ULTRASONIC SENSORS

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Abstract. Review of ultrasonic sensors used for navigation of mobile robots is presented. Peculiarities of propagation of ultrasonic waves in air are discussed, various measurement principles are analyzed. Features of various ultrasonic transducers used for radiation and reception of ultrasonic waves are discussed. It is shown that application of binaural or tri-aural method enables to increase the speed of data acquisition. For improvement of noise robustness coded sequences such as the Barker codes or maximal length sequences may be used. Application of a few different orthogonal coded sequences enables also to improve the data acquisition rate. Examples of advanced ultrasonic sensors employing coded signals; correlation processing and the tri-aural measurement principle are discussed.

Introduction

There are many possible ways to monitor the environment of the mobile robot. The largest amount of information is obtained through a vision channel and the stereoscopic effect and can serve for ranging purposes [1, 2]. The next level of monitoring provides laser scanners. There is a quite broad palette of them, beginning with a highly sophisticated camera that scans a broad 3D-angle ahead of the robot and ending up with simple low-energy emitters-receivers that provide unidirectional ranging.

Besides the visible light other bands of the electromagnetic wave spectrum were also used for ranging purposes (e.g. infrared emission or microwaves), but instead of electromagnetic waves the acoustic waves of ultrasonic frequencies may be used. Ultrasonic sonars provide a cheap and reliable means for robot localization and navigation [3-8].

It is necessary to point out that sensors, based on different physical phenomena, have also different drawbacks. Therefore, for improvement of the performance of ranging and navigational systems, a few sensing systems of different type, usually, optical and ultrasonic sensors are used simultaneously. Localization of the robot is performed by means of data fusion, obtained by various sensors [9-12].

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 unfavorable 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, including electrostatic transducers, piezopolymer films and special piezoelectric transducers will be analyzed later. 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. Propagation of ultrasonic waves

2.1 Ultrasound velocity

The principle of operation of sonars is based on measurement the delay time τ_s of ultrasonic pulses, reflected by obstacles. The distance is found in the following way [7]:

$$l = \frac{c\tau_s}{2}, \qquad (1)$$

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 [7]. In both cases the correction of the measured distance is carried out by a microprocessor.

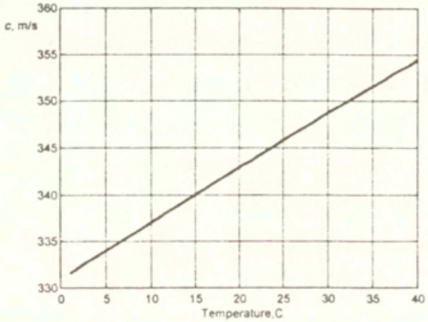


Fig. 1. Ultrasound velocity versus temperature in dry air

3 Attenuation of ultrasound in 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:

$$\alpha_{cl} = \frac{\omega^2}{2\rho c^3}\left[\frac{4}{3}\eta + (\gamma - 1)\frac{k}{C_p}\right], \qquad (3)$$

where $\omega = 2\pi f$ is the angular frequency, ρ is the density, η is the viscosity, $\gamma = C_p / C_v$ is the ratio of heat capacities at constant pressure and volume, respectively . Equation 3 can be rewritten as

$$\alpha_{cl} = r f^2 , \qquad (4)$$

where the factor r for air is $r = 1.24 \ 10^{-13}$ s^2/cm.

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

$$\alpha_r = \frac{M f'}{1 + \left(\frac{f}{f'}\right)^2} , \qquad (5)$$

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

$$f' = k_1 h^{1.3} \cdot 10^4 , \qquad (6)$$

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 complete absorption coefficient α is a sum of the particular absorption coefficients:

$$\alpha = \alpha_{cl} + \alpha_r . \qquad (7)$$

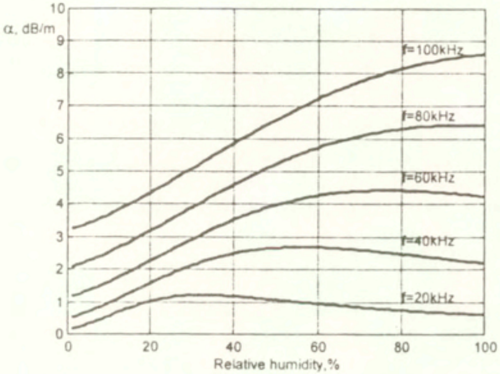


Fig. 2. Attenuation of ultrasonic waves in humid air at different frequencies

In Fig.2 the total absorption coefficient α in air at T = 20 ° C versus humidity at different frequencies is presented.

