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BINAURAL DETECTION OF MULTIPLE TARGETS WITH ULTRASONIC SONAR

Binaural technique enables to improve the speed of measurement performed by ultrasonic sonars, however, in presence of multiple targets this technique meets very serious ambiguity problem. In this case the number of targets detected exceeds the actual number of targets, e.g., there are additional non-existing targets found. the paper is devoted to development of signal processing procedures, enabling unique and robust measurement of a spatial position of multiple targets. The developed approach is illustrated by a computer simulation and experimental results, obtained by the multichanel ultrasonic sonar, developed in the Ultrasound Institute, Kaunas University of Technology

1. INTRODUCTION

One of the instruments which can be used for the navigation of autonomous or semi-autonomous are ultrasonic sonar [1,2]. The level of application depends on the task, but in general they can be used for :

- Detection of obstacles on the way of the robot;
- Measurement of the distance till obstacles on the way of the robot;
- Detection of the nearest obstacle around the robot;
- Measurement of the distance to the nearest obstacle;
- Measurement of distance and angular position of a single obstacle;
- Measurement of the distances and angular positions of multiple obstacles;
- Reconstruction of the geometry of surrounding medium;
- Recognition of the object in the surrounding medium.

The tasks are listed according to increasing difficulty. The first four tasks can be solved using simple single channel sonar with a wide directivity pattern or scanning of environment [3]. The other tasks are more complicated. In principle the measurement by one channel sonar can be used for measurement of distances and angular positions of single or multiple targets, too. In such a case the narrow beam sonar with mechanical or electronic scanning must be used [4]. But this simples application have some essential disadvantages. The first is slowness of a mechanical scanning system. Because of that scanning around a robot can be finished only during a few seconds. The second disadvantage is that the reflection from a flat planar surface can be not received at all. Of course, the scanning velocity may be increased using transducer array[5-7], but for a sufficient angular resolution the number of elements in the array and the number of steps during the scanning must be relatively big. On the other hand the minimal duration of a single measurement is limited by ultrasound propagation velocity.

In nature there is widely spread the binaural principle of orientation, such as stereo vision or detection of a noise source position by ears. The similar principle can be and is used in acoustic navigation systems [1,8,9]. However there are some problems of application of this principle in real instruments. The objective of this article is to analyze these problems and to propose possible solutions.

2. BASICS OF THE BINAURAL PRINCIPLE

The binaural method is based on the fact that the distance from a sound source (or reflector) till separately situated transducers are different. In Fig.1 these distances correspond to the R_1 and R_2 . If the measurements are performed using the first transducer it can simply calculated that the obstacle may be somewhere on the circular arc with the center at the transducer position and the radius R_1 . When the measurements are performed with second the transducer the possible positions of the reflector are situated on another arc with the radius R_2 and the center at the second transducer position. The crossection point of these two arc indicates the actual position of the target or obstacle.

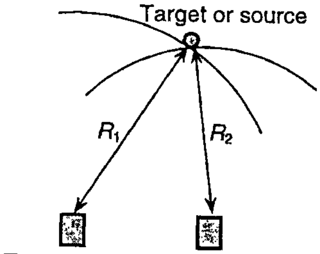

Fig.1 The explanation of the binaural principle

2. PROBLEMS

The main problem in implementation of the binaural approach is caused by presence of multiple obstacles in a real surrounding medium. As it was described beforehand, the position of an obstacle is defined as the crossection point of two arcs. In the presence of multiple targets, let us assume N, there will be measured distances between each receiver and target. In this case the number of crossection points will be N^2 , and only N of them will be real. Other N^2-N will be virtual, e.g. non-existing targets. The situation for 3 reflectors is presented in Fig.2a. In this case besides 3 real targets the 6 virtual targets will be detected. The theoretical solution of this problem is to use another one additional transducer. In this case the method becomes not binaural, but triaural (Fig.2b). The measured distances by third transducer create additional crossection points. The new position of the real target will be the same as for the previous binaural pairs and additional transducer. The positions of the virtual targets will be shifted. In such a way it is possible to separate the real targets from the virtual. However such a simple algorithm can work only in ideal conditions. In real situation the reconstructed position of real targets most probably will be shifted too. The reason of that are measurement error caused by turbulence, temperature deviations, different reflectivity conditions and etc.

