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Advances in Sea Coverage Methods Using Autonomous Underwater Vehicles (AUVs)

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1. Introduction

Due to rapid changes in modern technological development over the last several years, researches on small Autonomous Underwater Vehicles (AUVs) and Unmanned Underwater Vehicles (UUVs) appeared as important issues for various possibilities of application in the ocean. Military applications together with commercial need require practical details which are robust and cheap for realization as a product. In addition, works on coverage have been motivated by a wide range of real world applications that include non-humanitarian demining, deep-sea development sweeping and robotic spray-painting. Currently, many coverage applications utilize on-line coverage algorithms (Gabriely et al., 2003), where robots do not rely on a priori knowledge of a work-area, and thus must construct their motion trajectories step-by-step, addressing discovered obstacles as they move. This is the main contrast from the conventional off-line coverage algorithms, where robots are given a map of a work-area, and can therefore plan their paths ahead of deployment (Ge et al., 2005). In this paper, we focus on on-line coverage for underwater environment by multiple AUVs. Relevant works have shown that one of advantages of adopting multiple robots for a coverage task is the potential ability for more efficient coverage (Hazon et al, 2005). However, another advantage is that they usually offer greater robustness. Unfortunately,this important capability has been neglected in previous works done on on-line algorithms.

As far as the details of the on-line coverage methods, there are many kinds of covering motions that can be realized either by back-and-forth motions in vast cells, or by following a general Voronoi diagram in narrow cells (Acar et al., 2001). Exact cellular decomposition can also be achieved through the use of the boustrophedon decomposition (Choset, 2001) as well as through Morse functions (Acar, 2002). The boustrophedon approach has been extended in (Choset, 2001) to the multi-robot domain. Such form of coverage requires the coverage to be executed in formations, which may be accomplished in a variety of ways (Ge et al., 2005). Spanning Tree Coverage algorithms (Gabriely, 2003) have also been proposed for online coverage of an unknown and gridded environment by a robot.

For coverage with multi-robot teams, a frontier-based exploration technique has been used to guide robots towards the region between known and unknown areas on the map (Yamauchi et al., 1998). The Mark and Cover (MAC) algorithm has been proposed in (Wagner et al., 2000) with the proved convergence and the bounds on cover time of the algorithm. In (Yang & Luo, 2004), a neural network model has been used for exploration of a

Cartesian workspace by a robot, while avoiding local minima problems. The algorithm presented in (Wagner et al., 1999) allows robots to travel along the edge of the area to cover it, and then the robot clears only selected points visited to maintain the connectedness of the area. A market economy approach has been proposed in (Zlot et al., 2006), where coverage completeness has not been guaranteed.

While most of papers focus on the completeness and coverage time, the completeness with no missing area has not been properly addressed in undersea coverage. The completeness depends heavily on the sea current disturbance, and thus generates enormous impact on the performance of coverage algorithm. In this regard, the main structure of our approach is proposed as follows: First, we propose a new and efficient decentralized coverage method using single AUV. Second, we investigated the bound on the coverage time and the upper bound on the total traveling path length for complete coverage. Third, we propose an algorithm considering dynamic environment, i.e., hydrodynamics of AUV and modeling of sea current disturbances. This provides a practically potential possibility in the naval warfare such as Q-route survey, mine hunting, and minesweeping.

This paper is organized as follows: Section 2 briefly reviews the previous works closely related to our approach. In Section 3, we describe the problem in detail with definitions and solution approaches. Furthermore, we illustrate a modeling for AUV with hydrodynamics with sea current disturbances. Section 4 propose an efficient single AUV coverage method compared to the planar-based coverage algorithms. Section 5 proposes a new Multi-AUV coverage method with the mathematical analysis to compare the total traveling path length and coverage time for AUVs. Simulation results are presented in Section 7 for cases of a single AUV and Multi-AUVs, respectively. We finally conclude in Section 8.

2. Existing coverage technique

As well known, coverage technique is considered as an important central issue in utilizing the AUV for exploration in underwater terrain. Recently, several coverage algorithms have been suggested for on-line applications. On-line algorithms are usually needed due to the lack of a priori knowledge of the work-area, while the AUV must construct motion trajectories step–by-step, addressing detected obstacles as they move.

We will briefly introduce relevant works that are most closely related to our topic, i.e., Multi-AUV coverage technique for sweeping and surveillance in the dynamic underwater environment. Fundamentally, our concern is the coverage problem, which is one of canonical problems in robot motion planning. From a coverage algorithm's point of view, the main objective of this research is to investigate efficient methods for covering the littoral regions including mine reconnaissance, mapping, surveillance, and clearance. Among many various and different approaches to solving the coverage problem by robots, the centralized approach is known not to be robust enough especially when communication is limited between an operator and individual robots, and failures frequently occur. Thus, we rather focus on distributed on-line coverage methods in this work, and will review literature about this aspect. A large number of methods for solving the basic motion-planning problem have been reported (Latomb, 1991). The methods are based on a few different general approaches: road map, cell decomposition, and potential field (Latomb, 1991). The global path planning approach addressed in this paper is based on the cell decomposition method and particularly on the semi-approximate method (Hert et al., 1996). As stated in (Choset,2001),a cell decomposition breaks down the target region into cells such that coverage in each cell is

"simple" enough to make it easy to compute a path between any two robot configurations in the cell. Complete coverage is attained by ensuring the robot visits each cell in the decomposition. In this paper, we will look at three types of the decompositions: exact, approximate, and semi-approximate. The following surveys have been classified as core studies in understanding major approaches to coverage technique in robotics including Multi-AUVs in oceanography.

2.1 Exact cell

For a one-body mobile robot moving in the plane,where the environment is composed of polygons, an exact cell decomposition that results in a connectivity graph is a well-known planning approach (Latomb,1991). The free space of the robot is exactly partitioned into cells that are stored in a graph. The on-board global planner computes a path for the robot from this graph. Choset (Choset, 2001) is stated as Multi-AUV coverage technique using a exact cell decomposition. Kurabayashi et al.(Kurabayashi et al., 1996) suggest an off-line multi-robot coverage strategy using a Voronoi diagram-like and boustrophedon approach. They define a cost function to pseudo-optimize the collective coverage task. Rekleitis et al.(Rekleitis et al.,1997) use a visibility graph like decomposition of space to enable coverage with multiple robots. Here, the goal is to use the robots as beacons for each other to eliminate dead-reckoning error.

Butler et al.(Butler et al., 1999) develop one of a cooperative sensor-based coverage algorithm.The distributed coverage of retilinear environment (DCR) operates independently on each robot in a team. It applies to rectangular robots that use only contact sensing to detect obstacles and operate in a shared, connected rectilinear environment. The basic concept of DCR is that cooperation and coverage are algorithmically decoupled. This means that a coverage algorithm for a single robot can be used in a cooperative setting, and the proof of completeness is much easier to obtain.

DCR (Butler et al., 1999) is based on a complete single-robot coverage algorithm,i.e., contact sensor-based coverage of rectilinear environments ($CCRM$) which incrementally constructs a cellular decomposition of the environment (C). To produce cooperative coverage, $CCRM$ is enhanced with two additional components. Of these, the overseer is the more important. Its job is to take incoming data from other robots and integrate it into C, which it must do in such a manner that C remains admissible to $CCRM$. The cell is first shrunk to avoid overlap with existing cells, then added to C. Incomplete cells in C are reduced to avoid overlap with the new cell, and all connections between cells are updated to reflect this addition. It can be shown that the overseer of DCR indeed performs this operation in such a way that coverage can continue under the direction of $CCRM$ without $CCRM$ even knowing that cooperation occurred.

2.2 Approximate cell

In this approach, the environment is divided into a fine grid where each cell in the grid contains a flag identifying it as free space or not.The resolution of the grid must be very high in order to capture every important detail, resulting in a graph with very many nodes.Thus path planning is not very efficient and the decomposition does not give rise to a natural way of describing the environment, but it is easy to implement. As stated in (Choset, 2001), Wagner et al.(Wagner et al., 1996) investigate the ability of multiple robots, that communicate by leaving traces, to perform the task of cleaning the floor of an unmapped

building. More specifically, they consider robots that leave chemical odor traces that evaporate with time, and evaluate the strength of smell at every point they reach, with some measurement error. Wagner et al.(Wagner et al., 1997) analyze the problem of many simple robots cooperating to clean the dirty floor of a nonconvex region represented by an approximate cellular decomposition, i.e., a grid, using the dirt on the floor as the main means of inter-robot communication. Their algorithm guarantees task completion by k robots and they prove an upper bound on the time complexity of this algorithm. Again, robots communicate only through traces left on the common ground.

Borrowing ideas from computer graphics Wagner et al.(Wagner et al.,1996) preserve the connectivity of the dirty region by allowing an agent to clean only a so called noncritical point, that is: a point that does not disconnect the graph of dirty grid points. This guarantees that the robots will only stop upon completing their mission. An important advantage of this approach, in addition to the simplicity of the agents, is its fault-tolerance: even if almost all the agents cease to work before completion, the remaining ones will eventually complete the coverage.

2.3 Semi-approximate cell

Hert et al. (Hert et al., 1996) present an on-line terrain covering algorithm that relies on a partial unknown of space where the width of cells are fixed, but the top and bottom can have any shape. Their planar terrain-covering algorithm can be applied to both simply and non-simply connected environment. The simplicity of their algorithms lies in its recursive nature. An AUV utilizing this algorithm may start at an arbitrary point in the environment and will zigzag along parallel straight lines to cover given area. Portions of the area that either would not be covered or would be covered twice using the zigzag procedures are detected by the AUV and covered using the same procedure. These smaller areas are covered as soon as they are detected and inlets within inlets are treated in the same way. The recursive zigzagging procedure causes the inlets to be covered in a depth-first order. The algorithm requires that the AUV remember the points at which it enters and exits every inlet it covers. This assures that each inlet is covered only once. The algorithm has been designed with an emphasis on efficiency. That is, it guarantees complete coverage for the entire area without duplication of the AUV path and coverage area in the process of exploration. In subsequent discussions, we will present a new coverage method for both single and multi-AUV to efficiently cover the dynamic shallow water.

3. Problem statement

In this section, we describe topic, Multi-AUV coverage method for unknown environment considering hydrodynamics of AUV and outside disturbances. The purpose of this study is to develop an efficient method of complete 3-dimensional coverage of unknown oceanic environment without missing areas for AUVs. Missing areas in AUV exploration usually occur when AUV leaves off the reference path affected by complex internal and external factors. Internal factors include noise from the controller, sensors, and the cycle of control whereas external factors include ocean current, waves, wind and the temperature and the density of seawater. The white segments in the Fig.1 represent missing areas from the exploration by an AUV.

