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SONAR APPLICATIONS FOR UNDERWATER VISION

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ABSTRACT

In general the tasks associated with vision underwater include navigation, obstacle avoidance and bottom contour following. For all of these tasks a 3-D description of the underwater world would be desirable. Although it is sometimes difficult to recover 3-D information from 2-D data. that is underwater vision sensors must provide directly 3-D information and the vision processing must be able to handle 3-D imagery. the required hardware for a truly 3-D vision system for underwater application. with some minimum range requirement of 200 to 300 meters and good resolution, may be extremely complex and indeed not yet available. Also 3-D images may not always be necessary for the operation of an autonomous underwater vehicle, which can mean significant reductions in the processing. In this paper. the generation of a 3-D image representation using ride-scan sonar type data, which by definition contains only 2-D information, is described. The technique will not provide a truly 3-D image of the ocean topography. however, it is shown that the information can be sufficient to be used for bottom contour following or navigation given a cost function. This application is shown in simulation which was developed from real side scan sonar data.

1. INTRODUCTION

A capable vision system is an essential component in the development of an autonomous vehicle. Without some form of vision, 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 vision system can typically be classified into navigation, obstacle avoidance, bottom contour following (if required) and surveillance. The requirements of the vision system to satisfy each of these tasks can be described as follows: Navigation requires generation of images which can be transformed into landmarks and local and global area maps which contain an explicit description of the environment. These can then be used with pattern recognition and matching processes to position 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 vision system must have high resolution and if possible be able to generate a 3-D representation. For obstacle avoidance, the important requirement is that obstacles in the path of the vehicle are detected with enough advanced warning so that the vehicle can maneuver around the object. To some extent. the minimum performance of the obstacle avoidance system is very much dependent on the motion control and response and motion characteristics of the vehicle. This would require both long range and a vide field of view as well as real time images and processing over the full area of view. Under surveillance mode, the vision 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 threat object and its location can be determined. Bottom contour following can to some extent be considered vith obstacle avoidance except in those instances vhen the desired mode of operation is for the vehicle to move very close to the ocean bottom. In this case the bottom following vision 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 map. Each of these requirements can be translated into constraints on the choice of the sensors and the data conditioning algorithms.

Typically, machine readable vision images can be produced by video, active or passive sonar or laser systems. Each of these systems have their advantages and disadvantages when used on an underwater vehicle and some comparison between the systems is given in TABLE I. Video cameras usually have a limited range, not more than perhaps 20 feet under rather ideal conditions. However, high resolution images 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 for image generation can be designed to have a very long range. however, usually aonar systems have a poor resolution as compared to video images. The resolution (azimuth and range) can be Improved. but this will be accompsnied by a reduction in range. Resolution csn be increased by an increase in the frequency of operation of the aonar and by a shorter pulse width. However. increased frequency implies an increase in transmission absorption which reduces the range. Another disadvantage of active sonar systems is that under certain circumstances it may not be possible to operate an active sonar because it may be "too noisy". Passive sonar systems are ideal for surveillance operations. These offer very long range and can he uaed to determine directionality and thus bearing of the threat object. The main advantage apart from range is that these. by definition, are quiet systems. However. the main disadvantage is that only threat objects that generate a self noise level higher then the aobient noise levels in the vicinity of the passive sonar will be detected.

