Revista Ciencias Técnicas Agropecuarias, Vol. 27, No. 2, 2018, E-ISSN: 2071-0054, http://revistas.unah.edu.cu

ORIGINAL ARTICLE

Fundamentals, Design and Evaluation of an Ultrasonic Proximity Sensor with Thermal Compensation

Fundamento, diseño y evaluación de un sensor de proximidad ultrasónico con compensación térmica

http://opn.to/a/YNrOQ

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ABSTRACT. The objective of this work was to design and evaluate, under controlled conditions, a proximity measurement system based on ultrasonic acoustic echolocation, for its implementation in agricultural engineering systems. Likewise, the relevance of the sound propagation speed depending on environment temperature is demonstrated. For that reason, the experiment was conceived to be executed under three different conditions of propagation environment temperature: 20°C, 30°C and 40°C. A range of measurement interval of 60 cm to intervals of one centimeter was studied. With the data coming from the estimate, derived from the measurement carried out, a statistical analysis was made that allowed establishing that estimated data sets at 20°C, 30°C and 40°C, respectively, have a high association degree with the data reference set employed as pattern, with a Pearson´s correlation coefficient of 0,99 in each case. For this reason, it is possible to affirm that, in the range of distances studied, the device to be evaluated is highly lineal (99 %), repetitive and it has a precision comparable with that of the instrument used as pattern.

Keywords: proximity measurement, ultrasound, acoustic echolocation, temperature, propagation environment.

RESUMEN. Este trabajo se ha propuesto el diseño y la evaluación, en condiciones controladas, de un sistema de medición de proximidad basado en ecolocalización acústica ultrasónica, para su implementación en sistemas de ingeniería agrícola. Así mismo, se demuestra la relevancia de la dependencia de la velocidad de propagación del sonido con la temperatura del medio. Para ello, fue concebido un experimento ejecutado bajo tres condiciones de temperatura del medio de propagación: 20°C, 30°C y 40°C. El sistema en cuestión fue estudiado en un rango de medición de 60 cm, a intervalos de un centímetro. Con los datos provenientes de la estimación, a partir de las mediciones realizadas, fue efectuado un análisis estadístico en el que se pudo establecer que las colecciones de datos estimados para los tres niveles de temperatura estudiados, presentaron un grado de asociación elevado con la colección de datos de referencia empleada como patrón, con un coeficiente de correlación de Pearson superior a 0,99 en cada caso. Por esta razón se puede afirmar que, en el rango de distancias sometido a estudio, el dispositivo a evaluado posee elevada linealidad (99 %), repetitividad, así como una precisión comparable con la del instrumento empleado como patrón.

Palabras clave: medición de proximidad, ultrasonido, ecolocalización acústica, temperatura, medio de propagación.

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Received: 13/10/2017
Approved: 14/03/2018

INTRODUCTION

The growing tendency to automate complex production systems requires the use of components that are capable of acquiring and transmitting information related to the production process. Therefore, sensors and transducers have met these requirements. For this reason, it has been essential that in the last decades, measurement and control technologies have been nurtured of increasingly sophisticated components (Gomez & Lopez, 2009).

In the contemporary world, technologies based on the use of ultrasonic waves are considered viable. Therefore, they attract the interest of its application in dissimilar fields of science and industry (Gomez & Lopez, 2009).

Ultrasound is nothing more than an acoustic wave whose frequency is above the limit perceptible by the human ear (around 20 kHz). In nature, some species of animals, such as dolphins and bats, emit pulses of high frequency sound, using the resulting echo to facilitate orientation and search for prey in the darkness. This phenomenon is known as acoustic echolocation (Rincón, 2008).

For proximity, distance and level measurements, the sensors based on ultrasonic acoustic echolocation are used. They work free from mechanical friction and detect objects at distances ranging from a few centimeters to several meters (Cuamatzi *et al.*, 2010).

There are potential advantages in the use of these kind of systems in applications such as food storage, control of fuel consumption, volume of water stored in tanks, dams, micro-dams and wells, among others.

In Cuba, no research is reported on the use of these kind of systems in the control and management of agricultural processes. In this work, a design of a proximity measurement system based on ultrasonic acoustic echolocation is proposed; and the results of its evaluation under controlled conditions, for its future implementation in agricultural engineering systems, are exposed.