Moreover, due to the fact that usually the distance between transducers is at least 2-5 times smaller than distance to the target the crossection angle are small. Because of that the small distance measurements errors cause significant angular errors. As the consequence the reconstructed positions of the real targets, calculated using different pairs of transducers will be scattered and separation them from the virtual targets becomes doubtful.

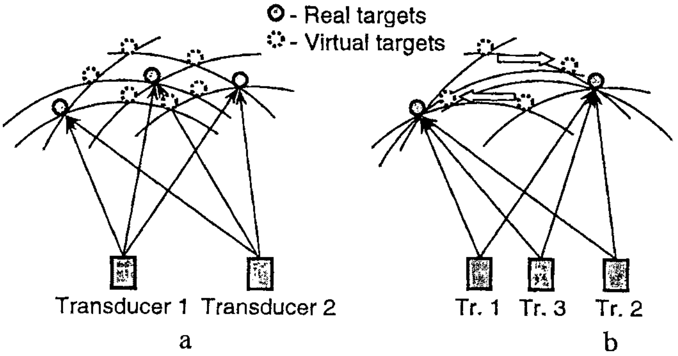

Fig.2. a - is the illustration of the problem of virtual reflectors in the presence of 3 targets; b - is the explanation of the shift of virtual reflectors in the presence of the third transducer

Another problem of the application of the approach discussed above is reliability of detection of each target. In the case of three pairs of transducers if one pair misses the target, the measurement can not be performed at all. Of course, it is possible to increase reliability of detection increasing the number of pairs, but such a way is not prospective because of a very big dynamic range of reflected signals. The dynamic range of reflected signals is caused by a high attenuation of ultrasound in air and big reflectivity variations of surrounding objects. As an example may be a planar wall, perpendicular to the ultrasonic beam and people as diffused reflectors. In this case if the sonar sensitivity will be set for such obstacles as walls, then the sonar will miss reflections from small objects. In general, this problem is caused by:

- High attenuation of ultrasound;
- Small and large reflectors;
- Planar and diffused reflectors.

Below these problems are discussed in some details, proposing solutions for them.

3. SOLUTIONS

The structure of the analyzed sonar is based on the transmission if the orthogonal coded sequences and detection of a delay time using cross-correlation analysis [10-12]. Such a structure enables to measure in noisy conditions and minimize the influence of simultaneously operating channels.

3.1 High attenuation of ultrasound

The ultrasound attenuation in air in the selected frequency range is relatively high. However, due to use of normalization of the cross-correlation function the maximums corresponding to the signals reflected from the obstacles at different distances, are almost of the same amplitude. Nevertheless, small targets can not be seen due to the limited dynamic range of AD converters. To increase the reliability of detection of far situated small targets a time varying gain was included in the sonar structure. The law of the time varying gain are selected in such a way that the signals reflected from a wide wall after amplifying would have the same amplitude at different distances. The wall, but not a small obstacle was selected as reference reflector for calibration of the time varying gain because in an opposite case the dynamic range of the AD converter would be exceeded.

3.2 Small and large reflectors

The use of the normalized cross-correlation function and time varying gain do not solve completely the problem of small and large reflectors. Such an approach is successful in the case of a single obstacle. In such a case the maximum of the cross-correlation function is close to the 1 for any size of reflector and the corresponding threshold level, for example 0.5, may be selected which guaranties a reliable detection of the targets and enables to avoid false detections, caused by noise. When there are few reflectors of a different size the normalization coefficient is proportional to the total energy of both signals and in the cross-correlation function the maximum corresponding to the smaller reflector will be much smaller (Fig.3). Even the value of maximum, corresponding to the bigger reflector, becomes essentially less then 1.

