Reprinted from June 1990, Vol. 112, Journal of Energy Resources Technology

J. M. Cuschieri
Center for Acoustics and Vibration.
Department of Ocean Engineering.
Florida Atlantic University.
Boca Raton. FL 33431

M. Hebert
Robotics Institute,
Carnegie Mellon University.
Pittsburgh. PA 15213

Three-Dimensional Map Generation From Side-Scan Sonar Images

The generation of three-dimensional (3-D) images and map building are essential components in the development of an autonomous underwater system. Although the direct generation of 3-D images is more efficient than the recovery of 3-D data from 2-D information, at present for underwater applications where sonar is the main form of remote sensing, the generation of 3-D images can only be achieved by either complex sonar systems or with systems which have a rather low resolution. In this paper an overview is presented on the type of sonar systems that are available for underwater remote sensing, and then a technique is presented which demonstrates how through simple geometric reasoning procedures, 3-D information can be recovered from side scan-type (2-D) data. Also presented is the procedure to perform map building on the estimated 3-D data.

1 Introduction

A capable remote sensing system is an essential component in the development of an autonomous vehicle. Without some form of remote sensing, the autonomous vehicle will not be able to navigate around stationary and moving objects except perhaps in well defined environments, where a map of the area is available. The tasks that must be carried out by an autonomous vehicle, for which information is required from the remote sensing system, can typically be classified into navigation, obstacle avoidance, bottom contour following (if required), mine hunting, classification and neutralization, and surveillance.

The rquirements of the remote sensing system for each of the foregoing tasks are as follows. Navigation requires the generation of images which can be transformed into landmarks and local and global area maps which contain an explicit description of the environment. These maps are then used together with pattern recognition and matching processes, to determine the location of the vehicle, and to navigate the vehicle through the optimum path that will satisfy some predefined cost function. For this purpose, the remote sensing system must have high resolution and, if possible, be able to generate a 3-D representation of the ocean bottom.

For obstacle avoidance, the important requirement is that obstacles in the path of the vehicle are detected well in advance so that the vehicle can maneuver around the objects. The required performance of the obstacle avoidance system depends on the control, response and motion characteristics of the vehicle. Obstacle avoidance thus requires both long range and a wide field of view, as well as real time images and processing over the full area of view. In the surveillance mode, the remote sensing system observes the environment and detects activities that can potentially be of threat to the vehicle.

The most important requirements for surveillance are extended range and directionality such that the location and range to threat objects can be determined. Bottom contour following has the same requirements as obstacle avoidance, except in those instances when the mode of operation of the vehicle is to move very close to the ocean bottom. In this case the bottom following system (altitude information) may be a completely separate system. Additionally, under certain circumstances the depth information can be used for navigation if an area map with depth information is available. The location of the vehicle is determined from the present and past depth readings as these match with the onboard depth map. Each of these rquirements can be translated into constraints on the choice of the sensors and the data conditioning algorithms.

Typically, machine readable images can be produced by video, active or passive sonar or laser systems. Each of these systems has its advantages and disadvantages when used in an underwater vehicle, and a comparison between these systems is given in Table 1. Video cameras usually have a limited range, not more than perhaps 20 ft under ideal conditions. However, high resolution, as compared to images from sonar systems, can be produced, especially with the use of stereo cameras. Also, video images can give information about the physical properties of the image, color and reflectance, which can be useful for identification of the object.

Active sonar systems can be designed to have a much longer range as compared to video cameras. However, although sonar may be the only type of remote sensing (vision) device that can be implemented because of the water turbidity, usually sonar systems have a poor resolution as compared to video. The resolution (azimuth and range) can be increased by increasing the frequency of operation of the sonar and by shortening the pulse width: but this will be accompanied by a reduction in range because of the increased absorption with the increased frequency. Another disadvantage of active sonar systems is that under certain circumstances it may not be pos-

---

Contributed by the Ocean Engineering Division for publication in the JOURNAL OF ENERGY RESOURCES TECHNOLOGY. Manuscript received by the Ocean Engineering Division, November 1987; revised manuscript received October 6, 1989.

