SYNTHESIS OF SONAR IMAGES IN THE PROCESS OF COMPARATIVE NAVIGATION

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The main source of image information in the system of comparative position plotting is the image of navigational sonar compared with a sonar chart generated on the basis of a bottom shape model. The paper presents a method of generating simulated sonar images indispensable in the process of comparative navigation.

INTRODUCTION

The stormy development of satellite positioning systems has brought about the cessation of operating radio-navigational systems used so far. A gap has arisen in this way and the question is often asked how navigation will be conducted, when GNSS is switched off or disturbed. In order to raise the reliability of navigation it is necessary for navigational information to be doubled. This problem occurs particularly in the case of underwater vehicles, because, as we know, radio-navigational systems do not function under water. In inland shipping, too, applying satellite navigation is not always possible, whereas using bathymetric information may sometimes be the only alternative. The basic merit of the method using underwater information is the direct reference to potential obstacles bound with the proximity of the sea bottom, which is the basic requirement for navigating in areas with small depth. In recent years there have been observed more navigational breakdowns caused by hitting the bottom or various submerged obstacles than by collisions with other vessels.

The concept of comparative navigation consists in using image information. Aerial, radar or sonar images can be the sources of information. These images will be compared with model images. One of the key problems in the process of navigational information using sonar images is to work out a method of generating a bottom chart for the purpose of comparing it with a dynamically obtained sonar image. For this purpose, methods are developed to model the shape of the sea bottom in order to obtain an image most suitable to be compared with sonar data (Stateczny, 2001, Łubczonek and Stateczny, 2003, Stateczny and Kozak 2005). The establishing of a position plotting algorithm continues to be an important problem. As in the case of methods based on images obtained by means of marine navigational radar, analytical methods of image matching and methods making use of artificial intelligence are the object of research and optimisation (Stateczny and Duda, 2005). A separate problem is the matter of attaching an object's position, determined in a local system, to an „external" global reference point.

What is also interesting is using methods of comparative navigation when the sailing unit's position is known and there is a model chart of the bottom available. This makes it possible to analyse the changes in the bottom (changes in the shape of the fairway) by comparing the sonar image and the model image, among other things the detection of artificial objects (eg. sea mines) or navigational obstacles (Stateczny, 2005).

The problems of comparative position plotting has been developed in Poland for nearly twenty years and has brought fruit in the form of numerous publications, like the monograph "Comparative Navigation" (Stateczny, 2001) and the team work "Methods of Comparative Navigation" (Stateczny (editor), 2004). The works so far have concerned mainly the conducting of navigation on the sea surface, with the marine navigational radar as the source of image information. A number of works also concern making use of sonar information in the process of comparative navigation. (Stateczny, 2005; Pałczyński, 2004 & 2005; Stateczny & Duda, 2004; Stateczny, Wąż & Szulc, 2003; Stateczny &Szulc, 2003; Stateczny, Borawski, Łubczonek & Stolarczuk, 2002).

In the range of construction of a sonar simulator work is carried out at the Department of Computing and Electrical Engineering Heriot Watt University on the adaptation of algorithms applied in image synthesis (Bell, 1997; Bell & Linnett, 1997; Bell *et alias*, 1999).

Wide research is also being carried out on the application of underwater information for positioning vehicles and other, mostly unmanned underwater devices (Whitcomb *et alias*, 1999; McLaren & Kuo, 1996; Leonard *et alias* 2001; Leonard *et alias*, 2001; Majumder S. *et alias*, 2001; Smith *et alias*, 1998; Ming *et alias* 2002; Fujimori *et alias*, 2000).

The task of the method presented in the paper is to generate a simulated sonar image based on input data: definition of the unit's route, parameters of the sonar transducer, bottom shape in the form of a regular net of rectangles and hydrologic parameters of the water depths. An algorithm for determining a simulated echo signal for a single sonar impulse constitutes the most essential element of the method. An approach called ray tracing has been applied, in which the hydroacoustic wave is represented by a bunch of curves corresponding locally to the direction of its propagation. Each of the curves, called rays, is analysed in order to determine the bottom element it intersects with. This permits the determination of intensity and return time of the elementary echo signal for a certain section of the acoustic wave, taking into consideration the directional characteristic of the transducer. The tracing of each curve is based on a hydroacoustic wave propagation model, which takes into account the inhomogeneity of the medium, changes of intensity and direction of wave propagation, and also the phenomenon of back reflection from a bottom with differentiated parameters. The model also provides for selected factors disturbing the formation of a sonar image, like noise, reverberation and multiple reflection.

