Experimental investigation of performance of the binaural sonar

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Introduction

Sonars operating in ultrasonic frequency range are widely used as collision avoidance sensors in mobile robots. They also provide relatively cheap and reliable means for robot localisation and navigation [1-4].The survey of the environment and estimation of spatial coordinates of surrounding objects is performed exploiting directional properties of antennas used for radiation and reception of ultrasonic signals.

Using conventional techniques survey of surrounding space and determination of the coordinates of obstacles is performed by means of a narrow ultrasonic beam, which is sequentially scanned in the region of the interest. The narrower ultrasonic beam, the better measurement accuracy and angular resolution of the bearing angle is obtained. The main problem is that the time necessary for performing such a scan is relatively long due to a low value of ultrasound speed in air. This problem may be overcome using measuring techniques, which do not require narrow ultrasonic beams and, consequently, the number of individual scans may be significantly reduced. For this purpose two different approaches may be applied – the equidistant and the binaural methods. The equidistant method is based on measurement of the distances between the object and two ultrasonic transmitters-receivers placed at different positions. The position of the object is found as intersection point of two equidistant circular arcs.

In the binaural method at least three ultrasonic transducers are used, however, one of them only transmits ultrasonic waves and other two are used as receivers. The equidistant curves are two intersecting ellipses, however at long distances they may be approximated by circles. If the object detected is inside the directivity pattern of the ultrasonic transducers, the bearing angle and distance between the sonar and the object can be found from a single measurement.

As the distance between transmitter-receiver pairs are usually less than the distance till the detected object, the intersection of ellipses or circles occurs at a small angle. Because of that, the various factors influencing the distance measurements, can cause the essential errors of bearing angle measurements. The binaural approach is a rather simple when the single point type reflectors are analysed. In a real situation, when there are distributed in space reflectors such as walls, columns, etc., performance of the binaural method is lower.

This paper is devoted to experimental investigation of the smart binaural ultrasonic sensor for semi-autonomous vehicles and assembly carriers, developed in Ultrasound Institute of Kaunas University of Technology.

Compression of dynamic range

In order to increase robustness of the sonar in presence of industrial noise the special technique is used for the measurement of the time-of-flight. This technique is based on use of coded sequences and calculation of cross-correlation function [5-7]. Such a techniques possesses an excellent performance when the time-of-flight till a single reflector is measured. But in a real situation the amplitudes of the ultrasonic signals, reflected from different reflectors, may be very different. Therefore, strong signals may suppress low-amplitude signals from the weak reflectors in a close vicinity of the strong reflectors. In this case the weak reflector will be masked by a strong one and may be lost even in the case of conventional cross-correlation processing. In order to compress the dynamic range, normalisation of the cross-correlation function is used. However, instead of a conventional normalised cross-correlation function a special normalisation procedure inside a moving time window has been developed.

Duration of the window dt_w is selected slightly longer than the total duration of the coded sequence, used for measurements. Normalisation inside the window is performed according to

$$R_{n_{xy}}(t) = \frac{f_{cr}(t)}{\sqrt{K_r K_s(t)}}, \qquad (1)$$

where $f_{cr}(t)$ is the cross-correlation function between the received and reference signals, $K_r = f_r(0)$, $f_r(t)$ is auto correlation function of the reference signal, $K_s(t)$ is the time dependent normalisation coefficient, value of which depends on the energy of the received signal inside the moving time window. When a high level signal is received, the corresponding normalisation factor is also increasing, what results in reduction of the values of the normalised cross-correlation function. Contrarily, at low signal levels the normalised cross-correlation function is increasing. That results in compression of a dynamic range and better detection of weak reflectors.

The correlation functions obtained using the conventional and the proposed normalisation are shown in Fig.1. The results presented indicate that using the proposed approach weak reflectors are revealed much better than in the case of the conventional normalisation. For example, most of the peaks in Fig.1c exceed the level 0.6-0.7, even those which in the case of conventional normalisation are below the level 0.1.