Table 1 Remote sensing hardware comparison

				ACTIVE SONAR			
CRITERIA	VIDEO	LASER RANGE FINDERS	PASSIVE SONAR.	PULSED ECHANICALLY SCANNED	CTFM ECHANICALLY SCANNED	PHASED MODULATION SCAN	MULTIPLE BEAM
Azimuth Resolution	HIGH	HIGH	MEDIUM	MEDIUM 1°-2°	MEDIUM 1°-2°	MEDIUM 1°-2°	LOW 5°-15°
Range Resolution	ERY HIGH < lcm	VERY HIGH < 1cm	---	HIGH 5-10cm	MEDIUM 6-10cm	HIGH 5-10cm	HIGH 5-10cm
Scan Rate (Image Update)	FAST	FAST	---	VERY SLOW	MEDIUM 30-50sec	FAST 6-10sec	NO SCAN 1-2s
Detection	NIL	NIL	NIL	HIGH	HIGH	HIGH	HIGH
Range	SHORT < 10m	SHORT 10-30m	VERY LONG 1-10Km	LONG 100-500m	LONG 100-500m	MEDIUM 50-200	LONG 100-500m
Availability	GOOD	XPERIHENTAI	GOOD	GOOD	GOOD	GOOD	GOOD
Angle of View	LIMITED COO-80°	WIDE 100°-180°	WIDE 100°-180°	WIDE 100°-180°	WIDE 100°-180°	WIDE 100°-180°	MEDIUM 60°-100°
Image Distortion	NIL	NIL	---	HIGH	MEDIUM	LOW	VERY LOW
Complexity	---	---	LOU	LOW	MEDIUM	HIGH	HIGH
Type of Image	2-D	3-D	---	2-D	2-D	2-D	3-D

*cannot be used for image generation of ocean bottom topography

sible to operate an active sonar. Passive sonar systems are in general ideal for surveillance operations. These offer a long range as compared to other forms of sensing devices, and can be used to determine bearing as well as range of incoming objects. The main advantage apart from range is that these, by definition, are quiet systems. However, the main disadvantage is that passive sonar is not only sensitive to threat objects that generate a self-noise level higher than the ambient noise levels in the vicinity of the passive sonar. but also to any other sound source within the range of the device.

Underwater laser range finders are still to some extent in the development stages. Laser systems have the advantages of high resolution, and if high-energy short wavelength laser (such as blue-green laser [1]) is used, the range can be up to 60 m (200 ft), which may be acceptable for a medium speed vehicle.

2 Applications of Active Sonar

Acoustic (active sonar) systems are presently the most extensively used systems for underwater image generation. For most of the tasks described in the foregoing, the ideal remote sensing system would provide a 3-D description of the world around it. In general it may be difficult and possibly more expensive to recover 3-D information from 2-D data, and therefore the employed sensors must directly provide for 3-D data and the processing must be able to handle 3-D imagery. For autonomous land vehicles, 3-D images are generated by stereo cameras. For underwater applications, stereo-acoustical techniques would in general be impossible to implement. Unless the separation distance between the two components of the system is several wavelengths, interference can result between the two transducers due to reverberation. which would reduce the performance of the system. Therefore, although ideally 3-D images are required, it may not be possible to generate 3-D images with good resolution with present systems.

A number of systems that generate 2-D images are commercially available. These systems use different methods of operation and there are trade-offs between resolution and speed of image refresh rates. In what follows, a description of some typical systems and their method of operation is given together with their major advantages and disadvantages. Following in the next section is a description of a post-processing technique that can be used with side scan sonar-type data to estimate a 3-D representation from essentially 2-D images.

Active sonar systems have in general the same basic principle of operation, where the area or object to be identified is insonified by acoustic energy and the range to the object is determined by measuring the time delay between the transmitted and returned (back scattered) signal [2]. Of interest in underwater moving vehicles is forward-looking sonar (FLS), since this will give the information required to plan the motion of the vehicle. The main differences between the various FLS that are available are mainly in the way the information is retrieved once the forward direction is insonified.

Generally available FLS can be categorized in four types which are pulsed mechanically scanned, continuous transmission frequency modulated (CTFM), which is also mechanically scanned, electronically scanned sonar and multiple beam sonar. The latter type comes in either of two forms, that is either with multiple projected and receiver beams or alternatively with a projected broad beam and multiple preformed receiver beams.

Pulsed mechanically scanned sonar is very similar to side scan sonar and information is obtained one sector at a time. The angular and range resolution are controlled by the beamwidth of the projector transducer and the duration of the pulse, respectively. To scan a wide angle of view, this system would be very slow unless the azimuth resolution is compromised. The time for a complete forward scan is dependent on the range and azimuthal beamwidth. A 90-deg forward scan for a range of 400 m and an azimuth beamwidth of 2-deg. would typically take about 48 s. To decrease the scanning time, either the range is reduced or the beamwidth increased resulting in a reduction in azimuth resolution. The relatively slow coverage rate is the main disadvantage of this type of FLS. its main advantage is its simplicity.