1. FORMULATING THE PROBLEM OF SONAR IMAGE SYNTHESIS

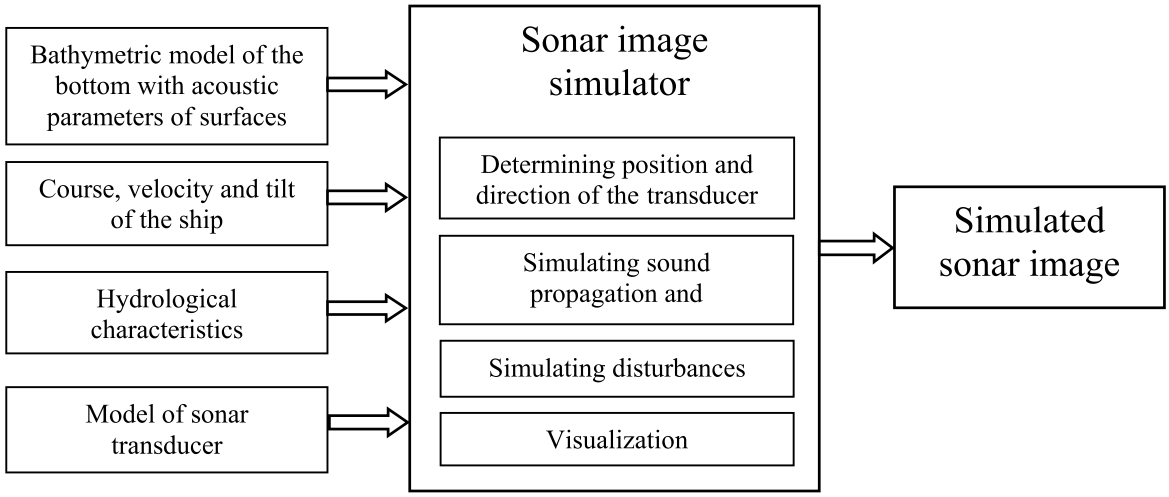

Fig.1 Schematic depiction of the sonar image simulation problem

The problem of generating a simulated sonar image has been schematically depicted in ***Fig. 1***. In order to create reliable simulation, a number of input data have to be considered, which can be divided into 4 groups:

Bathymetric model of the bottom with information on the kind of surface. This is a collection of data and interpolation algorithms making it possible to determine clearly the depth of the water area at each researched point. Its creation is based on real soundings made by vertical or multi-beam echo sounder. The depiction of the bottom shape plays an essential role in the process of sonar image synthesis, as the bottom is the main object reflecting the sound waves traced.

It is assumed in the conception presented that the bottom model is given in the form of a regular net of rectangles. The analysed area will have the shape of a rectangle with sides divided into respectively M and N equal sections. At each node point the water depth will be given. An example of a bottom model has been presented in ***Fig. 2***.

Yet the returning echo is affected not only by the bottom shape but also by the physical properties of the surface, and even of the subsurface layers. This is why each of the bottom elements (triangles or squares) is assigned to one of the surface classes described by a parameter set, like directional and dispersed reflection coefficient, damping coefficient etc.

Model of sonar transducer. The sonar image depends largely on the parameters of the acoustic beam emitted. In order to determine the parameters of the wave emitted it is necessary to determine the power of the transducer and the signal frequency. It is also essential to introduce a directional characteristic in the form of a directivity matrix in spherical coordinates $\boldsymbol{b(\theta,\varphi)}$. In order to specify the range of the sonar, the time between successive impulses and the detection treshold should be defined.

Route, speed and lists of the unit. In order to trace the propagation of the acoustic beam in the water depth it is necessary to determine the location and spatial orientation of the transducer at the moment of emitting the impulse, which further necessitates the knowledge of position, course and lists of the vessel at the moment. From the point of view of generating the whole image it seems to be most convenient to define the route and the change profile of the speed of the unit during the whole sounding time. This permits the calculation of position and course at any point of time. In order to take into consideration all the actual factors it would be worthwhile introducing also the time profiles of longitudinal and transverse list of the vessel. It is a matter of further research whether this is necessary for comparative navigation. It is assumed therefore that the data concerning location and orientation have the form of a set of records containing position, course, longitudinal and transverse list of the vessel for a number of points on her route.

