Experiments with Obstacle and Terrain Avoidance of Autonomous Underwater Vehicle

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Real-time obstacle and terrain avoidance is highly necessary for an autonomous underwater vehicle maneuvering near the rugged seafloor. This paper aims at an obstacle and terrain avoidance system for the deep-sea AUV built in SIA. This AUV will be used to survey deep-sea hydrothermal regions and need to follow rough terrain for obtaining stable acoustic or optical data. A new hybrid obstacle avoidance architecture will be proposed. The sonar image processing method and the real-time optimal obstacle avoidance method are summarized. Finnally the lake experiment results are given to demonstrate the presented methods' feasibility and validity.

Keywords—autonomous underwater vehicle (AUV); obstacle avoidance; terrain following; multibeam imaging sonar

I. INTRODUCTION

An autonomous underwater vehicle (AUV) is an unmanned, untethered, underwater vehicle that carries its own power source and relies on an on-board computer and build-in machine intelligence to execute a mission consisting of a series of preprogrammed instructions [1]. When an AUV is maneuvering near the rugged seafloor, real-time obstacle and terrain avoidance is highly necessary for its safety. The AUV must be able to detect unknown obstacles online and avoid collision with them autonomously.

Autosub6000 uses a Tritech Seaking mechanically scanned sonar system oriented to scan vertically in front of it to provide details of obstacles as well as changes in terrain (its terrain and obstacle avoidance is shown in Fig.1) [2]. The AUV DeDAvE is equipped with state-of-the-art sensor systems including obstacle avoidance sensors on its bow section [3]. ECA has recently integrated BlueView Technologies' P450E-15 sonar systems as forward-looking obstacle avoidance sonar on several AUV systems [4]. Although there have been some applications as shown above, current researches [8~10] still focus the obstacle detection and avoidance to solve some special problems.

This paper mainly describes the design and experiments of an obstacle and terrain avoidance system for the deep-sea AUV built in SIA last year. This AUV will be used to survey deep-sea hydrothermal regions and need to follow rough terrain for obtaining stable acoustic or optical data. Section I provides a brief presentation of the deep-sea AUV that we used to demonstrate the proposed obstacle avoidance method in Qiandao lake. Section II introduces the obstacle avoidance system of the deep-sea AUV, including the forward looking sonar, the automatic obstacle detection and autonomous avoidance decision. In Section III the experiment results are given in detail, in which AUV can hold the 8 meters altitude terrain following in the rugged region.

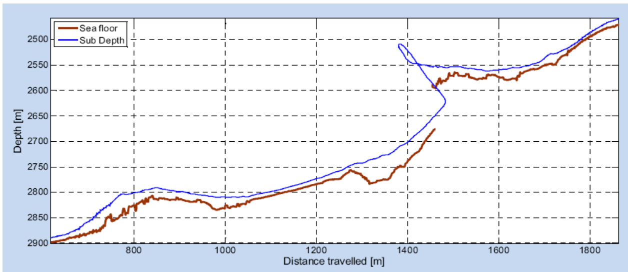

Fig. 1. Ocean floor and Autosub6000 depth profile during part of the 10m altitude terrain following ascent of the Casablanca Seamount. Note collision avoidance behaviour after 1.4Km.[2]

II. THE DEEP-SEA AUTONOMOUS UNDERWATER VEHICLE

The deep-sea AUV (shown as Fig.2) is designed and built by Shenyang Institute of Automation (SIA) from 2011 to 2014. The AUV, whose max diving depth is 4500 meters, is mainly used for the exploration of deep-sea sulfide resource in deep-sea hydrothermal regions.