The slow coverage rate can cause significant distortion in the generated images because of the vehicle motion, which would have to be compensated. This type of FLS can, however. be coupled to an intelligent system which can control the sectors to be scanned, and thus, to some extent, improve the coverage rate. For a relatively slow-moving vehicle, changes in the environment are also going to be relatively slow, except perhaps for other moving objects. Furthermore. the system can be instructed to limit its scan to those sectors where moving objects have been detected. If motion compensation is included for a high-speed vehicle, then instead of the sonar element being rotated to scan over a particular sector. the sonar element can be operated in a "rocker" mode [2]. In this case, the transducer is rotated about a horizontal axis parallel to the direction of motion instead of about a vertical axis. as in the sector scan mode. The main disadvantage of this operation is the limited scan angle. However, objects stay in the same line as they become closer to the vehicle which simplifies motion compensation.

CTFM mechanically scanned sonar systems address the problem of slow coverage inherent in pulsed mechanically scanned sonar, by transmitting a continuous sawtooth frequency slide signal. With this method of operation, the CTFM process transforms the range (time) information into the frequency domain in the form of frequency shifts. This improves the scanning rate as compared to the pulsed sonar. Typical scanning rates for CTFM sonar systems are 30 deg/s. That is, a ±90-deg sector can be scanned in 6 s, which is also the interval between image updates. Although this type of sonar has a much faster scan rate, it can still potentially distort the image output for a fast-moving vehicle if no compensation is allowed. The main advantage of CTFM sonar systems is the improved scan rate which thus allows a high azimuth resolution, typically about 1 to 2 deg. The main disadvantage of CTFM sonar systems is the range resolution. This is determined by the number of processor filters employed to detect shifts in the frequency, and for a fixed number of filters, the resolution degrades with increasing range. In general, the number of filters employed gives about one-tenth of the resolution of a pulsed mechanically scanned sonar. If the number of processor filters is increased to improve resolution, then the scanning rate will drop and the CTFM sonar loses its coverage rate advantage.

The "within pulse" electronic scanning sonar, generally referred to as phased modulation scanning, has a very fast scan rate, typically about 15 KHz, which is dependent on the pulse length and the sector angle of scan. For this system the sonar beam is scanned over the whole sector of interest for every range resolution cell, which is equivalent to the pulse length, hence "within pulse" scanning. The azimuth resolution is similar to that of the pulsed and CTFM mechanically scanned sonar systems. This type of FLS combines fast sweep rates with high-range resolution. Its main disadvantage is its complexity, especially the electronic steering. Because of the fast sweep rates, electronic scanning must be used. Also, this type of sonar is usually limited to high-frequency operation because of the otherwise large size of the required transducer array. When the beam is steered to the edges of the sector, away from the normal direction of the transducer, the effective length of the transducer array is reduced. To compensate for this, longer arrays or circular transducer arrays are sometimes used. For low-frequency operation, a larger transducer is required, and with the reduced effective aperture near the edges of the sector, the size of the required transducer will be impractical.

The FLS systems described in the foregoing operate very similarly to side scan sonar. That is, the beam pattern is narrow in the horizontal direction (approximately 1 to 2 deg), and wide in the vertical direction (approximately 80 deg). The images generated by these systems are 2-D images, similar to an aerial photograph when the object is illuminated from the side. From this 2-D information a 3-D representation of the ocean bottom contour can be estimated as described in Section 3. The resulting images can be used by the vehicle for navigation. provided the resolution is adequate. The estimated 3-D information can be used for optimum path planning given some desired set of operational modes and for bottom contour following.

Another type of FLS system for obstacle avoidance uses the concept of acoustic "whiskers." The "whiskers" are multiple acoustic beams that project in different directions to "watch" for obstacles. A typical arrangement presently used on an underwater vehicle is 3 horizontal layers of 5 acoustic beams per layer pointing to the front of the vehicle [3]. Systems with a larger number of beams in the horizontal direction are now becoming available. The main advantages of multi-beam sonar systems are the higher rates of data gathering which make these system less prone to platform motion distortion (the required compensation is much less for these systems as compared to other slower systems), the range resolution is related to the pulse length, and these have no moving parts. However, multi-beam FLS have rather poor azimuth resolution (typically 10 deg), although on some new and projected systems with 40 or more beams [2], a higher resolution is possible. The main disadvantages of multi-beam systems are the complexity in the hardware and the fact that a number of transducers are all pinging at the same time making the sound level generated by the system high as compared to other systems. If detection during the operation of the sonar is to be avoided, the fact that the generated sound level is higher for this system creates an additional disadvantage.

