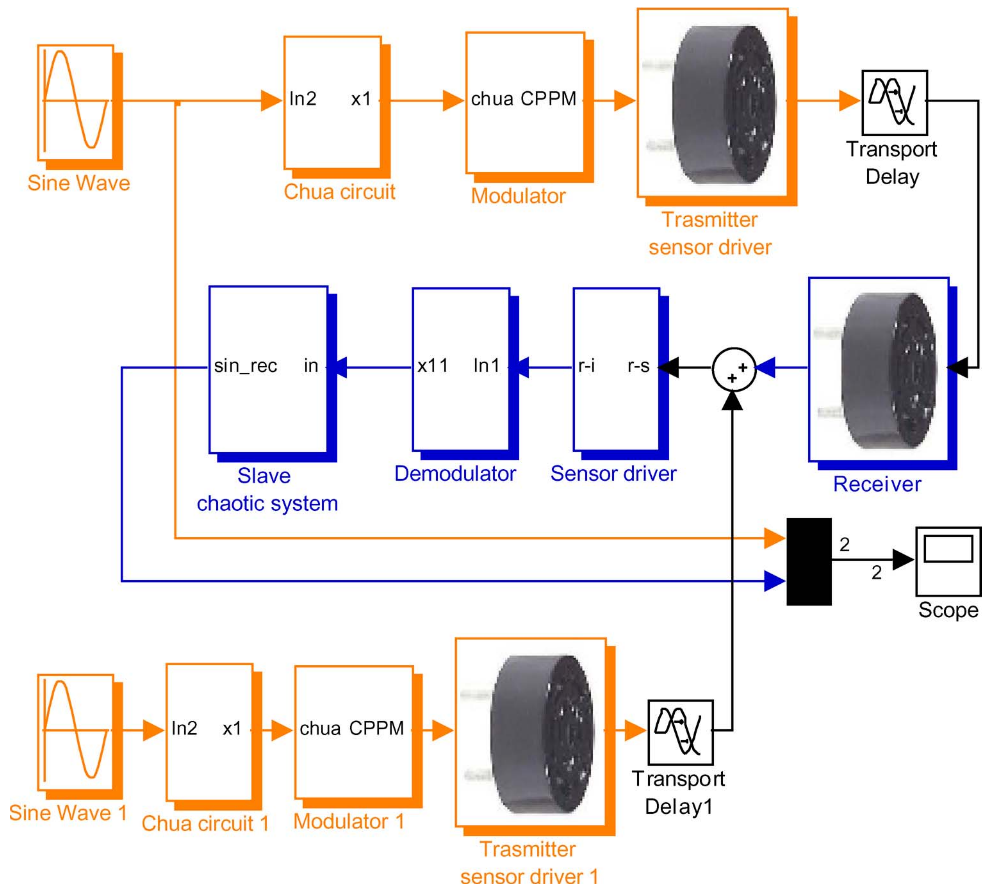


Fig. 11. Block scheme of the simulated system.

the transmitter and spurious pulses. Fig. 11 shows the block scheme of the simulated system. It is shown that the sensor driver of the radar system receives pulses generated by the transmitter and spurious pulses generated by a transmitter of another radar system whose chaotic system is not synchronized with that of the radar system in question. A delay of 0.011 s between the signals generated by the transmitter and those received by the receiver of the radar system is considered to simulate traveling and reflection by an obstacle of the signals themselves. The simulation results are given in Fig. 12.

Fig. 12(a) shows the waveforms of the chaotic signal generated by Chua's circuit in Fig. 11 and the signal recovered by the demodulator. Fig. 12(b) shows a zoom of the same signals in Fig. 12(a), where the recovered chaotic signal consists of a useful chaotic signal corrupted by pulses due to the spurious pulses received. Fig. 12(c) shows that the recovered signal is not suitable for recovering the sinusoid embedded in it; consequently, it is not suitable for distance measurements.

To avoid *crosstalk*, it is necessary to eliminate the pulses superimposed on the useful chaotic signal. To this end, it is convenient to examine the mechanism that produces these pulses. This can be done as in Fig. 12(d), which shows that the spurious pulses cause the ramp to reset before the correct time; consequently, they cause a discontinuity in the recovered signal. This problem can easily be solved via either hardware or software using a digital device. Two approaches, i.e., deterministic and probabilistic approaches, will be discussed.