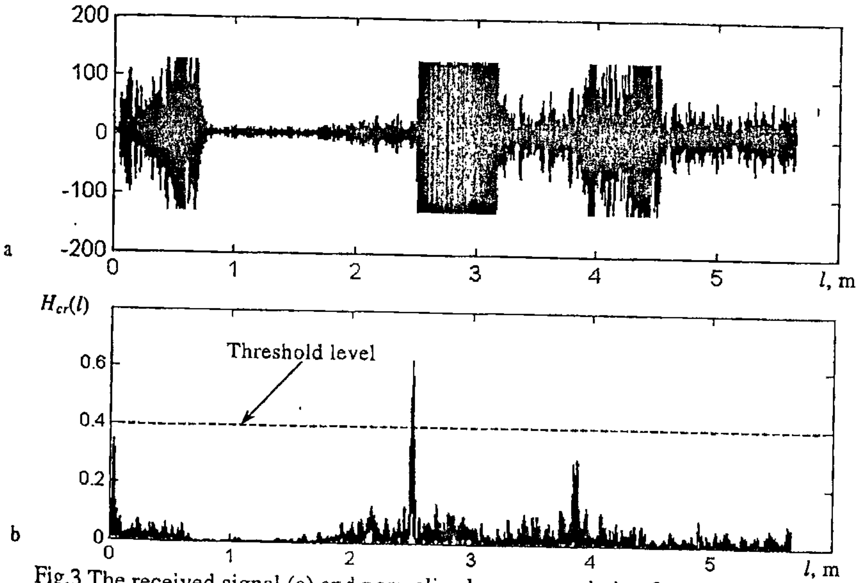

Fig.3 The received signal (a) and normalized cross-correlation function (b) in the case of two targets, where $H_{cr}(l)$ is the cross-correlation function between received signal and reference, l is the distance between the sonar and targets

To solve this problem the special normalization function with a moving window in the time domain has been developed. The value of this function depends on a signal energy in the segment corresponding to the position of the window. The window is moved along complete range of distances and for each position a new normalization coefficient is calculated. After completed operation we have time (or distance) varying normalization coefficient, presented in Fig.4.

The application of the time varying normalization enables to equalize maximum values of signals reflected by different targets. It possible to see from Fig.5 there are two strong reflectors at distances 2.5 and 4 meters and a small reflection from the obstacle at distance less then 5m. The amplitude ratio between the biggest and smallest reflector is about 2 This ratio without normalization for the same reflectors is about 10.

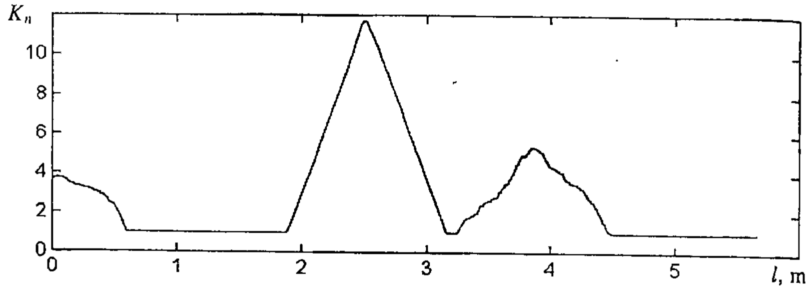

Fig.4 The example of the time varying normalization coefficient

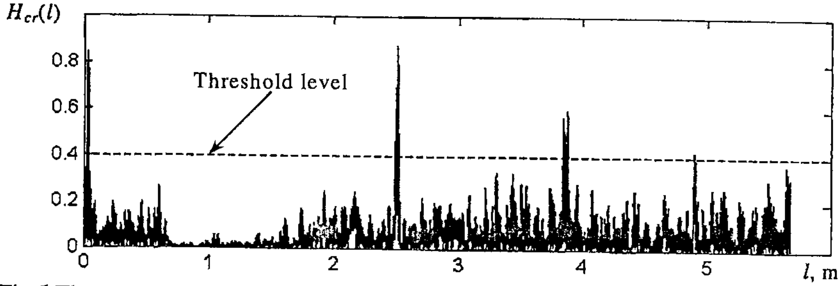

Fig.5 The cross – correlation function after application of the time varying normalization