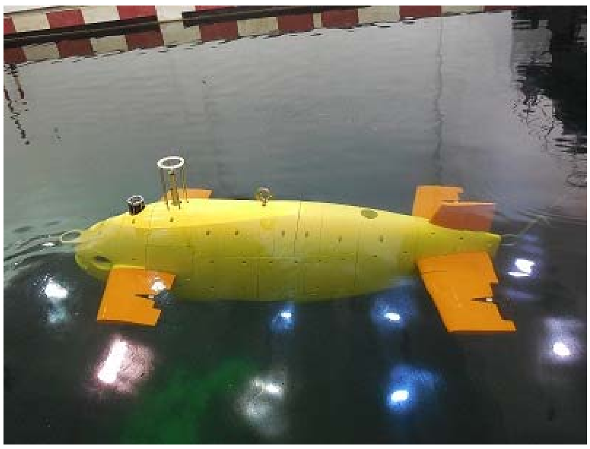

Fig. 2. The deep-sea AUV

This work is supported by the Key Research Program of the Chinese Academy of Sciences under the grant KGFZD-125-014 and by the Chinese National 863 Plan Program under the grant 2011AA09A102.

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Deep-sea hydrothermal systems have now been found along fast, intermediate and slow-spreading mid-ocean ridges, at intraplate volcanic centers, and in island arc settings, both in back-arc basins and in fore-arc areas [5].Shown as Fig.3, the main feature of those regions is with very rough terrain. In order to maneuver near the rugged seafloor to collect optimal or acoustic data, the AUV must be able to follow terrain and avoid collision with it autonomously. Current real-time obstacle avoidance method for simple obstacle scene can't meet the demand of the AUV's obstacle and terrain avoidance in such extremely complex environment. So this paper presents a type of new hybrid obstacle avoidance architecture in the following section.

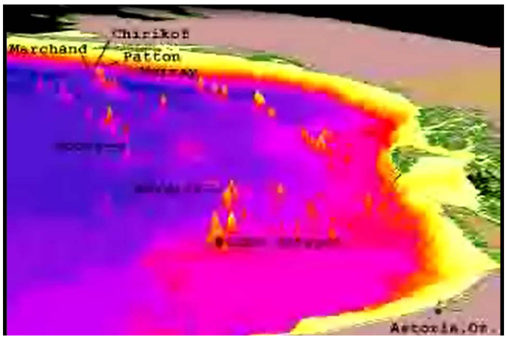


Fig. 3. Here in the Gulf of Alaska, chains of volcanic mountains are lined up across the seafloor.[6]

III. THE OBSTACLE AVOIDANCE SYSTEM FOR THE DEEP-SEA AUTONOMOUS UDERWATER VEHICLE

Two capabilities are necessary for AUV to avoid unknown obstacle autonomously in real time. The first is automatic obstacle detection – on the base of the sensed environmental information, to determine whether there are any obstacles. The second is autonomous avoidance decision - how to move to the target quickly and without collision with the indentified obstacles. They are closely linked. The automatic obstacle detection, which is basis and premise, provides real-time obstacle constraints for real-time obstacle avoidance. The autonomous avoidance decision, which is core, will plan an optimal behavior to avoid the obstacles based on the constraints of obstacles and current vehicle state.

A. The forward looking sonar

To realize the autonomous obstacle avoidance in unknown environment, AUV must be equipped by the forward looking sonar to acquire real-time and effective environmental information. The usual obstacle avoidance sonar includes the echo sounder, the mechanical scanning sonar and the multibeam imaging sonar. The echo sounder outputs one-dimension range information, which represents the nearest distance from sonar to obstacle within the beam. Its field of view is narrow, generally smaller than 10 degree. So many echo sounders are needed to cover the whole direction of view. The mechanical scanning sonar hosts one or two mechanically scanned imaging sonars in a single subsea pressure housing. It takes about 10 seconds to scan a circle (360 degree) and is more suitable for remotely operated vehicle.

The multibeam imaging sonar can provide real-time, crisp imagery of the underwater scene ahead. Recently, advances in sonar technology have enabled the development of reliable, high-resolution, multibeam imaging sonar that can acquire a real-time image of the perceived environment [7]. With the improvement of the multibeam imaging sonar technology and real-time sonar image processing technology, more and more AUV begin to select the multibeam imaging sonar as obstacle avoidance sensor.