From these calculations is possible to predict the minimal and maximal absorption coefficient values in air at different frequencies:

f = 60 kHz

α_{min} = 1.3 dB / m ; α_{miax}= 4.4 dB / m ;

f = 100 kHz :

α_{min} = 2 dB / m ; α_{max}= 8.7 dB / m .

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

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

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

The results presented indicate that 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. Fortunately, this is entirely sufficient for robots operating inside buildings.

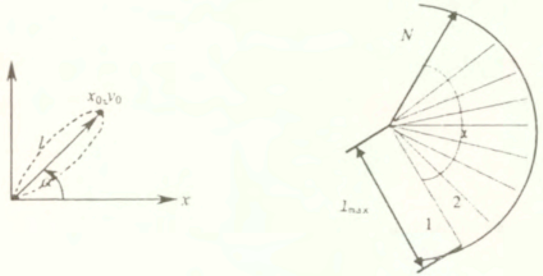
4. Measurement principles

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 [7]. 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 [13].

$$t_s = \frac{2l_{\max}}{c_a} + \Delta\tau \ , \qquad \textbf{(8)}$$

where Δτ 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 Δτ until the all multiple reflections reduce to a negligible level.



a b

Fig.3. Sequential scanning of environment

The complete scan will take a time

$$T_s = N\left(\frac{2l_{\max}}{c_c} + \Delta\tau\right). \qquad \textbf{(9)}$$

Here N is the number of ultrasound beam positions:

$$N = \frac{\Delta\alpha}{\Delta\beta_{0,5}} \ , \qquad \textbf{(10)}$$

where Δα 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 Δα=180°, $\beta_{0.5}$=10°, N=18, $l_{\max}$=5 m, Δτ=10ms, then the duration of the single direction measurement is

$$t_s = \tau_d + \Delta\tau \approx 40 \text{ ms.} \tag{11}$$

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

$$l = T_s\, v_{max} \tag{12}$$

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.

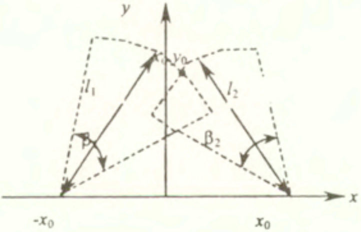


Fig.4. Equidistant method

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

$$(x - x_1)^2 + y^2 = l_1^2, \tag{13}$$

$$(x + x_1)^2 + y^2 = l_2^2, \tag{14}$$

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. 13, 14 and are given by:

$$x = \frac{\left(l_1^2 - l_2^2\right)}{4x_1}, \tag{15}$$

$$y = \frac{1}{2}\sqrt{2\left(l_1^2 + l_2^2\right) - \frac{\left(l_1^2 - l_2^2\right)^2}{4x_1^2} - 4x_1^2}. \tag{16}$$

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

In the binaural method also at least three ultrasonic transducers are used, however, one of them only transmits ultrasonic waves and other two are used as receivers. 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.

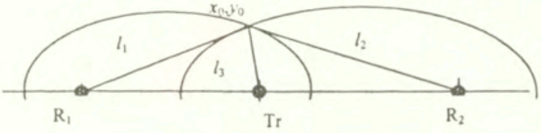


Fig. 5. Determination of the position of the reflector x_0, y_0 in one plane using binaural approach: the black dots indicate the positions of the transmitter Tr and the receivers R_1, R_2 correspondingly.

Directly are measured the distances ($l_1 + l_3$) and ($l_2 + l_3$) 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.

5 Ultrasonic transducers

Ultrasonic transducers in mobile robots are used as single elements or in phased arrays providing electronic scanning of am environment [13-16]. 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. For example, Polaroid 7000 type transducer has receiving sensitivity -43 dB at 50 kHz. Their main drawback is a relatively big lateral size (diameter D=25 mm), which approximately equals 3λ at f=50 kHz. It means, that they can't be used in arrays, because the spacing between elements in the phased array significantly exceeding the wavelength will cause high level sidelobes. On the other hand, directional properties of such a transducer (angular beam width 20^0) do not allow performing an electronic beam steering in a sector exceeding the angular width of an ultrasonic field radiated.

