Navigation of Autonomous Underwater Vehicle based on image recognition of Artificial Underwater Landmarks

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Abstract

In this paper a new underwater navigation method for an autonomous robot is proposed based on Artificial Underwater Landmarks (AULs) which are recognized by a vision system implemented in the robot. The Autonomous Underwater Vehicle(AUV) which cruises by deadreckoning suffers from position error accumulating gradually. When the error is within an acceptable range, the robot can find a specific AUL and correct the position and direction by refering to targets of the AUL. Then, the AUV continues to cruise by deadreckoning. To improve reliability of underwater vision system, a new underwater image processing strategy is introduced based on analysis of underwater vision environment. Configuration of the AUL, and shape and color of targets on it are designed to optimize image processing and recognition. Experiments were carried out to demonstrate the efficiency of the proposed navigation method by the intelligent AUV namely "Tri-Dog1".

1. INTRODUCTION

Investigation of shallow water structures such as dams, bridges, ports and fresh water environment which is closely related with human life, become a very important issues.

Even though Autonomous Underwater Vehicles (AUVs) are very efficient tools for the mentioned invest investigation task, AUVs are not utilized enough because of problems come from conventional navigation methods of them. Although the acoustic apparatus is widely used for the navigation of AUVs, its data has so severe noises especially close to the by underwater structures or surface of shallow water, that its application to AUVs operation involves many problems in terms of reliability.

We propose a new navigation method which depends on vision sensor instead of acoustic. Usually, an AUV cruises by deadreackoning. When the position error is accumulated, Artificial Underwater Landmarks (AULs)based on vision system which is installed at the some known position can reset the error. CCD camera mounted AUVs such as Tri-dog[3] and tan-tan[4]can carry out the proposed navigation. But AUV's vision performance has some internal and external limitations such as limited computing and lighting and severe underwater optical environment Considering all of these factors which affect the reliability of vision, we propose a new vision system for an AUV to overcome the above mentioned problems.

In section 2, difficulties of conventional navigation method and the new method is addressed. Efficient and reliable vision system is addressed in section 3 and the reliable design method of AUL and its applications are described in section 4. Experiment and the result to prove the efficiency of the proposed navigation method is given in section 5.

2. NAVIGATION METHODS OF AUVS

A. Coventional methods

In general, navigation method of AUVs can be classified into two groups.

1) Using external guiding tools: The most commonly method for navigation of AUV is using guiding tools such as acoustic apparatus, underwater cable, magnetic signal etc. Closed distance from underwater structure especially beneath of huge plane such as mega-float[7] or piers and near of shallow water surface, acoustic apparatus bring out inaccurate position data caused by multi-pass, surface noises etc. In addition, an acoustic apparatus needs periodical maintenance, repair and power supply.

When an AUV uses 'continuous' underwater cable or magnetic signal, its navigation is reliable based on highly accurate position reference. But it is very difficult to install or change 'a continuous cable' on the whole route especially on underwater structures. In case of long distance navigation of AUVs, installation of the extra guiding tools are economically suitable.

2) Deadreckoning: Deadreckoning is also used for navigation of AUV using internal sensors such as Ring Laser Gyro, Doppler Velocity Log etc. Deadreckoning enables the navigation of AUV to be more flexible and independent from condition of supporting system. But large deadreckoning sensors such as Ring Laser Gyro is hard to be mounted in a small AUV system and deadreckoning error is significantly accumulated that the navigation range will be wrongly affected, if there is no any kind of error modification tools.

For example, assume that we want to inspect a large oil storage tanker by an AUV. Visible range of underwater width is 1m and our interest of inspection is appearance of sacrificial anodes (length=2m) which are attached to the bottom of the large oil storage tankers (width=100m, length=400m,heigh=30m) at the Kamigoto island in Japan . Totally, 40km should be inspected by the AUV while the mission is completed. If an AUV cruises by deadreckoning, the allowable deadreckoning error is less than 0.005% (2m/40km =0.005%)of the distance traveled. Even highly ranked accurate navigation of an AUV by deadreckoning, its error is reported about 0.4% of the distance traveled [12]. Without proper modification of accumulated error, an AUV is hard to carry out this kind of inspection.

B. Proposed method

Since conventional navigation methods have difficulty to be implemented for the mentioned task, we propose a new method as schematically shown in Fig.1. This method can be explained in two consequent stages as follows.