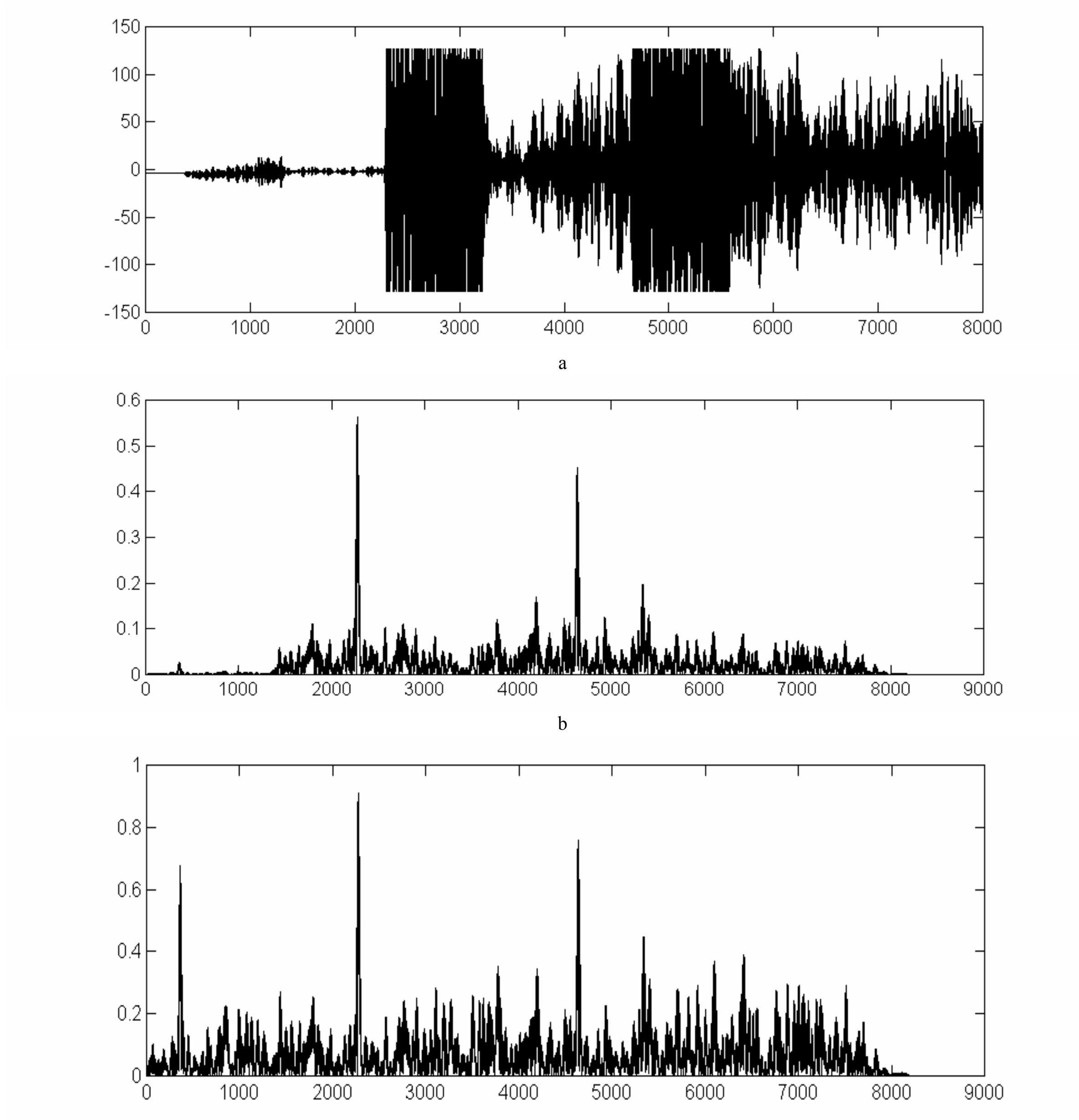


Fig.1. **The raw ultrasonic signal (a), conventional normalised cross-correlation function (b)and the moving window normalised cross-correlation function (c)**

Experimental results

Objective of experiments carried out in Ultrasound research centre, Kaunas University of Technology (Lithuania) was evaluation of a performance of the developed ultrasonic sensor. During these experiments a spatial resolution, accuracy of measurements of spatial coordinates and ability to detect and resolve objects, possessing very different reflectivity of ultrasonic signals were determined.

