ULTRASONIC BINAURAL METHOD FOR MEASUREMENT OF SPATIAL COORDINATES

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ABSTRACT

For measurement of spatial coordinates of the mobile object combined method based on ultrasonic binaural approach and infrared remote triggering was proposed. The source of low-frequency ultrasonic waves is fixed to the mobile object and is triggered remotely by infrared optical waves. The ultrasonic signals are picked up by two ultrasonic receivers and position of the ultrasonic source 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 results of experimental investigation are presented.

INTRODUCTION

In many applications it is necessary to determine position of mobile object with respect to the chosen reference point. For such purposes various ultrasonic techniques are exploited. One of the most popular approaches is use of active pulse echo sonar, however in environment with many targets detection of the necessary target may be not reliable enough.
The situation may be improved by means of active beacons fixed to the object, position of which should be measured. The active beacon transmits ultrasonic waves, which are picked up by a receiver situated at the known position. Recently for sonar applications binaural approach is used which enables to avoid scanning of ultrasonic beam and to increase speed of measurements [1-3]. However until now the binaural approach was not used for measurement of coordinates of active beacons. The objective of this investigation is development and analysis of the ultrasonic method, based on the binaural approach, for measurement of spatial position of the active beacon in air, fixed to a mobile object.

THE METHOD FOR MEASUREMENT OF SPATIAL COORDINATES

The proposed coordinate measurement method is based on a binaural principle. On the mobile object, coordinates of which are measured, a transmitter of ultrasonic waves is mounted (Fig.1). According to the binaural principle it is necessary to measure ultrasound propagation times t_1

and t_2 from the transmitter to two receivers (R1 and R2) placed at some distance from each other. The coordinates of the transmitter x_t, y_t can be calculated according to

$$x_t = \frac{c^2}{2L_0}\cdot\left(t_1^2 - t_2^2\right),$$
$$y_t = \sqrt{c^2 t_1^2 - \left(x + \frac{L_0}{2}\right)^2} \quad (1)$$

where c is the ultrasound velocity, t_1, t_2 are delay times of the ultrasonic waves from the transmitter till the first and second receivers, L_0 is the distance between the receivers.

Implementation of the binaural approach for measurements of coordinates in air meets some problems. Measurements may be performed only in the area, which is covered by overlapping directivity patterns of the transmitter and both receivers. It means that in order to have this area wide enough, the ultrasonic transducers must possess wide directivity patterns [3]. That leads to big signal losses caused by beam spreading and consequently to low signal/noise ratio. Additional measurement errors are due to temperature dependence of ultrasound velocity and influence of air turbulence or convection flows.

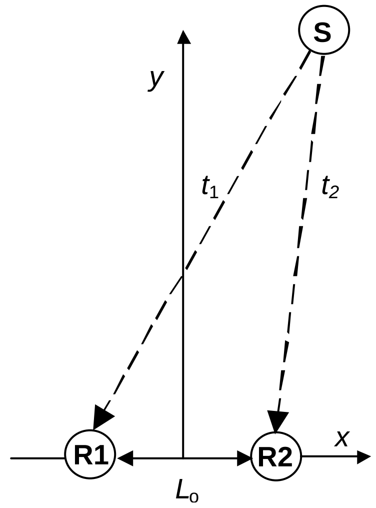

Fig.1. Measurement principle of the spatial coordinates of mobile object

In order to overcome these problems and to get a good noise robustness it was proposed to use coded ultrasonic signals and correlation processing, which should be carried out on-line [4,5].

