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Ultrasonic method for measurement of mobile object coordinates

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Abstract

In this paper a new method for measurement of proposed is mobile object coordinates. For measurement of spatial coordinates of the object combination of different methods was use. With the on object mounted low-frequency ultrasonic transducer emitted signals are picked up by two ultrasonic receivers. Position of the object is determined by the binaural method. For improvement of accuracy and noise robustness the delay time of the ultrasonic signals is determined on-line using correlation processing. Algorithm for tracking of ultrasonic pulses in the time domain was developed. Analysis of the measurement uncertainties and the results of experimental investigation are presented.

Keywords: object coordinates measurement, ultrasonic measurement, binaural method, signal cross-correlation, calibration of the system, uncertainty of measurement

Introduction

In many fields for determination of the coordinates of various moving objects the laser based, television and ultrasonic system are used [1-4]. These systems differ in a performance speed, amount of the information obtained, accuracy and of course in price. There are a big variety of ultrasonic systems used for similar purposes. The advantages of ultrasonic systems are simplicity in use, low sensitivity to the dust, fog or poor vision conditions caused by environmental factors and a relatively low price.

The objective of ultrasonic mobile object position measurement is to determine two coordinates – *x* and *y* in a selected axis system. There are two different fields of application. The first is where the emitted ultrasonic signal is reflected from a moving object and reflected signal is received by two or more receivers. This method is often fused or mobile robots [5-7]. The second field is where the ultrasonic signal emitted by the on a mobile object mounted ultrasound transducer and received by two receivers. This principle is called as a binaural method. In this method the sender emits a short ultrasonic pulse and two receivers placed at some distance pick-up these signals. The object coordinates are calculated from the ultrasound propagation times between the transmitter and receivers.

In this paper a new method for measurement of mobile object coordinates at long distances (up to 20 m) is proposed. In the ultrasonic coordinate measurement system combination of different methods was used:

- the binaural method for determination of moving object coordinates;
- the coded ultrasonic sequence for signal generation;
- the cross-correlation method for signal processing.

The objective of the work presented is to determine the reliability and potential accuracy of such measuring system.

Problem and approach

For localization of a mobile object one of the simple principle used is a binaural method [8-11]. For realization of this method in air by means of ultrasonic waves an ultrasonic signal transmitter and two receivers placed at some distance from each other are necessary. The transmitting ultrasonic transducer must be mounted on a mobile object (Fig.1).

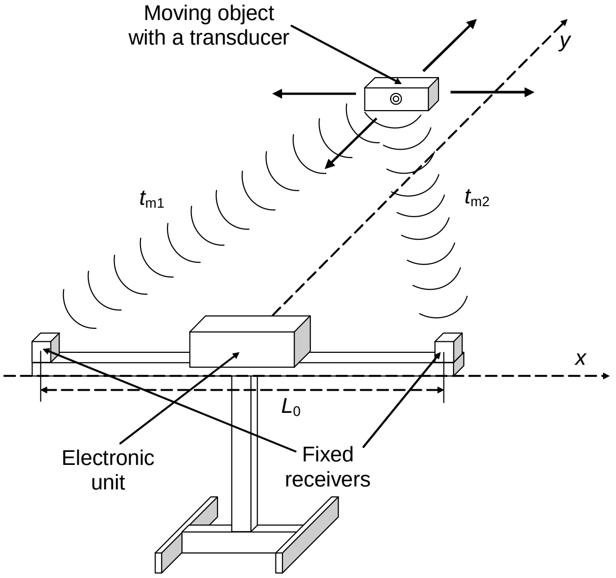

Fig.1. **Measurement principle of the coordinates of a moving object**

Then the coordinates of the mobile object at the point x_t, y_t can be calculated according to

$$x_t = \frac{c^2}{2L_0}\cdot\left((t_{m1}-t_d)^2-(t_{m2}-t_d)^2\right),$$
$$y_t = \sqrt{c^2(t_{m1}-t_d)^2-\left(x_t+\frac{L_0}{2}\right)^2}, \qquad (1)$$

where *c* is the ultrasound velocity, t_{m1}, t_{m2} are the measured delay times of the ultrasonic waves from the transmitter till the first and second receivers, t_d is the complete parasitic delay time in electronic and acoustic units, L_0 is the distance between the receivers.