1) In the first stage, the AUV is navigated by deadreckoning as far as the accumulated error is within an acceptable range. Before the accumulated error goes out of the acceptable range, the position should be reset by using some error modify tool. It should be worked properly where an acoustic apparatus causes problems and economical merits such as easy to setup, no maintenance and no energy consumption after installation are required.In addition,if it has sufficient compatibility to the common information systems which are visually understandable by human being, operators of Remotely Operated Vehicles (ROVs) and divers also could use this modify tool.

Introduction of Artificial Underwater Landmarks (AULs) associated with vision system can cover the above necessaries. AULs standing on the seabed or attached to the underwater strutures represent their absolute position and orientation, and some additional informations can be also included. Since these data are shown as configuration of AULs, heavy maintenance is not necessary. They do not consume energy after installation if they do not have active lighting system. As human can recognize visual information as AUV does, the data from AULs can be recognized by human. It can also provide rich information with inexpensive devices as far as visual system concerns. Underwater image has, however, many special noises comparing to images in air, such as back scattering and inhomogenous lighting.

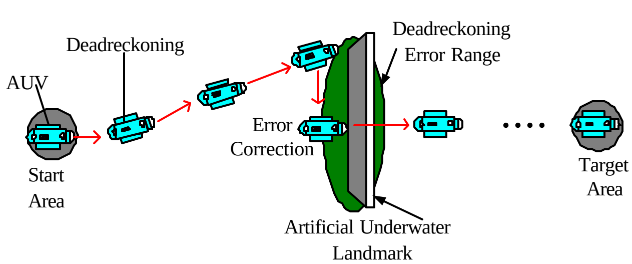


Fig.1 Pictorial View of the Proposed Method

It should also be emphasized that computing power for image processing is limited because all circuits boards should be put in pressure chambers, and that lights consume much energy which is troublesome for small AUVs.

2) In the second stage, the AUV tries to find an AUL and keeps a specified position to the AUL. The AUV can localize its position refering to the configuration of AUL. Thus, the accumulated error can be reset. Then, the AUV starts to the next destination by deadreckoning. By repeating these two stages continuously, the AUV can travel the mentioned task or long distance navigation.

3. DESIGN OF VISION SYSTEM

A. Color Extraction Method

Underwater image processing has many difficulties such as extremely high light absorption, marine snows, scatters etc. Different underwater image processing methods have been proposed to overcome their difficulties [16][17][18][19][20].

But these methods are hard to implement in the case of an AUV, because it has some other difficulties as below.

1)limited computing power: Even though real-time image processing is required for navigation of an AUV, the computing power of an AUV is strictly limited. An AUV has not enough computing power to implement conventional underwater image processing methods.

2) poor lighting sources: Most of the conventional underwater image processing methods used ROVs to take image materials for development of image processing method. ROVs have hundreds watts or number of kilo-watts lighting sources while an AUV has only dozens watts of them. Considering that underwater vision environment can be remarkably improved by powerful lighting sources, much more efficient image processing methods are required for the AUV than that of conventional.

3)difficulty of camera position: Due to difficulty of an AUV's positioning, camera 's images are restricted.

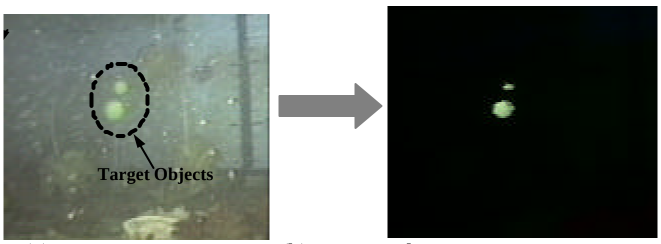
Considering there difficulties ,Balasuriya [21] proposed underwater image processing method for an AUV. This method includes three functions to recognize the target object as follows.

1) Elimination of specific underwater noises
2) Enhancement of the target object in the image
3) Detection of the location of the target

But this method spends much time for computing and has a weakness of brightness change which usually occurs in underwater environment[22].

We propose the color extraction method as a new underwater image processing method for the AUV[13][14]. Since underwater images are usually very monotonous, it is easy to identify an artificial object when it is painted in a brilliant color. Fig.2(a) shows a noisy underwater image of two yellow balls in an out-door pool and Fig.2(b) shows the extracted target object by the proposed method. It shows that the color extraction method reduces not only the noises in the image but also detects the target objects at the same time. The proposed method combines above three features into one.