TABLE 1

VISION HARDWARE EVALUATION

CRITERIA	VIDEO	LASER RANGE FINDERS	PASSIVE SONAR*	ACTIVE SONAR: PULSED MECHANICALLY SCANNED	ACTIVE SONAR: CTFM MECHANICALLY SCANNED	ACTIVE SONAR: PHASED MODULATION SCAN	ACTIVE SONAR: MULTIPLE BEAM
AZIMUTH RESOLUTION	HIGH	HIGH	HIGH	HIGH	MEDIUM	HIGH	LOW
RANGE RESOLUTION	VERY HIGH	VERY HIGH	—	HIGH	MEDIUM	HIGH	HIGH
SCAN RATE (IMAGE UPDATE)	FAST	FAST	—	VERY SLOW	MEDIUM	FAST	NO SCAN
DETECTION	NIL	NIL	NIL	HIGH	HIGH	HIGH	HIGH
RANGE	VERY SHORT	SHORT	VERY LONG	LONG	LONG	MEDIUM	LONG
AVAILABILITY	GOOD	EXPERIMENTAL	GOOD	GOOD	GOOD	GOOD	GOOD
ANGLE OF VIEW	LIMITED	WIDE	WIDE	WIDE	WIDE	WIDE	MEDIUM
IMAGE DISTORTION	NIL	NIL	—	HIGH	MEDIUM	LOW	VERY LOW
COMPLEXITY	—	—	LOW	LOW	MEDIUM	HIGH	HIGH
TYPE OF IMAGE	3-D	3-D	—	3-D	3-D	3-D	3-D

*Cannot be uaed for Image generation of ocean bottom topography.

Underwater laser range finders are still to some extent in the stages of development. Laser systems have the advantages of high resolution and if high energy short wavelength lasers (such as blue-grern lasers (1) are uaed. the range can be up to 200 feet, which may be acceptable for a medium speed vehicle.

2. Applications of Active Sonar

Acoustic (active sonar) systems are presently the most extensively uaed systems for underwater image generation. For most of the tasks described above. the ideal vision system provides a 3-D description of the world around it. In general it may be difficult and possibly more expensive to recover a 3-D information from 2-D data and therefore the sensors must provide directly 3-D data and the vision processing must be able to handle 3-D imagery. For autonomous land vehicles 3-D images are generated by stereo vision. For underwater applications, using acoustical techniques, stereo vision technique:: are in general impossible to implement because of two reasons. First, the two components of the system will increase the reverberation level hence reducing the performance of enrh component of the system and second the separation distance required between the two elements of the system would be rather large. Therefore. although Ideally 3-D images are to be generated. 3-0 images with good resolution may not be possible to genernte. at least with present systems.

A number of system?. that in general generate 2-D images are commercially available. These systems are different methods of operation and there area trade-offs between resolution and speed. 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 nest section is a postprocessing technique that can be used with side scan sonar type data to give a 3-D representation from essentially 2-D images.

All sonar systems have the same basic principle of operation. the area or object to be identified is insonified by acoustic energy. Thr range to the object is determined by measuring the time delay between the transmitted and returned (back scattered) signal (2). What is of great interest in underwater moving vehicles is forward look sonar (FLS), since this will give the information required to plsn 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 frontal view is insonified. Generally available FLS can be classified as. pulsed mechanicslly scanned. continuous transmission frequency modulated (CTFM), also mechanicollv scanned, electronically scanned sonar and multiple beam sonar.

Pulsed mechanically scanned sonar is very much similar to sidr scan sonar and information is obtained one sector at a time compared to a line at a time as with tide scan sonar. The resolution is determined by the beamwidth of the projector transducer and the duration of the pulse. To scan a wide angle of view, this system would be too slow unless rhe azimuth rrsolution is compromised. The time for each scan is dependent on the range and beamwidth, a 90 deg scan with a rangr of 400m and a beamwidth of 2 deg, would typically take about 48 seconds. To decrease the scanning timr. either the range hss to be reducrd or the beamwidth increased resulting in a reduction in azimuth resolution. The relatively slow coverage rate is thr main disadvsntage of this type of FLS. its main advantage is its simplicity. The slow coverage rate can cause significant distortion in the produced images because of the vehicle motion and this vould 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. The system can he 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 anis. 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 signal. With this method of operation, the CTFM process transforms the range (time) information into the frequency domain in the form of frequency rhifts. This improves the scanning rate as compared to the pulsed sonar. Typical scanning rates for CTFM sonar systems are 30 deg/second. That is, a 90 deg sector can be scanned in 3 seconds, which is therefore the interval between image updates. Although this is 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 vhich thus allows a high azimuth resolution, typically about 1 to 2 degrees. The main disadvantage of CTFM sonar systems is the range resolution. This is determined by the number of processor filters required to detect shifts in the frequency and for a fixed number of filters, the resolution degrades vith increasing range. In general, the number of filters employed give about one-tenth of the resolution of a pulsed mechrnically 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.