Though it is a simple principle, but implementation of the binaural approach for measurements of coordinates at long distances meets some problems.

The ultrasonic unit mounted on a mobile object must be autonomous. Therefore there is a problem of a synchronization between the mobile unit and the fixed basic unit. To solve this problem the infrared signal is used. The mobile unit includes also the ultrasonic generator, which operates in a stand-by mode. When it receives the infrared signal from the basic unit, then it transmits the ultrasonic signal.

The second problem is the signal propagation at long distances. The signal amplitude depends an a signal frequency as $1/f^2$, where f is the signal frequency. Therefore, a relatively low-frequency ultrasonic transducer (40 kHz resonance frequency) is used. To compensation of attenuation and diffraction of ultrasonic waves the time varying gain is used.

In a measurement system workplace may be different electrical and other equipment. They emit periodical or white noise during the measurement. To overcome these problems it was proposed to use coded ultrasonic signals and correlation processing, which should be carried out on-line.

Additional measurement errors are due to temperature dependence of the ultrasound velocity in air and influence of air turbulence or convection flows. The ultrasound velocity variations caused by the temperature are compensated using a temperature sensor. Then the ultrasound velocity c is calculated according to:

$$c = A_T \cdot T + B_T \ , \qquad (2)$$

where A_T and B_T are the some parameters, T is the temperature calculated from the temperature sensor data.

In order to reduce measurement errors caused by air turbulence, it is necessary to accumulate and average a few measurement results. In medium range applications (20 m) the length of the received ultrasonic signal may reach up to 30000 sampling points. Processing of such sequences using conventional cross-correlation algorithms takes too much time and is not suitable for on-line measurements. For the solution of this problem the advanced cross-correlation method for estimation of the delay time of ultrasonic signals was developed. The essence of this method is that the calculation of the cross-correlation function was splitted into two steps:

- during the first step the coarse delay time estimation of the received ultrasonic signal is obtained;
- during the second step the position of the signal in the time domain is found by means of the conventional cross-correlation algorithm in the time domain, but calculations are carried out only in a very narrow window.

Solution of the described problems in the ultrasonic measurement system of mobile object coordinates was given in [12].

Implementation

The developed ultrasonic measurement system consists of the mobile unit with the transmitter of ultrasonic waves, IR receiver, digital signal processor (DSP) and the basic unit with two ultrasonic receivers, IR generator and DSP (Fig.2).

The ultrasonic pulse is generated using commercial 40 kHz piezoelectric resonant transmitters. The transmitter in the mobile unit is triggered by infrared signal, which is generated and sent by the basic unit. The infrared signal consists of 20 pulses with the repetition frequency 36 kHz. In order to avoid the influence of an acoustic noise the ultrasonic signal is the phase manipulated 40 kHz M–sequence. The M– sequence consists of 32 elements, duration of each element is 5 periods of the carrier. The ultrasonic receivers are placed at the distance L_0=1m from each other, which is called the base distance. The received signals are amplified and digitised by the analogue-to-digital converter in the basic unit. The digitised signals from the basic unit are processed in DSP using the cross-correlation method. The basic unit is connected to the host PC type computer by the serial RS232 interface.

The ultrasonic system is controlled using service and demonstration program. This program is used for set up of meter parameters, demonstration of the correct performance and for experimental measurements.