IMPLEMENTATION OF THE METHOD

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

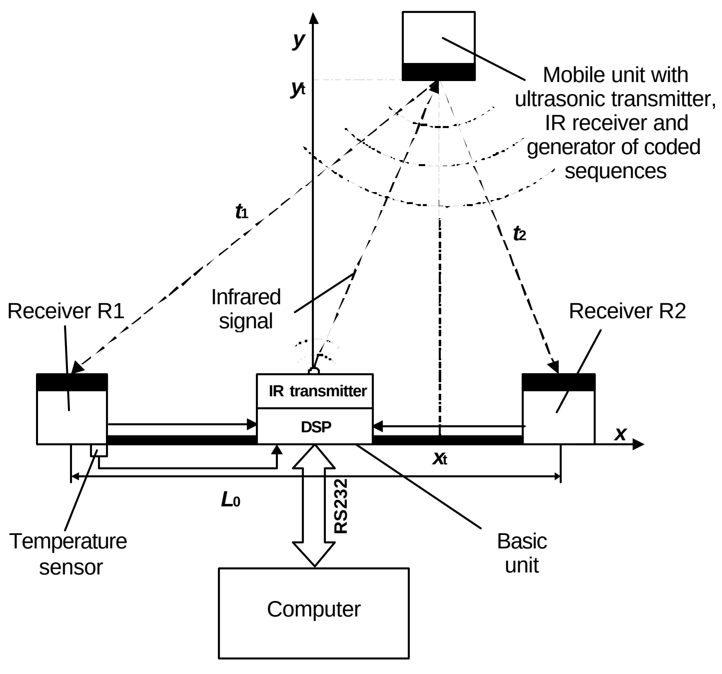

Fig.2. The structure of the ultrasonic system

The transmitter of ultrasonic waves 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 repetition frequency 36 kHz. In order to avoid the influence of an acoustic noise the 40 kHz ultrasonic signal is the phase manipulated by M – sequence. The M – sequence consists of 32 elements, duration of each element is 5 periods of the carrier. The receivers R1 and R2 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 analogue-to-digital converter in basic unit. The time varying gain is used for compensation of attenuation and diffraction of ultrasonic wave. The digitised signals from the basic unit are processed in DSP using cross-correlation method.
The basic unit is connected to the host PC type computer by a serial RS232 interface. The measurement errors caused by ultrasound velocity changes due to temperature variations are compensated using the temperature sensor mounted on the receiver R1.

SIGNAL PROCCESSING

In order to enhance noise robustness of the measurement system the received coded M-sequences must processed using correlation processing. Moreover, 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 (20m) the length of the received ultrasonic signal may reach up to 30000 sampling points (Fig.3). 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.

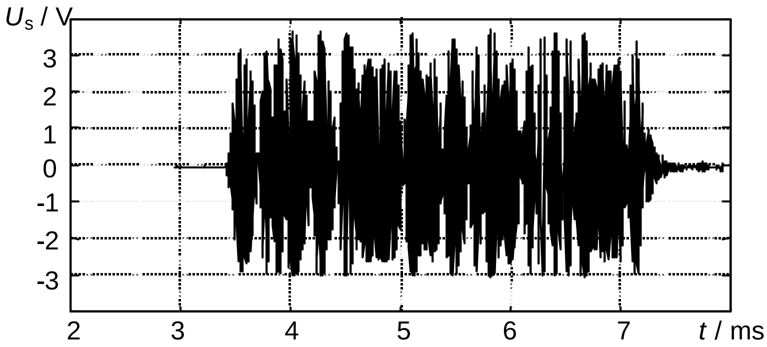

Fig. 3. Ultrasonic coded M-sequence received at 1 m from the mobile unit

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.

The duration of the first step depends on the distance and is longer for longer distances. The second step does not depend on a distance and is relatively fast. In the case of averaging the first step is performed only once for the first measurement. In averaging mode only the second step of algorithm is performed. Therefore, 10 measurements in averaging mode takes only 30% longer time then a single measurement.
Examples of cross-correlation functions obtained after the first step are presented in Fig.4a and b. In this figures it is possible to observe not only direct signal, but also signals reflected from other objects like floor (Fig.4c). The direct signal always is arriving the first, therefore in the case of a properly selected threshold level there are no ambiguity problems.