THEORETICAL FUNDAMENTALS

The determination of distance by means of acoustic echo detection is based on the measurement of the time that passes between the sound emission stimulus and the echo return (Texas Instruments, 1989; Vida, 2004; Romero & Peretti, 2017). Therefore, the distance between the sound source and the object that causes the echo will be:

$$D = \frac{1}{2} v_s t, m \tag{1}$$

where:

v_s: sound propagation speed, *m/s*;

t: interval of time passed between the emission of the sound and the echo reception, s

As it can be seen in Equation (1), the distance to be estimated also depends on the propagation speed of the sound waves. Several authors (Resnick & Holliday, 1966; Gran, 1970a; Dixon & Massey, 1972; French, 1974; Álvarez, 1981; Kino, 1987; Díaz-Calvo, 1989; Colectivo de Autores, 1998; Vida, 2004), have indicated that the latter is closely linked to the environment propagation temperature, which is detailed below.

The propagation speed or phase speed of the longitudinal mechanical waves in an elastic environment is given according to Newton's formula (Resnick & Holliday, 1966; Álvarez, 1981; Yavorsk & Detlaf, 1983; Colectivo de Autores, 1998):

$$v_s = \sqrt{\frac{\beta}{\rho}}, m/s \tag{2}$$

where:

β: environment elasticity modulus, N/m^2;
ρ: environment density, kg/m^3.

In the case of being a solid environment, the elasticity modulus is known as Young's modulus (Resnick & Holliday, 1966). In a liquid or gaseous environment, it is called the volumetric elasticity modulus (Resnick & Holliday, 1966; Gran, 1970b; Dixon & Massey, 1972; Álvarez, 1981; Yavorsk & Detlaf, 1983; Kino, 1987; Colectivo de Autores, 1998) and it is defined as:

$$\beta = -V\frac{\partial P}{\partial V}, N/m^2 \tag{3}$$

where:

P: environmental pressure, N/m^2;
V: environment volume, m^3.

Now, the propagation of the longitudinal mechanic waves in a gaseous environment causes a fast gas particle vibration. In consequence, the resultant compression-expansion sequence of the gaseous environment can be considered an adiabatic process (Gran, 1970a; Álvarez, 1981; Yavorsk & Detlaf, 1983; Colectivo de Autores, 1998). According to this consideration and assumed that the gaseous environment acoustically perturbed has a similar performance to the ideal gases, since the transformations take place to ambient pressure and temperature (Rougeron, 1977; Faires, 1987); then the following is settled down. The dependence of the sound propagation speed in a gaseous environment and its temperature, have quadratic relation (Álvarez, 1981; Yavorsk & Detlaf, 1983; Colectivo de Autores, 1998) and their analytic formulation is:

$$v_s = \sqrt{\frac{\gamma R}{M_o}T}, m/s \tag{4}$$

where:

R: gases universal constant, $N \cdot m/mol \cdot K$;
M_o: average molecular mass of the gaseous environment, kg/mol;
T: absolute temperature of the gaseous environment, K.

Equation (4) can be stated in a simpler way, only in function of a well-known pair of sound propagation speed and air temperature. This way, taking as reference the sound speed to the temperature of 0 ^{0}C (273,16 K) that according to Gran (1970) it is 331,7 m/s, equation (4) is:

$$v_s = v_{so}\sqrt{\frac{T}{T_o}}, m/s \tag{5}$$

Now, substituting the equation (5) in (1):

$$D = K_o t\sqrt{T}, m \tag{6}$$

where:

$$K_o = \frac{v_{so}}{2\sqrt{T_o}} = 10{,}03\ m \cdot s^{-1} \cdot K^{-½} \tag{7}$$

Equations (4) and (5) express clearly that any device that uses the sound speed to estimate other parameters, as the distance (equation (6)), should keep in mind the environment propagation temperature.

METHODS

The evaluation of the device was carried out under controlled conditions, with a relative humidity of 80% and an atmospheric pressure of 100 kPa. It was carried out on a surface at level, in a closed space avoiding this way the disturbing influence of air currents and temperature variations. To guarantee a good echo reflection, a wooden plane surface (pine) was used in a rectangular way (20×15 cm) aligned perpendicularly to the axis of sensor emission.

The measurement cycle of the proposed device consists of five phases:

1. Environment propagation temperature measure;
2. Acoustic excitation (ultrasonic) of the propagation environment;
3. Acoustic echo (ultrasonic) detection;
4. Measurement of the acoustic echo (ultrasonic) return time;
5. Distance estimation at which the echo originates (from equation 6).

The output signal of the temperature transducer incorporated in the proximity sensor under study, has been conditioned to indicate a temperature range between 5 ° C and 55 ° C, in an electrical signal from 0 to 5 V (Motorola, 1978; Texas Instruments, 1989; Devices, 1999). For its calibration, a bulb thermometer with an accuracy of 1 ° C was used as a pattern instrument.

