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ADVANCED ULTRASONIC SONARS FOR NAVIGATION OF MOBILE ROBOTS

The overview of ultrasonic sonars suitable for navigation purposes of mobile robots is presented. Physical principles used in ultrasonic sonars and basic limitations caused by a nature of ultrasonic waves are discussed. For improvement of noise robustness coded sequences such as the Barker codes or maximal length sequences may be used. It is shown that application of quasi-orthogonal coded sequences and binaural processing enables improve a measurement speed in the case of a dynamic environment. For estimation of the performance of the binaural ultrasonic sonar a special software simulating behaviour of the sonar in a dynamic environment of an arbitrary geometric shape has been developed.

Examples of advanced ultrasonic sensors employing coded signals; correlation processing and the binaural and tri-aural measurement principle are discussed. The experimental results, illustrating performance of the sonar are presented.

1. Introduction

Ultrasonic sonars provide a cheap and reliable means for robot localisation and navigation [1-8]. Sonars detecting objects under water and measuring distance to them are in common use since almost 50 years. Their good performance is due to the fact that water is an excellent transmitting medium for an ultrasonic wave. On the contrary, air is a very unfavourable medium for the ultrasonic wave propagation. There are two principal reasons for that: very low acoustic impedance and a high attenuation, the latter being proportional to the square of the frequency. The first problem can be overcome using low impedance ultrasonic transducers. The possible solutions are based on application of electrostatic transducers, piezopolymer films and special piezoelectric transducers. The second limitation caused by attenuation and scattering of ultrasonic waves in air is reduced choosing the frequency of ultrasonic waves in the frequency range of (20-100) kHz.

2. Physical principles used in ultrasonic sonars.

The principle of operation of sonar is based on measurement the delay time τ_s of ultrasonic pulses, reflected by obstacles. The distance is found in the following way [5]:

$$l = \frac{c\tau_s}{2}, \tag{1}$$

where c is the velocity of ultrasonic waves in air. It depends on the temperature of air and is given by:

$$c = c_0\sqrt{1+\frac{T}{273}}, \qquad (2)$$

where c_0=331,45 m/s is the ultrasound velocity in air at T=0 °C, and the temperature T is in degrees of Celsius °C (Fig. 1).

The change of a temperature by ΔT=10 °C ultrasound velocity changes by Δc=5,7 m/s, e.g., 1.7%. That results in the distance measurement error also 1,7%. In some cases such an error can be too large. It is compensated by means of an additional measurement channel, which measures the ultrasound velocity or the temperature [5]. In both cases the correction of the measured distance is carried out by a microprocessor.

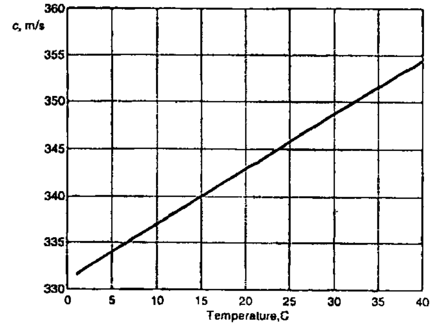


Fig. 1. Ultrasound velocity versus temperature in dry air

Attenuation of an ultrasonic wave in air is caused by absorption and scattering phenomena. The absorption itself is due to the classical absorption mechanism, which is for the viscosity and thermal conductivity of air, and also to the molecular thermal relaxation. The classical absorption coefficient is proportional to the second power of the frequency:

$$\alpha_{cl} = r f^2 , \qquad (3)$$

where f is the frequency, the factor r for air is $r = 1.24 \cdot 10^{-13}$ s²/cm.

The contribution of vibrational relaxation to the absorption is rather well predicted by the empirical formula:

$$\alpha_r = \frac{Mf'}{1+\left(\frac{f}{f'}\right)^2}, \qquad (4)$$

where $M = 1.25 \cdot 10^{-5}$ s/m is the empirical constant and

$$f' = k_1 h^{1.3} \cdot 10^4, \qquad (5)$$

is the relaxation frequency in Hz and k_1 is another one empirical constant. This part of the absorption coefficient strongly depends not only on the frequency but on relative air humidity h also. Higher humidity levels shift the relaxation frequency to higher frequencies.