As shown in Fig.5(c), underwater image has a few colors and distribution of there colors are concentrated on few background colors. Usually, underwater backgrounds would not have much changes by time and region. Numbers of colors in the underwater image is 1/8-1/6 of land image[14]. Comparing to gray scale image processing method which is widely used for underwater image processing,, the proposed method has several merits as below.



(a) Raw Image (b) Processed Image

Fig.2 Underwater Image Processing using by Color Extraction

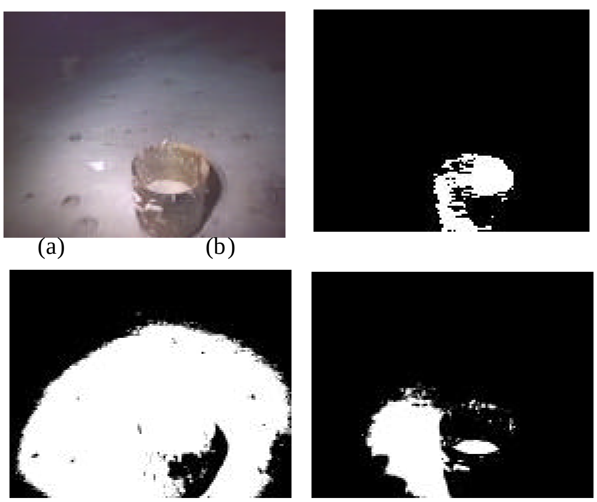

(a) (b) (c) (d)

Fig.3 A Corrosion-Resistant Copper Pot of Titanic

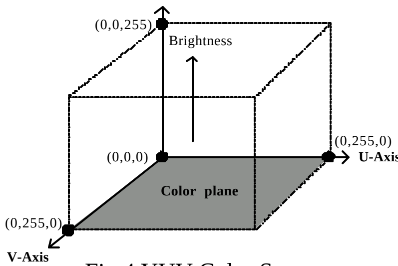


Fig.4 YUV Color Space

First, it is less affected on brightness change than gray scale image processing. When the viewing direction is changed or target object has a curved surface, brightness of the target object is also changed. Due to difficulty of an AUV's positioning ,this happens very frequently in the underwater environment.

Secondly, when the background is brighter than the target object which is often occurred close to the seabed, the proposed method can recognize the target object while gray scale image processing method has difficulty. Fig.3(a) is the bucket from the sunken vessel; The Titanic. Background is brighter than the bucket. the bucket can be extracted as fig.3(b) by color extraction method. But the gray scale image processing method can not extract the bucket image correctly. Fig.3(c) and (d) shows the binarized image with threshold 82,164.

B. Analysis of Underwater Environment

In color extraction method, selection of the target object's color is very important because color is the only information for recognition. Target object's color should be unusual color and easy to detect in underwater.

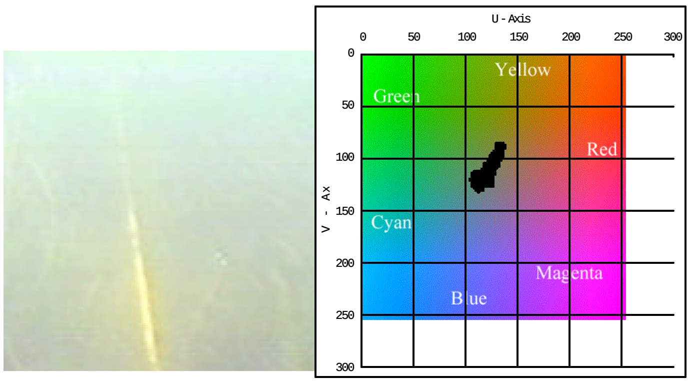
We propose reliable color selection method by the color analysis of environment as belows.

1) Analysis of background: The color extraction method uses two information; the brightness and the color. Our interest is the color information of the image, not brightness. If the brightness of the image is not considered in the color extraction method (i.e. 0 to 255 fully opened state) a change of the brightness hardly affects on extracting of the target object. The color of the image can be mapped to the YUV color space as show in Fig.4. and we use only UV values(color information). The color distribution of background's image can be plotted in UV plane. For example, the color distribution of the image Fig.5(a)can be analyzed like Fig.5(b) on UV plane. Fig.5(c) shows background's colors are concentrated in a small area.Using this analyzed result, we can select proper target object's color area.