Another form of scanning sonar is the "within pulse" electronic scanning sonar, generally referred to as phased modulation scanning. This type of FLS has a very fast scan rate, typically about 15 KHz, which is dependent on the pulse length and the sector angle of scan. 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 froquency operation because of tho reduced effective length of the sonar transducer vhen the beam is steered to the edges of the sector away from the direction normal to the transducer.

The FLS systems just described have a mode of operation which is very similar to that of side scan sonar, that is in general they have a narrov horizontal beam pattern (approximately 1 to 2 degrees), and a wide vertical beam pattern (approximately 80 deg). The type of images generated by these systems can in general be described as 2-D images, similar to an aerial photograph illuminated from the side. Hovever, from this information a 3-D representation of the ocean bottom contour can be generated as described in Section 3. The resulting images can then be used by the vehicle for navigation, provided the resolution is adequate. Additionally, this information can also be used for optimum path planning given some desired set of operational modes and for bottom contour following.

Another type of FLS systems for obstacle avoidance uses the concept of acoustic "whiskers". The "whiskers" are multiple acoustic beams that are pointing 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 multibeam sonar systems are the higher rates of data gathering, and thus to some extent these systems are not prone to platform motion distortion, the range resolution is related to the pulse length, and that there are no moving parts. Hovever, typically multibeam FLS have rather poor azimuth resolution (approximately 10 deg) although on some new and projected systems with 40 or more beams (2), a higher resolution is achieved. The main disadvantages of multibeam systems are the complexity in the hardware and the fact that a number of trsneducers are ell pinging at the same time making the system potentially very noisy. In basic terms the system can be considered to consist of an amslgamation of a number of individual sonar systems a11 looking in different directions simultaneously. Therefore either multiple identical channels are used which would make the system bulky or alternatively some form of multiplexing is used. The use of such FLS for contour generation vould 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 postprocessing. With side scan sonar type data, 3-D imsges can be obtained from geometrical 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, vith the only difference that for the FLS the information vould be in the form of angle/range as compared to a series of parallel lines of range information, the application of this technique is demonstrated on side-scan data obtained off shore 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 (Figure 1(a)). Typically the type of signal contained in this acoustical wave is a short duration transient, a chirp. The transmitted acoustic transient will be reflected off the ocean bottom with the reflections from near objects arriving first. Considering a line contour (Figure 1(b)), because of the upsloping face of the contour the returned signal from this face will arrive together with other returned signals making the instantaneous received signal level stronger. 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 and thus there is a period of time for vhich no signal is received, and thus what is generally referred to as an acoustic shadow is obtained behind the high point in the contour. The signal received from this simple contour geometry will be similar to the one shown in Figure 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. To enhance the difference in the received signal with time the signal is full wave rectified and the result is shown in Figure 1(e). All this processing is standard on most sidescan sonar systems.