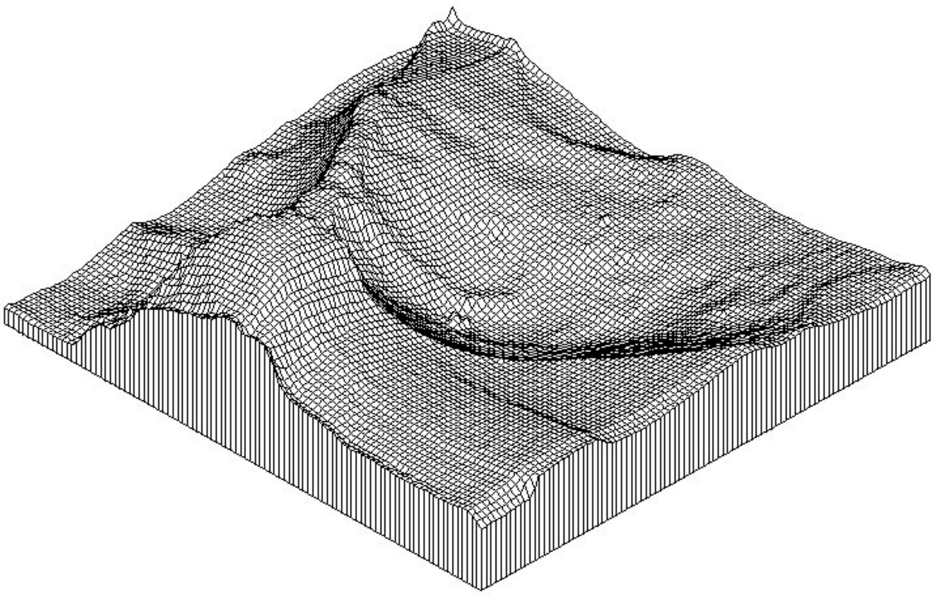

Fig.2 A bathymetric model in the form of a regular net of rectangles (GRID)

Hydrological model of the water depth. One of the main problems making it difficult to trace an acoustic impulse in the water depth is its inhomogeneity expressed by changes in temperature, pressure and chemical composition (salinity). These values significantly affect the velocity of sound, and thus indirectly the direction of wave propagation and time of reaching the object and back. The models existing in literature (Bell 1997, Coates 1990) assume that in the area covered by the simulated sounding the water depth has a layer arrangement, i.e. in all the points of the medium with equal depth, the hydrological parameters are equal too.

Therefore, the hydrological model of the water depth is to be considered as temperature profile ***t(d)***, salinity ***S(d)***, and pressure ***p(d)***, depending on the depth. Each profile is in the form of a table containing a continuum of values corresponding to the successive water layers. The sound velocity in a given medium point can be determined on their basis, among other things, as they are not values registered by ships in a routine way. In the case of applying a generator of simulated sonar images in comparative navigation, the hydrometeorological conditions typical for the prevailing weather and season should be taken into account when creating a sonar chart for a particular voyage.

Another solution (Bell 1997) is the direct measurement of sound velocity profile ***c(d)*** depending on the depth. This type of recording is not possible either for most of the sailing units.

With regard to the principle of sonar functioning the process of image generating can be divided into the generating of successive lines that are almost independent of each other. Each line represents a signal received as the echo of a signal impulse. In order for it to be generated it is first necessary **to determine the position and spatial orientation of the transducer** at the moment of impulse emission, made on the basis of data about the unit’s course and speed.

The main stage of the synthesis is the determination of the echo signal for a single sonar impulse, with the help of the algorithm of **wave propagation tracing and reflection from objects**, based on the concept of ray tracing, discussed more widely in Chapter 2.

In order for the calculated echo to be presented graphically, its **visualization** should be made.

The sonar image is subject to many disturbances of very different origin and nature. In order for the generated image to be made more reliable, it is necessary to simulate some of them. In the method diagram **generating disturbances** appears as a separate module, but actually disturbances may be introduced at any conversion stage, depending on their essence. At the stage of position plotting and transducer orientation there will remain fluctuations of speed, course and list. At the stage of echo impulse determination it is planned to introduce simulation of surface-bottom multiple reflections and to take consideration of reverberation. Underwater noise with proper characteristic will also be introduced.

The final effect of the generator's work for the input data set is the generated **simulated sonar image**. It is a matrix with as many lines as there were simulated impulses. The number of points in every line and the colour or brightness range applied depend on the visualization module, which should refect the way of displaying a particular model of the real sonar.