This section describes how this study was organized and performed. Specifically, this study uses AUV models that are actually in use instead of concentrating on theoretic research and, therefore, practicality is more emphasized in this study as it is based on the elements of reality such as AUV hydrodynamics and external factors such as sea current disturbances.
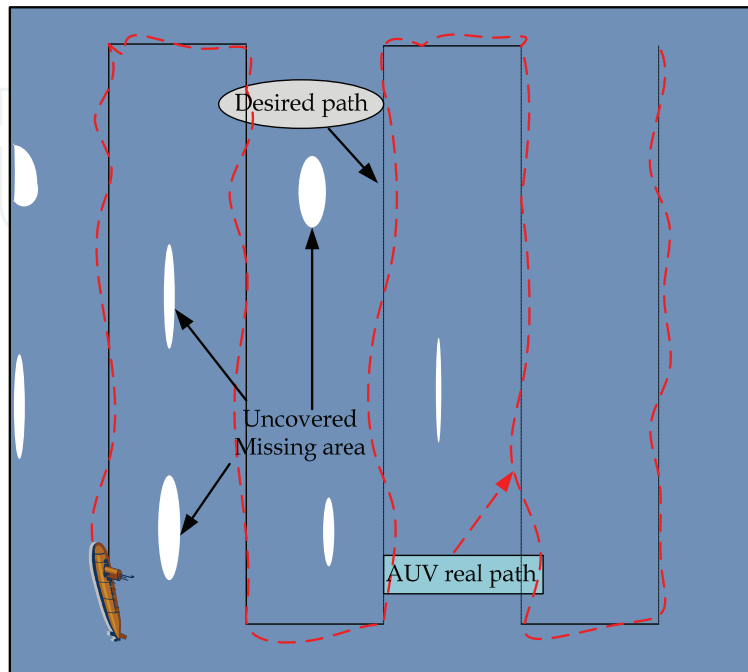

Figure 1. AUV missing areas caused by complex disturbances

3.1 AUV hydrodynamics

As AUV can navigate freely in 3-dimension space of underwater, its 6-degree of freedom motion has continuity and the equation of its motion reveals expansion on a major non-linear term, which should be considered according to the mode of motion. In this paper, the torpedo-type AUV was selected and the standard equation of motion for AUV (Fossen, 1994) was used. REMUS developed by WHOI (Prestero, 2001) was assumed the AUV model selected as an object of control for this study. The system of AUV movements could be simplified by breaking up its motion into vertical and horizontal factors. Fig. 2 shows coordinate frames that can be used to represent AUV motions.

$$M(v)\dot{v} + C_D(v)v + g(\eta) + d = \tau$$
$$\dot{\eta} = J(\eta)v \tag{1}$$

From Equation (1), the position and the orientation of the AUV are represented in earth-fixed frame by $\eta = [x, y, z, \phi, \theta, \psi]^T$ and the velocity of pitch, heave and surge and the angular velocity are represented in body-fixed frame by $v = [u, v, w, p, q, r]^T$. The transformation between the two coordinate frames can be done using Jacobian matrix. In the Equation (1), M is an inertial mass matrix, C_D is the matrix of Coriolis and centripetal caused by the rotation of the earth, $g(\eta)$ is the dynamic stability vector, which is the sum of buoyancy and gravity, d is the external disturbances, τ is the vector for the propulsive force of the AUV and $J(\eta)$ is the conversion matrix. The 6-degree of freedom equations can be deduced from the

above Equation (1). The reference to the detail process (Fossen, 1994) is made from the Equation (1). However, it is necessary to simplify the equation that signifies only the movements in the directions of *u-axis* and *v-axis* and the rotation on *w-axis*, as the underwater exploration by AUV is performed at constant depth. When developing AUV controls, the motion in the horizon plane is separated from that in the vertical plane. Although control designs only deal with two-dimensional planes, three–dimensional vehicle control can be achieved simply by running the horizontal and vertical control algorithms simultaneously.
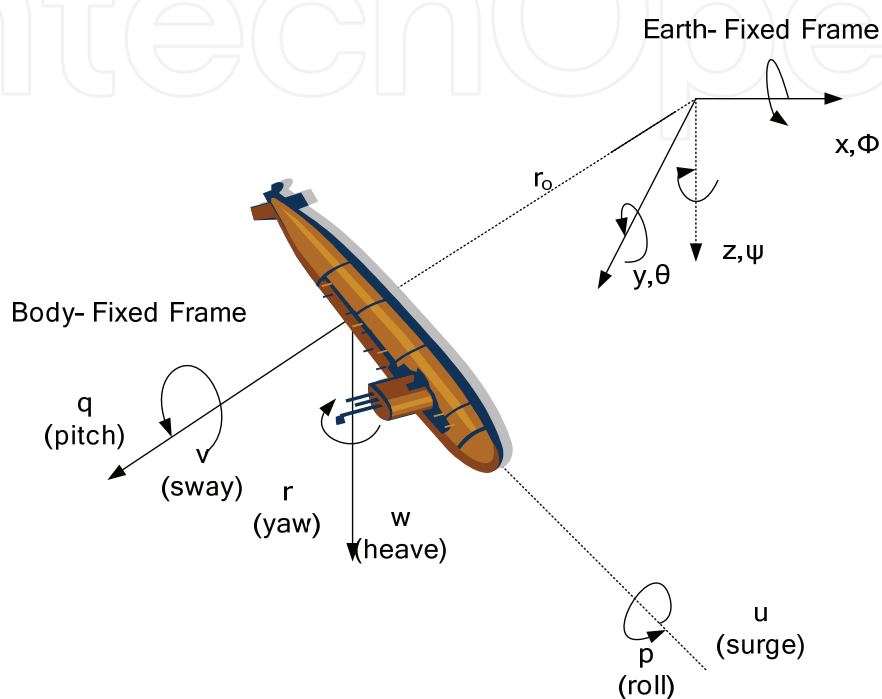

Figure 2. Earth-fixed frame and body-fixed frame for AUV

Assuming that the velocity of AUV motion in *u* direction results in constant forward surge at U_0 and neutralized buoyancy, the equation of horizontal motion in earth-fixed frame can be expressed as in Equation(2). The REMUS hydrodynamic coefficients for equations of motion in the horizontal plane obtained from research found in the (Prestero, 2001).

$$\dot{x} = U_0 \cos\psi + v\sin\psi$$
$$\dot{y} = U_0 \sin\psi - v\cos\psi \qquad (2)$$
$$\dot{\psi} = r$$

3.2 AUV controller model

An AUV move with speed in the dynamic environment it need efficient internal control system. As stated in (Yan & Robot, 2007), AUV guidance systems as follows: waypoint guidance by line of sight (LOS), vision-based guidance, and Lyapunov-based guidance. Among these guidance laws, LOS is one of the most widely used guidance strategies for AUVs due to its ease of implementation (Naeem et al., 2003). It has been applied to some single AUV navigation missions (Belkhouche et al., 2006) .The LOS guidance is based on the geometry of the interception scenario. The system can be described in a relative system of coordinates as shown in Fig.3, which shows the AUV and the target. The positions for target

and AUV in the reference frame of coordinates are given by the vectors (x_t, y_t) and (x_K, y_K). The notation in Fig .3 show that LOS_{GK} is the LOS of AUV-Target and Θ_{GK} is the line of sight angle. In dynamic, the LOS angel to the target is defined as follow :

$$\theta_{GK} = \arctan\left(\frac{y_t - y_k}{x_t - x_k}\right) \tag{3}$$

The steering angle factor β is equal to Θ_{GK}:

$$\beta = \theta_{GK} \tag{4}$$

Therefore, LOS controller was used to steer the AUV along the reference path. The choice of LOS controller was because it maintains stability well by using the geometric relation between current position of the AUV and its reference path of travel when a large directional error occurs (Healey et al., 1993). Also, PD Controller (Prestero, 2001) was used to control the AUV as it allows easy observation of movements.
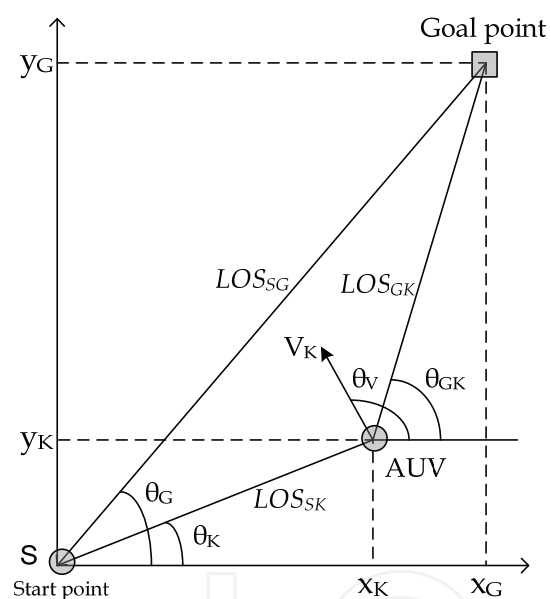

Figure 3. AUV LOS guidance controller in a static environment (without disturbances)

Performing a control input to Equation (2), which is the linearization of the horizontal element of the equation of AUV motion, the movements of AUV could be expressed by an equation of state, where the state parameters are velocity on y-axis (v), angular velocity on z-axis (r) and the angle of z-axis (ψ) in earth-fixed frame and the angle of horizontal steering wheel with control input $\delta(R)$.

3.3 AUV sensor model

AUV sensor model is based on Hert's algorithm (Hert et al., 1996). The AUV is a point moving in three dimensions. A fixed orthogonal coordinate system X =(x, y, z) is chosen with its origin at the AUV's starting point S and z axis passing through the earth's center. The AUV is equipped with sensors. The sensor allows the AUV to determine its own

coordinates relatives to X and those of any point detected in its sensing region. The sensing region is a rectangular polyhedron of dimension *l* x *w* x *h* (*length* x *width* x *height*), with the AUV at its center. These dimensions are chosen such that, from a vertical distance of *h*/2 from a horizontal plane, the AUV's sensor will take a sensing of a rectangle on the plane of dimensions *l* x *w*. The value *h*/2 is determined by the focal length of the AUV's sensors. The sensor also allows the AUV to determine the slope of the floor within its sensing region, which enables it to maintain the vertical distance of *h*/2 from the floor.

The sensed area is the portion of the ocean floor that the AUV can sense from a particular position *R*. This area is, in general, different from the intersection of the ocean floor with the sensing region. Rather, it consists of all points *p* on the floor that are in the sensing region and for which a line segment $\overline{pR}$ does not intersect the surface at any other point as shown in Fig.4.
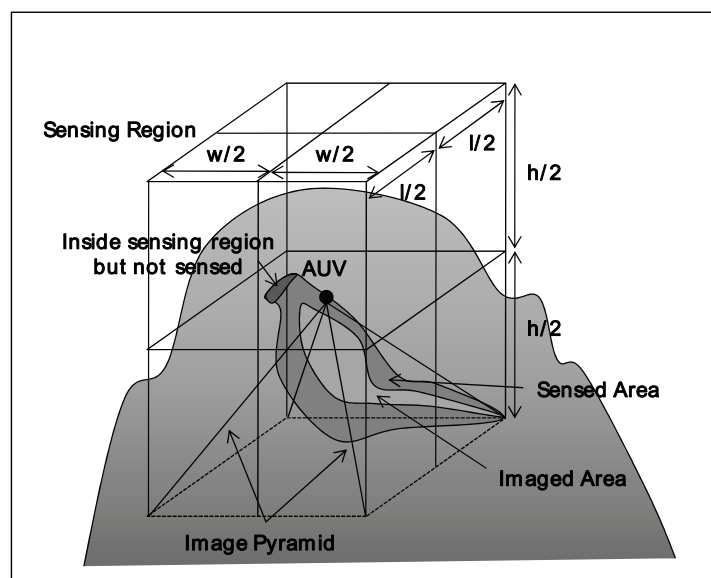

Figure 4. Illustrated AUV sensing model in underwater environment

The *imaged area* is the portion of the ocean floor of which the AUV takes a sensing from a particular position R. This will be some subset of the sensed area. In particular, it is the portion of the sensed area that lies within the *image pyramid*. This pyramid has its top at R in the center of the sensing region and base equal to the bottom of the sensing region (a rectangle of dimension *l* x *w*).

3.4 Underwater environment model

Although the topography of the actual ocean floor in exploration areas consists of complex structures, this paper assumed existence of vertically projectable surfaces only as shown in Fig. 5(b). The vertically projectable surface means the topographic surface on which only one cross point by a vertical line exist at any position. The structure in Fig. 5(a), for instance, is the typical example of vertically non-projectable complex surface on which a vertical line can have 3 cross points.