The total absorption coefficient α is a sum of the particular absorption coefficients:

$$\alpha = \alpha_{cl} + \alpha_r . \qquad (6)$$

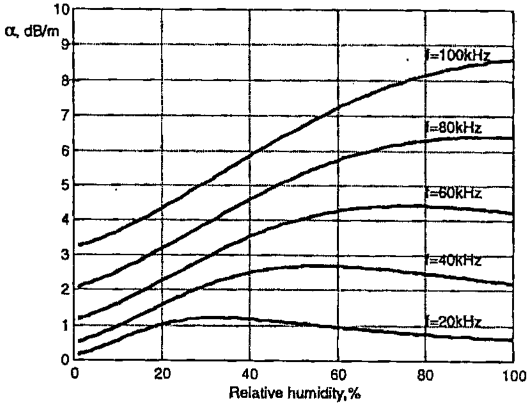


Fig. 2. Attenuation of ultrasonic waves in humid air at different frequencies

The total absorption coefficient α in air at $T = 20\,^{\circ}C$ versus humidity at different frequencies is presented n Fig.2.
From these calculations is possible to predict the minimal and maximal absorption coefficient values in air at different frequencies. For example, at $f = 60$ kHz:

$$\alpha_{min} = 1.3 \text{ dB / m}; \qquad \alpha_{miax} = 4.4 \text{ dB / m};$$

The losses in the pulse - echo mode due to the absorption for the distance $L = 5$ m are presented in Table 1.

Table 1. Losses of ultrasonic waves in humid air at different frequencies

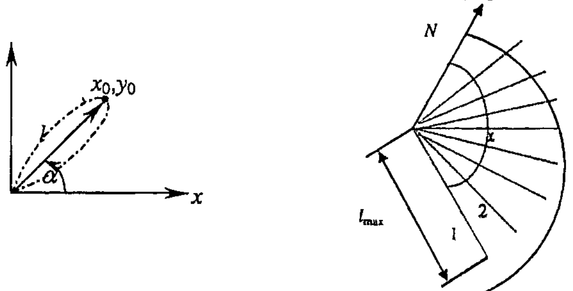
f, kHz	60	100	200
α_{min} , dB	13	20	52
α_{max} , dB	44	87	170

The results presented indicate that for ranging purposes in air it is rather unrealistic to use frequencies higher than $f = 100$ kHz.

The most common frequency range used for such purposes is (40 -60) kHz. Then the maximum distance at which an object can be detected by sonar of reasonably low power is of the order 20 to 30 m. That is entirely sufficient for robots operating inside buildings.
In the frequency range used for measurements due to a low velocity the wavelength of ultrasonic waves is rather short. For example, at the frequency f= 40 kHz, the wavelength is λ=9 mm. That enables with ultrasonic transmitters and receivers of reasonable dimensions to obtain a directional radiation and reception [5]. The survey of the environment and estimation of spatial coordinates of surrounding objects is performed exploiting directional properties of antennas used 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 (Fig.3). This can be performed either mechanically or electronically, but in the case of 2D survey only the electronic scanning should be used. Usually the position of the objects is given in polar coordinates in terms of a distance l and a bearing angle α (Fig.3a). 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. A single direction measurement requires a time [9, 11]

$$t_s = \frac{2l_{max}}{c_a} + \Delta\tau \,, \tag{7}$$

where $\Delta\tau$ is the additional interval between measurements in order to avoid an influence of multiple reflections. It is necessary to point out that a presence of the multiple reflections is an acute problem, because it can cause a false detection of the objects, which actually do not exist. Therefore, usually the interval between two subsequent measurements is increased by the time interval $\Delta\tau$ until the all multiple reflections reduce to a negligible level.



a

Fig.3. Sequential scanning of environment

The complete scan will take a time

$$T_s = N\left(\frac{2l_{\max}}{c_c} + \Delta\tau\right). \tag{8}$$

Here N is the number of ultrasound beam positions:

$$N = \frac{\Delta\alpha}{\Delta\beta_{0,5}}\ , \tag{9}$$

where $\Delta\alpha$ is the scanning sector and $\Delta\beta_{0.5}$ is the width of the directivity pattern at the 0,5 level. As it was mentioned beforehand, in order to obtain a good angular resolution and accuracy, the width of the ultrasonic beam must be small enough. For example, if $\Delta\alpha$=180°, $\beta_{0.5}$=10°, N=18, $l_{\max}$=5 m, $\Delta\tau$=10ms, then the duration of the single direction measurement is

$$t_s = \tau_d + \Delta\tau \approx 40 \text{ ms}. \tag{10}$$

One single complete scan of the 0 -180° sector takes a time T_s=18 × 40 = 0,72 s. During this time a mobile vehicle moving at the speed $v_{\max}$ will travel

$$l = T_s\, v_{\max} \tag{11}$$

which for $v_{\max}$=0.8m/s is 0.58m. It means, that due to a movement of the vehicle and a relatively low rate of measurements, the coordinates of objects detected are measured not in the absolute coordinate system, but in the coordinate system locked to the moving vehicle.

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 (Fig.4).

It is necessary to point out that each ultrasonic transducer is used both as a transmitter and a receiver of ultrasonic waves.