A. *Deterministic Approach*

Assume that the generated and recovered information signals are acquired by a digital device. It is then possible to force the recovered chaotic signal to either maintain the previous value if the difference of the actual value reconstructed and the previous value is greater than a given threshold or update its value in the opposite case. The effects of this approach are shown in Fig. 13. Fig. 13(a) shows that the number of pulses superimposed on the useful chaotic signal is drastically reduced; moreover, the generated and recovered sinusoids are shown in Fig. 13(b). Fig. 13(c) shows a particular of Fig. 13(b), where the delay of the recovered sinusoid from the generated sinusoid is about equal to the delay imposed to the transmitted signal.

B. *Probabilistic Approach*

This approach is based on the assumption that the minimum value $v_{\min}$ of the modulating signal is known. Then, when the first pulse is recovered by the receiver, a ramp starts, and the time after which the successive pulse is expected $t_{\exp}$ is computed as follows:

$$t_{\exp} = \frac{v_{\min}}{m} \tag{7}$$

where m is the slope of the ramp. Then, to cope with the spurious pulses, it is sufficient to start a counter when the aforementioned ramp starts and not transmit all the pulses that arrive

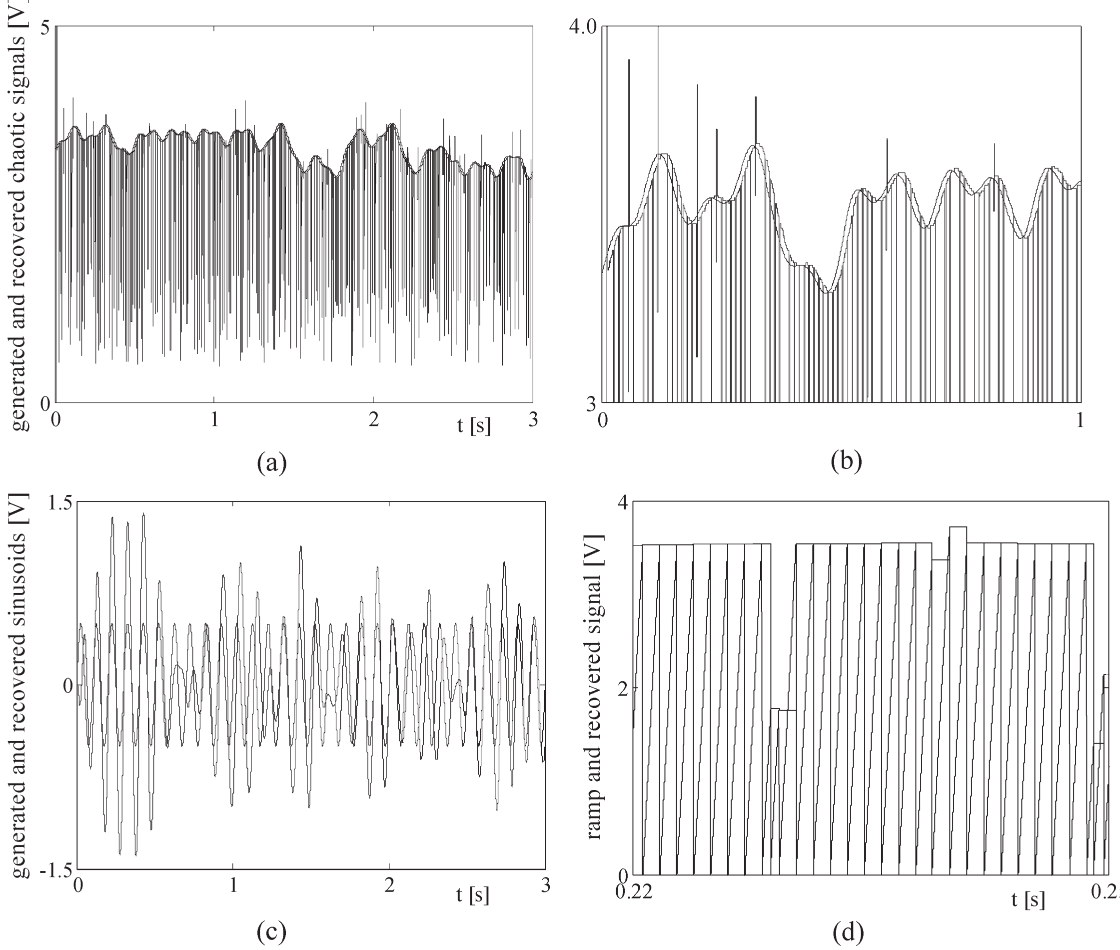


Fig. 12. Waveforms of some signals generated by simulation of the system in Fig. 10. (a) Generated and recovered information signals. (b) Zoom of the signals of (a). (c) Generated and recovered sinusoids. (d) Ramp and recovered information signal.