2. THE CONCEPT OF RAY TRACING

The elementary task for the simulator is to generate one line of image, which corresponds to the reception of one sonar impulse. In order to perform this, the route of the emitted hydroacoustic wave should be traced, in order to determine the echo signal. This wave has a spatial structure, and its energy propagates in various directions, returning from each of them with a different delay and signal level. In order to simulate this complexity, a division is made of the space covered by the sonar beam into $K*L$ of sub-space $S_{k,l}$ having one common point where the transducer is located. The division should be made in such a way that the wave propagating in each of them carries an equal energy (for an ideally spherical wave). This means that common surfaces of each sub-space with a sphere of single ray surrounding the transducer must have equal areas (***Fig. 3***).

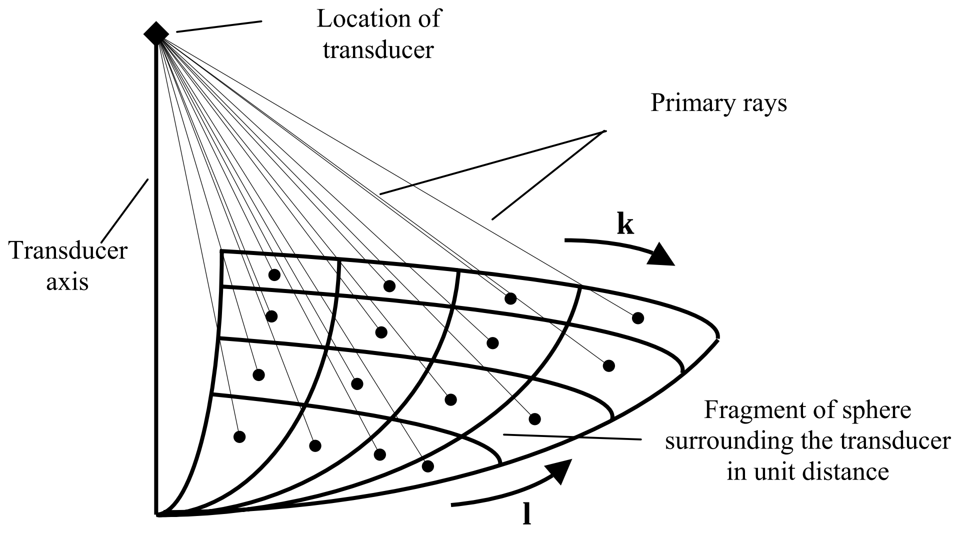

Fig.3 Space division and primary rays

The space division made corresponds to azimuth division (360°) into ***K*** equal angles and half the obtuse angle of beam φ_0 into ***L*** angles, the angles decreasing the further they are from the transducer axis. The sub-spaces are organised in a two-dimensional structure ***S(k,l)***, ***k=1..K, l=1..L***, where the coordinates ***(k,l)*** are similar to the coordinates in the spherical system (θ,φ), the coordinate ***k*** corresponding to the azimuth, and coordinate ***l*** determining the sub-space boundary in the form of cosine of angle φ_l.

$$\cos \varphi_l = 1 - l\,(1- \cos\varphi_0) / L \,,$$
$$\theta = k\, 2\pi / K \,, \qquad (2.1)$$

where:

α_0 - half the angle determining the width of the sonar beam,
L - coefficient of angle φ_0 division**,**
K - coefficient of azimuth division.

In each of the subspaces $S_{k,l}$ an elementary echo signal is calculated. For this purpose, the propagation should be traced of the sound wave section which is contained within this sub-space. This section is represented by the curve known as ray (analogically to the ray-tracing method applied in realistic image synthesis (Glassner 1994, Zabrodzki 1990)). Its beginning is at the point of transducer location. Its initial direction corresponds to the vector with a beginning at this point and its end at the central point of the surface constituting part of the common unitary sphere and a given sub-space (points marked in ***Fig. 3***). A ray so defined is then analysed (traced) according to the assumed hydroacoustic model in order to determine its trajectory, which should be in agreement with the sound propagation trajectory (***Fig. 4***).