As it was mentioned above, dynamic range of the processed signal is significantly compressed if the cross-correlation function is calculated in a moving window and normalisation of the function is performed using time dependent normalisation factor. In order to check an efficiency of this algorithm in the case of objects of a complex geometry, experiments were carried out using the mock-up of the column, which are inside the De Montfort laboratory (Fig.2). Block diagram of the set up used for measurements is shown in Fig.2. The mock-up of the column was placed 2m from the transmitter of ultrasonic waves. The reflected signals were picked up by the ultrasonic receiver placed at different distances from the transmitter. In order to determine ability of the sensor to detect the column at different orientation angles, the mock-up was rotated in the angular sector $\pm 90^{\circ}$. During these experiments not normalised and normalised in moving time window cross-correlation functions were measured. The results of these measurements are presented in Fig.3. They demonstrate advantages of the proposed a normalisation in a moving time window. Variations of the peak amplitude of the normalised cross-correlation function do not exceed 30%, but variations of the absolute cross-correlation function reach up to 80%. Also, the obtained results indicate that the sensor is able to detect column at almost all orientation angles.

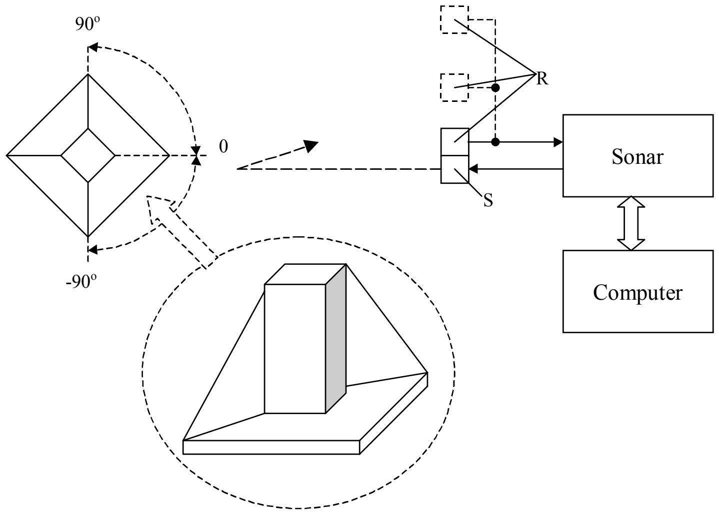


Fig.2. **Measurement set up and the mock-up of the column**

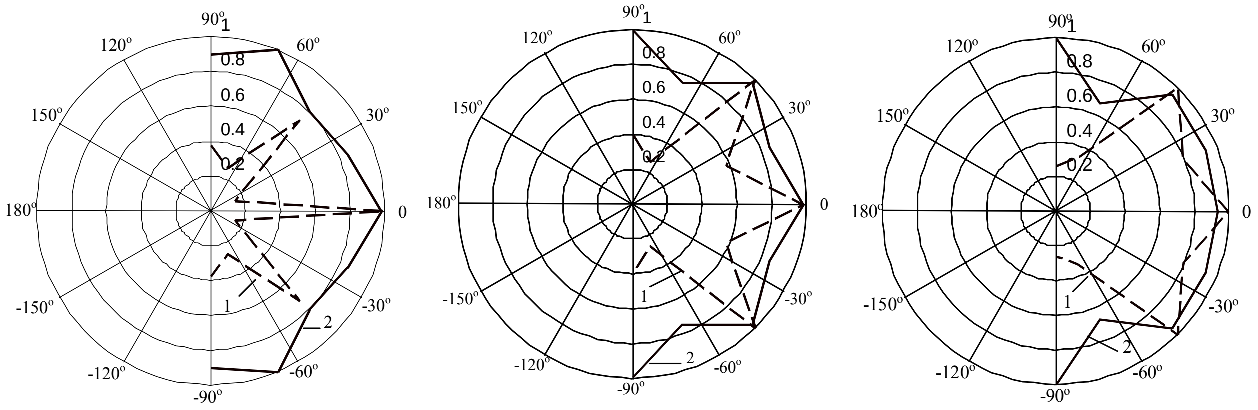
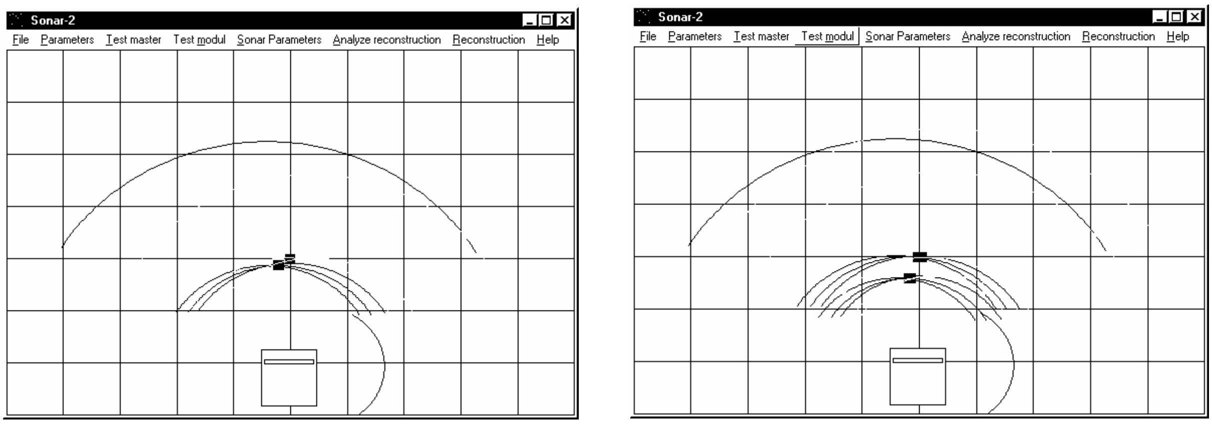


Fig.3. **Scattering diagrams of the column, shown in Fig.2. Solid line corresponds to the peak value of the normalised cross-correlation function, dashed line corresponds to the absolute cross-correlation function: a – distance between the transmitter and receiver 0m; b - 0.225m; c - 0.45m**