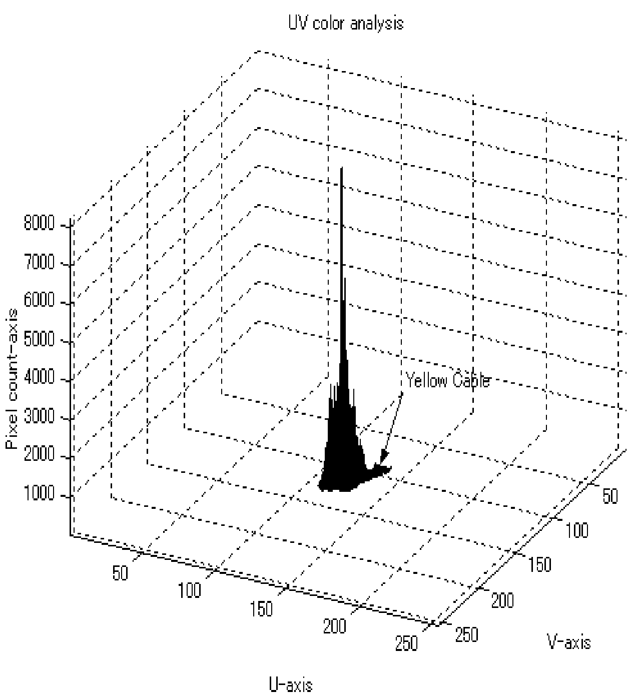
2)Selection of target object's color: The object's color is changed in underwater and on air. From the above analysis, we can estimate the proper target object's color in underwater; Not on air. For painting the target object, we should convert the object's color in underwater to air. But it is hard to estimate because there are too many factors effect on color in underwater. A color on air and in water is different. Because in water, absorption rate of a light depends on wavelength of a light. Detectable distance of colors are different respectively. In shallow water, environment change also effect on color .For example color of river or lake in hot summer is different from cold winter because numbers of plankton are different. Scatters and turbidity also affect on the color.

Since the change of color due to the mentioned factors are hard to predict, we used the physical color sample to find the exact color to paint.

Show as Fig.6(b),we put the color samples in underwater and this image is also analyzed by the proposed method. The result of the color sample analysis is also plotted on the Fig.6(c).If improper colors are removed, light green, yellow, orange will be remained . The detectable range of the color should be considered. The detectable distance of the color can be calculated using wavelength absorption rate in water[15] and formula of light absorption in water[23]. All of these remained colors can be detected from a long distance[24][25]. Environment effects should be considered also. Target area, as shown in Fig.6(b), is an outdoor pool and light green is not suitable one because a color of it may turns light green in warm day.As a result, orange and yellow is selected of the proper target colors.



(a) Raw Image (b) UV Analysis



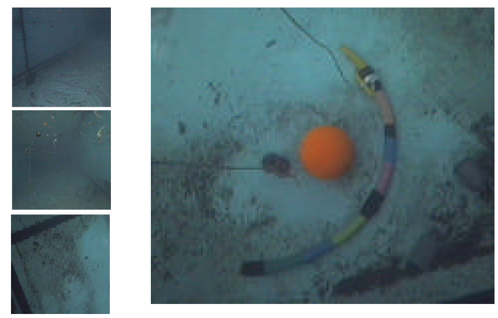
(c) Counts of Each Color

Fig.5 Underwater Image Color Analysis

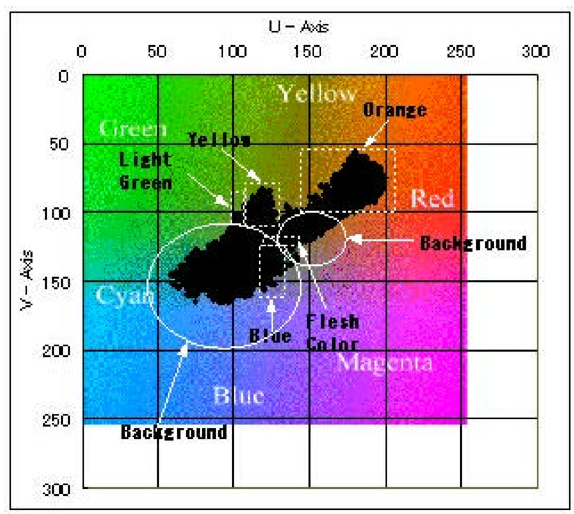
C. Change of AULs

The AUL has two kinds of changes. The one kind of change happens by a long time after installation of the AUL. This changes depends on the characteristic of the environment. If there is no direction ray from the sun light, discolor of the AUL arises from the sun light rays is insignificant. The effects of a marine fouling is considerable too. When an AUV used AUL frequently, changes of the AUL' colors or shape can be properly updated or whenever an AUV uses the AUL or it can be cleaned by an AUV.In case that an AUV does not use the AUL frequently, the sample of AUL which is installed at the convenient place to check, will notice the change of AUL's colors or shape. The AUL which is made from anti-fouling materials such as glass, can also prevent the change of the AUL.