3.3 Planar and diffused reflectors

Another one problem is reliable simultaneous detection of diffused and planar reflectors. The root of this problem is in the fact that even in the case of single reflector the maximums of the cross-correlation function for the planar reflectors are very sharp and values of maximums are close to 1, because the energy of the reflected signal are concentrated in a short time interval. In the case of diffused reflectors the energy of the reflected signal is dissipated and the maximum of the cross-correlation function is not so sharp with many side lobes. The maximal amplitude usually is essentially less then 1. The importance of detection of diffused reflectors is very high, because as such reflectors can be human beengs. It looks like impasse because the lowering of the threshold level may cause the false detection due to the noise in the cross-correlation function and a high level does not allow detection of diffused reflectors. The most important is detection of obstacles (diffused also) situated close to the sonar. Therefore detection of the "small" reflectors behind "strong" ones is less important.

We have developed a two level algorithm, which automatically increases the importance of "small" signals in front of which (at least 0.5m) there are no other obstacles. The essence of the algorithm can be described by such steps:

- The set of detected obstacles is created using the calculated cross-correlation function and relatively low threshold level (about 0.2). The set includes the amplitude and the delay time of detected obstacles. Of course, due to the low threshold level many false obstacles will be detected.
- The amplitude of each reflection is modified (increased) depending of how long empty period existing before the analyzed reflector. That is, if there is a long "silence" period,

the amplitude will be increased and if there are other reflectors close to the analyzed one, the amplitude will be unchanged.

- The reflections which are very close to each other are analyzed and left only those which have a bigger amplitude.
- The modified reflections are compared with the higher threshold level (about 0.6) and left only those, which have higher amplitude.

After execution of this algorithm, we have a set of reflectors, which corresponds to detection with a high threshold level, but on other hand is still sensitive to small single reflectors also.

4. EXPERIMENTS

The described technique, together with the advanced algorithm of the analysis of binaural data, was implemented in the five channel multiprocessor sonar, which was developed according to the INCO COPERDICUS project [10-12]. The experimental tests were performed in the DeMontfort University, Great Britain with a purpose to estimate the performance of the sonar in an environment close to the industrial one. In Fig.7-9 the lay-out of the Mechatronics Laboratory is presented with objects such as tables, chairs, various mechanical equipments and etc. Such objects in the chart are represented by grey rectangles. Their positions and dimensions are approximate. Of course, there are many other small objects situated in the room which are absent in this chart. The measurements were performed along different directions, at several positions denoted in the chart by crosses. Most typical results are presented in Fig.7-9.

In Fig.7 the sonar is oriented directly to the side wall of the laboratory. We can see the correct reconstruction of position and orientation of the wall. The column on the right side of the sonar is reconstructed for the position presented in Fig.7. The absence of the reconstructed columns on the right side of the sonar can be explained by a geometry of the columns. At the height of 1m they have rectangular cross-section with a very flat surface. That causes a specular reflection of the signal, therefore, as experimental investigation had shown [13], the columns can be detected in some directions only. The few artefacts in both images are due to presence of many reflectors in each received signal.

We can see the swarm of reflectors in Fig.8, when the sonar is oriented to the corner of the room, filled with a lot of different things such as boxes, wires, mechanical parts. Of course, it is almost impossible to reconstruct the position of each separate object, but it is possible to determine that there is no free way in that direction. In spite of a complicated situation, the position of the side wall was determined correctly.

A very interesting situation is presented in Fig.9. There was nothing in front of the sonar up to the height 2m. Higher there was a bridge crane construction, which forms the corner reflector in the vertical plane. The positions of detected reflectors corresponds accurately to the position of the components of the crane, denoted by the grey dashed line. This shows that the sonar has a wide directivity pattern in a vertical plane and can be used for determination of a position of the objects above the ground.

5. CONCLUSIONS

The novel method enabling to increase the reliability of detection of sophisticated targets has been developed. For the analysis of reflections special normalization of the cross-correlation function with time varying coefficient has been applied. The developed algorithms were implemented in the multiprocessor system and were tested in an environment close to the industrial one. The tests have shown that the such a sonar is capable to detect various kinds of obstacles and reconstruct their positions reliably.