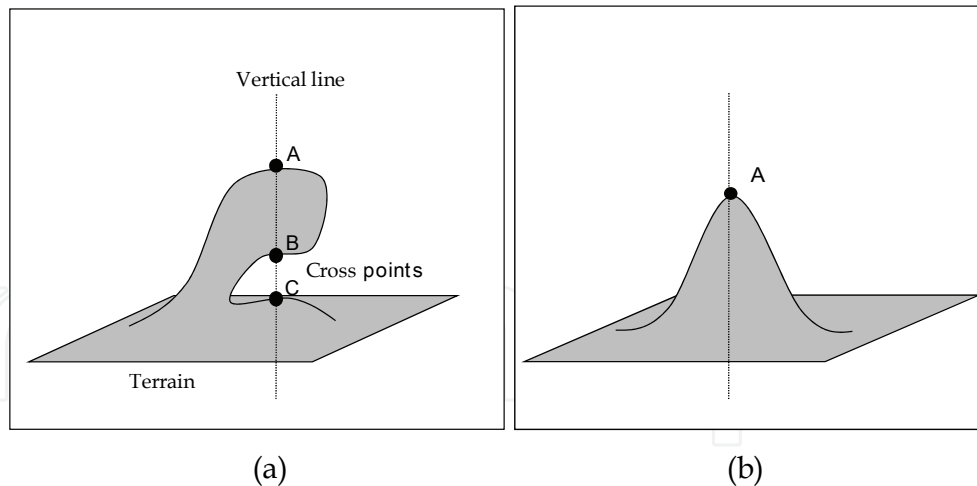(a)   (b)

Figure 5. Side view of environment model with cross points.

The reason for assuming the entire topography to be a vertically projectable surface was that the AUVs are to perform exploration maintaining the constant depth. As all the surface structures should be identified by viewing from the same height, the assumption that the surface topography is vertically projectable was necessary, which also allows 2-dimensional, instead of 3-dimensional, as shown in Fig.6, approach to the mapping of complex ocean geography.

We assume that area A in Fig.6 is bounded between two threshold surfaces, as shown in Fig.6(a), $z = z_{min}$ and $z = z_{max}$. Portions of the floor below z_{min} or above z_{max} are not to be covered as shown in Fig.6(a). The area is also bounded by a threshold slope, μ. Proportional to the image width w and is chosen to assure adequate overlap of the images. The range of possible values for μ is limited by the AUV's sensor parameters. In particular, if the focal range of AUV's sensor is $[a,b]$, then μ must be chosen to satisfy the relation:

$$\mu \ < \ \min\left(\frac{h}{3w},\frac{2(b-a)}{w}\right)$$

(5)

This assures that images of adjacent portions of the surface will overlap to some extent and every part of the surface that is to be imaged lies within the sensor's focal range as shown in Fig. 6(b). The boundary *B* of the area *A* consists of a number of simple, nonintersecting closed curves. These are intersections of the floor with the threshold surfaces and the curves along the floor where the slope is equal to μ as shown in Fig.6(b). The *planar area* A_p and *planar boundary* B_p are defined as the projections of the area A and boundary B on the *xy*-plane (i.e, plane $z = o$). The outer boundary is the boundary curve that contains all other boundary curves in its interior as shown in Fig.6(c).

In order for AUV to be able to recognize the topography of ocean floor viewing it as a vertically projectable surface, the oceanic topography are divided into 4 types, Cape, Bay, Inlet and Island as shown in Fig. 7. Their definitions are as follows:

- **Cape**: Cape is a convex structure as the area between point C1 and C2.
- **Bay:** Bay is a concave structure as the area between point B1 and B2.
- **Inlet**: Inlet is an area that has a cape point as its entrance and bay point as its end as shown in Fig. 7(b)
- **Island**: Island is an area isolated from the surrounding topographic structure.
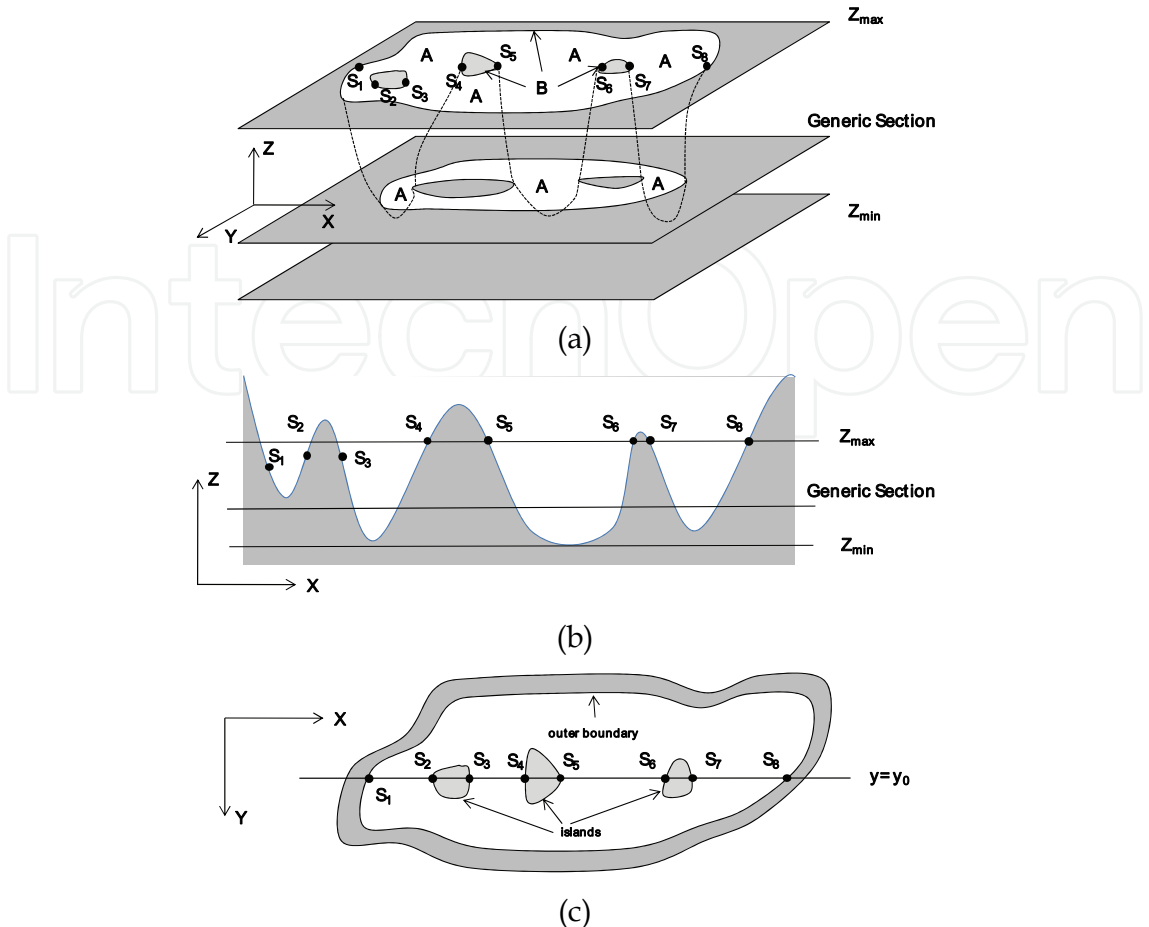
(a)

(b)

(c)

Figure 6. The procedure for converting 3-D underwater environment to 2-D terrain

Cape and Bay are considered here as the characteristic points. The classification used in this paper is based on Hert's method of classifying the topography. Fig. 7(a) shows the characteristic points of Cape and Bay. The vertical dashed lines in Fig. 7 represents the travel path of zigzagging AUV and the points B1, B2, C1 and C2 that meet with the dashed lines the characteristic points which allow recognition of certain oceanic topography when the AUV comes across them.

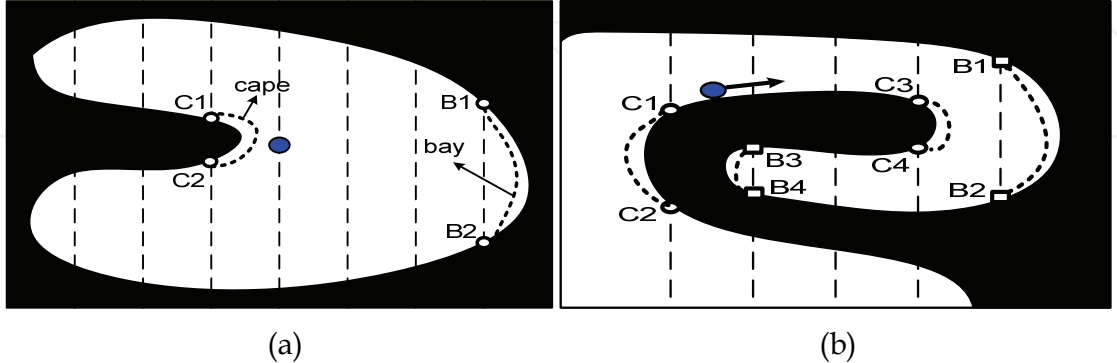(a)   (b)

Figure 7. Types of sea environment

When the AUV encounters the cape point C1, it knows that there is a space ahead for further exploration and when it crosses the bay points B1 and B2, it recognizes that the exploration of the space entered from the point C1 has been completed. However, Fig. 7(b) shows the

recursive structure of inlets where another inlet can be formed inside the inlet from the point C1. That is, an inlet can have another inlet in it. Such recursive characteristic of inlets provides answers to the question as to how to approach to the exploration of inlets. These answers will be discussed in the next section. The AUV that enters the inlet passing the point C1 keeps on moving until it reaches another inlet as it passes the points C3 and C4. It will know that the exploration of the inlet beginning from the point C1 has been finally completed when it encounters the point B1 and B2. The AUV exploring an island will not be able to correctly identify the island structure until it explores the area repeatedly as it enters the unknown environment when it enters an inlet. Therefore, the efficiency of topographic exploration of ocean environment lies very much in how the exploration of islands is dealt with. The Section 4 will discuss about the method of efficient coverage in relation to this issue.

3.5 External disturbance model

This paper attempted to reflect the effects of underwater external sea current disturbances, which is considered as the external factors of cross track error by using the model of underwater external disturbances. The shallow coastal water was chosen as the subject area. The major effects of oceanic current in coastal areas come from tidal current and stoke's drift. Considering these elements as well as the minimum and maximum currents and their fluctuations, a model was designed to determine the type of changes in the velocity of oceanic current using the First Gauss-Markov process (Fossen, 1994).

$$\dot{V}_C(t) + \mu_0 V_C(t) = w(t) \tag{6}$$

In the above Equation (6), $w(t)$ represents white noise with average value of '0' and μ_0 is a non-negative constant. As the AUV movements are horizontal, the velocity of oceanic current can be described 2-dimentionally in the body-fixed frame by the direction (β_C) and the velocity (V_C) as follows:

$$\begin{aligned} u_C &= V_C \cos \beta_C \\ v_C &= V_C \sin \beta_C \end{aligned} \tag{7}$$

where u_c is the velocity of oceanic current in x direction and v_c is the velocity of oceanic current in y direction in body-fixed frame coordinate. In order to apply this oceanic current model to the equation of AUV motion represented in body-fixed frame, the effect of the body posture is reflected also in the body-fixed frame as shown in the following Equation (8).

$$\begin{aligned} u_C &= V_C \cos(\beta_C - \psi) \\ v_C &= V_C \sin(\beta_C - \psi) \end{aligned} \tag{8}$$

The actual values of the changes in the velocity of ocean current and its direction would be applied to the implementation environment of the test in reality. The oceanic current represented in the body-fixed frame will have the effect on the movement of AUV as it is interpreted as a relative velocity and the final model will be complete reflecting the movement of AUV and the oceanic current as an external disturbance.

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix} \delta + \begin{bmatrix} -a_{11}\sin(\beta_C - \psi) \\ -a_{21}\sin(\beta_C - \psi) \\ 0 \end{bmatrix} V_C \qquad (9)$$

The above Equation (9) is the matrix version of the same equation expressed by arranging in terms of magnitude of change in velocity $\ddot{v}, \ddot{r},$ and $\dot{\psi}$, respectively. The δ is the value of the angle of the rudder obtained from the PD controller and LOS controller and b_1 and b_2 are the control constants for the rudder. The values a_{11} through a_{22} are the constants of the matrix obtained as the result of rearranging the equation in terms of $\ddot{v}, \ddot{r},$ and $\dot{\psi}$, respectively.

4. An efficient coverage method with unknown underwater terrain

In this section, coverage methods of exploring unknown shallow water floor are investigated. First, we researched one of existing efficient covering Hert's algorithm briefly and examined how proposed coverage method is improved compared with Hert's. Then, by applying proposed coverage method, Multi-AUV coordinated coverage with *Role Changing*, which is effective method for unknown terrain, is proposed.