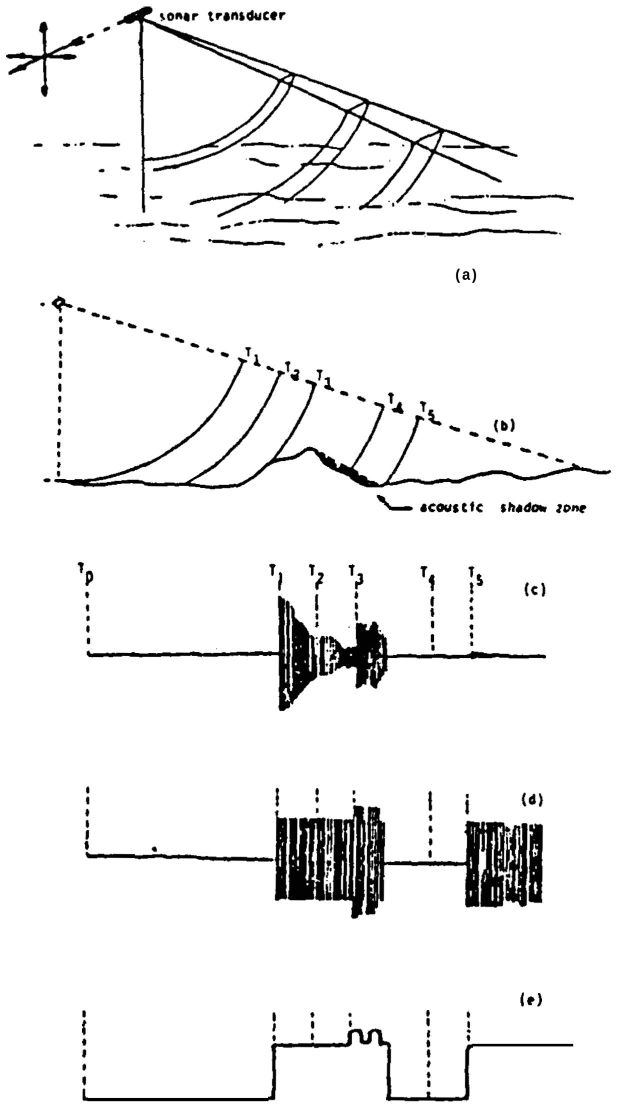


Fig. 1 Operation of a side scan sonar. (a) Acoustic wave output from sonar transducer: (b) bottom contour: (c) returned echo signal; (d) TVC processed echo signal: (e) rectified TVC output.

the rectified signal la the input to the graphics recorder and this controls the intensity of the image.

The sequence of the dlfferent 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 above of a positive contour displscement , the sequence of signal levels is as follows. Starting vith a normal level. the level then increases after which the level first goes back to the normal level and then goes to zero in the shadow area and then returns back to a normal level beyond the shadow region. If on the other hand the contour had a negative contour displacement then the sequrnce of levels vould be. starting vith a normal level. the signal then goes to zero signifying a shadow area. then the signal increases above the normal level due to reflections from the upsloping side of the far end

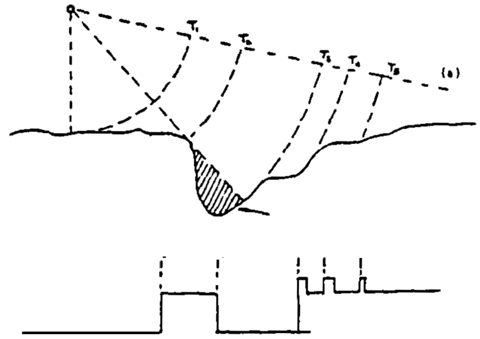


Fig. 2 Sequence of signal levels for a negative displacemrnt contour. (a) Contour: (b) rectified output signal.

of the negative displscement contour and finally the signal goes back to normal level (Figure 2).

Such difference in the sequence of signal levels can be used to determine the locstion of obstacles (positive displacement contour) or craters (negative displacement contours) in the ocean bottom. The height of the object or the depth of the crater is determined from the length of the shadow. Considering again a simple geometry (Figure 3). the height of the obstacle can be determined using similar triangles, giving

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

where H_t is the height of thr objects: R_s is thr range to the object; L_s is the length of the shadow; and H_f the attitude of the sonar transducer above the bottom. The resolution by which the height of an obstacle or the depth of a hale is estimated would be the same as the range resolution of the sonar, which thus is a function of the frequency and the duration of the projected acoustic transient.