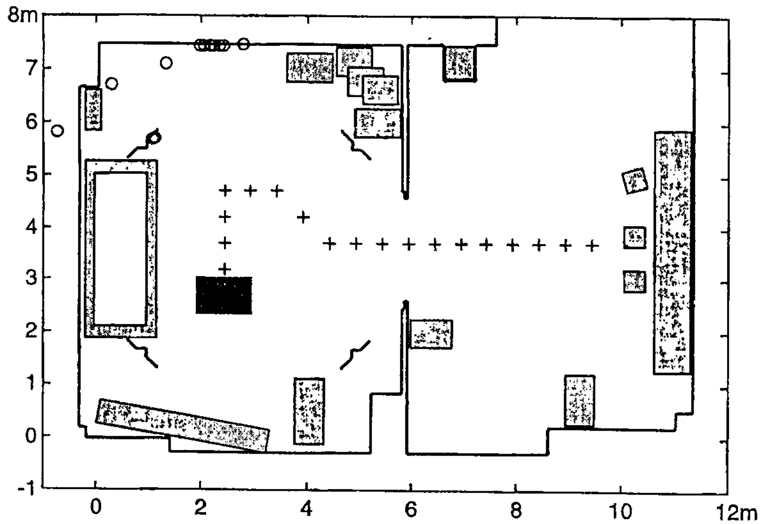

Fig.7 The detected objects (shown by small circles) at the position of the ultrasonic sensor shown by a black rectangle

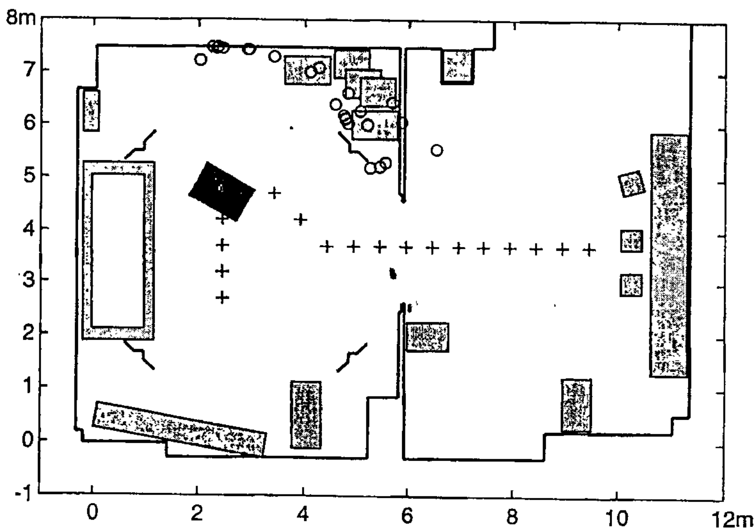

Fig.8 The detected objects (shown by small circles) at the position of the ultrasonic sensor shown by a black rectangle.

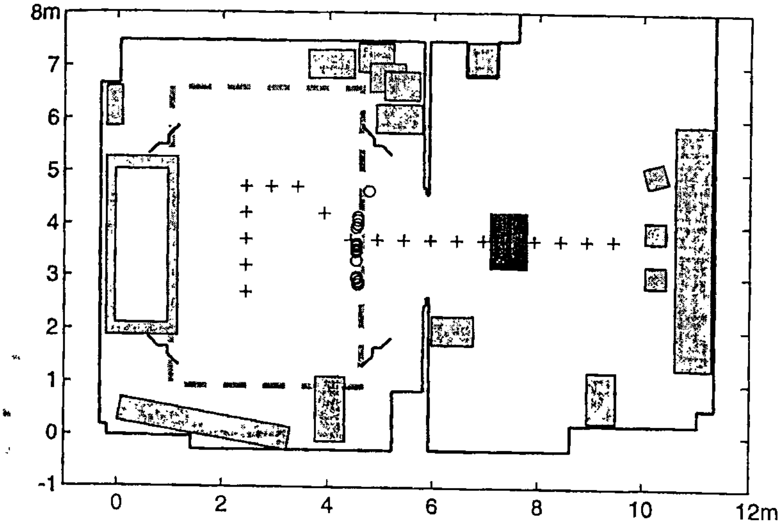

Fig.9 The detected objects (shown by small circles) at the position of the ultrasonic sensor shown by a black rectangle

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