The position of the object is found as intersection point of two equidistant circular arcs (Fig.4).

$$(x - x_1)^2 + y^2 = l_1^2\ , \tag{12}$$

$$(x + x_1)^2 + y^2 = l_2^2\ , \tag{13}$$

where $\pm x_1$ are the coordinates of the ultrasonic transducers and l_1, l_2 are the distances between the ultrasonic transducers and the object. The coordinates of the object are found as the roots of the Eq. 12, 13 and are given by:

$$x = \frac{\left(l_1^2 - l_2^2\right)}{4x_1}, \tag{14}$$

$$y = \frac{1}{2}\sqrt{2\left(l_1^2 + l_2^2\right) - \frac{\left(l_1^2 - l_2^2\right)^2}{4x_1^2} - 4x_1^2}. \tag{15}$$

In this case no high angular resolution is required, therefore quite wide ultrasonic beams may be used.

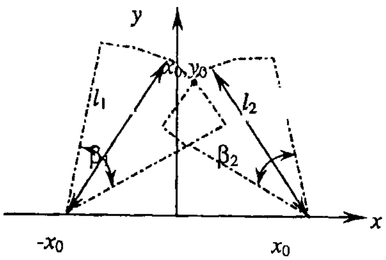


Fig.4. Equidistant method

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 [12-17]. If the object detected is inside the directivity pattern of the ultrasonic transducers, the bearing angle can be found from a single measurement. The equidistant curves are two intersecting ellipses, however at long distances they may be approximated by circles.

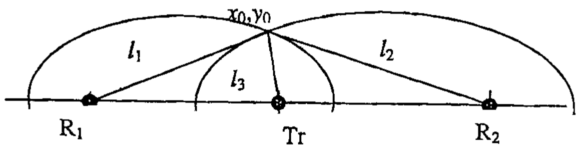


Fig. 5. Determination of the position of the reflector x_0, y_0 in one plane using binaural approach: the black dots indicate the positions of the transmitter Tr and the receivers R_1, R_2 correspondingly.

Directly the distances (l_1+ l_3) and (l_2+ l_3) are measured, which are found from the measured delay times $t_1$and t_2 , e.g., the times required for an ultrasonic signal to propagate from the ultrasonic transmitter to the reflector and back to the appropriate receiver:
In order to determine the position of objects in 3D space, two sets of ultrasonic transducers located in two perpendicular planes are required.

4. Ultrasonic transducers

Ultrasonic transducers are used as single elements or in phased arrays providing electronic scanning of am environment [18-27]. Until now the most popular ultrasonic transducers used in various applications possess active elements made from piezoelectric materials. Acoustic

impedance of piezoelectric ceramics is $30 \cdot 10^6$ kg/m^2 s, while that of air is $4.3 \cdot 10^2$ kg/m^2 s. This tremendous difference - 10^5 times causes large transduction losses.
One of the ways to solve this problem is to use capacitance or electrostatic ultrasonic transducers. The well known Polaroid transducers can be a good example. They operate in the frequency range suitable for applications in robotics (40-60 kHz) and possess a fairly good efficiency.
Recently, using micromachining technology, wide band electrostatic transducers for airborne ultrasound applications have been developed [18-20]. They usually consist of membrane coated by conductive material and rigid substrate. When polarizing and high frequency exciting voltages are applied between membrane and substrate, an electrostatic force arise, which sets the membrane into motion. Ultrasonic transducer consisting of a circular silicon nitride membrane and silicon substrate generates ultrasonic waves in the frequency range 1.8-4.6 MHz and possesses 20% bandwidth [19]. Instead of silicon polymer films such as Mylar can be used. The bandwidth achieved in the latter case is from 170 kHz to 1.9 MHz [18]. The main drawback of such transducers is that they are not yet commercially available and their frequencies are outside the frequency range used in sonars. Their reproducibility is bad and, as it was noted in [18], fabrication of the transducers with polymer films is more art than science.
The mismatch problem is solved using piezoelectric materials with lower acoustic impedance, or matching acoustic impedances of air and transducer by means of special matching layers. In the first approach novel materials like composite piezoelectric ceramics or piezopolymer films are used [23-25]. The acoustic impedance of piezoelectric composite material is $(4\text{-}10) \cdot 10^6$ kg/m^2 s, what improves matching of impedances a few times. The impedance of piezopolymer films can be even less, therefore, this type of transducers have been used for generation and detection of ultrasonic waves in air [22-23].
The PVDF transducers vibrating in the thickness mode are wide-band and can operate up to a few MHz [24]. The best performance in air is obtained at frequencies below 150 kHz. Then the bandwidth obtained is of order 20 -30 kHz [25]. The main drawback of the PVDF transducers is their lower efficiency compared with piezoelectric ceramics.
Usually, there is trade-off between efficiency and bandwidth: the more efficient transducers are resonant devices with high quality factors, what limits the frequency bandwidth. One of possible solutions is to exploit piezoelectric transducers, which are used in alarm systems, such as MURATA type transducers. They fulfil most of the requirements (cost, efficiency, frequency range), however their main drawback is a narrow bandwidth.

