

A Solution to the Ambiguity Problem in Depth Contouring

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Abstract

Depth contours on a chart are important for safe navigation. The ambiguity problem can appear when points of equal depth are joined in contouring. Unreasonable solutions may mistake a shallow area for a deep one, which could result in a potential danger for navigation. A solution is presented to solve the ambiguity problem using constrained lines formed by two shallow depths. The constrained lines are used to limit the joining of the points with equal depth. Experimental results demonstrate that the proposed solution can reduce the dangers of producing non-existent deep areas in bathymetric contouring.



Résumé

Sur une carte, les isobathes sont importantes en ce qui concerne la sécurité de la navigation. Le problème de l'ambiguïté peut apparaître lorsque des points de profondeur égale se rejoignent sur le tracé de l'isobathe. Certaines solutions non fondées rationnellement peuvent prendre par erreur une zone peu profonde pour une zone profonde, ce qui peut entraîner un danger potentiel pour la navigation. Une solution est présentée pour résoudre le problème de l'ambiguïté en utilisant des lignes contraintes formées par deux faibles profondeurs. Les lignes contraintes sont utilisées pour limiter la réunion de points d'une égale profondeur. Des résultats expérimentaux ont montré que la solution proposée peut réduire les dangers liés à la création de zones profondes non existantes dans le tracé bathymétrique.



Resumen

Las isobatas en una carta son importantes para la seguridad de la navegación. El problema de ambigüedad puede aparecer cuando puntos de igual profundidad se unen en el trazado de la isobata. Soluciones no razonadas pueden confundir un área somera por una profunda, lo que podría resultar en un peligro potencial a la navegación. Una solución se presenta para resolver el problema de ambigüedad utilizando líneas forzadas formadas por dos profundidades someras. Las líneas forzadas se utilizan para limitar la unión de puntos con igual profundidad. Los resultados experimentales demuestran que la solución propuesta puede reducir los peligros de producir áreas profundas no existentes en los contornos batimétricos.

A depth contour, a line connecting points of equal depth below the hydrographic datum, is used to represent submarine relief. With the advent of the electronic navigational chart, it gives the facility to mariners for setting up a safety depth contour, depending on the draft of the vessel. The safety depth contour will be highlighted on the display and an alarm will be provided when crossing this contour (Vatsa and Chauhan, 2002). With the evolution of the Electronic Chart Display and Information System (ECDIS) from a static display to provide real-time or forecast information, a “tide-aware” ship’s safe contour needs to be acquired (Brennan et al., 2003, 2007). The depth contour has increasingly become a crucial feature for safe navigation. Nowadays there are two methods for contouring, i.e., triangulation and grid contouring (Kennie and Petrie, 1990). Contouring from triangulated data uses a triangulation technique and interpolates values based on the original data. Contouring from gridded data generates a set of gridded nodes using the neighboring original data points, and then interpolates positions of depth contours based on the regular gridded data. These methodologies for contouring have been continuously improved in recent years (Brennan et al., 2003; Li and Zhu, 2003).

However, the ambiguity problem still exists when joining points of equal depth whichever method is used to plot contours. In triangulation contouring, when four depths form a quadrangle and each edge has a point of equal depth as shown in Figure 1(a), various triangulations will lead to differences when joining points with equal depth. Similarly, if a grid cell has four points of equal value during grid contouring (as shown in Figure 2(a)), ambiguous results may appear when these are joined. Obviously, the different joinings will result in dissimilar submarine terrain representations and discrepancies in areas marked for safe navigation. Although the differences may be local and small, it is important to estimate submarine terrain and navigable areas without error. If the problem is not solved, it will result in potential dangers by indicating deep areas that in fact are shallow.

For navigation safety purposes, a conservative rule in contouring is to expand shallow areas and shrink deep areas (IHO, 1994; NSBQT, 1999; Russom and Halliwell, 1978). All depths less than and equal to the contour value should be compartmentalised into the shallow area in the plotting of the depth con-

tour and deep areas cannot be extended to places without depths (Ye and Liu, 1991). When ambiguous joining of points with equal depth appears, the conservative rule should be utilized. Traditional solutions for the ambiguity problem can possibly mistake a shallow area for one that is deep, which is dangerous for navigation safety. The objective of this paper is to analyze the ambiguity problem during depth contouring, improve traditional solutions, avoid mistaking shallow areas for deep ones, and make contour plotting more reasonable.