The other kind of change happens in the navigation of an



(a) Background (b) Sample Objects



(c) Colors Distribution

Fig.6 Color Analysis of Underwater Environment and Sample

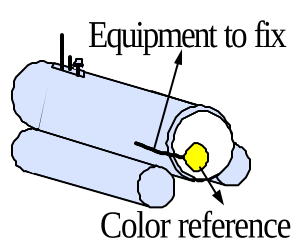


Fig.7 Physical Color Reference

AUV. The sun light is strongly affects on the vision condition in shallow water. As shown in Fig.7, we propose the physical color reference to detect the change of underwater vision condition on real-time.

4. DESIGN OF AULS

It is necessary to divided a complex vision process into several simple and easy processes to improve reliability of vision system in the case of severe underwater vision environment.

We propose three simple and reliable processes to be carried out the mentioned deadreckoning error correction. Shown as Fig.8, an AUL consists of three parts which correspond to three processes. The positioning tool which modify the deadreckoning error is located in the middle part of the proposed AUL. Both sides of the positioning tool, the guiding tool which helps an AUV to detect the AUL is located like a wing. The information tool which provides necessary information to an AUV is located in the center area of the positioning tool.

A. Guiding Tool

When an AUV should detect the proposed AUL for modification of the deadreckoning error, the guiding tool like a long colored cable ensures the AUV for detecting the proposed AUL in severe underwater vision environment if it covers all deadreckoing error range. When a Doppler Velocity Log is used as a deadreckoning sensor which is installed in the AUV "Tri-dog1"(Ura lab's latest AUV, the first launch was carried out at Nov. 1999), error is estimated

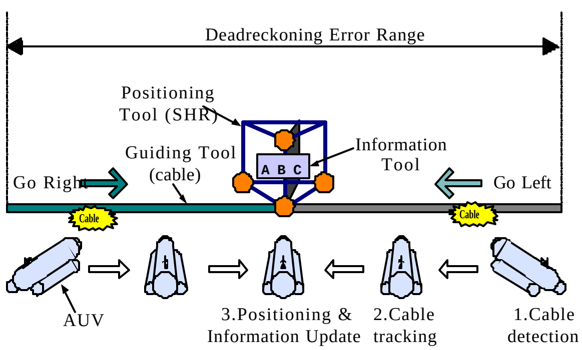


Fig. 8 Example of Proposed Artificial Underwater Landmarks

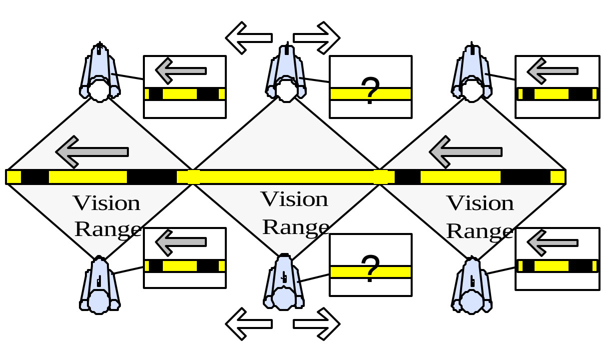


Fig.9 Guiding Tool for Independent of Viewing Direction

about 0.4% of travelling.So that necessary length of the cable is 4m in case that the Artificial Underwater Landmarks are put on in every 1kms.

There are two types of deadreckoning error; cross-track and along-track error. Numbers of cables which are installed in cross-track or along-track direction of traveling from the center point of the proposed AUL, allows an AUV to detect cables easily in the deadreckoning range. But considering difficulties for target objects installation in the underwater, numbers of cables should be reduced as possible. If an AUV cruises forward until a cable is detected, the deadreckoning error range can be covered by two cables
which is installed the cross direction of traveling as shown in Fig.9. The colored cable can be detected by the proposed color extraction method. After finding the cable, the AUV turns until the cable is located on parallel center in the captured image of the robot. Then the AUV recognize the pattern of the cable by the projection process method. Without the above process, the AUV can mistake the pattern of the cable. Because when the cable is laid on the angled direction in the robot image, the pattern of the cable cannot be recognized correctly by the projection process method.