6. Application of orthogonal signals

Speed of measurements of ultrasonic sensors may be increased using for different directions different orthogonal coded sequences [8, 11]. These signals are emitted not waiting until the signal reflected by the most remote objects will arrive (Fig.6).
The transmitted ultrasonic pulses Tr.P1, Tr.P2 are mutually orthogonal signals, for which the following conditions are fulfilled:

$$E_{ij}(T) = \int_0^T f_i(t) f_j(t) dt = \begin{cases} E, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases} . \quad (16)$$

Here i, j are numbers of the transmitted pulses, E is the energy of the pulse, $f_i(t)$ and $f_j(t)$ are the waveforms. For this purpose such quasi-random signals as the maximum length-sequences (MLS) can be used. Due to the orthogonal properties of the signals caused by transmitted pulses at different directions, the multiple reflections received at the direction 2, but caused by the pulse transmitted at the direction 1 can be efficiently suppressed by means of the correlation processing.
At i-th direction the signals reflected by objects and caused the "correct" i-th transmitted pulse at the output of the receiver are given by

$$u_{out}(t) = \int_{t_1}^{t_2} \left[\sum_j u_j(t) \right] f_i(t) \neq 0 . \tag{17}$$

Correspondingly, at (i+1)-th direction for the multiple reflections caused by the pulse transmitted at i-th direction we shall obtain

$$u_{out}(t) = \int_{t_1+t_s}^{t_2+t_s} \left[\sum_j u_j(t) \right] f_{i+1}(t) \approx 0 , \tag{18}$$

e.g., due to orthogonal properties of the signals at the adjacent directions, the signals caused by multiple reflections are suppressed.

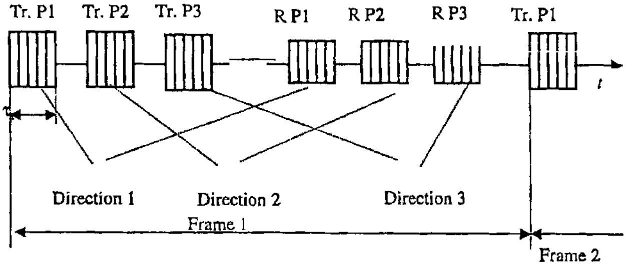


Fig.6. High speed scanning using quasi-random coded sequences:

In this case the speed of measurements may be increased up to

$$k = \frac{\tau_d + \Delta\tau}{\tau_i} \tag{19}$$

times. If f=40 kHz, and the pulse transmitted consists of 40 periods, the pulse duration is τ=1 ms and k= 40. Thus, the duration of a single complete scan of environment may be up to 40 times shorter than in conventional pulse-echo measurements.

In a noisy environment for ranging purposes coded signals like the Barker and Golay codes, maximum length-sequences (MLS) are used. MLS are quasi-random signals periodic in the time domain with a period possessing $(2^m - 1)$ different states, where m is the order of the sequence. The value of the current code element d_j is found from the values of m previous elements:

$$d_j = \sum_{j=1}^{m} a_j d_{m-j} = a \oplus a_1 d_{j-1} \oplus \ldots \oplus a_m d_{j-m} . \tag{20}$$

where $\oplus$ means adding by modulus 2, a_j are coefficients and d_j is either 1 or 0. Application of such signals enables to increase the energy of the ultrasonic signals radiated and to improve the signal/noise ratio. After the matched filter or the correlator these signals are compressed what ensure a good spatial resolution and accuracy of measurements. On the other hand, MLS are quasi-orthogonal, therefore they are well suited for the approach discussed before. However, in the case of ultrasonic systems operating in air ultrasonic transducers used for transmission and reception of the ultrasonic waves are narrow band devices and significantly distort the signals. That reduces a performance of such systems, especially based on the correlation processing.

In order to determine applicability of such signals in ultrasonic systems transmission and reception of binary phase-modulated MLS via band-limited ultrasonic transducers was investigated. The experiments were carried out with the binary 0° – 180° phase modulated

signals, which were transmitted by MURATA 40kHz ultrasonic transducers. The bandwidth of the ultrasonic transducers was improved by means of electric matching circuits, which were introduced between the electronic unit and the transducer.
The examples of the 31 element maximum length sequences transmitted by the MURATA type array and the resulting cross-correlation function obtained by the signal processor are presented in Fig.7.