The Blueview multibeam imaging sonar is chosen as the deep-sea AUV's forward looking sonar. Its technical specifications are listed in Table I. The sonar is mounted on the AUV's bow section with about 5° upward installation angle from the horizontal plane.

Table. I The technical specifications of Blueview P450-130-D sonar

Technical specifications	**Values**
Frequency	450kHz
Field-of-View	130°
Max. Range	250m
Beam Width	1° ×15°
Number of Beams	768
Beam Spacing	0.18°
Range Resolution	5cm
Update Rate	Up to 10Hz
Weight in Air	7.57kg
Weight in Water	3.58kg
Depth Rating	6000m

B. The automatic obstacle detection

Considering with the special features of the Blueview sonar image obtained by the previous trials, we proposed the sonar image processing method including 3 steps: filtering, image segmentation and morphologic processing. A software developer kit (SDK) was provided by Blueview Technologies Inc. to accomplish the interaction between the control computer and the sonar. We integrate OpenCV and the SDK into the obstacle and terrain avoidance software. Some filter functions in OpenCV can be directly used such as median filtering, mean filtering and so on.

A fuzzy k-mean clustering algorithm is presented in the segmentation, in which n data object is divided into k subclusters with internal clustering and external dispersal. The clustering center updates according to the orientation principle, while the mean square deviation serves as a similarity measure function. The morphologic processing translates the gray image into the binary image, in which obstacle grid is denoted by 1 and free grid is denoted by 0.

C. The obstacle and terrain avoidance method

A new hybrid obstacle avoidance architecture (shown as Fig.4) is proposed. We regard the controlled object of the real-time obstacle avoidance as an augment system comprising of sensors and controllers, in which the velocity controller, depth /altitude controller and the attitude controller for movement, the position controller and trajectory controller for path following are included.

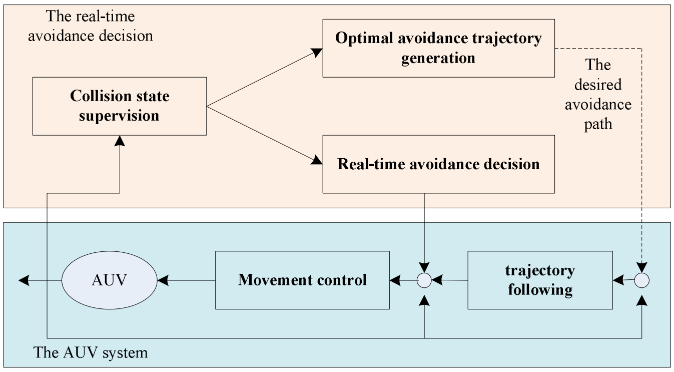


Fig. 4. The obstacle and terrain avoidance system for the deep-sea AUV

While these controllers try to hold the steady motion in three-dimensional space for the deep-sea AUV, the real-time obstacle avoidance system will require the AUV to rapidly reduce the speed and deviate from the desired path for the purpose of avoiding obstacles. It can be said that the movement control and the obstacle avoidance are contradictory and dependent each other. Motion control and trajectory control expects the AUV's movement state to be stable as soon as possible. On the contrary real-time collision avoidance expects the AUV to maneuver as fast as possible to avoid collision.

To balance between them, we innovatively integrate the real-time avoidance decision of the movement plan level into the optimal avoidance trajectory generation of the path plan level. So the hybrid real-time optimal obstacle avoidance architecture is proposed for the deep-sea AUV under the multiple dynamic constraints. The architecture comprises of three parts: the collision state supervision, the real-time avoidance decision and the optimal avoidance trajectory generation, in which the supervision is the core part. The supervision is responsible for activating the other modules. The real-time avoidance decision periodically outputs the desired velocity, depth or heading to the movement control. The optimal avoidance trajectory will be generated when activated.