In order to guarantee a reasonably short blind zone, it was established that the acoustic excitation of the propagation environment lasted 0.5 ms. Likewise, to tentatively guarantee a measurement range of around 10 m, the maximum time interval for acoustic echo detection was 65 ms. In this way, the measuring cycle of the device was adjusted to 70 ms. That way, a latency time of at least 5 ms for the resting of the acoustic medium was guaranteed.

Independently of the fact that the probes used to manipulate the ultrasound signal allow the sensor to measure distances up to the order of meters, the device was evaluated in a range of distances restricted to 60 cm. This is due to the fact that the sensor is basically designed for the measurement of distances of that order, with a high linearity and immunity to the effects of variations in the environment propagation temperature. Similarly, the measurements were made at intervals of one centimeter, under the same conditions of relative humidity and atmospheric pressure, in a homogeneous acoustic environment. This procedure was applied in the same acoustic environment at three different temperatures.

The environment temperature values selected were 20 ° C, 30 ° C and 40 ° C, achieved from the environment irradiation with a lamp of infrared light of 350 W and 110 V, capable of emitting a radiation cone of 60 °. The selection of these temperature values to carry out the experiment is given because it is estimated that for potential sensor applications, the working temperature will be in the range of 20 ° C to 40 ° C.

The distances estimated from the procedure described in the preceding paragraphs were grouped into three data sets, according to the corresponding environment propagation temperature. Each data set includes the measurement result of the time passed between the emission of the ultrasonic pulse and the echo detection. Then, from it, the distance estimated in each case is determined according to equation (6).

For each experiment 40 samples were taken, that is to say a range of distances was studied of up to 60 cm to intervals of one centimeter, considering a blind area of 20 cm.

To obtain the reference data set, a metric tape with a precision of 0,1 cm was used like pattern instrument.

Later, the estimated data sets were compared statistically with the reference data set, from which linearity and repetition of the device were checked based on the determination, in each case, of the association degree between the estimated variables and the pattern variable.

For processing, analysis and presentation of the data obtained from experiments software Matlab 7.1 release 2008b was used.

RESULTS AND DISCUSSION

Keeping in mind the outlined theoretical fundamentals, the proposed proximity measurement system has a transducer of temperature AD595 incorporated. Besides, it has a pair of ultrasonic transducers 10CK40R/T for the emission / reception of the ultrasonic signal. The system also has the subsystems for the ultrasonic pulse generation and the echo detection that, in a combined way, allow measuring its return time. In Figure 1, the proximity ultrasonic sensor block diagram designed concerning these considerations is shown.

In Figure 2, the results obtained in the experiment, for the three environmental temperature conditions (20 ° C, 30 ° C and 40 ° C) foreseen in its conception, are shown.

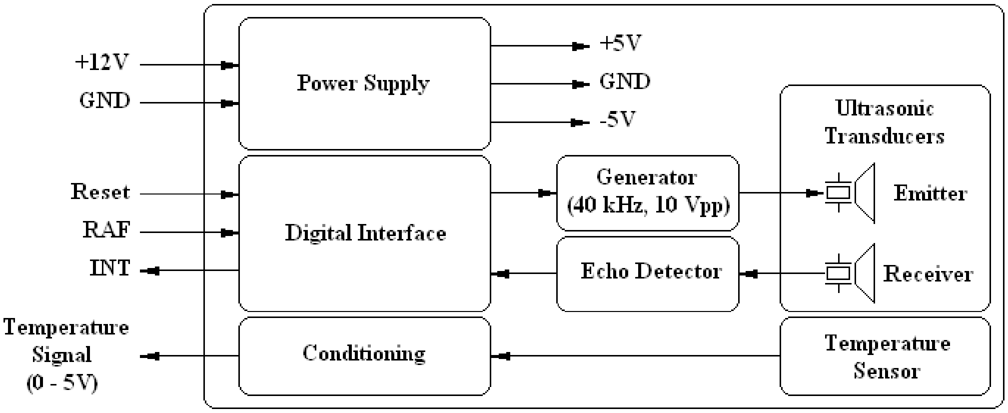

FIGURE 1. Block diagram of the ultrasonic proximity sensor studied.