The performance of the ultrasonic sensor is characterised by a spatial resolution, accuracy of measurements and ability to determine boundaries between border of a reflector and an empty space. There are two parameters characterising the spatial resolution - a lateral resolution and the depth resolution. The spatial resolution is the minimal distance between two point type reflectors at which the sensor still can resolve them as separate reflectors. This resolution experimentally was determined using two point-type reflectors, located at different distances from the ultrasonic sensor. The image of the environment obtained in this case by means of the sonar is shown in Fig.4. It has been found that lateral and depth resolutions of the sensor is better then 10cm. If the distance shorter, then two reflectors are observed as one object.



a

b

Fig.4. **Image of two point-type reflectors obtained with the developed ultrasonic sensor: a – distance between reflectors 0.2m; b- distance between reflectors 0.45m**

Accuracy of determination of spatial coordinates of obstacles in a general case depends on the location of the obstacles with respect to the sensor. It may be different at different points in the plane of measurements. The measurements usually are carried out in a horizontal plane, e.g., parallel to a floor. Uncertainty of spatial coordinates was determined using a point-type reflector, which was located at various points in front of the sensor. As a point-type reflector 60mm diameter cylinder was used. The cylindrical shape reflector in a horizontal plane possesses angular scattering diagram very similar to the scattering diagram of the point type reflector. The reflector was placed at the distances 1, 2 and 3m from the ultrasonic sensor and was shifted across symmetry axis of the ultrasonic beam. The results of experiments are shown in Fig.5. The dots indicate actual positions of the reflector; the crosses correspond to the positions of the reflector determined by the ultrasonic sensor. From the experiments follow that the uncertainty of measurements along symmetry axis of the sensor does not exceed ± 0.04m, across is less than ± 0.05m.