IV. FIELD TRIAL RESULTS

In January 2015 we completed the deep-sea AUV's first field trial on Qiandao Lake. The AUV's obstacle and terrain avoidance capability is tested in a very rough region, whose topography is described by Fig.5. The black areas represent the shore or islands above the water line. The average depth of the whole field trial region is about 60 meters in the C point area and about 40 meters in the D point area. There are many mountains on the lake floor in the D point area, which are represented by red areas. The line CD is the AUV's desired path set up in advance.

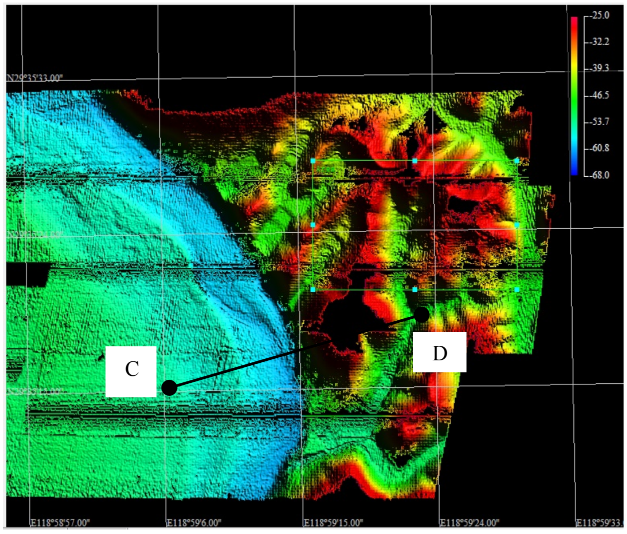


Fig. 5. The topography of the field trial region for obstacle and terrain avoidance

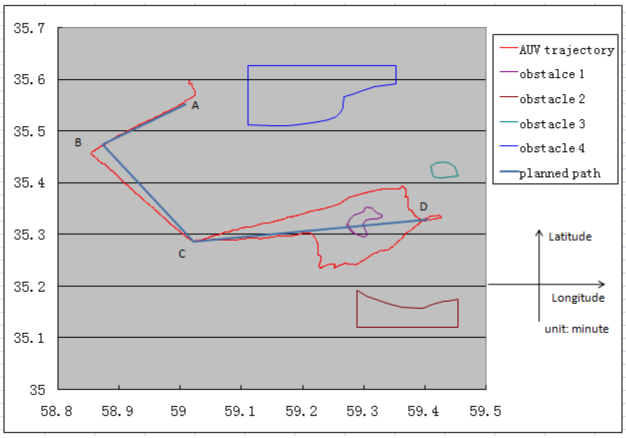


Fig. 6. The desired paths and the field trial areas for the deep-sea AUV

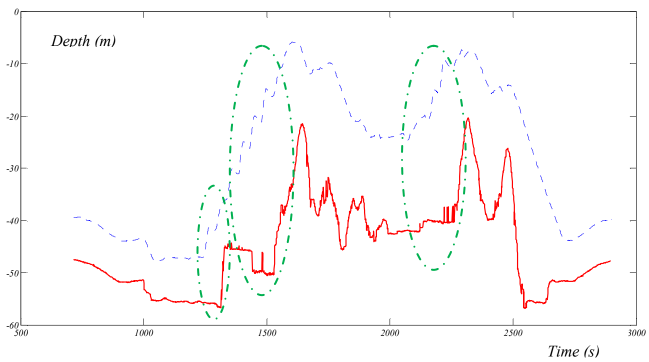
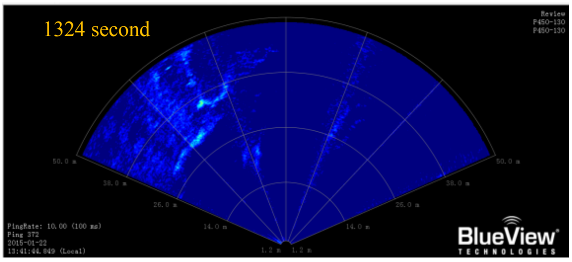