After detecting the colored cable, the AUV should move along the cable to the error correction region where the AUV can find the positioning tool.

B. Positioning Tool

- *Signboard system*

To correct the deadreckoning error, an AUL represents two kinds of information. The first one is for the position information to correct the deadreckoning error. When the AUV has found out the target AUL, the AUV should obtain the position information such as absolute position from the AUL to correct deadreckoning error. Authors proposed a reliable position information update method for AUVs using pattern matching and 1dimensional barcode [28]. It is based on the line detecting technique which is especially reliable in the underwater visual environment. The second one is for heading angle reference correction. Heading angle is the most important parameter which determines accuracy of navigation path of the AUV. Usually, heading angle is measured by a maganetic compass. However, external magnetic anomaly fields interferes with the compass accuracy. It is not unusual that underwater soil contains some ferrous elements resulting in vast and local magnetic interference effects. To solve this problem, accurate value of heading angle should be calculated using its relative position to the AUL whose direction is precisely pre-determined. This position should also be measured based on the image of the AUL. This should be realized by a not-complicated method and a not-heavy image processing.

Considering above mentioned conditions, we introduce the signboard system which originally proposed by

Arai[26] as shown in Fig.10. The signboard system provides the AUV with the orientation and the distance associated an efficient calculation and a simple 2D image processing. It also brings the AUV proper accuracy as a deadreckoning error correction tool. It is generally recognized the position error of signboard system is less than 3% of the distance measuring. However it is initially designed for the ground purposes, some modification is necessary for underwater environment.

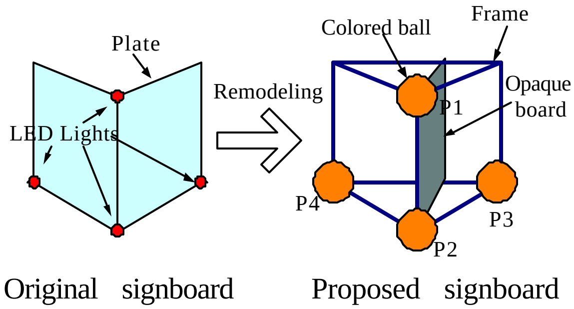


Fig. 10 Remodeling of signboard system

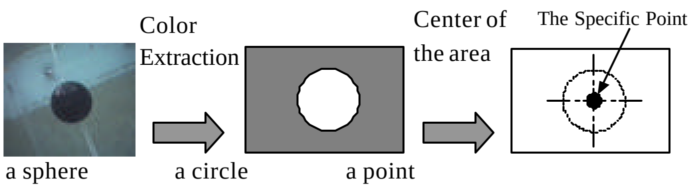


Fig. 11 Proposed method to detect the predefined point

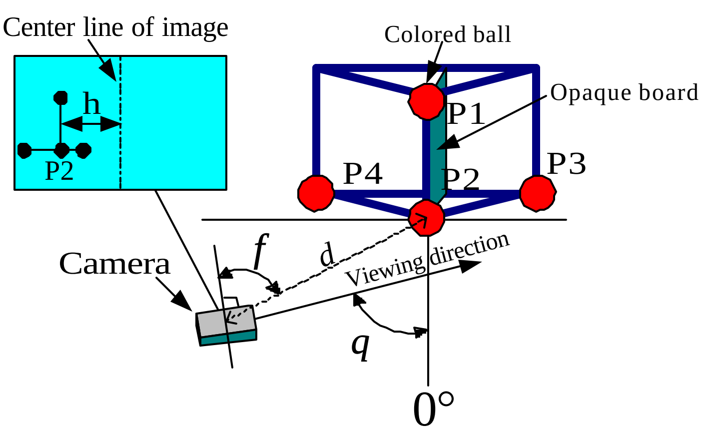


Fig. 12 Signboard system for Heading angle Reference(SHR)