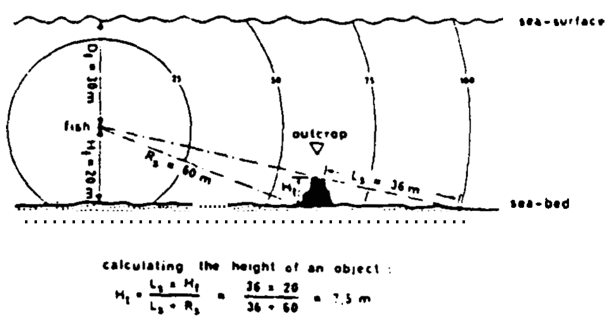


Fig. 3 Geometry to determine obstacle height from acoustic shadow length.

A simulation of a typical sequence of signal levels snd the calculated height of obstacles and craters is shown in Figure (4), where Figure 4(a) represents a typic31 bottom contour that will generate the rectified signal shown in Figure 4(b) and Figure 4(c) shows the computed contour. As can be observed by comparing Figures 4(a) and (c), the computed contour is only an approximate representation of the actual contour. The curvatures of the actual contour

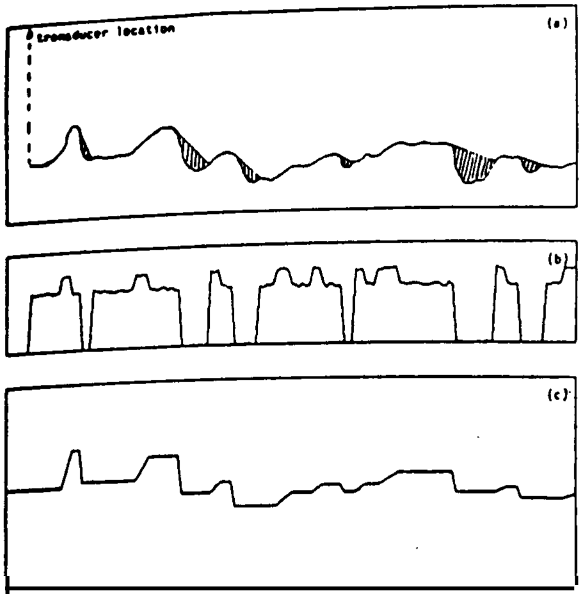


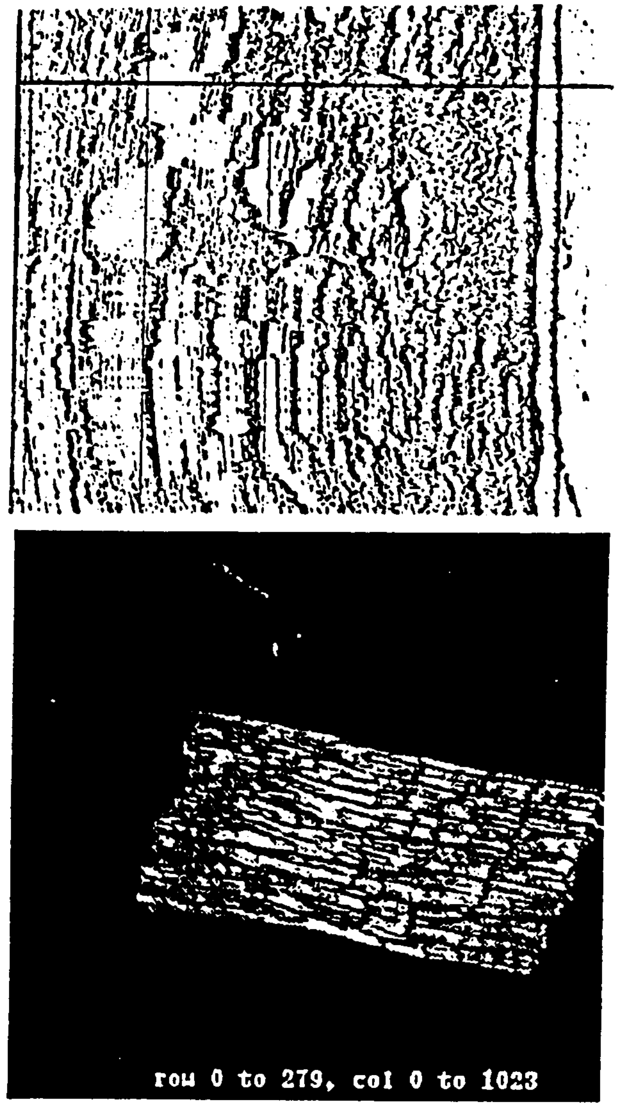
Fig. 4 Results of contour estimates for simulated data. (a) Actual contour (shaded areas are in the acoustic shadow zones): (b) rectified aonar output: (c) estimated contour.

are not determined. However. this is also a function of the resolution of tho sonar system.