Ambiguity in Plotting Depth Contours and its Influence on the Representation of Submarine Terrain

An important step during contouring is to interpolate positions of the contour values for each edge based on the values of the known nodes, and the use of linear interpolation is very popular (Kennie and Petrie, 1990). Then the interpolated points of all edges are connected up according to specified rules. Finally, the polylines from the connected points are further smoothed.

Ambiguity and Traditional Solutions in Triangulation Contouring

If each edge has a point of equal value in a depth quadrangle that consists of four soundings, different triangulation methods will result in the points being joined in different ways. It is known that the Delaunay method is used to form triangles in the majority of terrain modeling packages based on the triangulation method (Kennie and Petrie, 1990; Liu and Gong, 2001; Li and Zhu, 2003). When Delaunay triangulation is performed, the quadrangle, composed of four depths, is partitioned into two triangles. The method of joining points of equal depth is shown in Figure 1(b) (the shaded area, more than 10 metres, is the deep area). However, if the triangulation is shown as Figure 1(c), the deep areas obviously change. Thus, the area represented using diagonal lines in Figure 1(d) is regarded as the deep one.

If topographic characteristic lines are known during contouring on land, constrained Delaunay triangulation will be used for local optimization (Floriani, 1992; Liu and Gong, 2001). If a triangle threads a topographic characteristic line, the triangle will be deleted and the local network will be reconstructed (Liu and Gong, 2001). However, submarine terrain

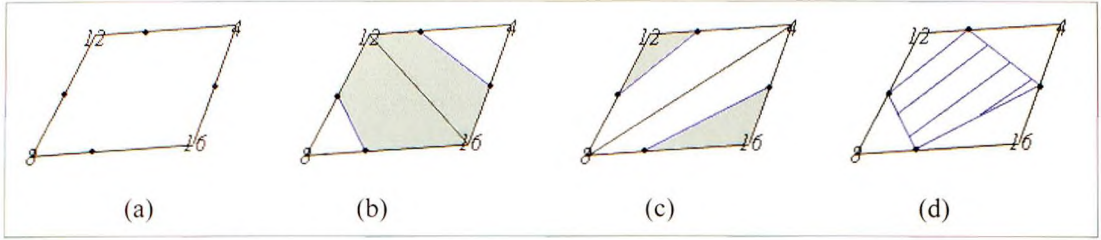


Figure 1: Ambiguity in triangulation contouring.

cannot be directly viewed due to the covering water, and the topographic characteristic lines can only be acquired accurately by well-positioned samples of sounding (Zhang et al., 2005). Unreasonable triangulation can possibly lead to the potential danger of producing non-existent deep areas.

Ambiguity and Traditional Solutions in Grid Contouring

Considering an individual grid cell (Figure 2), a simple linear interpolation is carried out along each edge of the grid in turn based on the values of the nodes and the positions of the contour values are obtained for each edge by interpolation. However, when each edge in a grid has a point of equivalent value, the ambiguity problem will occur, as indicated in Figure 2 (Kennie and Petrie, 1990; Liu and Fang, 1997; Li and Zhu, 2003; Zhang et al., 2005). If the points of equal value are joined as shown in Figure 2(b), but the actual seafloor is represented as shown in Figure 2(c), the possible shallow area represented using diagonal lines in Figure 2(d) is improperly classed as deep.

Several traditional solutions to solve the ambiguity are as follows:

1. A method of joining to the nearest point. As shown in Figure 3, if the points of equal a_1 depth and a_2 are found in a certain grid cell and a_2 locates in the edge AD, and there are other points of equal depth in other edges AB, BC and CD,

the following point should be a_3 since it is the nearest one to a_2 of all points with equal depth in the grid cell ABCD (Hu et al., 1987).

2. A method based on direction changes. It is believed that contour lines seldom change direction abruptly. As shown in Figure 3, the points of equal depth a_1 and a_2 locate in a grid cell ADEF and a_2 in the edge AD, and there is a point of equivalent depth in each edge AB, BC and CD. According to minimum direction change, the following point should be a_3 , not a_4 or a_5 (Wang et al., 1993).

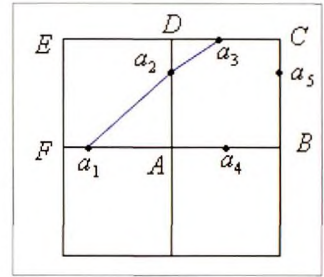


Figure 3: Ambiguity in tracing equivalent points.