The multiple beam sonar system can be considered to consist of an amalgamation of a number of individual sonar systems all pointing in different directions simultaneously. Therefore, to process the data, either multiple identical channels are used, malting the system bulky, or alternatively some form of multiplexing is used. The use of such FLS for contour generation would require an inordinate number of beams making this type inappropriate for such a task.

3 3-D Contours From Side-Scan-Type Sonar Data

Having discussed the modes of operation of the general types of FLS systems, apart from the multiple beam-type, 3-D representation of the ocean bottom contour can only be generated through post-processing. With side-scan sonar-type data, 3-D image estimates can be obtained from the geometric scaling of the 2-D images. Vertical resolution of objects in the insonified area can be estimated from knowledge of the length of the acoustic shadow behind the object of interest and the location above the bottom of the sonar transducer. Since the operation of the FLS for which this technique is applicable is similar to that of side-scan sonar, with the only difference that for the FLS the information would be in the form of radial lines as opposed to parallel lines of slant range, the application of this technique is demonstrated on side-scan data obtained offshore in the local area.

The operation of a side scan sonar can be described as follows [2]. A fan-shaped beam is radiated by the sonar transducer (Fig. 1(*a*)). Typically, the type of signal contained in this acoustical wave is a short-duration transient, which may consist of a gated CW pulse. The transmitted acoustic transient will be reflected off the ocean bottom with the reflections from near objects arriving first. Considering a line contour (Fig. 1(*b*)), because of the upsloping face of the contour the returned signal from this face will arrive together with other returned signals malting the instantaneous received signal level stronger. The increase in the signal level is dependent on the slope (angular dependence) of the sea floor acoustic backscatterer (object). It is assumed here that the objects to be mapped are much larger than the wavelengths of the acoustic sonar signal. The size of the objects that can be identified would depend on the threshold that discriminates the return signal for an intensified return.

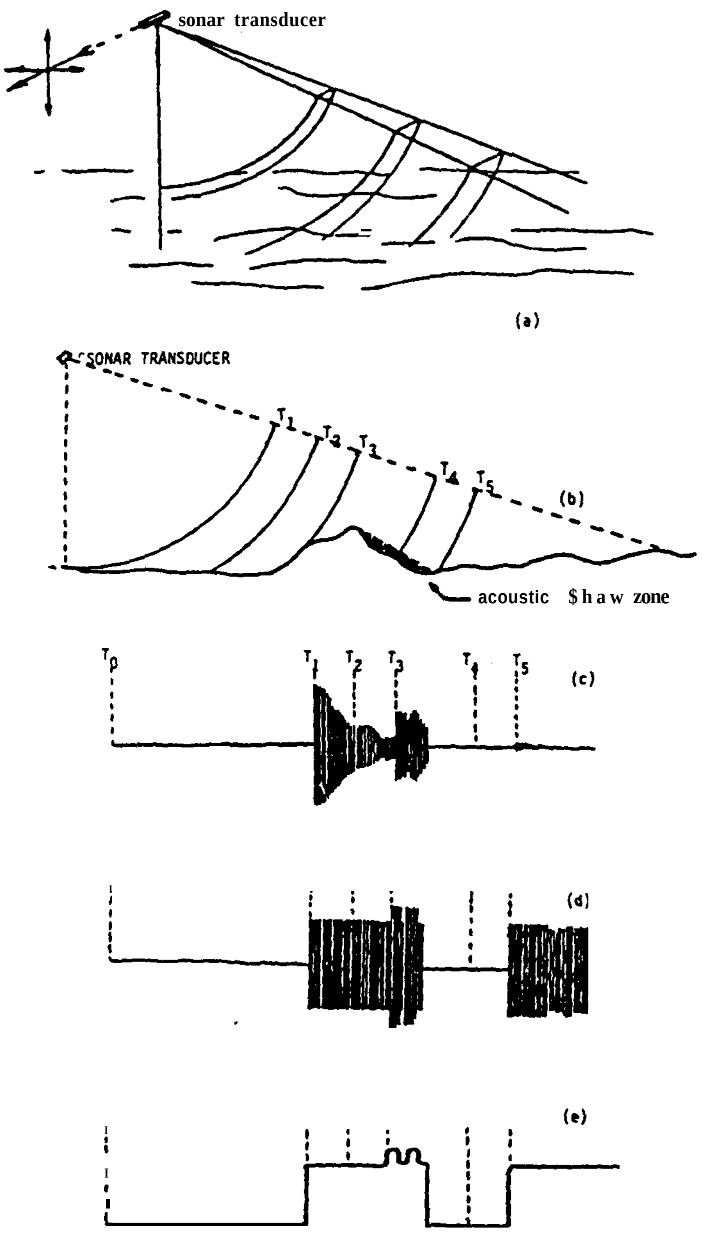


Fig. 1 Operation of a side run sonar. (*a*) Acoustic wave output from sonar transducer; (*b*) bottom contour; (*c*) returned echo signal; (*d*) TVG processed echo signal, (*e*) rectified TVG output.