before $t_{\exp}$; after this, the first pulse that arrives is transmitted to the demodulator, which causes the reset and restart of the ramp. The results are similar to those previously obtained. This is shown in Fig. 14, where the generated and recovered sinusoids are displayed. These waveforms are the same as those shown in Fig. 13(b), except for the initial transients; the phase difference of the generated and recovered sinusoids is the same as that shown in Fig. 13(c).

Note that the implementation of the probabilistic method can easily be carried out via hardware on low-cost components. Moreover, several simulation experiments have shown that the described approach is also able to hook the correct sequence of pulses if the first pulse does not belong to the aforementioned sequence.

V. Performance of the Proposed Method

Some tests have been carried out, with the aim of verifying if the performances of the proposed method depend, in a crucial way, on both the amplitude and frequency of the reference sinusoidal signal. The results of these tests, which were performed for amplitude and frequency chosen in the ranges [0.5,1] V and [1, 10] Hz, respectively, showed that the value of the measured distance does not change. Obviously, a decrease in frequency implies an increase in the time required for the distance measurement; an increase in the amplitude causes greater excursions of the information signal and, consequently, an increase in the mean frequency of the modulated signal.

Other tests have been performed under different signal-to-noise (S/N) ratios, with the aim of verifying the performance of the proposed method. These tests have been carried out, assuming that the reference sinusoidal signal is generated by a stable oscillator, and consequently, the measurement noise is due to the crosstalk. In this paper, the S/N ratio is measured as the ratio of the spurious pulses captured by the sensor driver of the receiver but generated by other sensors and the pulses generated by the sensor under test. The results of these tests, corresponding to a delay time inserted in the path of the signal between the transmitter and the receiver of the sensor (cf. Fig. 10) that is equal to 0.01 s, are shown in Table I. This table has been constructed, considering the last 20 measures of the phase difference of the reference and recovered sinusoidal signals, in the time interval [1, 3] s, and computing the mean and the standard deviation (Std).

Finally, some tests aimed at studying the performance of the proposed method for detecting objects moving with radial velocity v_r relative to the ranging system have been carried out. Fig. 15 shows a result that refers to $v_r = 2/3$ m/s, assuming an initial distance corresponding to a time delay of 10 ms and omitting the initial transient, which, obviously, takes place only