As stated in (Hert & Lumelsky, 1996), key to on-line terrain-covering algorithm is a simple zigzagging pattern of motion in which the AUV moves back and forth along successive grid lines, sweeping across an area either from left to right or from right to left. Fig. 8(a) shows the path of a AUV moving in this fashion in a simply connected area, the boundary of which contains only two bays and no capes. By starting at one of the bay points on the boundary S_P and zigzagging until it encounters the other bay, the AUV is able to cover the entire area.

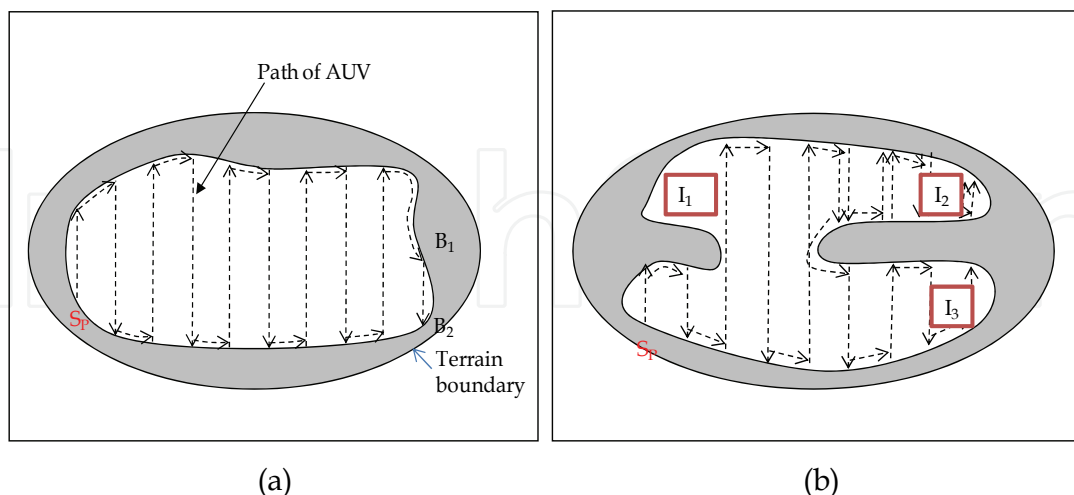(a)   (b)

Figure 8. AUV zigzag manner of unknown area for covering procedure

However, as Fig. 8(b) illustrates, this simple zigzagging motion will not suffice to cover areas with boundaries that contain capes, nor will it work when the area is not simply connected or when the starting point is chosen arbitrarily. The inlet labeled I_1 in Fig. 8(b) is never encountered by the AUV as it zigzags along the grid lines, and thus remains

uncovered. In contrast, the AUV must resurvey its path in inlet I_2 in order to reach the inlet I_3. Inlets such as I_1 and I_2 are referred to as diversion inlets, or simply inlets, since they require that the AUV divert from its normal zigzagging motion in order to cover them efficiently.

However, this backtracking is both undesirable and unnecessary. Since the AUV can know each inlet as it is moving, it can immediately make a diversion from its path to cover this inlet and then return to the point at which the diversion was made, and continue on its covering way. In this way, the entire area will be covered without any extensive backtracking. This is the strategy of the method presented here. Further, the procedures presented assure that every inlet is covered only once.

In addition, the proposed method of coverage was the result of the consideration of all the variable factors that influence the actual navigation of the AUVs. Therefore, as Hert assumed the width of exploration path applied during zigzag navigation to be ideal, this study also used his concept as the basis and concentrated on the method of exploration. However, the question of how do we determine the ideal width of exploration path considering real situation should also be a very important point of consideration in this study. How can we find the most useful exploration width? We will try to find the answer from the cross track error (CTE) that arises during the exploration with AUV.

It is generally possible to assume that AUV can perform exploration without creating missing areas by setting the exploration intervals without external disturbances to twice the range of the sensor. However, the CTE in actual exploration still creates missing areas due to imprecise exploration width as shown in Fig. 1.

It means that the exploration width should be reduced from twice the sensing range to the marginal width that would not cause missing areas after all. However, as the velocity of the oceanic current in the exploration area is variable by time although its flow is consistent, it is not easy to find the marginal exploration width that would allow the AUV to navigate shortest distance without causing any missing areas. Therefore, we would suggest to efficient exploration width (EEW), if not marginal width, that would allow the AUV to navigate shortest distance without causing any missing areas. Hert has suggested an exploration method without considering EEW.

4.1 Conventional covering method of Hert

We will look into the method of the exploration of oceanic topography. The conventional method of Hert for the exploration of a given geographic area is based on continuous exploration following the exploration path using basically online-based zigzag navigation. The advantage of Hert method is obvious compared with previous exploration methods, which are based on the assumption of simple oceanic environment. Hert, on the other hand, assumes complex unknown area instead of known square-cut areas as an object of exploration. This approach has an advantage, apart from the fact that it shortens the path length, in that it is more realistic because, after finishing the exploration of a given area, many exceptional situations are considered also to ensure no missing areas arise.

The proposed coverage method in this paper also adopts this advantage of Hert method and is the result of further improvement of Hert algorithm, which we introduce here. Hert's method is based on largely dividing the oceanic environment into two categories: one with islands and the other without.
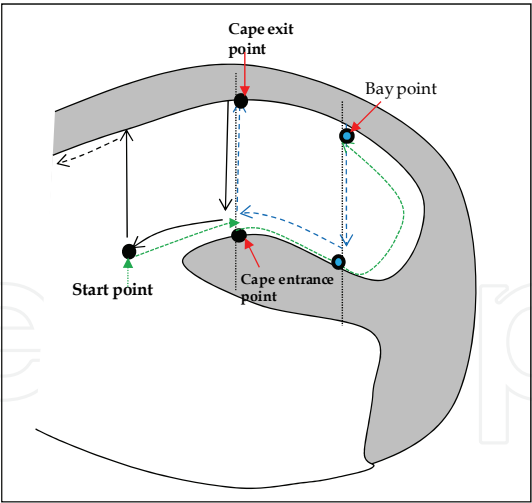
Figure 9. Hert's algorithm for simply connected area (inlet)

In the oceanic environment without islands as shown in Fig.9, AUV navigates in zigzag pattern until it encounters an inlet. Upon crossing the cape point, which is the entrance of an inlet, it navigates along the boundary of the inlet until it comes across with a bay point, which indicates that it reached the end of the inlet. Then the AUV moves to the other bay point and resumes zigzag navigation exploring to see if there is any other structure within the inlet until it exits from the inlet. Furthermore, it will store the information on the cape points in order to prevent from exploring the same area again later, which he termed as 'crossing the lock'.

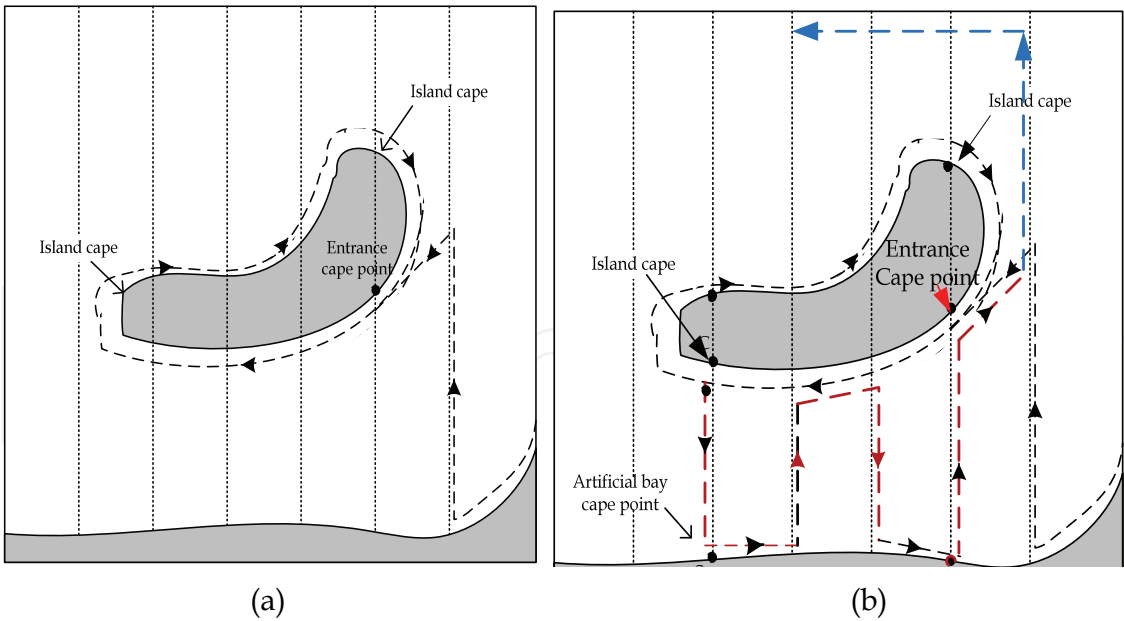| (a) | (b) |

Figure10. Hert's algorithm for non-simply connected area (island)

In the oceanic environment with islands as shown in Fig. 10, exploration is performed in the same way as in the case when there is no island. An island characteristically has 4 cape points without any other points. As it is initially an unknown environment, as shown in Fig.10(a),the AUV starts navigating along the boundary of the island as it encounters a cape

point. The AUV will eventually return to the original position and recognize that it is an island. Then the AUV navigates along the boundary from the entry point to the opposite cape point and returns in zigzag pattern exploring the topography of the one side of the island as shown in Fig. 10(b). The AUV then travels to the other side of the island and navigates toward the original point in zigzag pattern exploring the topography of that side of the island as shown in Fig. 10(b).

4.2 Calculating an efficient exploring width (EEW)

We believe that Efficient Exploring Width (EEW) can be found from the model of AUV movement using CTE values.
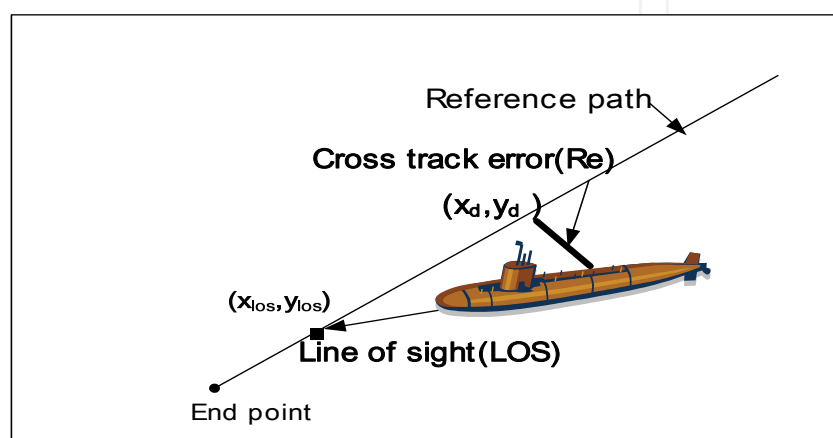

Figure 11. Illustrated cross track error by AUV

The value of CTE is, as shown in Fig. 11, a vertical distance of AUV from the reference path. The reference path is first determined but deviation occurs as the AUV navigates because of oceanic current. LOS controller sets a point on the reference path at the unspecific distance from the AUV as a new target point and determines the angle ψ_r from this set point (x_{los}, y_{los}) to return to the reference path. CTE(Re) is then calculated as shown in Fig. 11. The process of finding the efficient exploration width is as follows:

At first, the twice sensing range is used considering the sensing range of AUV when there is no external disturbance. When external disturbance exists, missing areas will occur due to deviation of AUV position. The deviation of the AUV is expressed as CTE. If the exploration width is reduced from the twice the sensing range by the distance that causes missing areas, the adjustment of the exploration width can be kept minimal while ensuring no occurrence of missing areas, thereby allowing to set the efficient exploration width. If the value of CTE, marked in dashed line in Fig. 11, can be calculated whenever AUV is in motion, EEW can also be calculated using the CTE value. At worst, the deviation of the AUV will be largest when the value of CTE is at maximum. If the exploration width is reduced by the maximum value of CTE, the resulting width would be the maximum width without causing any missing areas and would, therefore, be the efficient exploration width, which can be expressed with the following equation :

$$EEW = 2 * R_{MAX} - 2 * MAX\,CTE \qquad (10)$$

(a) Exploration width:2 * R_{MAX} (b)Exploration width:2* R_{MAX}-2*MAXCTE
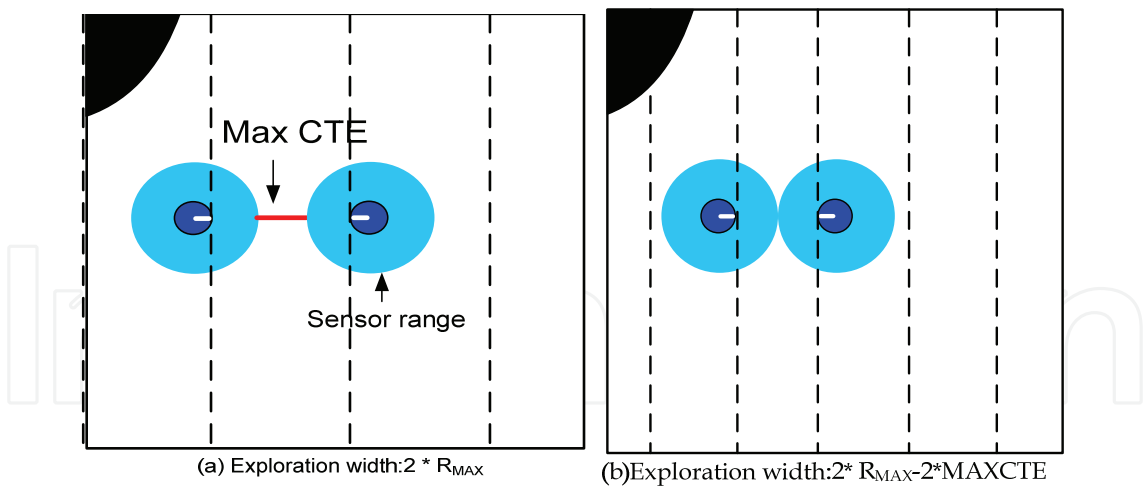
Figure 12. Calculating of EEW using CTE

Here, R_{MAX} is the maximum sensing range of AUV. As indicated in Fig.12(a), the exploration width calculated by subtracting the largest CTE value obtained during navigation from the twice the sensing range of AUV will not cause any missing areas. Although the deviation of AUV will not be as much as the maximum value of CTE every time external disturbance occurs, reducing the exploration width sufficiently using its maximum value would eliminate the possibility of missing areas occurring in advance as shown in Fig.12(b). This can be considered as a trade-off between accuracy and efficiency. Simulation may be used to verify the usefulness of this method of determining the exploration width. The exploration width calculating technique proposed in this study is based on the above described method.

4.3 Proposed coverage method

The bottom line of the limitations of existing Hert algorithm lie in the question of efficiency. One limitation is that internal information is not utilized for the planning of path for the exploration of inlets. The other is that the existence of island can only be established only after completely circulating the island and further exploration of surrounding areas has to follow even if these areas have already been covered. Our proposed technique to overcome such problems is as follows:

First, the exploration of inlets without islands is performed as shown in Fig. 13.

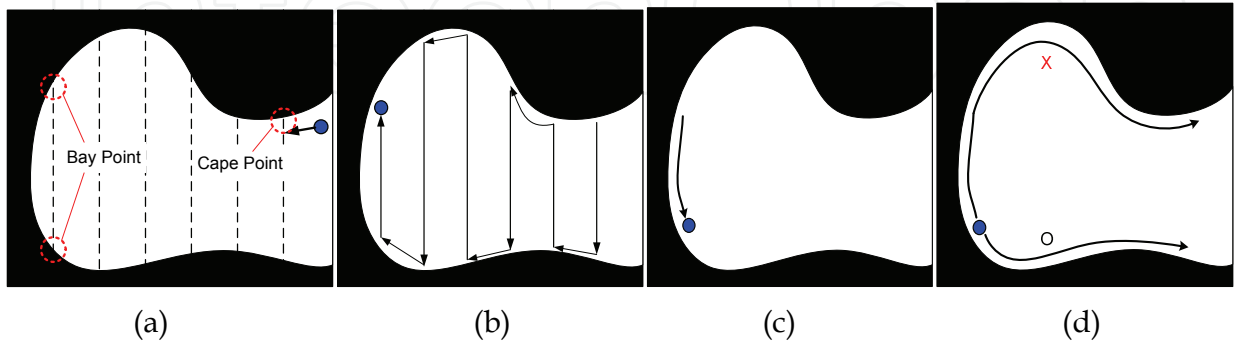(a)   (b)   (c)   (d)

Figure 13. The proposed coverage method for simply connected area: (a) Entering inlet, (b) Exploring inside inlet in zigzag manner, (c) Moving along the boundary of the opposite bay point, (d) Escaping from inlet along the planned short path

As shown in Fig.13(a), the AUV which has been exploring in zigzag movement detects a cape point and enters the inlet. Unlike Hert's method, AUV does not enter the inlet by following the boundary but, instead, explores the inlet in zigzag movements, which will not only allow accurate establishment of the entry of the inlet but also complete coverage of the inside of the inlet by zigzag exploration. Therefore, ocean environment in the inlet can be explored faster than Hert's method. Also, in multi-AUV operation where two entrance areas of the inlet are locked, one AUV can alert the others while entering the inlet preventing collision. Covering the inlet with zigzag movements can also ensure finding of other topographic structure between the bay points as shown in Fig.13(b). By using the topographic structures in the inlet recognized by zigzag exploration, exit route from the inlet can be planned and short route can be identified as shown in Fig. 13(d). When there is another inlet inside the inlet, which is the recursive characteristic of the inlet structure, the AUV covers the inner inlet first, return to the original inlet and continue exploration.

When an AUV finds another inlet while exploring the inlet, it will cover the lower-level inlet first according to the depth-first order and if there is yet another lower level inlet, it will cover the new inlet first, and so on. In other words, exploration of multi-level inlets is performed in the opposite order of entry procedure covering the lowest level inlet first and the highest level inlet, which is entered first, last. So, it is in FILO (Fist-in-last-out) sequence. The following Fig. 14 shows the method of exploration in the area where islands exist.

(a)   (b)   (c)
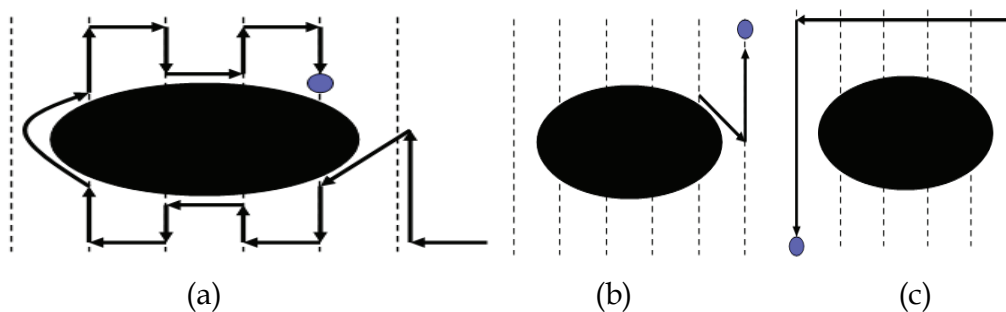
Figure 14. Proposed coverage method for non-simply connected area (island)

Unlike Hert's method in which AUV circles around the island and covers the surrounding area again, this method can identify an island with only one circulation effectively saving time and navigation distance as shown in Fig.14(a). Once the AUV completes its path around the island, it can leave the island, move to the opposite side of the island and continue exploration as shown in Fig.14(c). This movement method will allow the AUV to explore the surrounding oceanic environment of the island. This improved covering procedure is well described in Table 1.

5. An efficient coverage method for Multi-AUV

The below proposed algorithm was developed by improving the efficiency of the Hert's method. The method of multi-AUV operation using this algorithm is discussed here. The most important point to consider for multi-AUV operation is that collision between the AUVs has to be prevented. Efficient distribution of AUVs for the saving of time and navigation distance can also be another point of consideration. This paper attempts to address these points using the technique of dynamic role assignment mechanism (Luiz Chaimowicz, 2002). By using this method, each AUV can be given a different assignment and their role can be dynamically modified to deal with changing such as avoiding collision.

Local Variable:
S_p:the first presumed start point during the AUV moving around inlet or island.
Procedure *CoverInletorIsland*
  Step 1 <Detect Cape point>
             do
         move with zigzag manner for covering;
                 if an inlet entrance cape point is detected then
                     CoverInletorIsland();
           until AUV reaches a bay point or an artificial bay point or
                 AUV returns to start point s_p;
                 if AUV reaches a bay point or an artificial bay point
then
                 CoverInlet();
                 move along planned short route to s_p;
  Step 2 <Define types of terrain>
         return inlet's entrance point or return to S_p;
         if AUV detects 4 cape points and there is no bay *then*
                 define *island terrain*;
                 CoverIsland();
          else if AUV detects bays more then one *then*
                 define *inlet terrain*;
                 CoverInlet();
  Step 3 <End covering mission>
         back to an entrance point or s_p;
                 lock doorways capes;
         if AUV is at S_p *then*
           move along grid line of S_p until boundary is hit;
           end mission;
                 else
             repeat **Step 1** ~ **Step 3**

Table 1. The proposed coverage algorithm for non-simply connected area (island)

5.1 Definition of dynamic role assignment

The definition of dynamic role assignment is based on the technique of Luiz Chaimowicz (Luiz Chaimowicz, 2002). A team of AUVs must be coordinated to execute cooperative tasks and they have to synchronize their actions and exchange information. In this approach, each AUV performs a role that determines its actions during the cooperative task. According to its internal state and information about the other AUVs and the task received through communication, an AUV can dynamically change its role, adapting itself to changes and unexpected events in the environment. The mechanism for coordination is completely distributed. Each AUV has its own controllers and takes its own decisions based on local and global information. In general, each team members has to communicate explicitly with other AUVs to gather information but they normally need not construct a complete global state of the system for the cooperative execution. We consider that each team member has a specification of the possible actions that should be performed during each phase of the

cooperation in order to complete the task. These actions must be specified and synchronized considering several aspects, such as AUV properties, task requirements, and characteristics of the environment. The dynamic role assignment will be responsible for covering the correct actions to each AUV and synchronizing the cooperative execution.

Before describing in detail the role assignment mechanism, it is necessary to define what a role in a cooperative task is. Webster's Dictionary defines it as follows:

> Definition 5.1 *(a) Role is a function or part performed especially in a particular operation or process and (b) role is a socially expected behavior pattern usually determined by an individual's status in a particular society.*

Here, a role is defined as a function that one or more AUVs perform during the execution of a cooperative task. Each AUV will be performing a role while certain internal and external conditions are satisfied, and will assume another role otherwise. Thus, a role depends on the internal AUV state and on information about the environment and other AUVs, and defines the set of controllers that will be controlling the AUV in that moment.

In (Shehory et al., 1998), a role is defined as the specification of an AUV's internal and external behaviors. A formation is a set of roles, decomposing the task space. Each AUV knows the current formation and keeps mapping from teammates to roles in the current formation. Our definition is similar, the main difference being that we do not have the concept of formation, and we use a more formal model to describe roles and role assignments, as it will be further explained in the next sections. As mentioned before, each role defines a AUV controller and the role assignment allows the AUVs to change their behaviors dynamically during the task execution.