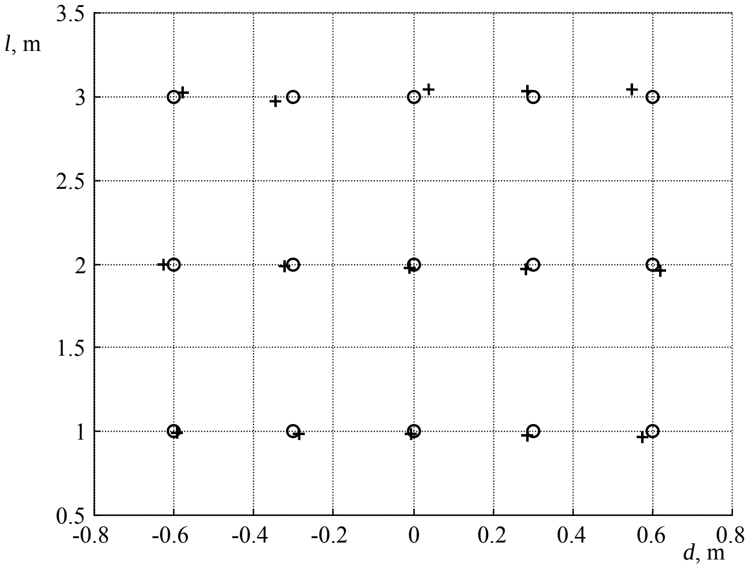


Fig. 5. **Accuracy of measurements of spatial coordinates of the point-type reflector: the dots (o) indicate actual positions of the reflector, the crosses (+) correspond to the positions of the reflector determined by the ultrasonic sensor**

Other problems arise in the case of planar reflectors. The first one is that a reflection strongly depends on the angle between the reflector and sonar. For bigger angles (>20°) the signal can be completely reflected away and does not arrive to a receiver. For small angles (<20°) the performance of the sonar is good and distance to the wall can be measured with errors less then 0.05 m as well the angle with errors less then 4°. The reconstructed wall positions for the perpendicular and inclined orientation are presented in Fig.6. For navigation of mobile robots it is very essential that the sensing system would be able to distinguish a border between plane obstacles and empty space. This task arises when the robot is navigating through a door. In order to determine ability of the sensor differentiate boundary between a planar reflector and empty space, experiments were carried out with the planar strip type reflector. The width of the reflector was 0.7 m, the height 1.4 m. At each distance the measurements were performed several times shifting the “wall” across measurement direction and determining the position of the wall boundaries. The results of measurements at different distances between the ultrasonic sonar and the planar reflector are presented in Fig.7. The dashed lines indicate actual position of the left and right edge of the reflector; the dots correspond to the mean value of 10 measurements.