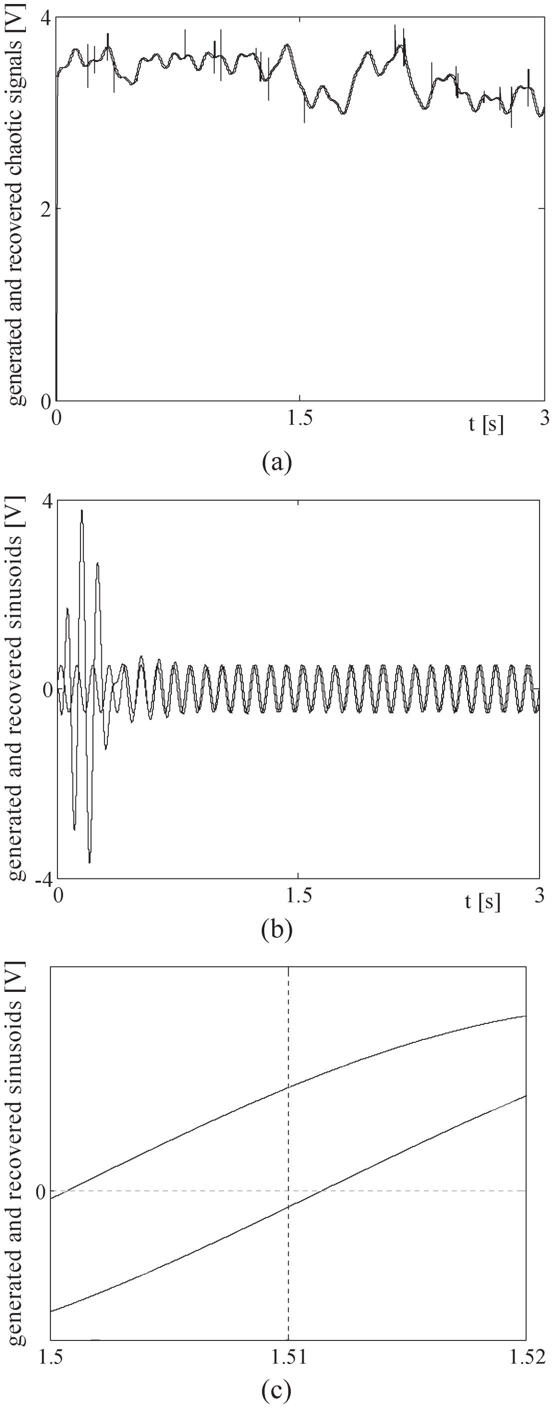


Fig. 13. Waveforms of signals generated into the radar system using the digital approach. (a) Generated and recovered chaotic signals. (b) Generated and recovered sinusoids. (c) Particular of (b).

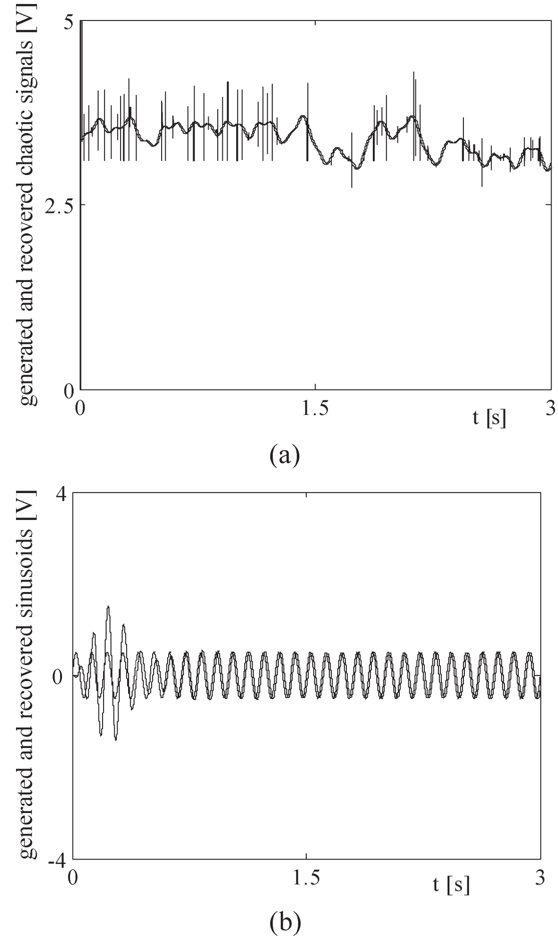


Fig. 14. Generated and recovered sinusoids. (a) Generated and recovered chaotic signals. (b) Generated and recovered sinusoids.

TABLE I
PERFORMANCE OF THE METHOD UNDER DIFFERENT S/N RATIOS

S/N	Mean	Std
0/2930	0.01	0.000173
296/2930	0.01005	0.000686
390/2930	0.01015	0.000822

at the beginning of the measurement process. Fig. 15 shows the reference delay, consisting of a constant part corresponding to vehicles at rest and a linear part corresponding to vehicles moving at the aforementioned indicated velocity, and the computed delay time between the reference and recovered sinusoids. This delay time is computed by measuring the time interval that elapsed between two successive crescent zero crossings of the two aforementioned sinusoids. In Fig. 15, for each pulse (broken line), the rising edge corresponds to the process for computing the aforementioned elapsed time interval. The top represents the measurement results, i.e., the delay time to be measured. The failing edge corresponds to the reset of the measurement process. During the second part of the reference delay waveform, the maximum tracking error is less than 4%. Note that this error also includes the Doppler effect, which, in this paper, is of minor importance due to both the small velocity of the vehicles compared with that of the sound and the small execution time of the measurement.

CPPM has also been employed in [14]–[16]. In [14] and [15], the cross correlation of the transmitted signal and the received echo is computed; it presents two peaks, whose distance in time is equal to the TOF of the transmitted signal. Computation of the cross-correlation function requires a time window width that is many times higher than the period of the reference sinusoid relative to the method described here.