5.2 Modeling

The dynamic role assignment can be described and modeled in a more formal framework. In general, a cooperative Multi-AUV system can be described by its state *(X)*, which is a concatenation of the states of the individual AUVs:

$$X = [x_1, x_2, ..., x_N]^T \tag{11}$$

Considering a simple control system, the state of each AUV varies as a function of its continuous state (x_i) and the input vector (u_i). Also, each AUV may receive information about the rest of the system (z_i) that can be used in the controller. This information consists of estimates of the state of the other AUVs that are received mainly through communication. We use the hat (^) notation to emphasize that this information is an estimate because the communication can suffer delays, failures, etc. Using the role assignment mechanism, in each moment each AUV will be controlled by a different continuous equation according to its current role in the task. Therefore, we use the subscript $q, q = 1, ..., S$, to indicate the current role of the AUV. Following this description, the state equation of each AUV i, $i = 1, ..., N$, during the execution of the task can be defined as :

$$\dot{x}_i = f_{i,q}(x, u_i, \hat{z}_i) \tag{12}$$

Since each AUV is associated with a control policy,

$$u_i = g_{i,q}(x_i, \hat{z}_i) \tag{13}$$

And since $\hat{z}_i$ is a function of the state X, we can rewrite the state equation:

$$\dot{x}_i = f_{i,q}(X) \tag{14}$$

or, for the whole team,

$$\dot{X} = F_{\Sigma}(X), \; where \; F_{\Sigma} = [f_{1,q1,...,}f_{N,qN}]^T , \; q_i \in \{1,...,S\} \tag{15}$$

The equations shown above model the continuous behavior of each AUV and consequently the continuous behavior of the team during the execution of a cooperative task.

5.3 Role assignment

The role assignment mechanism allows Multi-AUV coordination in the execution of cooperative tasks. As mentioned before, dynamically assigning and exchanging roles, the AUVs are able to perform the task more efficiently, adapting to unexpected events in the environment and improving their individual performance in benefit of the team.

Basically, there are two types of role assignment as shown in Fig.15

The main jobs of AUV are scanning and covering which are defined as follows:

- *SCANNING:* Movement activity in zigzag pattern to identify inlets. The purpose is to locate the cape points rather than to enter the inlets. When an inlet is identified, its entrance data are collected and transmitted to the central database.
- *COVERING:* Exploration activity performed in the inlet using the scanning data from the database.

Covering activities can be performed using improved method described in this paper Section 4. To do this, a central database through which AUVs can communicate as well as a database manager is required as shown in Fig. 15.
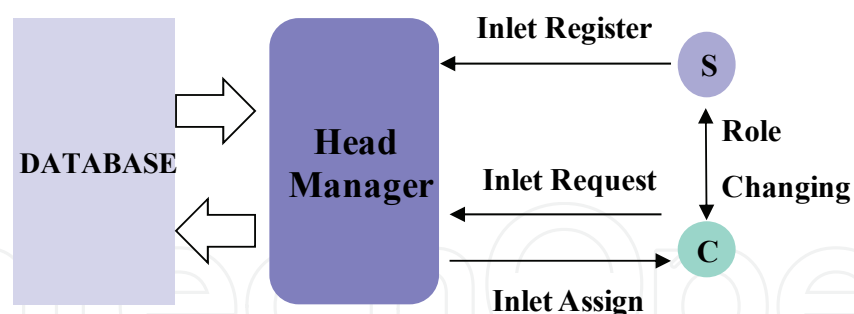

Figure 15. System configuration of dynamic role assignment

Not all the AUVs need to be assigned of a role from the beginning. Instead, only one AUV may take up the role of scanning and begin exploration. Once it encounters an inlet, then each of the other AUVs is given an assignment of covering in sequence and enters the inlet. If an AUV with covering assignment completes its coverage when the scanning AUV is still unable to find the entrance to another inlet, then the covering AUV will have to wait as it has further covering to do. In order to reduce waiting time to improve the efficiency of the whole operation of topographic exploration, the roles of AUVs need be modified. For effective role distribution and prevention of collision during the performance of changed roles, the below rules must be observed.

- *Rule 1*: **There must be only one AUV present in one inlet.**
- *Rule 2*: **If two AUVs must be present because of the existence of an island, the one that entered the inlet later exits the inlet first.**

The Rule 1 must be observed to avoid collision between AUVs. If an island is large in size, two AUVs may have to work in the same inlet risking the danger of collision. However, if the one that entered the inlet later exits the inlet first, the danger can be minimized. Fig. 15 shows role change in the work flow when two AUVs are operated.
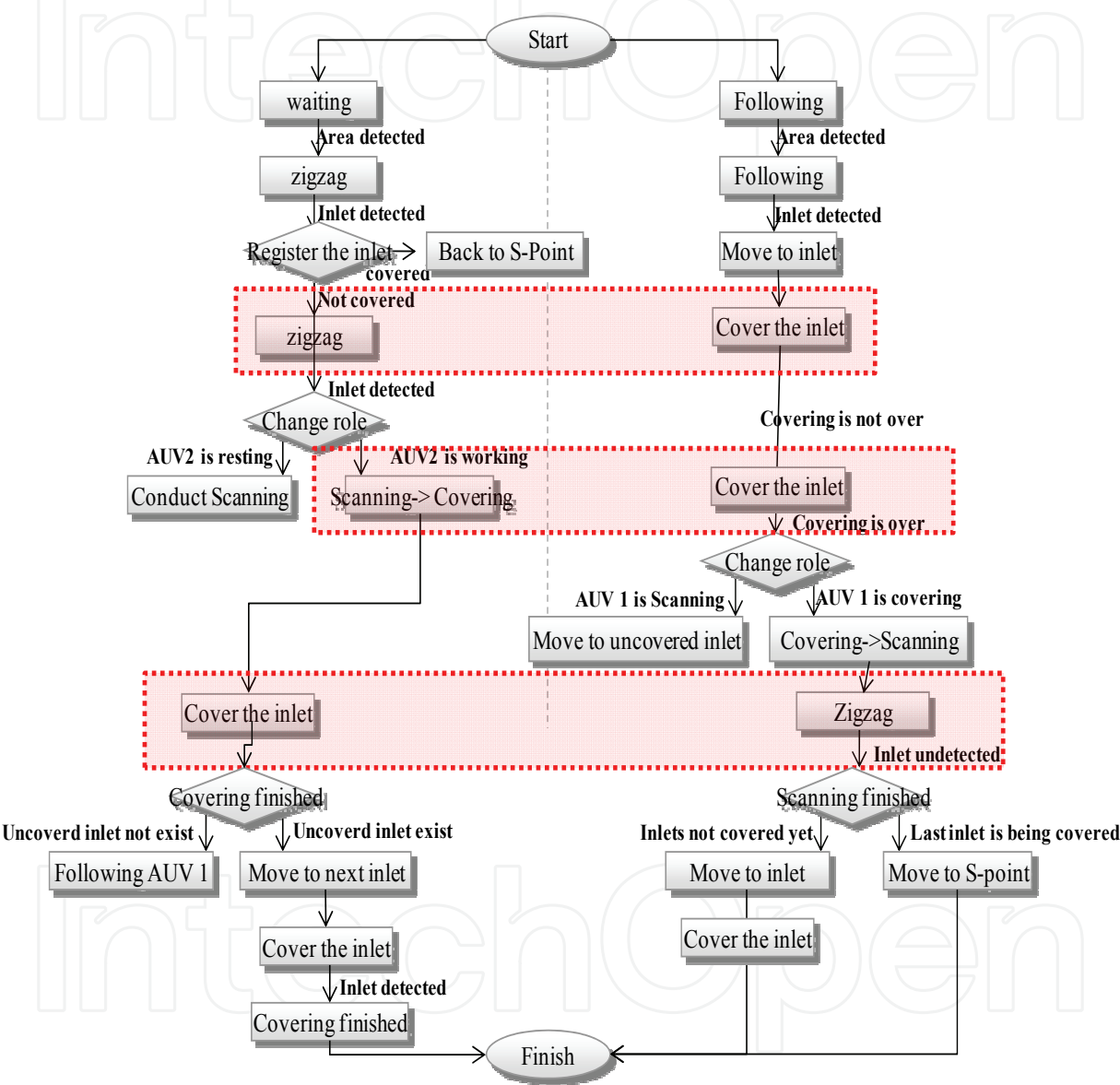

Figure 16. Simulated Multi-AUV work flow

6. Mathematical verification and comparison

The covering algorithm described above is an improved version of Hert's algorithm and is intended to eliminate inefficiency problems of the Hert's algorithm. However, it will be validated in the simulated test environment. Before the simulation test, the proposed

method will first be verified mathematically to prove that it is an effective method in terms of total path length.

Area exploration method is broadly divided into the exploration of known topography and that of unknown. Hert's algorithm is based on Seed Spreader (Lumelsky,1990) technique developed for the exploration of known area and the validity of the method has been proved in terms of path length compared with the Seed Spreader technique. Total path length based on the worst situation using Hert's algorithm (Hert et al,1996) can be described as in Equation (16).

$$l_{tp} \leq l_{gs} + 3l_{id} + 2l_{bc} + 3l_{ib} + 2l_{cb} \tag{16}$$

Here, l_{tp} is the maximum covered path length according to the Hert algorithm. In Hert's algorithm, an exploration consists of 4 procedures: *coverArea, coverInletorIsland, ExitInlet, and ReturntoS*. The total path length $l_{tp,}$ is calculated by adding the maximum navigation distance in each process. The definitions of the parameters used in Equation (16) are listed in Table 2.

Parameters	Descriptions
l_{tp}	Total path length
l_{bc}	Length of the planar outer boundary curve
l_{ib}	Sum of the lengths of the planar island boundary
l_{gs}	Sum of the lengths of all grid line segments in area
l_{id}	Sum of the lengths of all inlet doorways
l_{cb}	Sum of the lengths of all capes on boundary

Table 2. Parameters defined in the Hert's algorithm

The exploration procedures in Hert's method that make up the total path length are as described below. When the entire coverage area is divided into a number of uniform exploration width, AUV will navigate along the grid line in each path in zigzag pattern. Each grid line will be passed only once and each boundary area will be covered not more than once as well. First, the coverArea stage spans the area of coverage along the boundary and ends when the AUV reaches a bay. Coverage of the entire area is completed by repeating this procedure by locking the inlet that has been covered, repeating the coverage of the same area can be avoided. The maximum path length required to cover this procedure is $l_{gs}+l_{id}+l_{bc}+l_{ib}$. Second, during the procedure of CoverInletorIsland, AUV first explores the inlet which has not been covered yet. The path length for this procedure should not exceed the total length of capes in the inlet. For all inlets, the path length of this procedure is not greater than l_{cb}. When the AUV reaches an inlet, it begins to move along its boundary until it reaches a bay if it is an inlet or until it returns to its original position if it is an island. The total path length of this procedure does not exceed $l_{bc}+l_{ib}$. When the AUV identifies the current topographic structure as an island, it will continue to explore along the artificial bay for half a circle and the path length of this procedure does not exceed l_{ib}. When the AUV leaves the inlet, it should return to the starting point S_p which will not exceed l_{ib}. The total path length for coverInltorIsland procedure, therefore, shall not exceed $l_{bc} + 2l_{ib} + l_{cb}$.

Finally, the procedure for each AUV to exit the inlet is called exitInlet in which AUV will pass the doorway at least once. As the AUV has already passed the doorway during coverArea procedure, this segment is not calculated again here. When the AUV returns to the starting point, a length of l_{id} is added. It is the maximum length required for the AUV to cover the locked doorway.

6.1 Path length of the proposed coverage method

It is not easy to describe the total path length in the proposed method of coverage using the same notations used in Hert's algorithm. In order to display how much the total path length can be reduced in the proposed algorithm, it is necessary to split the boundary, island and inlet, which are the coverage areas of Hert's algorithm, into (l_{lb},l_{sb},l_{ba}), (l_{bi},l_{si}), (l_{ld},l_{sd},l_{bd}) so that the total path length can be compared with the result from proposed algorithm using new notations. The total path length in the proposed algorithm is calculated by the following Equation (17):

$$l_{tp} \leq l_{gs} + 4l_{id} + 2l_{ba} + \frac{1}{2}\left(3l_{sb} + l_{lb}\right) + \frac{1}{2}\left(l_{bi} + l_{si}\right) + l_{ex} + 2l_{bd} + \frac{3}{2}l_{sd} + \frac{1}{2}l_{ld} + l_{cb} \qquad (17)$$

The definitions of the parameters used in the Equation (17) are listed in Table 3.