3. Subdivision once again (Kennie and Petrie, 1990; Li and Zhu, 2003). Another method is to split the grid cell into four grids or triangles, and assign the average value of the four grid nodes to the central points.
4. Interpolation based on fitting function. By considering neighboring nodes, a type of fitting function is employed to interpolate the contour (Kennie and Petrie, 1990; Liu and Gong, 1997).

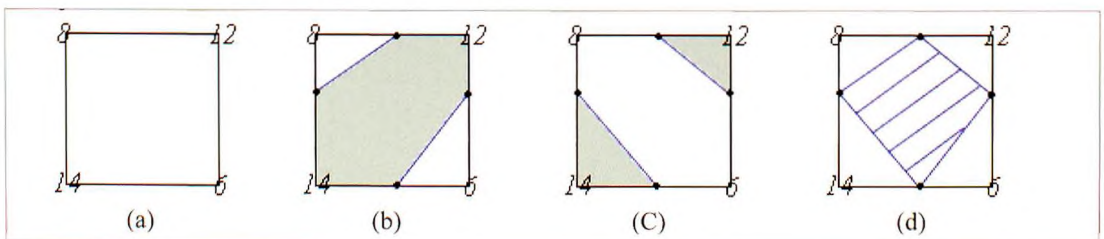


Figure 2: Ambiguity in grid contouring.

These traditional methods have been used to solve ambiguity for the past several decades. However, they do not consider the special needs of safe navigation (Zhang et al., 2005). Most of them are correlated to the different start points and directions (i.e., different start points and searching directions possibly make the results different), so it is possible to produce unreasonable contours from these traditional methods.

Rules and Control Methods of Shallow Depth Constraint

Rules of Shallow Depth Constraint

Due to the actual seafloor being covered by water and thus invisible, the rule of expanding shallow areas and shrinking deep areas is used to solve this problem when an ambiguity occurs (NSBQT, 1999; Zhang et al., 2005). Areas without detailed depth information would be considered on the shallow side rather than the deep one. So a constraining rule should be employed in contour plotting, namely that two shallow depths (e.g. the point P_1 and the point P_2 in Figure 4 and Figure 5) in the quadrangle are used to form a constrained line segment P_1P_2 , and no contours can thread the constrained line. Joined means will become unique when using the constrained line segment and thus mistaking shallow areas for deep ones will be avoided.

Delaunay Triangulation Constrained by Shallow Depths

When ambiguity appears, a control condition is given for safe navigation. The result of using Delaunay triangulation is shown in Figure 4(b), which shows that it is possible to transfer a shallow area to a deep one, and so the triangulation should be improved during this process. For use on land, topographic characteristic lines are employed, and triangles intersecting them are located and deleted; then the local network is optimized (Floriani, 1992; Liu and Gong, 2001). However, the seabed is invisible and submarine topographic characteristic lines are difficult to obtain accurately by hydrographic sampling. The constrained segment P_1P_2 is used as a virtual topographic characteristic line segment to optimize the local network. The final network is shown as Figure 4(c) after local optimization. Delaunay triangulation, constrained by shallow depths, can make the result unique and avoid mistaking shallow areas for deep ones.

Grid Contouring Constrained by Shallow Depths

As shown in Figure 5, in grid contouring, if a point of equal depth a_1 is found in one edge of a quadrangle, which point a_2, a_3 or a_4 will be chosen as the next point of equal depth? A basic rule for solving the ambiguity is that the two joined points should locate on the same side of the constrained line segment

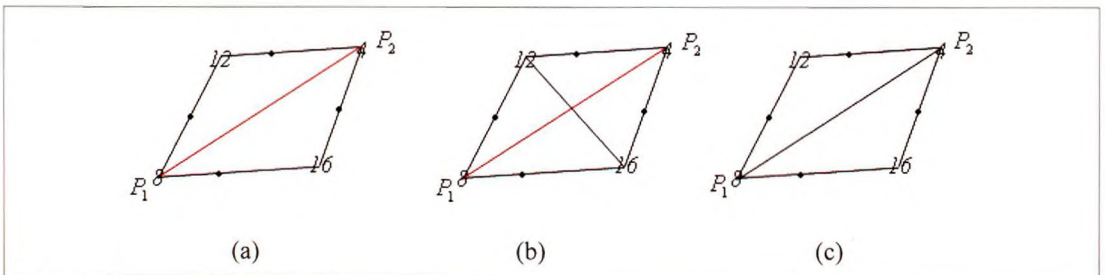


Figure 4: Local reconstructing of network.