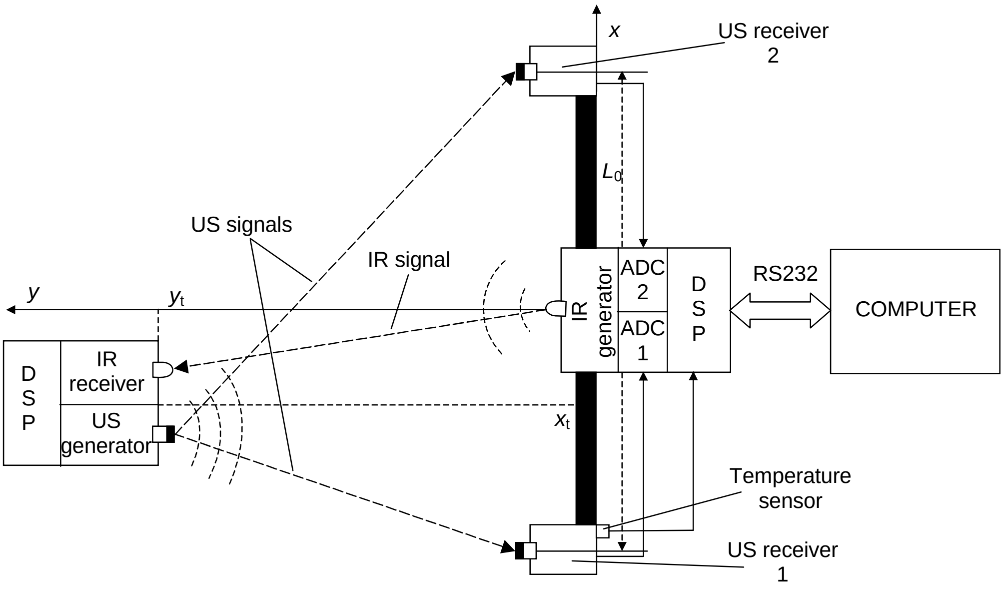

Fig.2. **The generalised structure of the ultrasonic measurement system of mobile object coordinates.**

The measurement process of mobile objects coordinates is performed according to the algorithm presented in Fig.3.

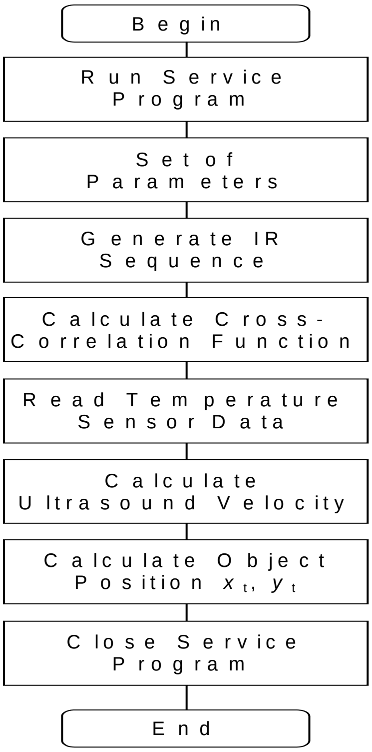

Fig.3. **The algorithm to the measurement of the mobile object coordinates**

The result of this algorithm are coordinates of the object x_t and y_t calculated from Eq.1.

Experimental results

The objective of the experiments was estimation of the measurement accuracy in closed spaces and determination of potential limits of measurements [13]. The measurements were performed in the following steps:

- calibration of the system;
- acquisition of the reference signal at the given position;
- measurements at the prescribed points along a few directions parallel to the measurement base at various distances from the ultrasonic receivers.

The aim of the calibration of the system was estimation of the parasitic delay time t_d in electronics and acoustics. For this purpose the reference signal was used. The reference signal was acquired at the distance L=1 m in front of the first receiver. The example of the reference signal is presented in Fig.4.

The distance between the transducer and the first receiver is determined by the cross-correlation method. The parasitic delay time t_d was determined by comparing mechanical and ultrasonic measurements and calculated according to the formula

$$t_d = t_{c1} - \frac{L}{c}, \tag{3}$$

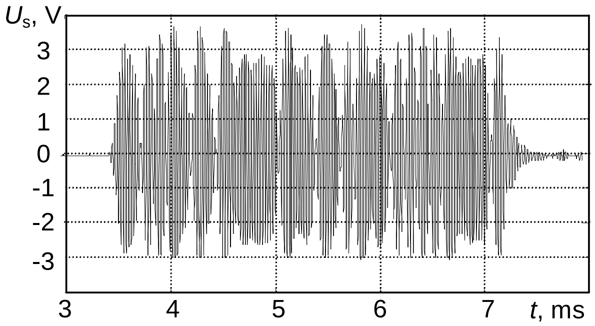

Fig.4. **The reference signal coded with M-sequence at the distance 1 m in front of the first receiver**

where t_{c1} is the measured delay time from the transmitter till the first receiver; L is the mechanical by measured distance between the transmitter and the first receiver, c is the ultrasound velocity calculated from Eq.2.