Recently, using micromachining technology, wide band electrostatic transducers for airborne ultrasound applications have been developed [17-19]. 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 [18]. Instead of silicon polymer film such as Mylar can be used. The bandwidth achieved in the latter case is from 170 kHz to 1.9 MHz [17]. 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. In spite of that, ultrasonic phased arrays with electrostatic transducers have been developed [20, 21]. The linear array developed in University of Notingham consists of 16 elements and operates at frequency 100 kHz. The arrays are manufactured using a printed circuit technology by the conductive paint method. The length of an individual element was 20 mm. The arrays with spacing between elements λ and $\lambda/2$ were produced and investigated. In the transmitting mode the sound pressure level between 8 and 17 Pa was obtained. The maximum area of coverage is up to 120°.

It is necessary to point out, that an additional shortcoming of electrostatic transducers is a high polarizing voltage (up to 400 V).

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 [22-24]. 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 [22-24].

The PVDF transducers vibrating in the thickness mode are wide-band and can operate up to a few MHz [23]. The best performance in air is obtained at frequencies below 150 kHz. Then the bandwidth obtained is of order 20 -30 kHz [24]. The PVDF transducers can be exploited to construct linear arrays also. The linear array consisting of hemicylindrical PVDF transducers operating at two different frequencies - 61 kHz and 86 kHz have been developed [25, 26]. The array consists of 10 equispaced transducers. The individual elements operate in the length extensional mode. That enables to increase the resonant frequency up to 200 kHz, but for applications in robotics frequencies below 100 kHz are used. Two-way insertion losses of the array are 90 dB.

The main drawback of the PVDF transducers is their lower efficiency compared with piezoelectric ceramics. Also, the arrays with the PVDF as well as with electrostatic transducers are not commercially yet available. Therefore, arrays with low-cost, but efficient piezoelectric transducers are of significant interest for airborne ultrasonic applications. 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 fulfill most of the requirements (cost, efficiency, frequency range), however their main drawback is a narrow bandwidth.

6 Binary phase modulated signals

In a noisy environment for ranging purposes coded signals like the Barker and Golay codes, M-sequences are used. 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. 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 a transmission of binary phase-modulated signals via band-limited electromechanical circuits was investigated. The experiments were carried out with the binary $0^\circ - 180^\circ$ phase modulated signals, which were transmitted by MURATA ultrasonic transducers and demodulated by means of the special demodulation procedure. The examples of the signals used in the experiments are given in Fig.6a. 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 ultrasonic phase modulated signal, obtained at the output of the MURATA type electrically matched transducer is presented in Fig.6b. The results presented indicate, that ultrasonic transducer transforms binary signal into the phase modulated binary coded sequence.

It allows for generation of electric driving signals to exploit digital approach, which significantly simplifies the structure of an electronic generator and improves its stability and accuracy. In this case the electronic generator creates a binary (0, 1) level signal (Fig.6a), the phase of which is also modulated by a binary quasirandom code, for example, the Barker code or the maximum length sequence (MLS). If there are M samples obtained after A/D conversion then the cross-correlation sequence is given by

$$\hat{R}'_{xy}(\tau) = \sum_{k=0}^{M-|m|-1} x(k)* y(k+m) \quad . \qquad (17)$$

The calculation of the cross-correlation function is performed much faster if instead of the direct convolution the received signals and the reference signal are transformed into the frequency domain, using FFT, multiplied and transformed back into the time domain.

In order to increase the speed of calculations, the Fourier transform of the reference signal is calculated in advance and stored in the DSP memory. In this case calculation of the cross-correlation function of two signals consisting of 8192 points takes less than 120 ms. The examples of the 11 element Barker code transmitted by the MURATA type array and the resulting cross-correlation function obtained by the signal processor are presented in Fig.6 and Fig.7.