Parameters	Descriptions
l_{pt}	Total path length of proposed method
l_{sb}	Sum of the lengths of the short boundary of area
l_{lb}	Sum of the lengths of the long boundary of area
l_{ba}	Sum of the lengths of the bay of area
l_{sd}	Sum of the lengths of the short boundary of inlet
l_{ld}	Sum of the lengths of the long boundary of inlet
l_{bd}	Sum of the lengths of the bay of inlet
l_{si}	Sum of the lengths of the short boundary of inlet
l_{bi}	Sum of the lengths of the long boundary of Island
l_{ex}	Length of getting out of the area based on calculated short path

Table 3. Parameters defined in proposed coverage method to compare with Hert's

Using the parameters define in Table 3, the total path length can be calculated as follows:
As in Hert's algorithm, new proposed algorithm also consists of 4 procedures. The required path length for the first procedure, coverArea is:

$$l_{gs} + l_{id} + 2l_{ba} + \frac{1}{2}\left(3l_{sb} + l_{lb}\right)$$

The required path length for the second procedure, coverInletorIsland is:

$$2l_{ib} + 2l_{bd} + l_{sd} + \frac{1}{2}\left(l_{bi} + l_{ex}\right) + l_{ex} + \frac{1}{2}\left(l_{ld} + 3l_{sd}\right)$$

This includes the distance of movement from the start point to the inlet and the distance of returning to the entrance of the inlet after covering the bay. The required path length for the third procedure for leaving the inlet, ExitInlt is l_{cd}. The required path length for the final procedure, ReturntoS is l_{gs}.

6.2 Comparison of two algorithms

The total path length required in Hert's algorithm and in the proposed algorithm was described in the above section 6.1. However, these two calculation method can not be compared easily as they do not share common parameters. Therefore, the Equation (16) for Hert's algorithm is modified relative to the Equation (17) as follows:

$$l_{tp} \;\leq\; l_{gs} + 5l_{id} + l_{ba} + l_{bd} + \frac{1}{2}(3l_{lb} + l_{sb}) + \frac{1}{2}(5l_{bi} + 3l_{si}) + \frac{1}{2}(3l_{ld} + l_{sd}) + l_{cb} \tag{18}$$

This Equation (18) is the modification of Equation (17), only using the same parameters as used in Hert's algorithm. This new Equation (18) is identical to the original equation except that it was designed for comparison purpose using the same parameters. For direct comparison, Equation (17) and (18) are combined as follows:

$$\begin{aligned}
l_{pt} &\;\cong\; l_{tp} + \left(l_{bd} + l_{sb} + l_{bd} + l_{sd} + l_{ex}\right) - \left(l_{lb} + l_{ld} + l_{id} + 2l_{bis} + l_{si}\right) \\
&\;\cong\; l_{tp} + \left(l_{ba} + l_{sb} - l_{lb}\right) + \left(l_{bd} + l_{sd} - l_{lb}\right) + \left(l_{ex} - l_{id} + 2l_{bi} + l_{si}\right)
\end{aligned} \tag{19}$$

Equation (19) can be split as follows:

$$l_{lb} \;>\; l_{ba} + l_{sb} \tag{20}$$

$$l_{lb} \;>\; l_{bd} + l_{sd} \tag{21}$$

$$l_{id} + 2l_{bi} + l_{si} \;>\; l_{ex} \tag{22}$$

Equation(20) and (21) can be explained as follows: Comparison of path length between Hert's algorithm and proposed improved algorithm is based on the worst scenario. The proposed algorithm was developed to supplement the lack of scheme in Hert's algorithm. The implication of this modification is, as explained in the previous section, that the proposed method, which uses environmental data for the coverage of inlets and islands, results in the reduction of path length. Equation (22) represents the shortest total path length from the coverage area after the exploration. This may differ depending on the characteristics of the topography, but it will certainly reduce the navigating distance as it uses the shortest path. The efficiency of the proposed algorithm was proved to have path reducing effect in the above 3 aspects.

7. Simulation results

In order to verify the performance of the proposed method, a simulation of the environment was designed. In order to minimize the difference from the real oceanic environment, REMUS developed by Hydroid was selected as a model as described in Section 3 and the characteristics of real oceanic environment were applied as much as possible using the oceanic current model. REMUS as shown in Fig.17 is torpedo-shaped flight vehicle of 4 feet in length and maximal 7.5 inch in diameter. The cruise speed of the vehicle is V=1.53 m/s and operating depth range is from 40 to 100 ft deep. Fig .18 shows that the vehicle which has roughly 80

pound as vehicle. Its four fins on either side or forward of the propeller allow pitch and yaw motions for maneuvering. The simulation mission scenario is simply designed to explain how the algorithm is working. The sea current flow speed is defined as $a = 0.5$ m/s which is slower than the vehicle speed, but changes in direction in different simulation.

Figure 17. The REMUS was developed by Woods Hole Oceanographic Institution (WHOI)

7.1 Single AUV Coverage without sea current disturbance

In the simulated environment, the verification of the efficiency of the proposed algorithm was performed first under the ideal conditions without applying AUV dynamics and sea current disturbances. Simulation was performed using complex terrain and simple terrain.

| (a) | (b) |

Figure 18.Types of underwater terrain: (a) Simple Terrain. (b) Complex terrain

Coverage method	Covered path length(m)	Covering time(sec)
Hert's	1353.99	1354
Proposed	1311.33	1311
improvement	42.66(3.17%reduction)	43

Table 4. Simulation result of simple terrain

The maps of the oceanic terrains were prepared as BMP files of 800 (H) x 600 (V) pixels. One pixel represents 100cm x 100cm and sensing range and exploration width were specified to be 20 pixels and 40 pixels, respectively. The results of the test in the terrains described in Fig. 18(a) are shown in Table 4. Table 5 shows that path length was reduced by 3.17% and time by 43 seconds using the proposed method. These results are the proof of the efficiency of the proposed exploration method in finding an inlet, entering it in zigzag pattern up to the bay point and returning via shortest distance, as explained above. This is more confirmed by the test using more complex terrain which resulted in greater difference as shown in Table 5.

Coverage method	Covered path length(m)	Covering time(sec)
Hert's	2022.75	2023
Proposed	1795.32	1795
improvement	227.43 (11.27% reduction)	228

Table 5. Simulation result of complex terrain

As indicated by the results in Table 5, it can be predicted that the efficiency of the proposed method will be more pronounced in the exploration of complex terrains in shallow sea. This also indicates that the proposed method would be useful for operations that are usually carried out in shallow seawater such as mine countermeasure (MCM) operations, rescue operations and assaults.

7.2 Single AUV coverage with sea current disturbance

In this section, we will look into the results of exploration using the proposed algorithm applying internal and external factors of cross track errors. From simulation test, missing areas caused by cross track errors could be identified as shown in Fig. 19.
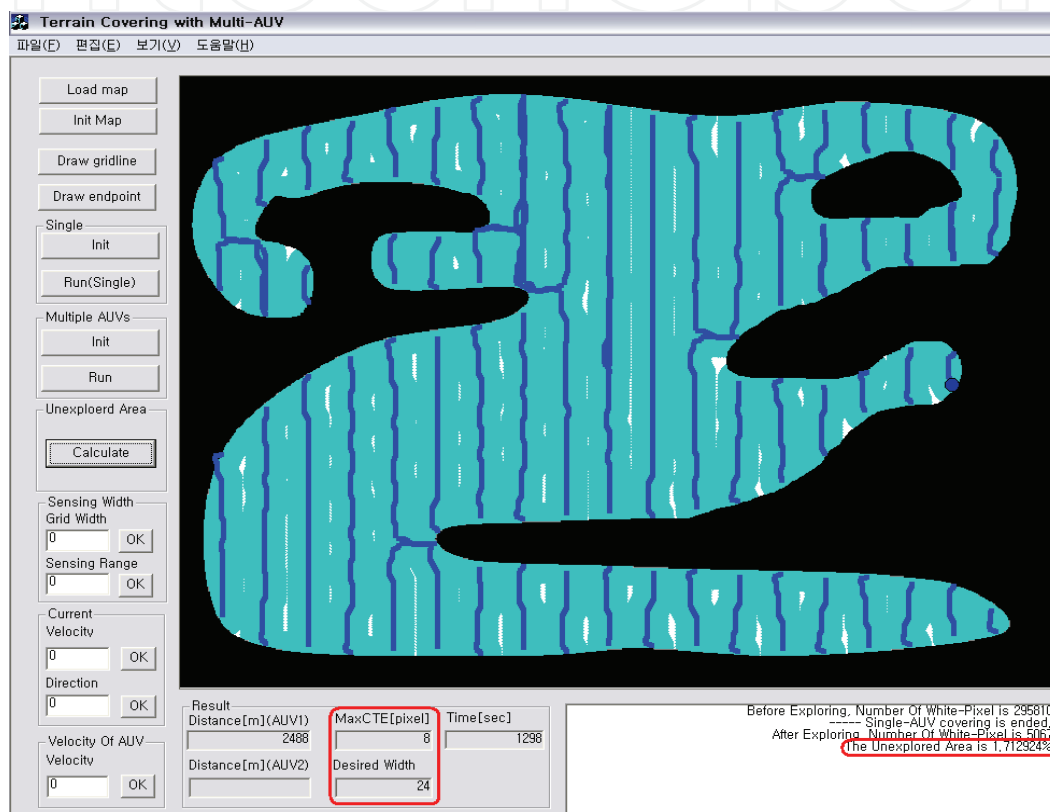
Figure 19. Single AUV coverage with sea current in simulation

The results of simulation test are shown in Fig. 19 where missing areas are revealed as white areas and indicated at the right bottom of the screen. The exploration width and maximum CTE required for resolving these missing areas are indicated at the bottom center of the screen. The existence of missing areas such as these can be fatal in military operations where accuracy is critical. The EEW value from this test was modified to 24 (2x20 – 2x8) after re-calculation. White missing areas were eliminated completely from the results of the test performed again using this new value. The new results indicated that using the new value 24 as EEW, variability of the path caused by CTE has been fully optimized although exploration path length and time were longer because of reduced exploration width.