Experimental investigation was carried out in a closed hall. During the experiments measurements were performed at the distances 10 and 20 meters in the y-axis direction and up to 10 m with a step 2m in the x-axis direction. The actual positions of the mobile unit were determined by means of mechanical measurements. At each point ten measurements were carried out. Using a solid-state sensor DS1820 the measurement of the air temperature was carried out.

The absolute error of measurement results is presented in Fig.5. In this figure x_{mean} and y_{mean} coordinates represent the mean values of with ultrasonic system measurements coordinate's results and x_0 and y_0 - the mechanically measured coordinates. The results are presented at different distances - 10 and 20 m. The absolute error along the x-axis does not exceed 8 cm and from the y-axis – 13 cm in the range of the distances up to 20 m from the receivers and up to ±10 m from the symmetry axis.

The uncertainty of measurements of spatial coordinates was characterized by a standard deviation [14]. In our case the position of the active beacon is given by two – x and y coordinates, therefore the total uncertainty was determined from the uncertainties of measurements of x and y coordinates:

$$s(x,y) = \sqrt{s^2(x) + s^2(y)}\,. \tag{4}$$

The spatial distribution of these uncertainties is presented in Fig.6.

The experimental standard deviation of the measurements results with the ultrasonic system does not exceed ±0,09 m.

The real sector of the coordinates measurement, is determined from the measurements results at different points. This determined sector is shows in Fig.7. In the near zone this sector depends on directivity patterns of the used ultrasonic receivers. The selected receiver's directivity pattern width was $\pm45^{o}$ degrees. To cover $0\text{-}180^{o}$ sector in the horizontal plane the measurement system must be turned.

The parameters of the proposed ultrasonic system are achieved with the base distance 1 m. To achieve better metrological results a longer measurement base should used.

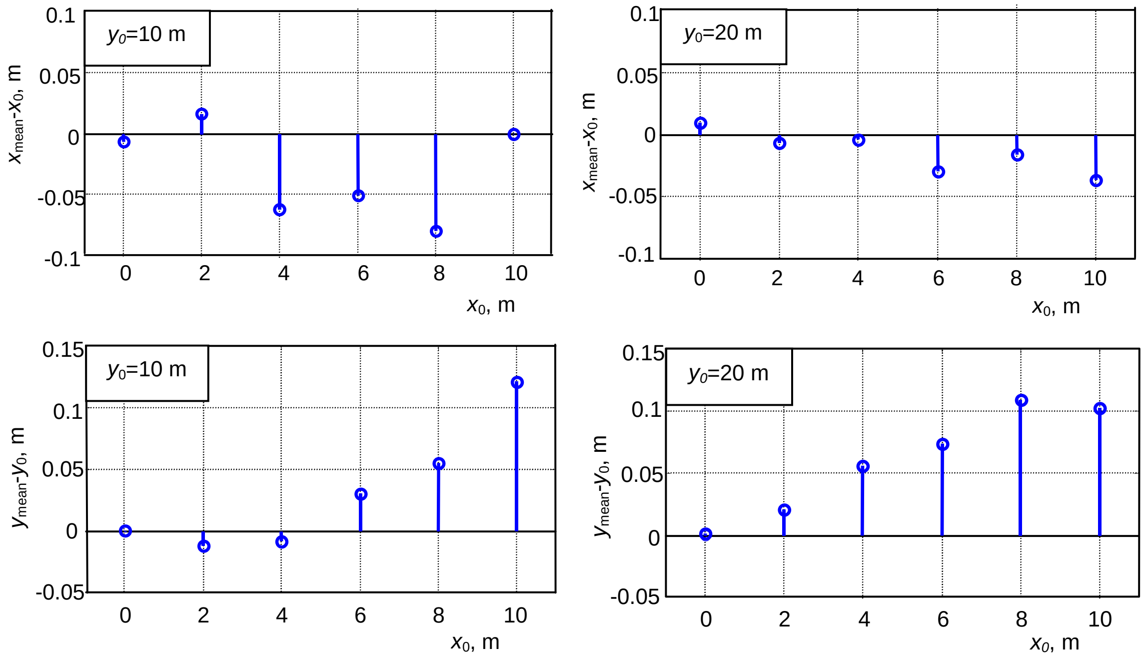

Fig.5. **Absolute measurements errors of the ultrasonic system at different distances**