Beyond the maximum height of the bottom contour no reflections will be received until a line of sight is again established with the ocean bottom. Thus, there is a period of time for which no signal is received, and what is generally referred to as an acoustic shadow is obtained behind the highest point in the contour. The signal received from this simple contour geometry will be similar to the one shown in Fig. 1(*c*). This received signal is passed through an amplifier with a time-varying gain (TVG), which compensates for the spreading losses and the absorption of the sound waves as they propagate through the water. Figure 1(*d*) represents the received signal after it is passed through the TVG amplifier and corrections made for slant range distortions as is typical in most side-scan systems. To facilitate the identification of sections in the return signal which are intensified in level, the received signal is full-wave rectified; the result for this procedure for the example shown here is demonstrated in Fig. 1(*e*). All this processing is standard on most side scan sonar systems; the rectified signal is the input to the graphics recorder and this controls the intensity of the image.

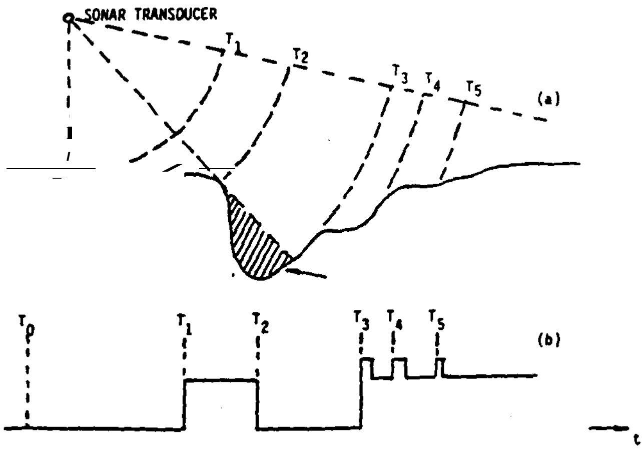


Fig. 2 Sequence of signal levels for a negative displacement contour. (*a*) Contour; (*b*) rectified output signal.

The sequence of the different levels of the received time signals is influenced by whether there is a positive (upward) displacement in the contour or a negative (downward) displacement. For the case described in the foregoing of a positive contour displacement, the sequence of signal levels is as follows. Starting with some nominal level, the level first increases and then after returning to the nominal level goes to zero in the shadow area. Finally, the signal returns to the nominal level after the acoustic shadow region. If on the other hand the contour had a negative displacement, then the sequence of levels would be, starting with the nominal level, the signal first goes to zero signifying a shadow area, then intensifies due to reflections from the upsloping side of the far end of the negative displacement contour, and finally the signal returns to the nominal level (Fig. 2).

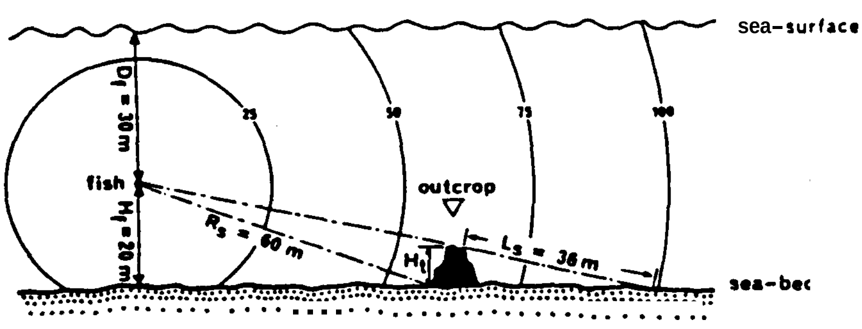
This difference in the sequence of signal levels can be used to determine the location of obstacles (positive displacement contour) or craters (negative displacement contours) in the ocean bottom. From the returned time signal the slant range to the object and to the end of the acoustic shadow and the depth of the tow body can be determined. Based on a nominal or measured acoustic wave propagation speed, the height of the objects or the depth of craters is determined from these parameters. Considering the simple geometry of Fig. 3, the height of the obstacle can be determined from the relationship

$$H_t = L_s \frac{H_f}{L_s + R_s}$$

where H_t is the height of the object; R_s is the range to the object; L_s is the length of the shadow; and H_f the altitude of sonar transducer above the bottom. That is, the returned time signal now represents a spatial variation of the ocean bottom contour. The resolution by which the height of an obstacle or the depth of a hole is estimated would be a function of the range resolution of the sonar.