7.3 Multi-AUV coverage with sea current disturbances

The results of the exploration test using dynamic role assignment mechanism, as shown in Fig.20, which was proposed in this study as the exploration method for two-AUV operation, are summarized in Table 6.
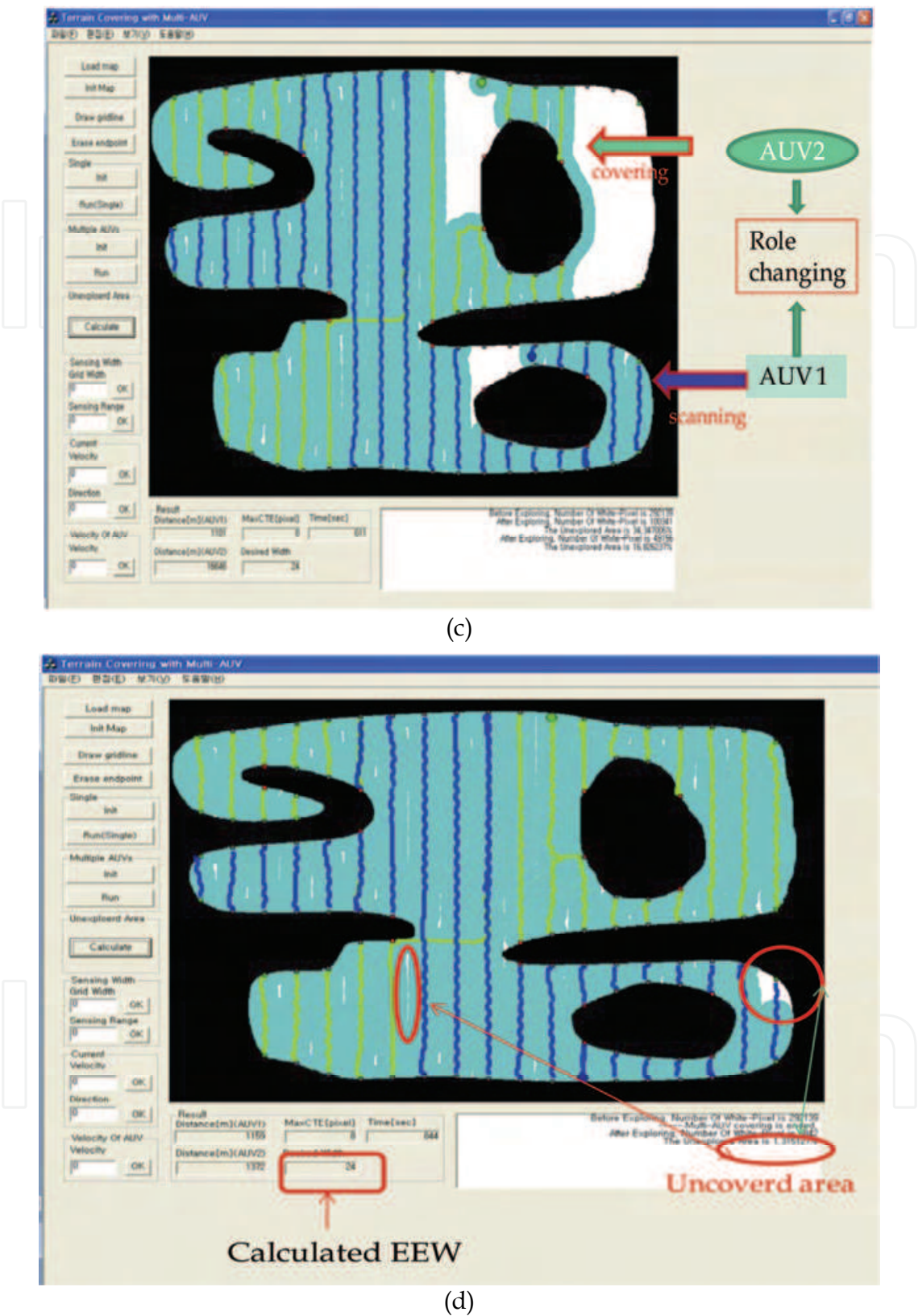

(a)

(b)

(c)

(d)
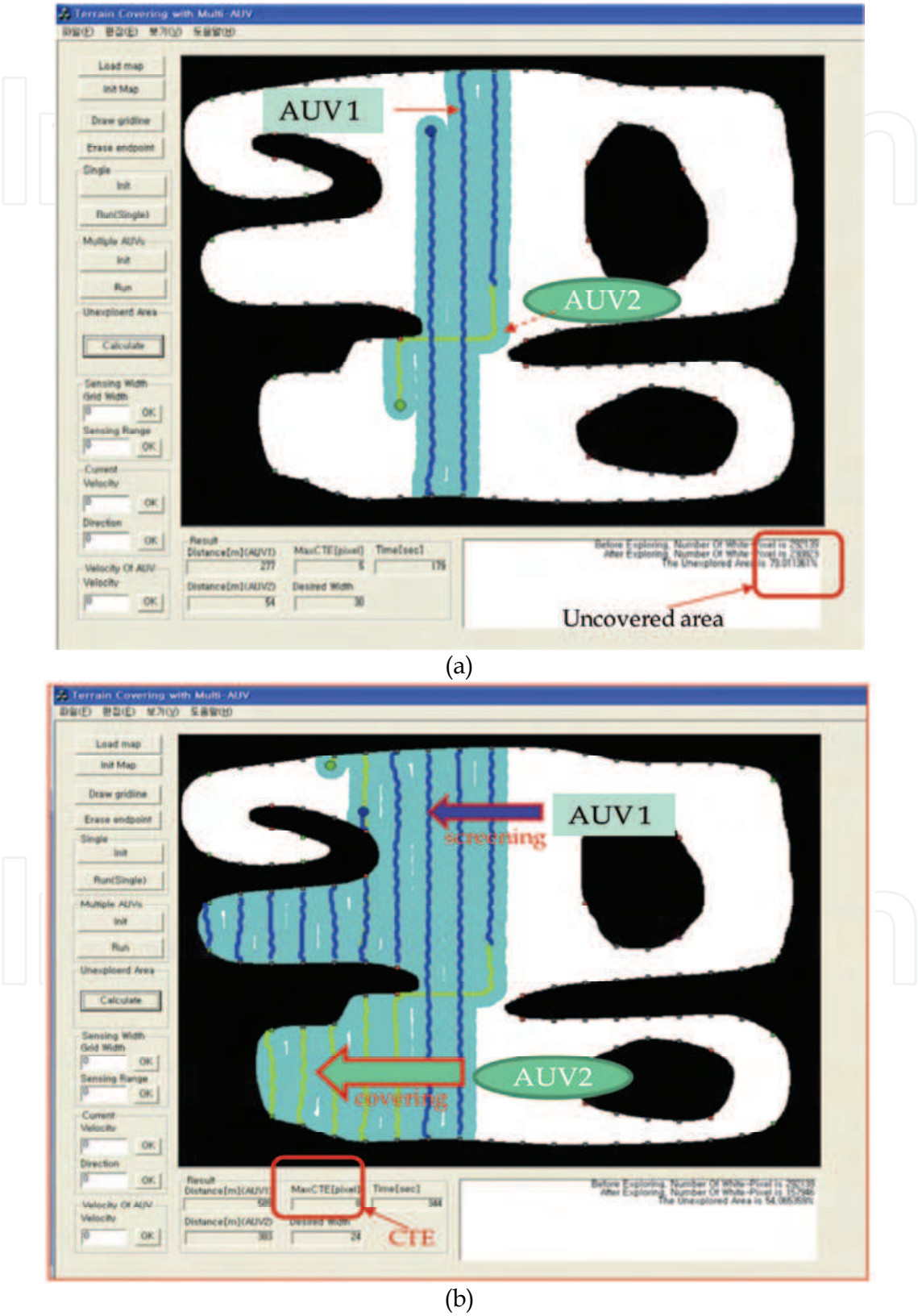
Figure 20. Multi-AUV simulated the covering method in an unknown terrain without EEW by following steps: (a) The AUV starts covering to detect cape. (b) Two AUVs define coverage roles.(c) Two AUVs change role considering coverage situation.(d) Results after completed coverage

Mode	Total Distance(m)	Time(sec)
Single-AUV	1797.72	1298
Multi-AUV	1979.32	800

Table 6. Simulation result compared to single AUV and Multi- AUV

As can be seen from these results, total time taken for entire exploration was reduced considerably although total path length of the two AUVs was increased. Also, it could be confirmed that dynamic assignment of the roles of covering and screening in this multi-AUV operation using the new proposed method was successfully carried out in accordance with the environmental characteristics.
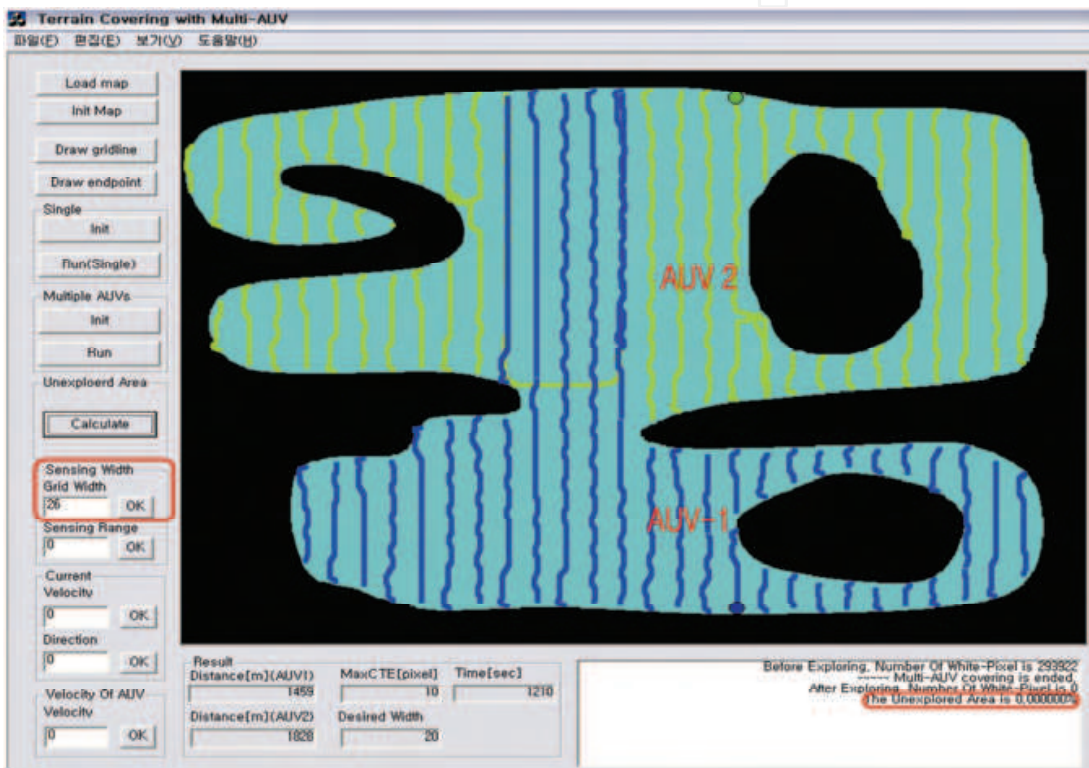
Figure 21. Simulation result of Multi-AUV with EEW

Fig. 21 shows the results of exploration using two AUVs. These results also confirmed that the problem of missing areas could be resolved by applying re-calculated EEW.

8. Conclusion

This paper presents an on-line coverage method for the exploration of unknown 3-dimensional oceanic terrains using multiple autonomous underwater vehicles (AUVs). Based on the concept of planar algorithm developed by Hert, this study attempts to develop an improved method. Instead of theoretical research, it focuses on practical aspect of exploration considering the equation of motion for AUVs that are actually used in oceanic exploration as well as characteristics of complex oceanic topography and other realistic variables such as sea current. These elements of consideration are used to calculate cross track error (CTE) and path width. The validity of the improved algorithm for terrain

coverage was first verified mathematically and then simulation of the real underwater environment was used to prove it by analyzing the path length and time taken for the coverage as well as missing areas, which is the key element of efficiency. In order to apply the improved method to the Multi-AUV operation, each AUV was assigned of covering or screening role by means of dynamic role assignment mechanism. Finally, the proposed method was tested in simulated environment where optimal exploration width was calculated and complete exploration without missing areas was successfully proven. We expect future study to employ REMUS, which we used as a model, and to resolve the hypothesis-based communication problems as well.

Also, the results showed that Multi-AUV operation has advantage over single AUV operation. The proposed method of this study will not only be useful to commercial applications but to mine counter-measure (MCM) and rapid environmental assessment (REA) as part of a naval military operation as well. We also believe that it will be ideal for use in variable oceanic environment particularly in shallow water terrains

9. Acknowledgement

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Recent Advances in Multi Robot Systems

Edited by Aleksandar Lazinica

To design a team of robots which is able to perform given tasks is a great concern of many members of robotics community. There are many problems left to be solved in order to have the fully functional robot team. Robotics community is trying hard to solve such problems (navigation, task allocation, communication, adaptation, control, ...). This book represents the contributions of the top researchers in this field and will serve as a valuable tool for professionals in this interdisciplinary field. It is focused on the challenging issues of team architectures, vehicle learning and adaptation, heterogeneous group control and cooperation, task selection, dynamic autonomy, mixed initiative, and human and robot team interaction. The book consists of 16 chapters introducing both basic research and advanced developments. Topics covered include kinematics, dynamic analysis, accuracy, optimization design, modelling, simulation and control of multi robot systems.

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