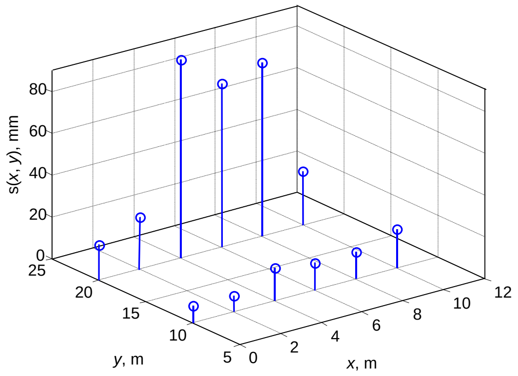

Fig.6. **The experimental standard deviation modulus**

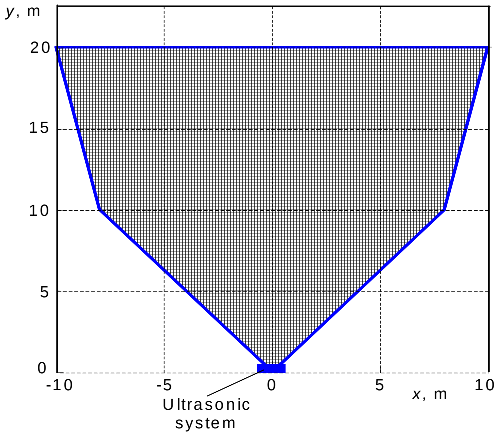

Fig.7. **Sector in which measurements of coordinates may be performed**

Uncertainties of measurements

The coordinates of the mobile object can be calculated according to Eq.1. Because all parameters are independent and uncorrelated then the standard uncertainties of the coordinate's measurements can be obtained from Eq.1 as

$$\begin{aligned} u(x) &= \sqrt{\begin{aligned}&W_c{}^2(x)\cdot u^2(c)+W_{L_0}{}^2(x)\cdot u^2(L_0)+\\ &+W_{t_1}{}^2(x)\cdot u^2(t_1)+W_{t_2}{}^2(x)\cdot u^2(t_2)\end{aligned}}, \\ u(y) &= \sqrt{\begin{aligned}&W_c{}^2(y)\cdot u^2(c)+W_{t_1}{}^2(y)\cdot u^2(t_1)+\\ &+W_{L_0}{}^2(y)\cdot u^2(L_0)+W_x{}^2(y)\cdot u^2(x)\end{aligned}}, \end{aligned} \tag{5}$$

where $u(c)$, $u(L_0)$ are the standard uncertainties of the velocity of sound and the distance between the receivers; $u(t_1)$, $u(t_2)$ are the standard uncertainties of the times of flight when $t_1=t_{m1}-t_d$ and $t_2=t_{m2}-t_d$.

The sensitivity coefficients of the coordinates x and y are given by

$$\begin{aligned} W_c(x) &= \frac{\partial x}{\partial c}=\frac{2x}{c}, \\ W_{L_0}(x) &= \frac{\partial x}{\partial L_0}=-\frac{x}{L_0}, \\ W_{t_1}(x) &= \frac{\partial x}{\partial t_1}=\frac{2xt_1}{t_1^2-t_2^2}, \\ W_{t_2}(x) &= \frac{\partial x}{\partial t_2}=-\frac{2xt_2}{t_1^2-t_2^2}, \end{aligned} \tag{6}$$

$$\begin{aligned} W_c(y) &= \frac{\partial y}{\partial c}=\frac{t_1^2 c}{y}, \\ W_{t_1}(y) &= \frac{\partial y}{\partial t_1}=\frac{t_1 c^2}{y}, \\ W_{L_0}(y) &= \frac{\partial y}{\partial L_0}=-\frac{x+\frac{L_0}{2}}{2y}, \\ W_x(y) &= \frac{\partial y}{\partial x}=-\frac{x+\frac{L_0}{2}}{y}, \end{aligned} \tag{7}$$