Ambiguities can be created if returns from different objects arrive at the same time at the receiver. However, because of the fact that with a FLS, portions of the same area are continuously mapped as the vehicle moves forward, some of these ambiguities will be eliminated Since simultaneous arrivals would only occur for one observation location. For other observation locations, the arrivals from the Same two objects would be discriminated.

A simulation of a typical sequence of signal levels and the calculated height of obstacles and craters is shown in Fig. 4, where Fig. 4(*a*) represents a typical bottom contour that will generate the rectified signal shown in Fig. 4(*b*) and (*c*) shows the computed contour. As can be observed by comparing Figs. 4(*a*) and (*c*), the computed contour is only an approximate



calculating the height of an object :

$$H_t = \frac{L_s \times H_f}{L_s + R_s} = \frac{36 \times 20}{36 + 60} = 7{,}5\ m$$

Fig. 3 Geometry to determine obstacle height from acoustic shadow length

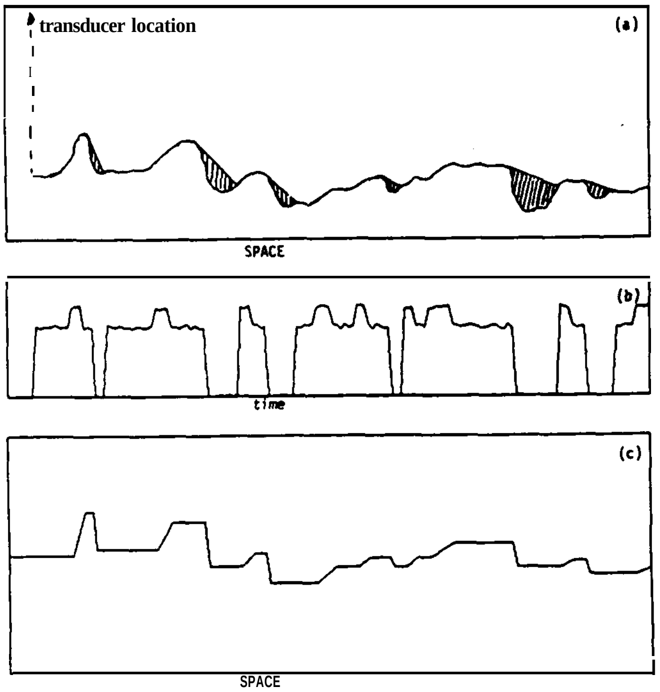
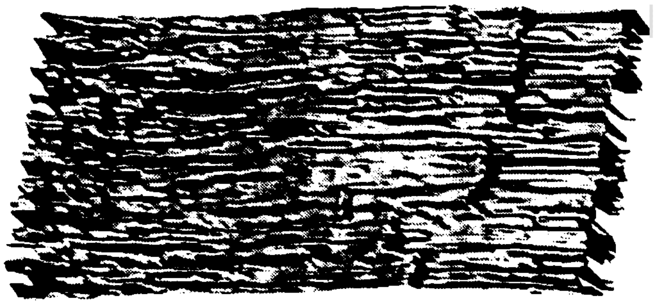


Fig. 4 Results of contour estimates for simulated data. (*a*) Actual contour (shaded areas are in the acoustic shadow zones); (*b*) rectified sonar output; (*c*) estimated contour.

(*a*) Output of side-scan sonar recorder



(*b*) Estimated contour for same area

Fig. 5 Estimated bottom contour for real data

representation of the actual contour. The curvatures of the actual contour are not determined. However, this is also a function of the resolution of the sonar system.

Using this technique, it is possible to estimate a 3-D representation of the ocean bottom over which an autonomous vehicle can navigate according to some cost function. For example, to go from point A to point B over some bottom, lower risk and a less expensive mission is obtained if the vehicle stays as close as possible to the bottom. This is demonstrated using side-scan sonar data collected off the shore of Boca Raton. The outline of the processing used to generate machine usable images for the optimum path planner is described in the next section.