Using this technique it is possible to generate a 3-D image of the ocean bottom over vhich an autonomous vehicle can navigate according to some cost function such as to go from point A to point B lower risk and a less expensive mission is obtained by staying as close as possible to the bottom always finding the maximum depth. This is demonstrated using aide 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. While collecting the data apart from generating a hard copy, records vere also made on a magnetic tape recorder. The data was then digitally processed to extract the contour information. To remove errors between contour data obtained from each line (time signal). a least squares error method was used to adjust the overall height of each contour line. The results of the analysis is shown in Figure (5) where Figure 5(a) shows tho output of the sidescan graphics recorder and Figure 5(b) shows the estimated contour data.

4. Vision Processing

Tho 3-D reprerentation of the bottom contour is the input to a vision module for an autonomous underwater vehicle. The architecture (4) of a typical virion system is shown in Figure (6). The module is divided into four submodules which convert the rav sensor contour to a high-level description of the sensed environment. First, the sensor data is corrected, that is. it is put in a sensor-independent format such as an regular elevation map. Second, objects which are not part of the bottom contour are separated from the background. Then, local geometric attributes, such as slopes or curvatures, are computed at each data point. Lastly, the data is converted into a graph of regions which constitute the high level description of the scene.



Pig. 5 Estimated bottom contour for real data. (a) Output of side scan sonar recorder: (b) estimated contour for same area.

Based on this architecture. ve have developed a vision module for bottom contour description from side-scan aonar data. The virion module producer a description of the bottom surface based on curvature properties which is a set of regions identified as "hill" or "valleys". The virion 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 rurface (Figure 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 axis of the image, the curvatures are computed by estimating the first and second derivatives of $f(x,y)$ at erch 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 3x3 neighborhood of a point. the

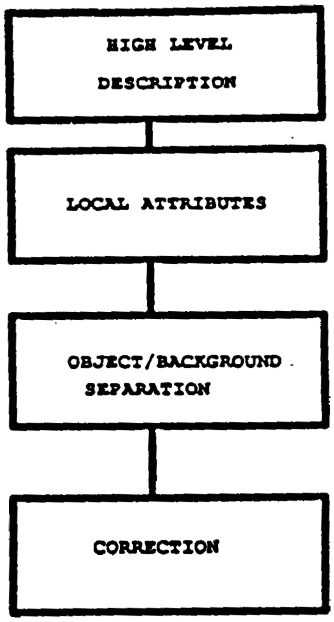


Fig. 6 Architecture of the Vision module.

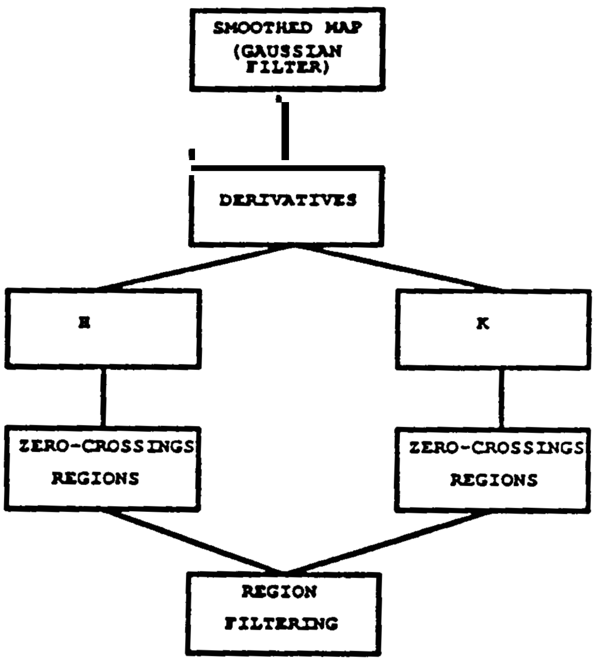


Fig. 7 Generating the H-K representation.