Taking into account Eq. 5, 6 and 7 we obtain

$$u(x)=\frac{c^2}{L_0}\sqrt{\begin{array}{l}\left(t_1^2-t_2^2\right)^2\left(\dfrac{u^2(c)}{c^2}+\dfrac{u^2(L_0)}{4l_0^2}\right)+\\+t_1^2u^2(t_1)+t_2^2u^2(t_2)\end{array}},$$

$$u(y)=\frac{1}{y}\sqrt{\begin{array}{l}t_1^2c^2\left(t_1^2u^2(c)+c^2u^2(t_1)\right)+\\+\left(x+\dfrac{L_0}{2}\right)^2\left(\dfrac{u^2(L_0)}{4}+u^2(x)\right)\end{array}}, \quad (8)$$

where the standard uncertainties of the delay times can be determined as

$$u(t_1)=\sqrt{u^2(t_{c1})+u^2(t_d)},$$
$$u(t_2)=\sqrt{u^2(t_{c2})+u^2(t_d)}. \quad (9)$$

$u(t_{c1})$, $u(t_{c2})$ are the standard uncertainties of the delay time calculated by cross-correlation method; $u(t_d)$ is the standard uncertainty of complete parasitic delay time.

The calculated standard uncertainties are: $u(L_0)$=0.29 mm, $u(t_{c1})$=1.9 µs , $u(t_{c2})$= 1.9 µs , $u(t_d)$= 1.9 µs , $u(c)$=0.18 m/s.

The numerical values of the calculated and experimentally determined measurement uncertainties in *x* and *y* directions are presented in Table 1.

Table 1. **The calculated and experimentally determined measurement uncertainties**

Coordinate (x,y), m	Calculated standard uncertainty		Experimental standard uncertainty	
	$u(x)$, mm	$u(y)$, mm	$u_E(x)$, mm	$u_E(y)$, mm
(0,10)	4,11	1,71	9,86	1,15
(5,10)	4,9	3,48	6,65	4,14
(10,10)	6,77	7,94	8,1	8,6
(0,20)	8,22	3,38	19,1	1,6
(5,20)	8,66	4,33	14,2	3,5
(10,20)	9,83	6,7	16,7	8,45

The experimental standard uncertainty of the measurements results obtained by the ultrasonic coordinate meter was calculated as:

$$u(k)=\sqrt{\frac{\sum_{i=1}^{n}(k-\bar{k})^2}{n(n-1)}}, \quad (10)$$

where k are the values of the measurement results, $\bar{k}$ is the mean of the n measurements.

Conclusions

The analyzed ultrasonic method for measurement of mobile object coordinates can reliably determine spatial coordinates in the range of the distances up to 20 m from the receivers and up to ± 10 m in a lateral direction. High robustness and the good accuracy of measurements were achieved due to application of ultrasonic coded sequences and correlation processing, which is carried out on line by a digital signal processor.

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Mobilių objektų koordinačių matavimas ultragarsiniu metodu

Reziumė

Pasiūlytas naujas mobilių objektų koordinačių ultragarsinis matavimo metodas. Erdvinėms koordinatėms matuoti panaudota kelių skirtingų metodų kombinacija. Judančiame objekte sumontuoto žemadažnio ultragarsinio siuntiklio spinduliuojami signalai priimami dviem ultragarsiniais ėmikliais. Objekto koordinatės nustatomos binauriniu metodu. Kad būtų tiksliau nustatomos koordinatės ir pagerėtų signalų atsparumas triukšmui, ultragarsiniai vėlinimo laiko signalai fiksuojami naudojant koreliacinį apdorojimą realiuoju laiku. Tam sukurtas naujas signalų apdorojimo algoritmas. Straipsnyje pateikti eksperimentinio tyrimo rezultatai ir įvertintos šiuo algoritmu nustatytų objektų erdvinių koordinačių matavimų neapibrėžtys.

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