To illustrate the use of the foregoing described procedures, the signal from a side-scan sonar system is post-processed to estimate the ocean floor elevations. The signal output is taken from a side-scan sonar system at the point before it is input to the graphics recorder. Thus, the signal is compensated for geometric spreading and corrected for slant range to horizontal range discrepancies. Since at this stage the purpose of the exercise is to illustrate the concept of operation, scaling factors were not included. However. these are only a function of the setting of the side-scan sonar range, depth of tow body and speed of tow, all of which if required can be input into the processing algorithms to scale the generated images into appropriate dimensions. To be able to make some comparisons, while recording the processed return signal on magnetic tape, a hard copy was also generated through the side-scan graphics recorder. The data on the magnetic tape which is essentially a time signal, but which through the scaling factors can be related to range, is digitally processed to extract the contour information.

To remove some of the errors between contour data obtained from consecutive contour lines, a least-squares error method was used to adjust the overall height of each contour line. The results of the analysis (unscaled) are shown in Fig. 5 where Fig. 5(*a*) shows the output of the side-scan graphics recorder and Fig. 5(*b*) shows the estimated contour data.

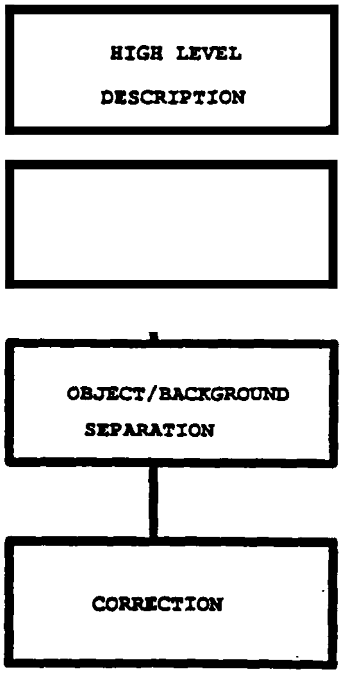


Fig. 6 Architecture of the vision module

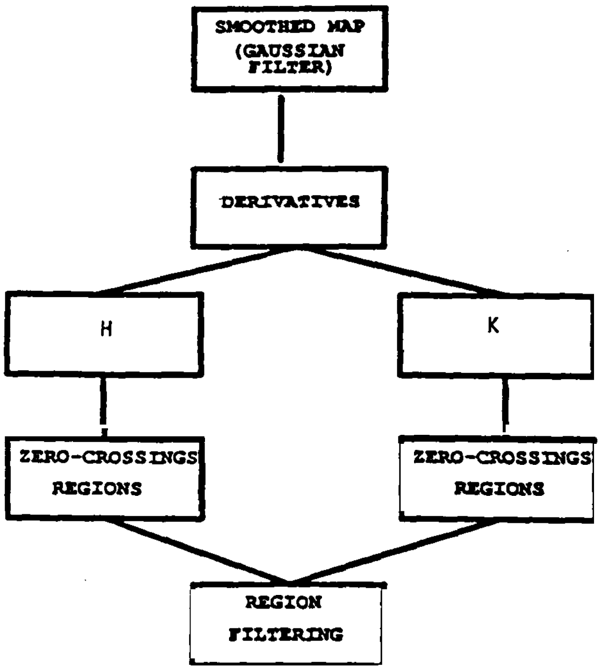


Fig. 7 Generating the *H-K* representation

The comparison between the side scan hard copy output and the estimated contour data from the post-processing is not obvious. However, if one examines the two figures closely, one can match the ridges (dark lines) on the side-scan graphic image to ridge locations (dark lines) in the estimated contour data. The light areas in this figure represent valleys. The orientation of the two images is the same that is the right edge of Fig. 5(*b*) corresponds to the right edge on Fig. 5(*a*).

4 Vision Processing

The 3-D representation of the bottom contour is the input to a vision module for an autonomous vehicle. The architecture of a typical vision system is shown in Fig. 6 [4]. The module is divided into four submodules which convert the raw sensor data to a high-level description of the sensed environment. The procedure of the vision processing is as follows. First, the sensor data is corrected, that is, arranged into sensor-independent format such as a regular elevation map. Second, objects which are not part of the bottom contour are separated from the background. Third, local geometric attributes, such as slopes or curvatures, are computed at each data point. Finally, the data is converted into a graph of regions which constitute the high level description of the scene.