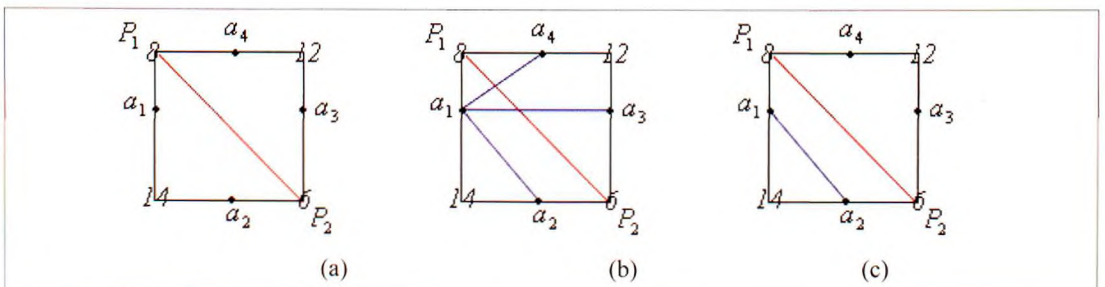


Figure 5: Different joining means in a grid.

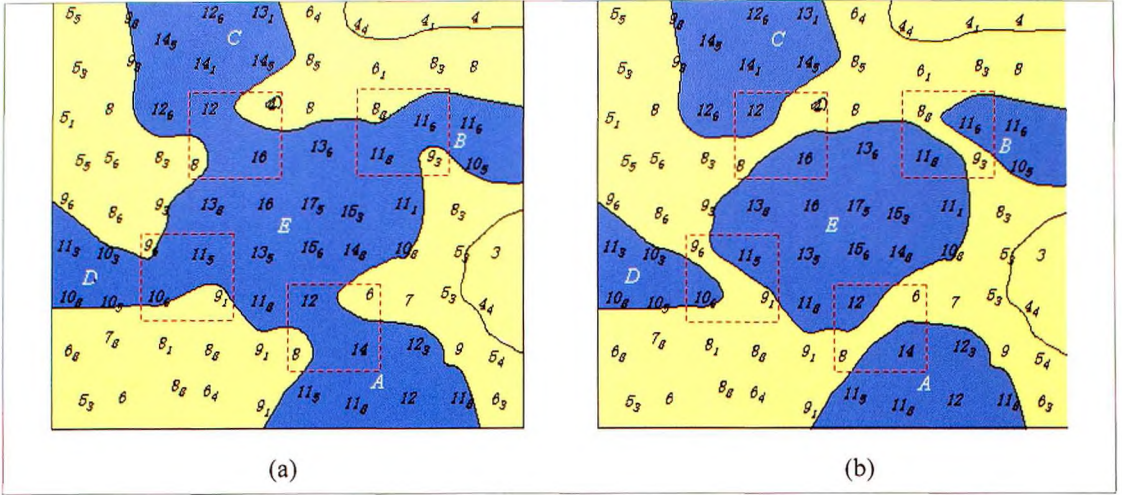


Figure 6: Contours obtained from different triangulations.

P_1P_2 formed by two shallow depths.

The given positions of P_1 and P_2 can be located by a pair of coordinates (x_{P_1}, y_{P_1}) and (x_{P_2}, y_{P_2}) , respectively. Similarly, the positions of a_1, a_2, a_3 and a_4 are denoted using $(x_{a_i}, y_{a_i}) = 1, 2, 3, 4$. The following equation is used to compute a value.

$$F(i) = [(y_{P_2} - y_{P_1})x_{a_i} - (x_{P_2} - x_{P_1})y_{a_i} - x_{P_1}y_{P_2} + x_{P_2}y_{P_1}]$$

$$[(y_{P_2} - y_{P_1})x_{a_i} - (x_{P_2} - x_{P_1})y_{a_i} - x_{P_1}y_{P_2} + x_{P_2}y_{P_1}]$$

$$i=2, 3, 4 \quad (1)$$

If $F(i) > 0$, a_i and a_1 locate on the same side of P_1P_2 , and a_i is the next point of equal value adjacent to a_1 in the contour. In Figure 5, the following results are computed: $F(2) > 0, F(3) < 0, F(4) < 0$. So a_2

is the following point adjacent to a_1 , and the joining is shown in Figure 5(c). In the later search, a_3 and a_4 will be connected. The result from this solution is unique, and it is independent of the different start points and directions when searching for points of equal depth.