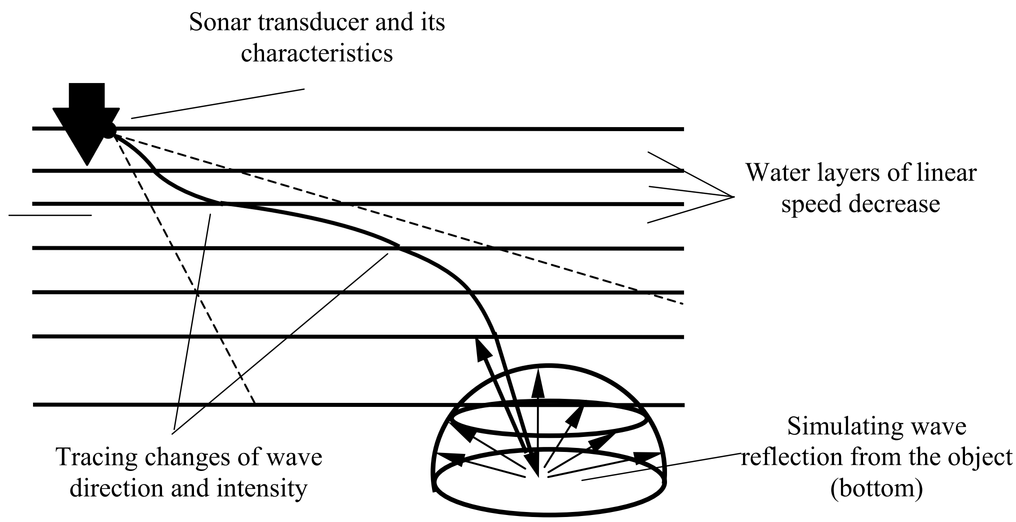

Fig.4 Hydroacoustic ray tracing

It was assumed that in a given layer of the medium sound velocity changes in a linear way along with the depth. With this assumption, the wave propagates inside the layer along a circle (Bell 1997, Coates 1990). The tracing should result in determining whether the impulse emitted into a given sub-space hits an object, and if so, which of them. The finding of a hit object consists in looking in the bottom model for surfaces cut by the ray and choosing the nearest of them. The purpose of tracing the ray is also to determine the time of the wave reaching the object and back and the intensity of the signal returning to the transducer. For this purpose, consideration was given in the model to the phenomenon of wave dispersion and its damping by the medium, back reflection in the direction of the transducer, and reverberation.

It can be said that after tracing one ray there is calculated the echo of the impulse emitted into the sub-space corresponding to this ray. The intensities of elementary echoes corresponding to all sub-spaces are then summed**,** creating in effect a simulated echo signal for a single sonar impulse.

While determining the intensity of the elementary echo for sub-space $S_{k,l}$ account is taken of the directional characteristic of the transducer. It is given in the form of spherical directivity matrix $b(\theta,\varphi)$ $\{ \theta \in <0,90>, \varphi \in <-90,90>, 0 \leq b(\theta,\varphi) \leq 1 \}$. It describes one quarter of the characteristic. It is assumed at the same time that the characteristic has two symmetry axes. Matrix $b(\theta,\varphi)$**,** however, must be transformed to coordinates (k,l) according to formulae *(2.1)*, assuming thus the form of matrix $b'(k,l)$, $k=1..K$, $l=1..L$.

The directional characteristic of the sonar transducer additionally affects the level of signal emission according to the formulae (Stepnowski 2001):

$$SL_0 = 171 + 10\log P_e + 10\log\frac{\eta}{100} + DI \ , \qquad (2.2)$$

where:
SL₀[dB] – signal level on transducer axis,
Pe[W] - electrical power of the transducer,
η[%] - electroacoustic efficiency of the emitting transducer,
DI[dB] - indicator of the transducer directivity, given by the formula:

$$DI = 10\log\frac{4\pi}{\int_0^{2\pi}\int_0^{\pi/2} b^2(\theta,\varphi)\sin\theta d\theta d\varphi} \ . \qquad (2.3)$$

For each primary ray $p_{k,l}$, $k=1..K$, $l=1..L$, the emission level is equal to:

$$SL = SL_0 + 10\log b'(k,l) \ . \qquad (2.4)$$

Coefficients K and L are method parameters. The degree of space division of acoustic wave propagation depends on them. Increasing these coefficients improves the accuracy of simulation due to the larger number of rays and more accurate modelling of the transducer's directional characteristic. Unfortunately, the number of calculations increases considerably too, and so does the time of image generation. Selection of these values will be the object of separate research.

3. SUMMARY

Alternative methods of navigation continue to be the researchers' object of interest in the world. The admiration and euphoria caused by implementing satellite systems is frequently replaced by concern about the reliability and safety of navigation. As they are autonomous and directly bound with the surroundings and potential threats they will always remain within the field of interest of navigators.

The method of synthesis of the sonar image presented in the paper can find application in the construction of an autonomous system of bathymetric navigation.

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