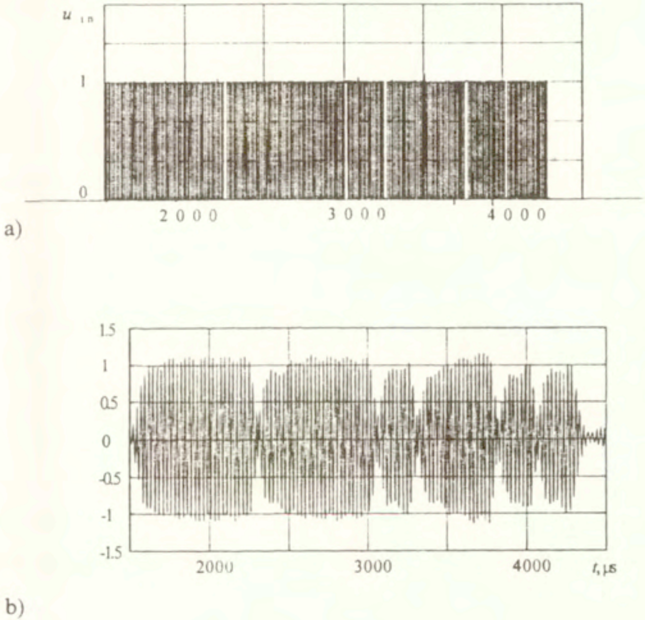


Fig.6. The binary phase modulated Barker code at the input (a) and the output (b) of the ultrasonic transmitter. The white strips in the input signal (a) correspond to the phase changes 180°.

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. The algorithm of automatic delay time measurement is described in [27].

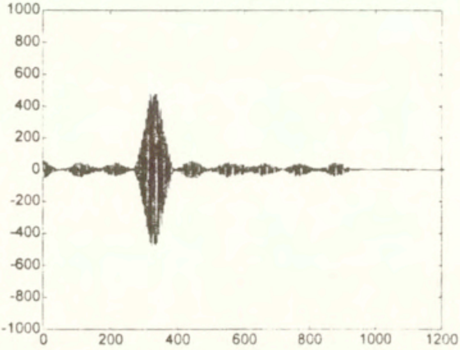


Fig.7. Correlation processing results obtained by the signal processor TMS520C50 in the case of the 11-element Barker code. The processing time is 120ms.

7 Application of orthogonal signals

Speed of measurements may be increased using for different directions different orthogonal coded sequences [13]. These signals are emitted not waiting until the signal reflected by the most remote objects will arrive (Fig.7).

The transmitted ultrasonic pulses Tr.P1, Tr.P2 are mutually orthogonal signals, for which the following conditions are fulfilled:

$$E_{ij}(T) = \int_0^T f_i(t) f_j(t) dt = \begin{cases} E, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases} \quad . \qquad \textbf{(18)}$$

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

$$u_{out}(t)=\int_{t_1}^{t_2}\left[\sum_j u_j(t)\right]f_i(t)\neq 0. \qquad \textbf{(19)}$$

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

$$u_{out}(t)=\int_{t_1+t_s}^{t_2+t_s}\left[\sum_j u_j(t)\right]f_{i+1}(t)\approx 0, \qquad \textbf{(20)}$$

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

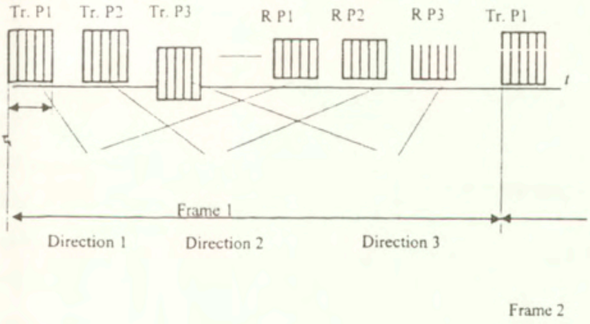


Fig.8. High speed scanning using quasi-random coded sequences:

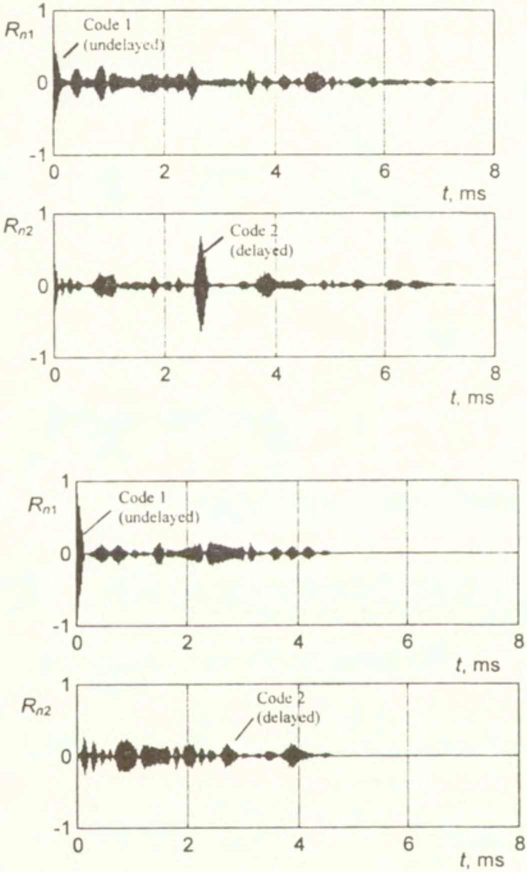
In this case the speed of measurements can be increased up to

$$k=\frac{\tau_d+\Delta\tau}{\tau_i} \qquad \textbf{(21)}$$

times.