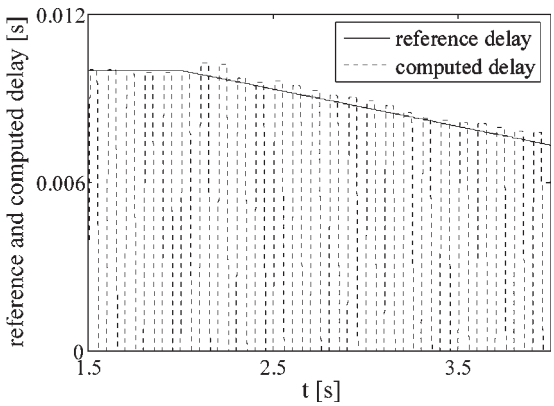


Fig. 15. Measurements for moving vehicles with a relative velocity of 2/3 m/s. The maximum values of the broken line waveform represent the computed delay between the reference and recovered sinusoids.

Consequently, the method based on the computation of the cross-correlation requires a measurement execution time that is many times higher than the method described here. Moreover, the cross-correlation computation is onerous and time consuming, whereas the computation of the delay between the reference and recovered sinusoids is simple and saves time.

The cross-correlation method allows overcoming the multipath fading problem [15], because the correlation peak due to direct reflection is much higher than other possible peaks due to multiple reflections of the same signal. The authors think that the method described in this paper is also able to cope with the multipath fading problem. This is because this method recognizes in advance the signal directly reflected and treats the other received signals, comprising the signal coming from multiple reflections, as spurious signals canceling them.

In [16], a method aimed at improving safety in communication systems that rejects, at the same time, noise and interference signals is described. The described algorithm employed for rejecting the interference signals, based on a windowing process around the expected arrivals of the useful pulses, could be included in the measurement scheme illustrated in this paper. However, the two approaches for rejecting crosstalk described in this paper are simpler and can be implemented on low-cost circuitry; moreover, they do not require the prediction of the arrival times of useful pulses and the generation of windows around these times for acquiring the useful pulses themselves.

VI. Experimental Setup and Result

The ultrasonic sensors used for the experimental setup consist of Elcart sensors with separate units for the transmitter and receiver; the essential characteristics given by the manufacturer are presented as follows:

Supply voltage (Max):	20 V
Cross sensitivity:	-67 dB $\pm$ 6 dB
Frequency:	40 kHz
Capacity:	1600 pF.

To obtain a signal that is suitable for driving the transmitter, a circuit has been realized based on two NE556 timers, which generate a CPPM signal consisting of a train of pulses whose duration and mean frequency are 122 μs and 1 kHz, respectively; when the signal is in the high state, a clock at a frequency of 41 kHz is enabled, and the generated signal is suitable for driving the transmitter. The receiver of the sensor displays the characteristics of a passband filter centered at 41 kHz. The received signal consists, as already stated, of a sequence of oscillating waveforms at the aforementioned frequency; this signal is rectified, filtered by a low-pass filter with a bandwidth of 10 kHz, and then applied to a threshold comparator that squares it. The output signal, which is given by a train of pulses, drives the demodulator.

The experimental realization of the Chua's circuit has been performed using an interconnection of three adder–integrator circuits, which implement (3); a saturation block, which implements the function

$$y(x) = 0.5\left(|x+1| - |x-1|\right)$$

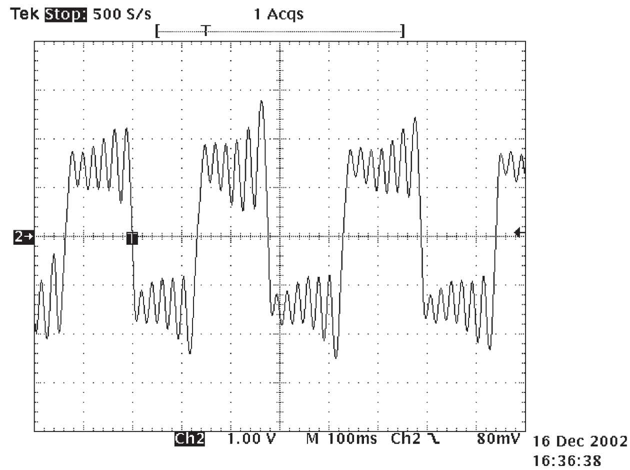
and an adder circuit, which implements the function $f(x)$. The adder–integrator circuits, saturation block, and adder circuit implementing $f(x)$ are realized using two TS914 integrated circuits, each containing four operational amplifiers (OPAs); another OPA is employed to realize an adder circuit to obtain the information signal, i.e., the sum of the chaotic signal x and the reference sinusoid. The experimental results regarding the chaotic signal x and the double-scroll attractor on the $x-y$ plane obtained by means of the master Chua's circuit, without the additional sinusoidal signal, are depicted in Fig. 16.