Experiment and Discussions

An example is used to test the proposed solution. The result shown in Figure 6(a) is derived from Delaunay triangulation contouring without a constraint. The result, after local optimization using the constraint by two shallow depths, is exhibited in Figure 6(b). In Figure 6, the safe areas have been changed

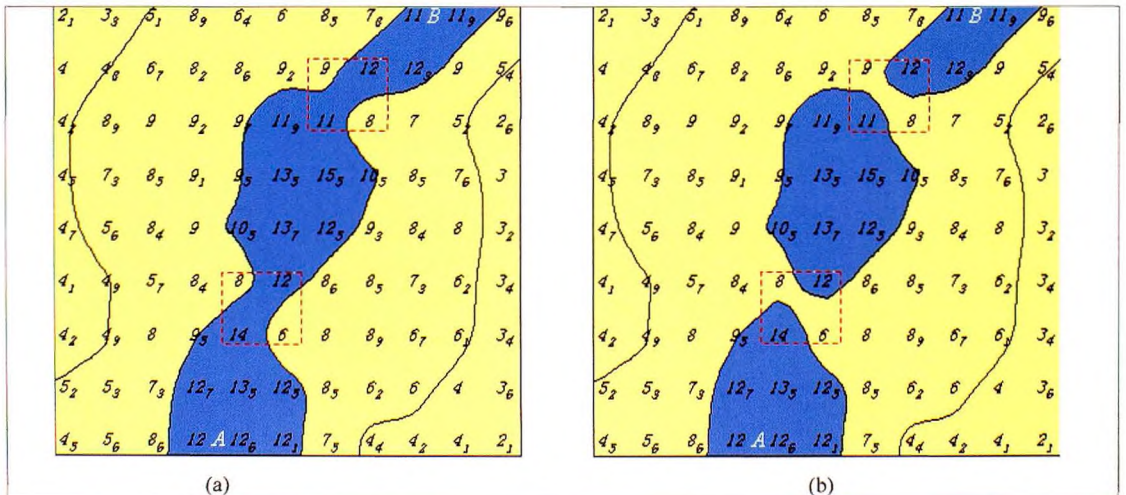


Figure 7: Contour difference from different solutions.

after using the constraint. (The safe depth is 10 metres, the blue areas in the charts are navigable, and red dashed rectangles highlight places at which ambiguity appears.) Figure 6(a) shows that the blue areas (e.g., *A*, *B*, *C*, *D* and *E*) are connected to one another if the constraint is not used. If the constraint is used, areas *A*, *B*, *C*, *D* and *E* are isolated, and it is not possible to navigate between them. In fact, if the actual terrain is as shown in Figure 6(a), but is represented as shown in Figure 6(b), it only wastes navigable resources. On the contrary, if the actual terrain is as shown in Figure 6(b), but is represented as shown in Figure 6(a), there will be a potential danger for navigation.

Another example is used to test for grid contouring. When each edge of a grid has an equal value point, and the traditional solutions (e.g., the method based on the nearest point or direction changes) are used, the result is as shown in Figure 7(a). If the constraint with shallow depths is used, the result is as shown in Figure 7(b). According to traditional solutions, there is a possible channel from area *A* to another one *B*, represented as navigable as shown in Figure 7(a). However, the channel is not navigable for vessels with the draft of 10 meters as shown in Figure 7(b). If the shallow depth constraint is not applied, an un-navigable channel is incorrectly considered as a navigable one.

Conclusions

The joining of points with equal depth during contouring may cause an ambiguity problem. The traditional solutions possibly mistake shallow water areas for deep ones and result in incorrect representation of the seafloor terrain, which will lead to potential danger for navigation. This paper presents a solution using constrained lines formed by two shallow depths to control contouring. The constrained lines are employed as virtual topographic characteristic lines to optimize and reconstruct a TIN locally in triangulation contouring. The lines are used to determine the means of joining points with equal values during grid contouring. Experimental results demonstrate that the presented solution can reduce the dangers of producing non-existent deep areas in bathymetric contouring. Certainly, the proposed solution applies a conservative rule for safe navigation, and more effective solutions would require more detailed and accurate information on the actual submarine topog-

raphy; this would need very time-consuming data acquisition and might only provide a small gain in display efficacy.

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