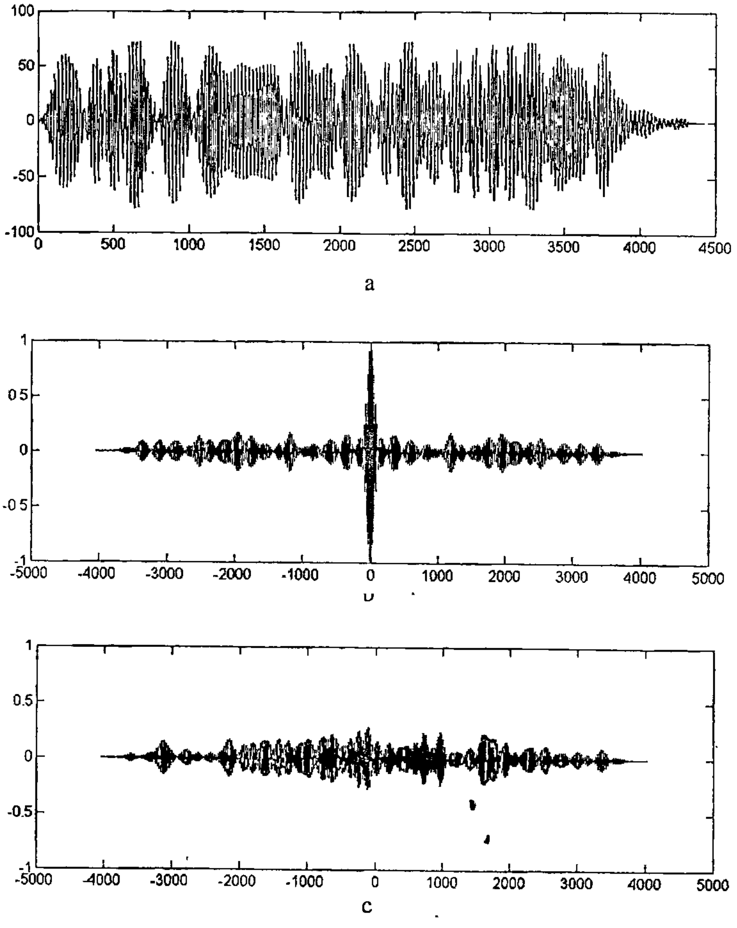


Fig.7. The 31 element phase modulated maximum length sequence M0, corresponding autocorrelation function and cross-correlation function between two different sequences M0 and M1

The delay time of the ultrasonic signal and, consequently, the distance from the sensor till the reflector are determined from the location of the cross-correlation peak in the time domain [30]. The results presented show a rather good selectivity and spatial resolution of the coded ultrasonic signals. That enables to improve significantly data acquisition rate of ultrasonic sensors.

7. Advanced ultrasonic sensors for navigation of mobile robots

As an example of an advanced ultrasonic sensor, operation of which is based on the principle described above, we shall present the ultrasonic sonar developed in the Kaunas University of Technology [9, 10, 28, 29]. In order to provide a safe and reliable navigation of a mobile robot, the ultrasonic sensor consists of two side looking sonars and two main electronically steered sonars directed at different directions (Fig.8). All these separate units operate simultaneously and the data obtained by them are fused together. That ensures a high speed of data collection, which is essential in the case of dynamically changing environment. The side looking sonars determine the distance to the flat objects, like walls, which are parallel to the movement direction of the robot.

Operation of the ultrasonic sensor presented is based on the following main principles:

- surrounding objects are detected using coded ultrasonic pulses and correlation processing;
- the coordinates of objects are determined using tri-aural approach together with electronic scanning of the ultrasonic beam in space;
- transmission and reception of ultrasonic signals is performed by two-dimensional phased arrays.

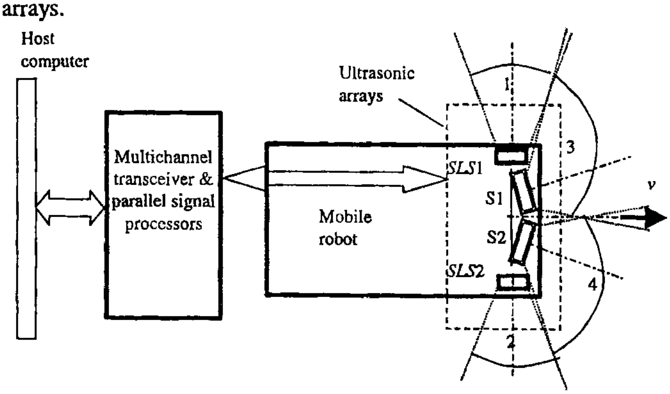


Fig.8. The structure of the ultrasonic sensor: SLS1, SLS2 are the side looking sonars, S1, S2 are the main electronically steered sonars, 1, 2, 3, 4 are the areas covered by corresponding sonars.