The CPPM has been realized as follows: The input stage is a buffer, followed by an OPA, which carries out the aforementioned addition of a constant signal, thus obtaining an always-positive modulating signal. An inverting integrator generates the ramp signal, which is compared with the modulating signal. The output of the comparator is a sequence of pulses, and the time interval between two successive pulses is proportional to the value of the modulating signal at the instant of the second pulse. The reset is carried out by means of a switch in parallel to the capacitor of the integrator.

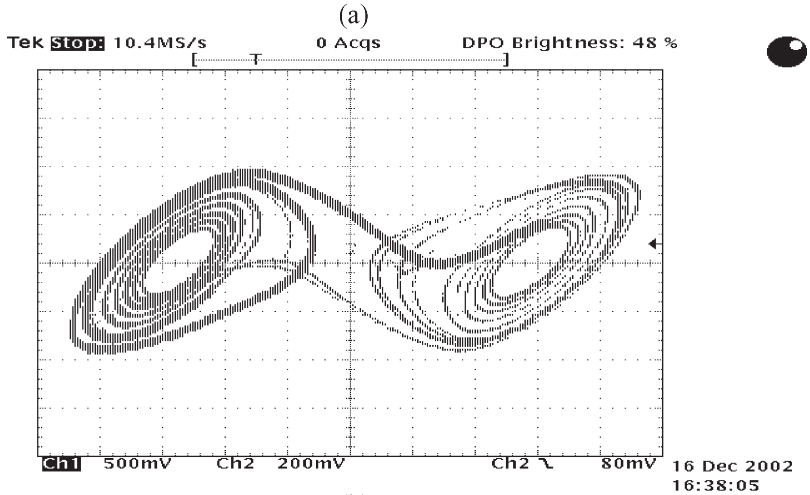
The demodulator generates a ramp with the same slope as that generated in the modulator at the beginning of a pulse of the received signal recovered from the sensor driver. The value of the ramp reached at the beginning of the successive pulse is equal to the recovered modulating signal. The information signal is then recovered by subtracting from this signal the aforementioned constant.

The recovered pulse sequence, the ramp generated in the demodulator, and recovered modulating signal are shown in Fig. 17. Fig. 18 shows the waveforms of the variable x generated by the master system and the same variable given by the slave system when it is supplied by the demodulated chaotic signal. Fig. 18 also shows the efficiency of the synchronization of the master and slave chaotic systems.

Finally, Fig. 19 shows the reference and recovered sinusoids when the transmitter and the receiver are placed face to face, i.e., at a distance equal to zero. Note that the reference sinusoid has been shifted slightly higher to distinguish it from the recovered sinusoid.



(a)



(b)

Fig. 16. Experimental results relative to the master Chua's circuit. (a) x versus time. (b) Double-scroll attractor on the $x-y$ plane.

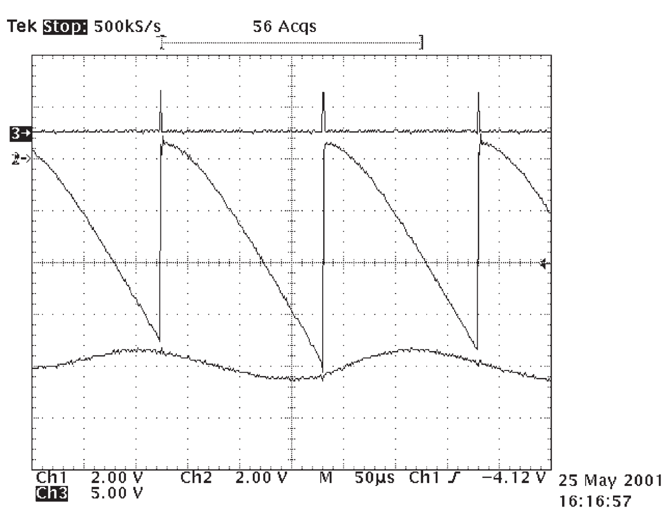


Fig. 17. (Upper trace) Recovered CPPM signal, (middle trace) ramp, and (lower trace) the recovered modulating signal.