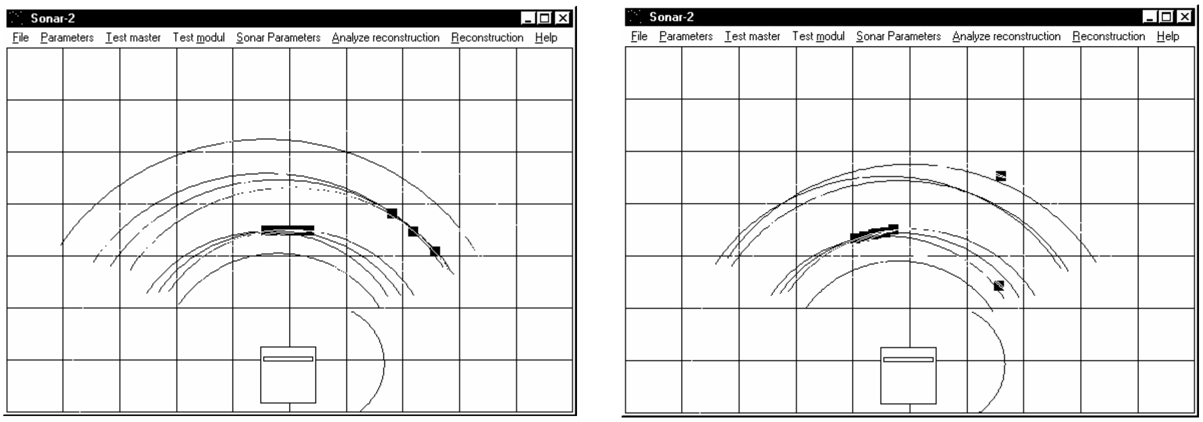


Fig. 6.**Reconstructed positions of the plane wall in perpendicular case and under the angle**

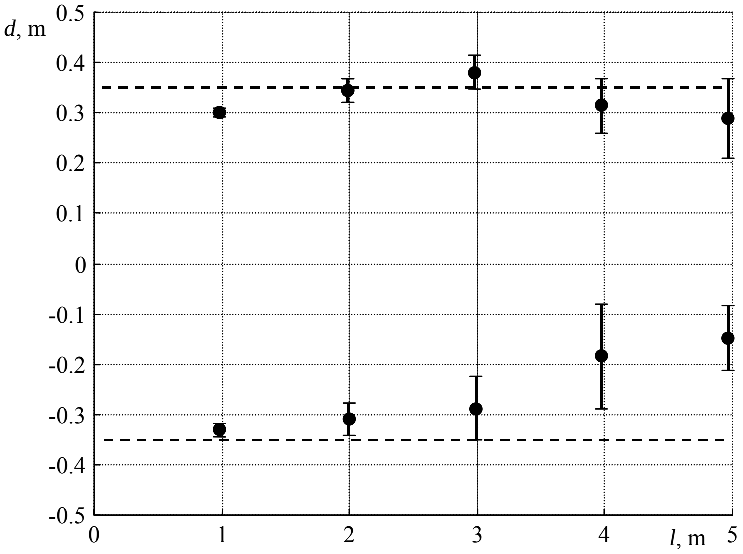


Fig. 7.**Estimation of the borders between boundaries of the planar strip-type reflector and empty space. The dashed lines indicate actual position of the borders, the dots correspond to the measurement results**

The vertical lines in the vicinity of the dots show standard deviation. The results presented indicate that at distances shorter than 2-3m the ultrasonic binaural sensor reproduces the border between a planar reflector and empty space with error less than 50mm, what is sufficient for navigation purposes. At the same time, the sensor enables to estimate the width of a planar strip. At distances exceeding 3m, the measured width is smaller than the true value, and variation of the measurement results is higher.

Conclusions

The experimental results obtained prove that performance of the ultrasonic binaural sensor is sufficient for navigation purposes of semi-autonomous vehicles.

Acknowledgments

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Binauralinio sonaro kokybės parametrų eksperimentinis tyrimas

Reziumė

Straipsnyje pateikti įvairių objektų erdvinių koordinačių nustatymo binauraliniu sonaru eksperimentinio tyrimo rezultatai. Matavimo objektais parinkti taškiniai reflektoriai (kampinis reflektorius, 0,05 m skersmens vamzdis), plokštuma (1,40x0,70 m) ir specifinės konfigūracijos kolonos maketas. Tirtas išilginis ir skersinis erdvinis skiriamumas, atkuriant šių objektų koordinates 1…5 m atstumu nuo sonaro. Nustatyta, kad, atkuriant taškinio reflektoriaus koordinates erdvinis skiriamumas 1…3 m atstumu išilgai sonaro simetrijos ašies yra ± 0,04 m, skersai – ± 0,05 m. Du šalia esančius taškinius reflektorius sonaras išskiria erdvėje, kai atstumas tarp jų didesnis nei 0.1 m. Sudėtingos konfigūracijos kolona užfiksuojama efektyviau, kai koreliacinei funkcijai normuoti naudojamas slankiojančio lango normavimo koeficientas.

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