In order to increase the update rate, ultrasonic signals are transmitted by electronically steered ultrasonic phased arrays. Steering of the array is performed digitally delaying driving signals, which are generated by the coded sequence generator. At different directions different orthogonal coded sequences are transmitted. That enables to increase the pulse repetition rate and to reduce the influence of a reverberation noise. Ultrasonic signals are transmitted by phased arrays, in which 40kHz piezoelectric transducers are used [29].

The use of electronically controlled arrays allows performing all operations in the real time, what enables the sensor to adapt to a dynamic environment. The commands required for the adaptation are obtained from the host computer. In order to reduce the processing time of the received ultrasonic signals the signal processing is performed by 5 parallel digital signal processors. The correlation processing enabled to achieve good noise robustness, which is essential for robots operating in a manufacturing environment. The information obtained from the parallel signal processors is processed by the master processor, which produces the ultrasonic image of the surrounding environment using binaural and tri-aural approach. From the image obtained the coordinates – the distance and the bearing angle of the objects in the range from 0.5m up to 5m are determined.

Simulation of performance of the ultrasonic sensor

In order to evaluate performance of the ultrasonic sensor in any arbitrary environment simulation software was developed. It enables to test various medium reconstruction algorithms used in the sonar and to optimise positioning of transmitters and receivers. The simulation is based on the calculation of the signal propagation path transmitter - obstacle – receiver. Due to the different reflection mechanisms the obstacles were classified into three categories: a point type reflector, walls and 90°-corner type reflector. The results of simulation are presented in Fig.9 and 10.

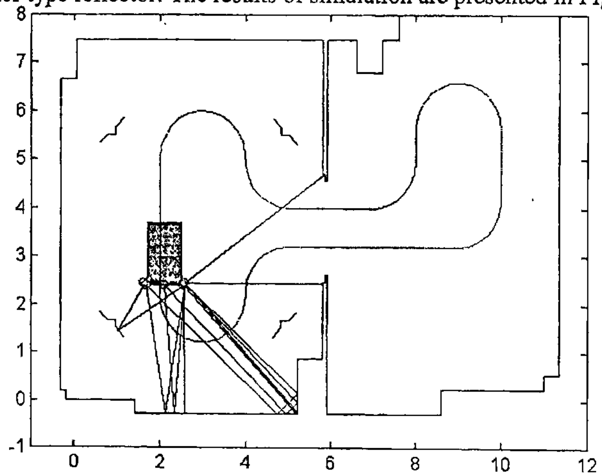


Fig.9. Beam paths of the received signals at one position of the robot in the simulated environment of the laboratory in the De Monfort university

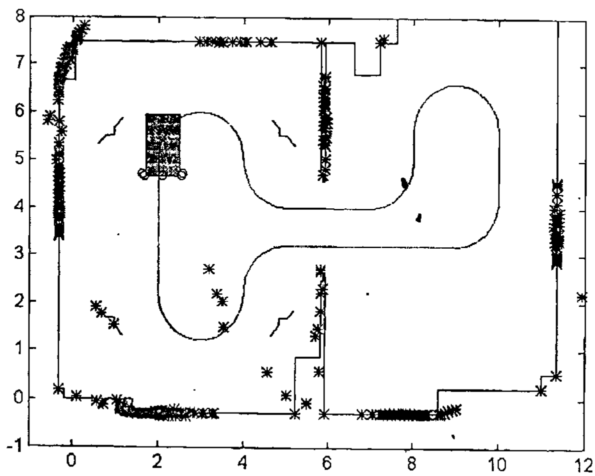
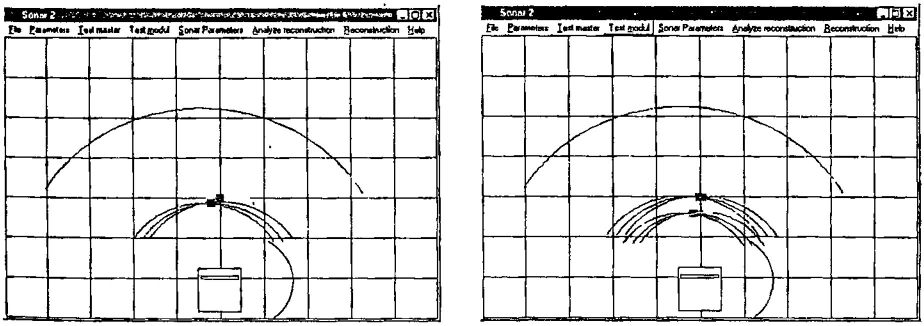


Fig. 10. Example of reconstruction of objects in the laboratory of the De Montfort university. By '*' are denoted walls and corners detected by the sonar when the robot moved along the route denoted by a solid line in the middle of the rooms

The performance of the ultrasonic sensor was estimated in a virtual environment corresponding to the environment of the laboratory in the De Montfort University. The laboratory consists of two rooms, layout of which is shown by solid lines. It has been assumed that the sensor was mounted on the VOLVO semi-autonomous vehicle, which moved along the route denoted by a solid line in the middle of the rooms. Fig.9 illustrates propagation paths of the ultrasonic signals, which are reflected by particular obstacles and received by the receivers. Example of reconstruction of objects in the laboratory is presented in Fig.10. The results obtained indicate that the developed sensor enables to determine quite accurately positions of various reflectors in the laboratory.