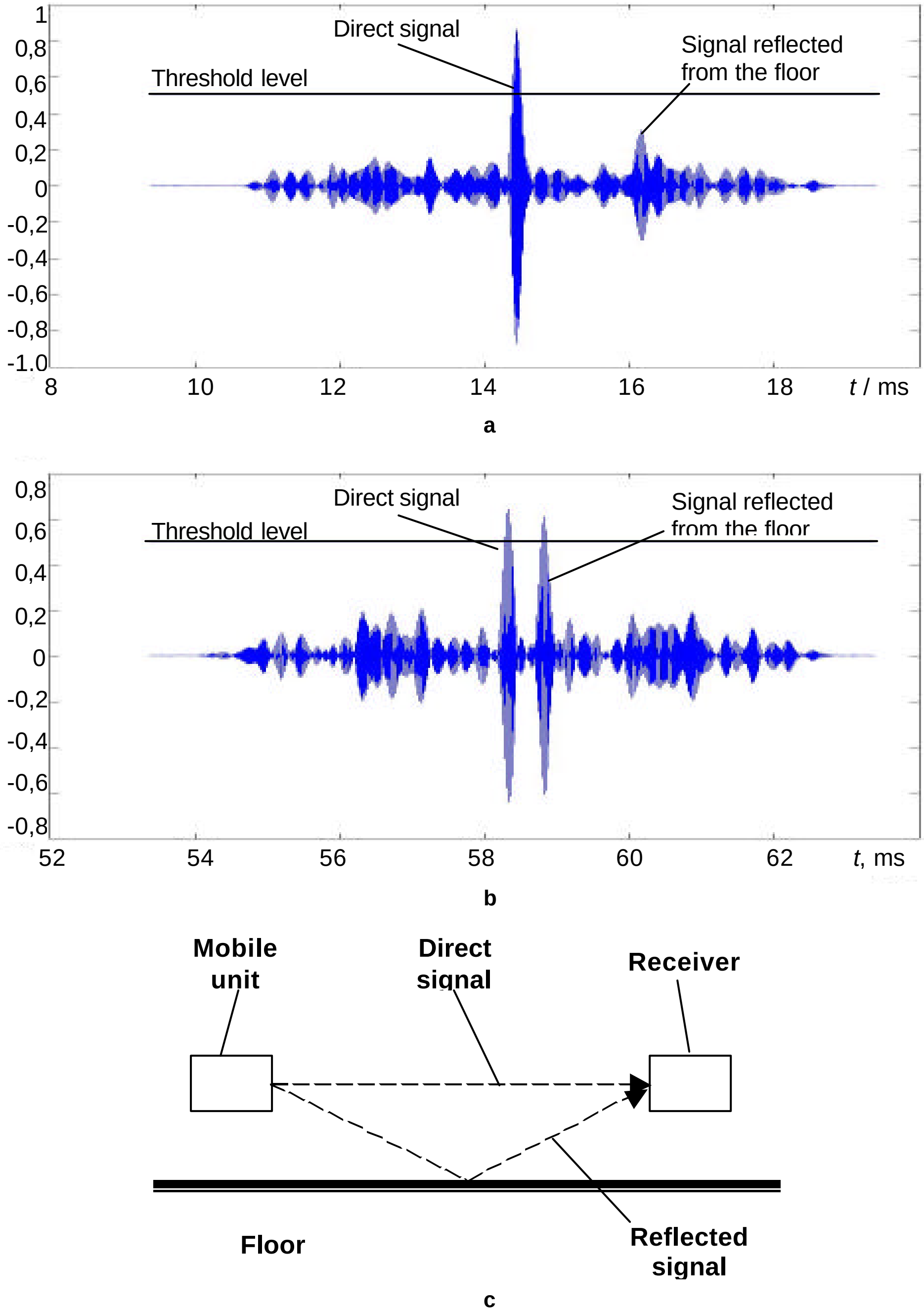

Fig.4. Cross-correlation function of the experimental measurement: a – short distance (5 m); b – long distance (20 m); c – propagation of ultrasound waves

EXPERIMENTAL INVESTIGATION

The proposed method and developed ultrasonic meter were investigated experimentally [6]. The objective of the experiments was estimation of measurement accuracy in closed spaces and determination of potential limits of measurements. Experiments were carried out in closed hall. The position of the mobile unit was changed step-by-step up to 20 meters in front direction from the receivers and up to 12m in the perpendicular direction (Fig.5).

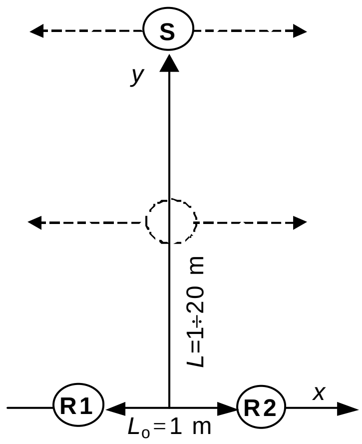

Fig.5. Scanning direction of the mobile unit during measurements

During the experiments measurements were performed at the distances 1, 5, 10, 20 meters in the *x*-axis direction and up to 10 m with a step 2 m in the *y*-axis direction. The actual positions of the mobile unit were determined by means of mechanical measurements. At each point ten measurements were carried out.

The uncertainty of measurements of spatial coordinates was characterised by a standard deviation. 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:

$$s(x,y) = \sqrt{s^2(x) + s^2(y)} \,, \qquad (2)$$

The spatial distribution of these uncertainties is presented in Fig.6. The origin of coordinates in Fig.6 corresponds to the position of the basic unit (Fig.2).

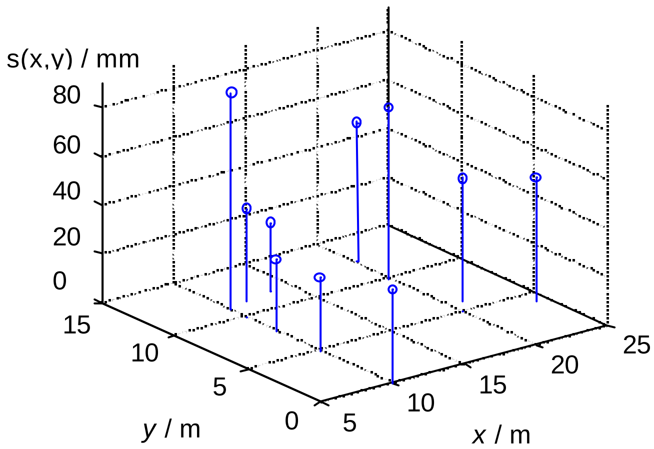

Fig.6. Graphical illustration of the experimental standard deviation modulus

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

Table 1

Coordinate (x,y), m		(0, 10)	(5, 10)	(10, 10)	(0, 20)	(5, 20)	(10, 20)
Calculated standard uncertainty	*u(x)*, mm	4.11	4.9	6.77	8.22	8.66	9.83
	u(y), mm	1.71	3.48	7.94	3.38	4.33	6.7
Experimental standard uncertainty	$u_E(x)$, mm	9.86	6.65	8.1	19.1	14.2	16.7
	$u_E(y)$, mm	1.15	4.14	8.6	1.6	3.5	8.45

Conclusions

The proposed ultrasonic binaural method enables measurement of spatial coordinates of mobile objects in air up to 20m. The best accuracy is obtained close to the symmetry axis of the measurement system and does not exceed 9mm in x direction and 20mm in perpendicular y direction even at 20m from the mobile unit. High robustness and 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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