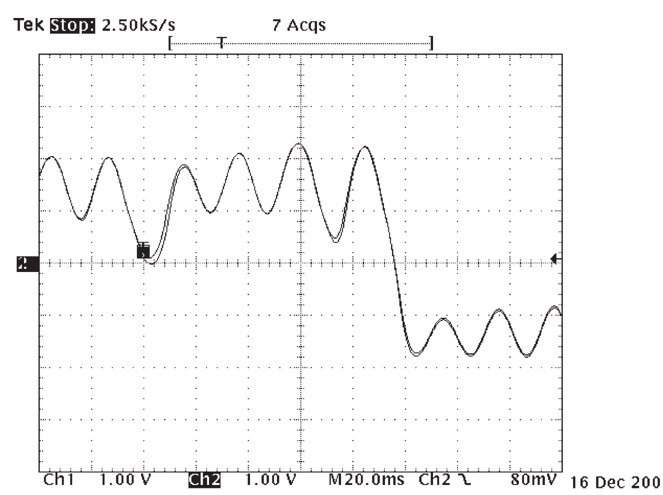


Fig. 18. Comparison between the signal x generated by the master system (under the synchronization symbol) and the same variable generated by the slave system using the synchronization scheme.

VII. Conclusion

This paper describes the theoretic and experimental aspects of a novel method of distance measurement based on ultrasonic sensors, which solves the *crosstalk* problem. To do this, advanced concepts such as chaotic signals, CPPM, synchronization of chaotic systems, and chaotic pulse position demodulation are employed together. The CPPM and demodulation allow recovery of the modulating signal shifted by the TOF and then the information signal shifted by the TOF without attenuation or amplification. This allows recovery of the reference

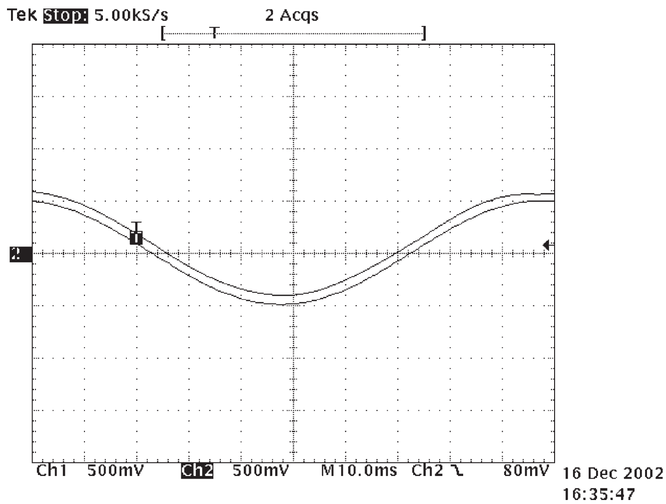


Fig. 19. (Upper trace) Reference and (lower trace) recovered sinusoids. (The reference sinusoid is shifted up for the sake of clarity.)

sinusoidal signal by subtracting the chaotic signal generated by the slave system from the recovered information signal. To cope with the *crosstalk*, two simple approaches, which can be implemented via either hardware or software based on the *cleaning* of the spurious pulses either after the recovery of the modulating signal (the deterministic approach) or before such a recovery (probabilistic approach), are proposed. The measurement method requires the use of ultrasonic sensors with separate transmitter and receiver units. Simple electronic circuits are needed for the experimental implementation of the approach in practice. Future developments could be the realization of the whole measurement system and the implementation of an algorithm that solves the problem of the *multipath fading*.

References

[1] M. Poloni, G. Ulivi, and M. Vendittelli, "Fuzzy logic and autonomous vehicles: Experiments in ultrasonic vision," *Fuzzy Sets Syst.*, vol. 69, no. 1, pp. 15–27, Jan. 1995.

[2] F. Russo and G. Ramponi, "Fuzzy methods for multisensor data fusion," *IEEE Trans. Instrum. Meas.*, vol. 43, no. 2, pp. 288–294, Apr. 1994.

[3] F. Alonge, G. Di Bernardo, F. M. Raimondi, F. Italia, and M. Lavorgna, "Fuzzy data fusion for real-world mapping using 360° rotating ultrasonic sensor," in *Proc. IFAC-IFIP-IMACS Conf. Control Ind. Syst.*, Belfort, France, May 20–22, 1997, pp. 447–452.