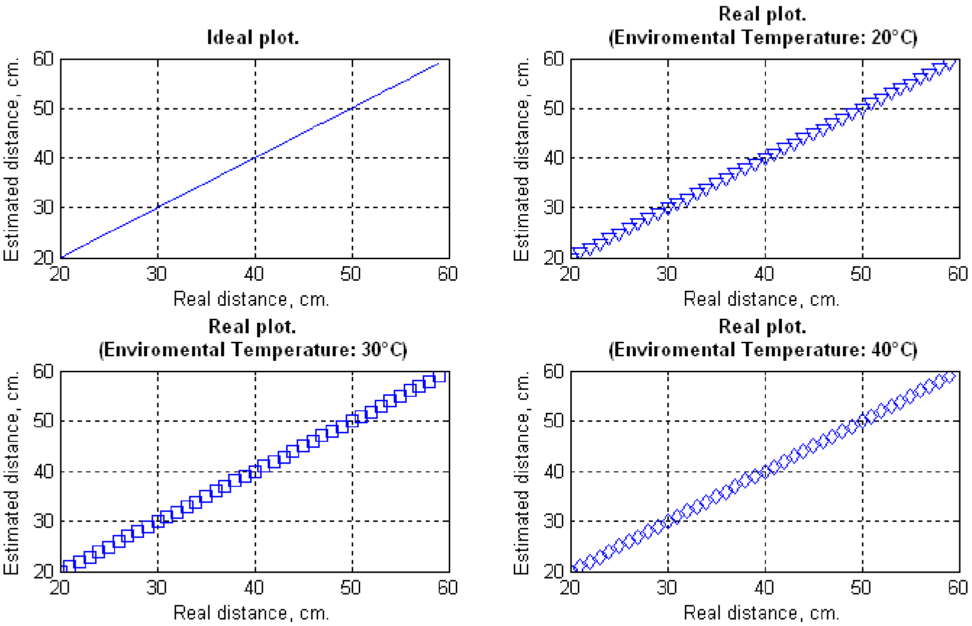

FIGURE 2. Graphs that relate the distance estimated in each case with the real distance (of reference).

In Table 1, it is shown the statistical summary of the data sets corresponding to echo return time measurements, under the three temperature conditions of the propagation environment provided for the experiment. There, it can be seen that, for the environment temperature range studied, the variation coefficient of the echo return time has a difference that can exceed 1.7%. This is due to the effect on the echo return time, of the increasing in the sound propagation speed with the increase in the environment temperature.

In Table 2, it is shown the statistical summary of both the data set of reference distance and the data sets obtained by distance estimation, based on echo return time measurements performed under the conditions marked. It can be seen that the variation coefficient of the estimated distance, in the environment temperature range studied, differs by less than 0.03% from one case to another. This observation illustrates the convenience of taking into account the environment temperature measurement for the distance estimation, as indicated by equation (6). This allows having an estimated variability in distance at least 57 times smaller than that obtained in direct measurement of the echo return time. This confirms that the sensor has a high immunity to temperature variations of the environment and, consequently, a high repeatability.

It is also appreciated, that there is a similarity between the estimated distance data sets. However, the determination of the association degree between the reference data set and each estimated distance data sets, allowed giving a conclusive character to this analysis (Dixon & Massey, 1972; Guerra *et al*., 2006).

To establish the association degree between the reference distance values set and the distance estimated values sets under environment temperature conditions of 20 ° C, 30 ° C and 40 ° C, an analysis was made from the Pearson´s correlation coefficient (Dixon y Massey, 1972; Guerra *et al*., 2006). Then, it was observed that there is a strong association degree between the estimated distances with environment temperature of 20 ° C, 30 ° C and 40 ° C and the reference distance, with a correlation coefficient in all cases of 0, 99.

These results are based on the accuracy achieved in the time base of the system. It also contributes, in this sense that, since the measuring range studied (60 cm) is relatively small, an almost perfect homogeneity is achieved in the propagation environment.

From this high value of association degree between the variables subjected to analysis, it can be affirmed that, at least in the range of distances under study, the device to be evaluated has high linearity (99%), repeatability, as well as a precision comparable to that of the instrument used as pattern.

TABLE 1. Statistical summary of the data sets corresponding to echo return time measurements

	20°C	**30°C**	**40°C**
Average echo return time, ms.	2,27678	2,25045	2,23223
Standard deviation , ms.	0,674806	0,667651	0,661778
Variation coefficient, %.	45,5363	44,5757	43,7950

TABLE 2. Statistical summary of the estimated distance data sets from echo return time measurements made

Data Set	**Reference**	**20°C**	**30°C**	**40°C**
Average, cm.	39,5000	39,4313	39,4303	39,4298
Stándard deviation, cm.	11,6905	11,6872	11,6987	11,69
Variation coefficient, %.	29,5961	29,6395	29,6693	29,6476

CONCLUSIONS

A proximity sensor was developed based on ultrasonic acoustic echolocation, equipped with the capability to work under conditions that involve variations in the environment propagation temperature. It was found that the distance estimated data sets at 20 ° C, 30 ° C and 40 ° C, respectively, have a high association degree with the distance data set used as a reference, with a Pearson´s correlation coefficient of 0 , 99 in all cases. In the range of distances under study, the device to be evaluated has high linearity (99%), repeatability, as well as a precision comparable to that of the instrument used as pattern.

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