Experimental investigation of the ultrasonic sonar

Objective of experiments carried out in the Ultrasound institute, Kaunas University of Technology was evaluation of a performance of the developed ultrasonic sensor [31]. 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.11. It has been found that lateral and depth resolution of the sensor is 10cm. If the distance shorter, then two reflectors are observed as one object.



a . b

Fig.11. 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 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.12. 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.

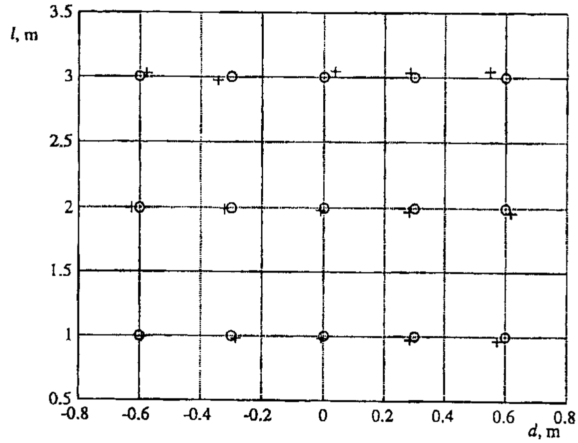


Fig. 12. Accuracy of measurements of spatial coordinates of the point-type reflector: the dots (o) indicate actual positions of the reflector, the crosses (+) correspond to the positions of the reflector determined by the ultrasonic sensor.

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 0.7m, the height 1.4m.

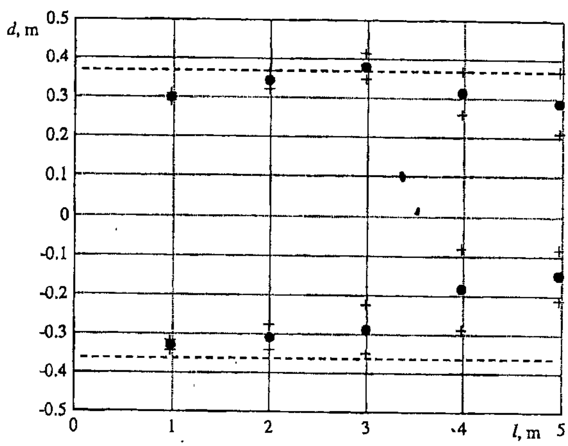


Fig.13. Estimation of the borders between boundaries of the planar strip-type reflector and empty space. The dashed lines indicate actual position of the borders, the dots correspond to the measurement results

The results of measurements at different distances between the ultrasonic sonar and the planar reflector are presented in Fig.13. 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.

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.

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REFERENCES

[1] M. Drumheller. *Mobile robot localization using sonar.* IEEE Trans. on Pattern Anal. and Machine Intelligence. Vol. 9, No.2, 1987, p.325-332.

[2] R. Magori. *Ultrasonic presence sensors with wide range and high local resolution.* IEEE Trans. on Ultrasonics, Ferroelecterics and Frequency Control, No.2, 1987, p.202-211.

[3] R. Magori. *Signal processing for smart ultrasonic sensors.* Proceedings of 3rd Annual European Computer Conference, 1989, p.21 -26.

[4] G. Drunk. *A new system architecture for mobile autonomous robot IPAMAR.* Proc. of 3th Int. Congress in Advanced Robotics, Versailles, 1987.

[5] R. Kazys, K.Kundrotas, V. Dzimidavicius, L.Mazeika, A. Borkowski. *Programmable ultrasonic range finder for mobile robot.* Robotersysteme., Vol.7, 1991, p.101 -106.

[6] Kai-Tai Song, Wen-Hui Tang. *Environment perception for a mobile robot using double ultrasonic sensors and a CCD camera.* IEEE Transactions on Industrial Electronics. Vol. 43, No. 3, p. 372-379.

[7] F. Wallner, R. Dillmann. *Effiecient mapping of dynamic environment by use of sonar and active stereo-vision.* Proc. of the International Symposium on Intelligent Robotic Systems, Grenoble, 1994, p.1-13.

[8] Min Kee Park, Mignon Park. *Obstacle recognition using the vision and ultrasonic sensor in a mobile robot.* Journal of the Korean Institute of Telematics and Electronics. Vol. 32B, No.9, p.18-25.