[4] J. Borenstein and Y. Koren, "Error eliminating rapid ultrasonic firing for mobile robot obstacle avoidance," *IEEE Trans. Robot. Autom.*, vol. 11, no. 1, pp. 132–138, Feb. 1995.

[5] K. W. Jorg and M. Berg, "Mobile robot sonar sensing with pseudo-random codes," in *Proc. IEEE Int. Conf. Robot. Autom.*, Leuven, Belgium, May 16–20, 1998, pp. 2807–2812.

[6] S. Shoval, I. Ulrich, and J. Borenstein, "Computer obstacle avoidance systems for the blind and visually impaired," in *Intelligent Systems and Technologies in Rehabilitation Engineering*. Boca Raton, FL: CRC, 2000, pp. 414–448.

[7] S. Shoval and J. Borenstein, "Using coded signals to benefit from ultrasonic sensor crosstalk in mobile robot obstacle avoidance," in *Proc. Int. Conf. Robot. Autom.*, Seoul, Korea, May 21–26, 2001, pp. 2879–2884.

[8] T. Yang, C. W. Wu, and L. Chua, "Cryptography based on chaotic systems," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 44, no. 5, pp. 469–472, May 1997.

[9] G. M. Maggio, N. Rulkov, M. Sushchik, L. Tsimring, A. Volkovskii, H. Abarbanel, L. Larson, and K. Yao, "Chaotic pulse-position modulation for ultrawide-band communication systems," in *Proc. UWB*, Washington, DC, Sep. 28–30, 1999.

[10] G. Kolumban, M. P. Kennedy, and L. O. Chua, "The role of synchronization in digital communications using chaos—Part II: Chaotic modulation and chaotic synchronization," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 45, no. 11, pp. 1129–1140, Nov. 1998.

[11] G. Kolumban, M. P. Kennedy, and L. O. Chua, "The role of synchronization in digital communications using chaos—Part I: Fundamentals of digital communications," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 44, no. 10, pp. 927–936, Oct. 1997.

[12] L. Fortuna, M. Frasca, and A. Rizzo, "Chaos preservation through continuous chaotic pulse position modulation," in *Proc. ISCAS*, 2001, pp. 803–806.

[13] T. Matsumoto, L. O. Chua, and M. Komuro, "The double scroll," *IEEE Trans. Circuits Syst.*, vol. CAS-32, no. 8, pp. 797–818, Aug. 1985.

[14] L. Fortuna, M. Frasca, and A. Rizzio, "Chaotic pulse position modulation to improve the efficiency of sonar sensors," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 6, pp. 1809–1814, Dec. 2003.

[15] L. Fortuna *et al.*, "System for detecting distances using chaotic signals," U.S. Patent 6 738 313 B2, May 18, 2004.

[16] H. Abarbanel *et al.*, "Chaotic carrier pulse position modulation communication system and method," U.S. Patent 6 310 906 B1, Oct. 30, 2001.

Francesco Alonge (A'01–M'02) was born in Agrigento, Italy, in 1946. He received the Laurea degree in electronic engineering from the University of Palermo, Palermo, Italy, in 1972.

He is currently a Full Professor of automatic control with the Department of Systems and Control Engineering, University of Palermo. His research interests include electrical drive control (including linear and nonlinear observers, stochastic observers, and parametric identification), robot control, parametric identification and control in power electronics, UAV motion control in aeronautics, and instrumentation and measurement systems.

Marco Branciforte was born in 1968. He received the M.E. degree in electronic engineering from the University of Catania, Catania, Italy, in 1996.

In 1996, he joined the International Institute of Volcanology, where he designed and built electronic circuits for remote sensing and volcanological signal processing. He is currently with the Automotive Product Group, ST Microelectronics, Catania, where he is a Researcher in the power train and safety field. He has worked on UWB radar for automotive applications. His current research interests include ABS systems.

Francesco Motta was born in Catania, Italy, in 1975. He received the B.E. degree in automation engineering from the University of Palermo, Palermo, Italy, in 2003.

Starting 2004–2006, he was a Professor with the University of Palermo. He is currently with Acheia s.r.l., Salemi, Italy, where he is a Manager in the biomass sector. His research interests include ultrasonic radar systems and control of electrical drives.