Fig. 8 Smoothed [illegible] tho ocean bottom

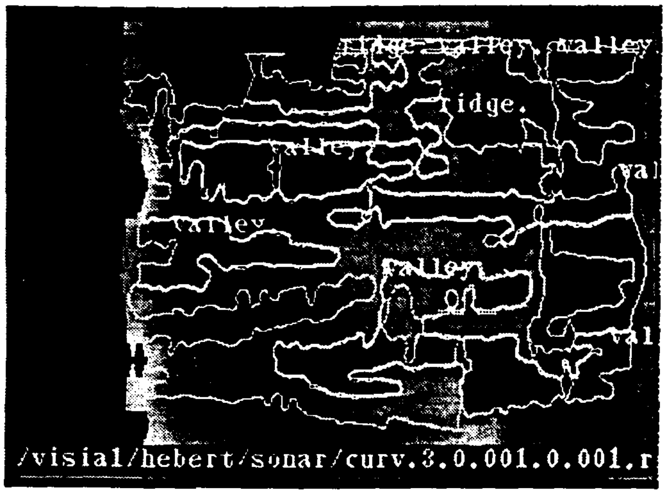


Fig. 9 Surface description of ocean bottom used for path planning

Based on this architecture, a vision module is developed for bottom contour description from side-scan sonar data. The vision module produces a description of the bottom surface based on curvature properties. The description is given in the form of regions which are identified as "hill" or "valleys." The vision processing proceeds in three steps:

1 Correction: The elevation map image produced by the sonar is smoothed by a Gaussian filter.

2 Local attributes computation: The mean curvature, H, and the Gaussian curvature, K, are computed at each point of the surface (Fig. 7). If the elevation map is viewed as a function $z=f(x,y)$. where z is the elevation, and x and y are the axes of the image, the curvatures are computed by estimating the first and second derivatives of $f(x,y)$ at each point and deriving the first and second fundamental forms matrices. The derivatives of $f(x,y)$ are estimated by approximating $f(x,y)$ by a quadratic form in a neighborhood around each point. Precisely, assuming that, in a 3×3 neighborhood of a point, the surface $z=f(x,y)$ is approximated by a quadratic function

$$z_{ij}=A_i^2+B_j^2+C_{ij}+D_i+E_j+F$$

where A, B, C, D, E, F are the coefficients of the quadratic function which is fitted on the measured data. These coefficients change with position and are determined using either a least-squares fit or by using a finite difference technique. For a 3 x 3 neighborhood i and j are between −1 and 1. The second derivative with respect to x is given by

$$\frac{d^2f(x,y)}{dx^2} - \tau(z_{ij-1} - 2z_{ij} + tu_{+1})$$

The formulas for the other derivatives are similar. It is important to note that this technique uses local operators which are very sensitive to local noise. This is the reason why first a Gaussian smoothing is sometimes applied.

3 Region extraction: Each point is classified into a symbolic class such as "hill," "valley," or "ridges," based on the signs of the two curvatures H and K. Eight such classes are theoretically possible; however, in this case only the three classes that can be discriminated based on the resolution of the sonar data are considered. The points which belong to the same class are then grouped into connected regions which constitute the final description.

These three steps have been applied to the side-scan sonar images of Fig. 5. Figure 8 shows the smoothed image and Fig. 9 shows the segmentation of the surface into labeled regions. This description depends on the amount of smoothing applied. As a result, one can obtain descriptions at several level of details by using different filter sizes.

The description of the bottom surface produced by this type of vision processing is used for three purposes: it reduces the amount of data to be used by the navigation modules, it provides the required symbolic information for a local path planner, and it can be matched against a preexisting map for position estimate.

5 Conclusion

In conclusion, this paper describes simple post-processing to generate a **3-D** representation from essentially **2-D** information. The generated images can be used by an autonomous underwater vehicle for path planning. The processing required to retrieve the **3-D** representations from the **2-D** information is rather simple and possibly it is even less than the processing that would be required to directly generate **3-D** images. This would be apart from the additional hardware that a direct **3-D** image system would probably require.

The results presented here are only preliminary results that show good promise and there is some matching between the hard copy generated by the graphics output of the side-scan sonar system and the estimated images. Improvements in the processing algorithms to make them more robust, and thus be able to process the data without any human input, are presently being investigated.

References

1 Rampal, V. V.. "Blue Green Lasers and Their Military Potential." *Defense Science Journal*, Vol. 33(2), 1983. pp. 183-193.

2 Gilmour, G. A.. "High Resolution Sonar." Westinghouse Electric Corporation. Report Number OER 7621.1976.

3 Cyr, R.. "A Review of Obstacle Avoidance/Search Sonar for Submersible Applications." 12th Annual Meeting of the Association for Unmanned Vehicle Systems, Calif., 1985.

4 Hebert, M.. and Kanade, T.. "Outdoor Scene Analysis Using Range Data," IEEE International Conference on Robotics and Automation, 1986.