surface $z = f(x,y)$ is approximated by a quadratic function

$$z_{ij} = A_i^2 + B_j^2 + Cij + D_i + Ej + F,$$

where i and j are between -1 and 1, then the second derivative with respect to x is given by:

$$\frac{d\, f(x,y)^-}{d\, x^2} \qquad ij-1 \qquad ij+1\ /\ ,$$

the formulas being similar for the other derivati· It is important to note that this technique uses ' local operators which are very sensitive to local noise. This is the reason why we first apply a Gaussian smoothing.

3. Region extraction: Each point is classif into a symbolic class such as "hill", "valley", o "ridges", based on the signs of the two curvature and K. Eight such classes are in theory possible consider only the three classes that can be discriminated based on the resolution of the sona data. The points which belong to the same class then grouped into connected regions which constit the final description.

These three steps have been applied to the sidescan sonar images of Figure (5). Figure (8) the smoothed image, Figure (9) shows the segments of the surface into labeled regions. This descri depends on the amount of smoothing applied. As a result, one can obtain descriptions at several le of details by using different filter sizes.

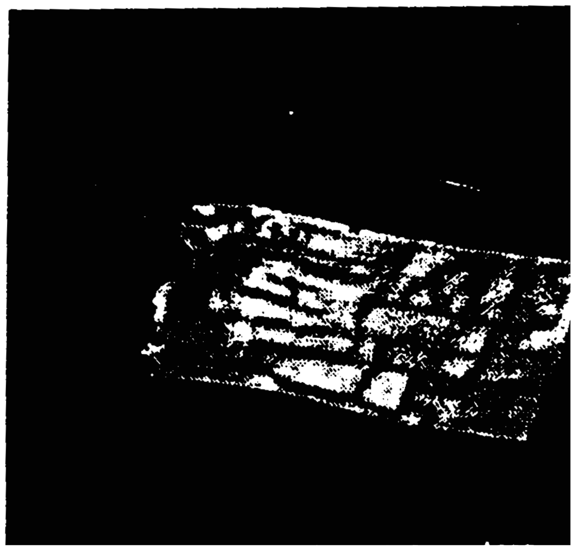


Fig. 8 Smoothed elevation map of the ocean battom.

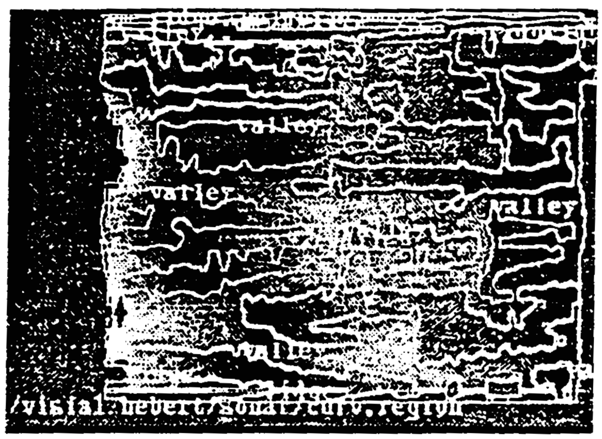


Fig. 9 Surface description of ocean bottom used for path planning.

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 pre-existing map for position estimate.

CONCLUSION

In conclusion, this paper describes simple postprocessing to generate a 3-D representation from essentially 2-D information. The generated images are 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 very good promise and there is some matching between the hard copy generated by the graphics output of the side scan sonar system and the generated images. Improvements in the developed algorithms to make them more robust and thus can process the data without any human interference are presently being investigated.

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