[9] R. Kažys. *Smart ultrasonic sensor for semi-autonomous robots.* Mechatronics'98. Proceedings ot the 6th UK Mechatronics International Conference, Skovde, Sweden, Pergamon, Amsterdam-Tokyo,1998, p.489-494.

[10] R. Kažys. *Smart systems for robot vision.* Proceedings of the 5th International Symposium on Methods and Models in Automation and Robotics. Miedzyzdroje, Poland, 1998, Vol.3, p.827-832.

[11] R. Kažys, L.Svilainis, L. Mažeika. Application of orthogonal ultrasonic signals and binaural processing for imaging of the environment. Ultrasonics, 2000, Vol.38, No.1-8, p.171-175.

[12] M.M. Moller. Autonomous mobility with triaural sonar system. Proceedings of the International Symposium on Intelligent Robotic Systems. Pisa, Italy, 1995, p.25-30.

[13] R.Kuc. Biomimetic sonar recognizes objects using binaural information. J. Acoust. Soc. America, vol. 102, No.2, Pt.1, 1997, p. 689 - 696.

[14] H. Peremans, K. Adenauert, J.M. Van Campenhout. A high resolution sensor based on tri-aural perception. IEEE Trans. on Robotics and Automation, Vol.9, No.1, 1993, p.36-48.

[15] W.D. Rencken, H. Peremans, M. Moller. Tri-aural versus conventional sonar localisation and map building. Proceedings of JAS-4 conference, Karlsruhe, 1994.

[16] H.Peremans. Broad beamwidth ultrasonic transducers for tri-aural perception. J. Acoust. Soc. America, vol. 102, No.3, 1997, p. 1567 - 1572.

[17] B. Kreczmer. Orientation and position determining of a mobile robot equipped with ultrasonic sensors. Proceedings of the international Symposium on Intelligent Robotic Systems, Grenoble, 1994, p.231-237.

[18] D.W. Shindel, D.A. Hutchins. *Applications of micromachined capacitance transducers in air-coupled ultrasonics and non-destructive evaluation.* IEEE Trans. on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 42, No.1, 1995, p.51-58.

[19] M.I. Haller, B.T. Khuri-Yakub. *A surface micromachined electrostatic ultrasonic air transducer.* IEEE Trans. on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 43, No.1, 1996, p.1-6.

[20] K. Inoue, Y. Suzuki, S. Ogawa. *Fabrication of ultrasonic sensor using silicon membrane.* Found.Sensors & Actuator Technology, Stockholm,. Sweden, 1995, vol.3.

[21] W.S.H. Munro, C. Wykes. *Arrays for airborne 100 kHz ultrasound.* Ultrasonics, Vol. 32, No.1, 1994, p.57 -64.

[22] P.Webb, C.Wykes. *High resolution beam forming for ultrasonic arrays.* IEEE Trans. on Robotics and Automation, Vol.12, No.1, 1996, p.138-146.

[23] J.S. Schoenwald, J.F. Martin. *PVF2 transducers for acoustic ranging in air.* IEEE Ultrasonic Symposium Proceedings, 1983, p.557-580.

[24] C.C. Habeger, W.A. Wink. *Development of a double-element pulse echo, PVDF transducer.* Ultrasonics, Vol.28, No.1, 1990, p.52-54.

[25] M.I. Haller, B.T. Khury-Yakub. *1-3 composites for ultrasonic air transducers.* IEEE Ultrasonic Symposium Proceedings, Tucson, 1992, p.937-939.

[26] L. Capineri, A.S. Fiorillo, L. Masotti, S.Rocchi. *Array of RVDF sensors for ultrasonic imaging in air.* IEEE Ultrasonic Symposium Proceedings, Cannes, 1994, p.487-490.

[27] L. Capineri, A.S. Fiorillo, L. Masotti. *Piezo-polymer transducers for ultrasonic imaging in air.* IEEE Trans. on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 44, No.1, 1997, p.36-43.

[28] R. Kažys, L. Mažeika, R.Šliteris, L. Svilainis. *Smart ultrasonic vision system for mobile robots.* Proceedings of IAPR workshop on Machine Vision Applications, Chiba, Japan, 1998, p.347-350.

[29] R. Kažys, L. Mažeika, L. Jakevičius. *Beamforming by means of 2D phased ultrasonic arrays.* Ultragarsas, (Ultrasound), Kaunas, Technologija, Nr.1(29), 1998, p.12-15.

[30] R. Kažys. *Delay time estimation using the Hilbert transform.* Matavimai (Measurements), Kaunas, Technologija, Vol.3, No.1-2, 1996, p.42-46.

[31] R. Kažys, L. Mažeika, O. Tumšys. Experimental investigation of performance of the binaural sonar. Ultragarsas (Ultrasound), Kaunas, Technologija, Nr.2(35), 2000, p.35-39.