If f=40 kHz, and the pulse transmitted consists of 40 periods, the pulse duration is τ_1 =1 ms and k= 40 times. Thus, the duration of a single complete scan may be up to 40 times shorter than in conventional pulse-echo measurements.

Experimental results illustrating the presented approach are given in Fig.9. In these figures the signals obtained after the correlation processing are presented.



a)

b)

Fig.9. Application of quasi-orthogonal MLS codes for distance measurements

An ultrasonic receiver receives two quasi-orthogonal MLS codes of order n=5 with different delays. The MLS are not strictly orthogonal; therefore these two codes were selected as the best candidates from the complete set of all possible codes of such a length. Duration of each MLS signal is 31 element, each of which consists of 10 periods of high frequency oscillations. The frequency equals to the resonant frequency of the ultrasonic transducer. It is necessary to point out, that the duration's and delays of the signals are such that they partially overlap in the time domain. The necessary code may be selected choosing the appropriate reference signal used in the correlation processing. For example, if as the reference signal is used the quasi-random code No.2, than after correlation processing only the signal transmitted by this code is left (Fig.9a). Correspondingly, the reference signal No.1 enables to select the undelayed code No.1 and to suppress the delayed signal No.2 (Fig.9b). 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.

8 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 sensor developed in Kaunas University of Technology [15, 28]. 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.10). 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.

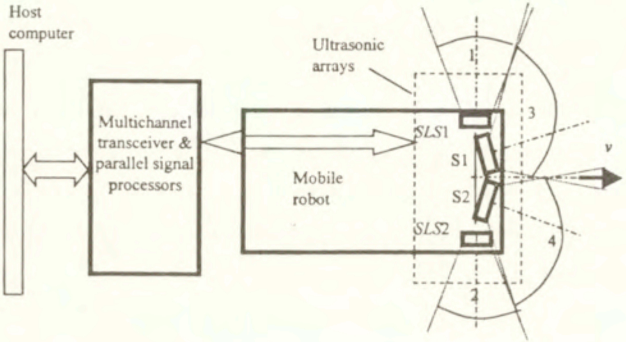


Fig.10. The structure of the ultrasonic sensor: SLS1, SLS2 are the side looking sonars, S1, S2 are the main electronically steered sonars, 1, 2, 3, 4 are the areas covered by , corresponding sonars

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 [16]. The diameter of the transducers is 10 mm, which slightly exceeds wavelength. In order to reduce the level of parasitic side lobes in a directivity pattern of the array, densely packed honeycomb-type arrays are exploited (Fig.11a). The directivity pattern of such an array in a horizontal plane is presented in Fig.11b.

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 via the LON Works interface. 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.

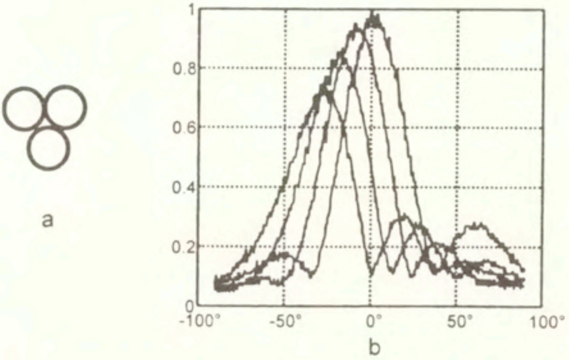


Fig.11. Directivity patterns (b) of the 1x2 honeycomb array (a) in the horizontal plane at deflection angles 0, 10°, 20°, 30°.

The information obtained from the parallel signal processors is processed by the master processor, which produces the ultrasonic image of the surrounding environment using 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.

Acknowledgements

The European INCO-COPERNICUS program No.ERB IC15-CT96-072 and Lithuanian National Science Foundation sponsor this project.

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