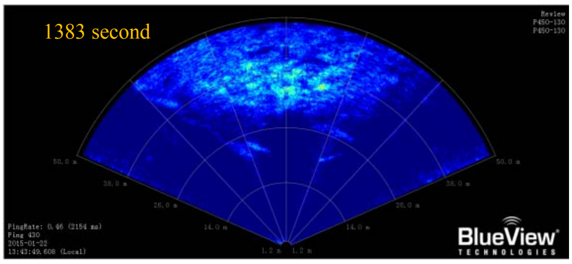
Fig. 7. The lake floor (red solid line) and the deep-sea AUV depth (blue dotted line) profile in the successful dive.

In Fig.6 we can see the whole picture of the desired paths including AB, BC, CD and DC. The desired velocity is 0.8

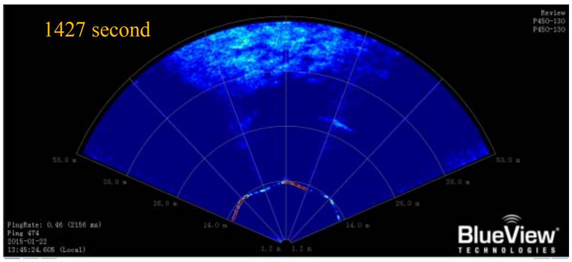
knot and the desired altitude is defined at 8 meters. The deep-sea AUV launched and started its mission near the A point. The red line represents its track in one successful dive. Obviously it is collision-free with all of the obstacles. From the horizontal trend, the AUV turned right to avoid the obstacle 1 during the movement from the path point C to the path point D. And the same avoidance strategy was adopted when the AUV sailed from the path point D to the path point C. Also, the vertical collision avoidance behavior is certainly involved in the dive.



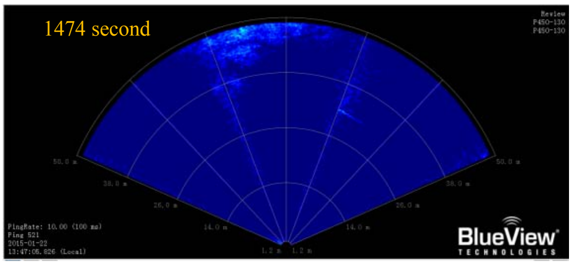
(a) The sonar image at 1324 second in which an obstacle appeares on the left



(b) The sonar image at 1383 second in which the obstacle is about 36 meters in the front of the AUV



(c) The sonar image at 1427 second in which the obstacle is about 40 meters in the front of the AUV



(d) The sonar image at 1474 second in which the obstacle is about 50 meters in the front of the AUV

Fig. 8. The sonar images cut in the first attempt of vertical collision avoidance behavior.

The lake floor and the deep-sea AUV depth profile in the successful dive are shown by Fig.7. The AUV tried ascent for three times (circled by the ellipses with green dot dash line). The following is the detailed explanation of the first time.

As shown in Fig.7, the AUV goes into vertical collision avoidance behavior and begin to ascend because obstacle is detected at 1324 second. The sonar image at that moment is shown in Fig.8(a). The AUV firstly ascended for 5 meters until 1383 second. But from the sonar image it can be seen that the obstacle is about 36 meters in the front of the AUV. So the AUV continues to ascend. The distance between the obstacle and the AUV is getting farther and farther along with the AUV's depth is smaller (shown in Fig.8). Until 1518 second the depth minimum is arrived and the AUV has to convert to horizontal collision avoidance behavior and move round the obstacle finally.

V. Conclusion and Future Research

The deep-sea AUV lake experiment results we obtained are the first step of our studies on obstacle and terrain avoidance based on sonar image analysis. These results demonstrate that the proposed obstacle avoidance system can lead the AUV to avoid unknown obstacles even during the 8m altitude terrain following in the rugged region. But some problems have also been exposed in the experiments. In the future the main problems to be solved are to estimate the obstacle's height according to the sonar image sequences and to add the vehicle's maneuverability limits into the avoidance decision.

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