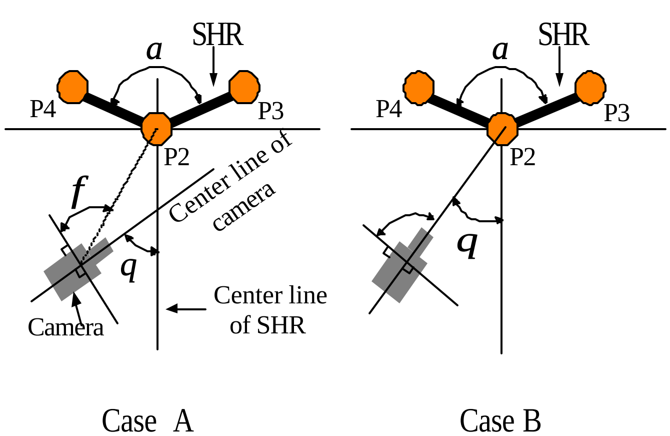


Fig. 13 Upper View of SHR

■ *Remodeling of signboard system*

The left hand side of Fig.10 shows the original signboard system which was proposed by Arai[26] for implementation on the ground. It has four LED lights for identification of the specific points. As the AUL for underwater use is required no energy consumption after installation, LED lights are substituted with four colored balls as shown in the right hand side of Fig.10.

As shown in Fig.11, the center of each ball can be easily extracted in the image captured by a CCD camera. The center of the ball in the image is located at the position of the corresponding LED light as shown in the left hand side of Fig.10. Since the ball are fitted on a frame type structure, the AUV can detect the location of each ball from any direction.

Based on the mentioned experiments in pool, it was found that orange color can be widely used. In some cases depending on the surrounding, other color, for example yellow or blue,may be more preferable. Diameter should be determined based on transparency of water. Surface of ball should be rough to prevent reflection effects.

When the camera is in the angle of P4P3P2, P3 maybe seen between P2 and P4. This situation is very confusing for image processing algorithm, an opaque board is fitted behind P1 and P2 to obstruct the view of the farmost ball as shown in Fig.10.

■ *Algorithm derivation*

The proposed Signboard system for Heading angle Reference (SHR) is shown in Fig.12. P2, P3 and P4 are colored balls located in a horizontal plane and P1 is the one above P2. Distances between the center of each pair of balls are denoted by $\overline{P1P2}$, $\overline{P2P3}$ and $\overline{P2P4}$, which are designed as the same length L in the followings. Angle P4P2P3 is denoted by a, which was determined 140° based on the error optimization analysis[26].

In the followings, it is assumed that heel angle of the AUV is negligible. Because the target vehicle of this research is "Tri-Dog1"or "Tantan"of which is center of gravity locates at sufficiently low from the center of buoyancy resulting in high stability in the pitch and roll motions. It is also assumed that effect of elevation of the camera from the horizontal plane P2 P3 P4 on the orientation of the camera is also negligible, because it can be estimated using the output of the altimeter, and the AUV is located in the similar level of the SHR.

If the camera is in the same level of the plane P2 P3 P4, the accuracy in correction of orientation and distance is more accurate than some different levels because of decrease of degree of freedom. It is not difficult to move the camera in this plane, since the AUV can control the altitude.

The focal length of the camera is denoted by *f*. The relative position of the camera from the SHR can be determined by distance *d* and angle q as shown in Figs.12 , Fig.13. Let respecting lengths in the image of $\overline{P1P2}$, $\overline{P2P3}$ and $\overline{P2P4}$ be l_1, l_2 and l_3. The angle f is the angle between the line intersects perpendicularly with the center line of camera and the line from camera to P2 as shown in Fig.13. The horizontal distance from the center line of the image to P2 is denoted by *h* as shown in Fig.8. When the center line of camera orients to P2 as shown in case B of Fig.13, the f is $90°$ and *h* is 0 as shown in Figs.12 and 13. If not, it can be calculated by *h* as shown in case A of Figs.12 and 13.

- **Estimation of the distance:**

Distance d is given by

$$d = \tan^{-1}\frac{Lf}{h}. \qquad (1)$$

- **Estimation of the orientation:**

For calculation of q, the SHR system requires that at least 3 colored balls are visible in the image area. There are two geometrical conditions for calculation of q, i.e. 3 balls are visible and 4 balls. We proposed two different methods for calculation of q.

1) 4 balls are visible :

f and q can be given by the following equations;

$$f = \tan^{-1}\frac{f}{h} \quad (0 < f < 180°), \qquad (2)$$

$$q = \tan^{-1}\left(\frac{G_1}{G_2} - \frac{p-a}{2}\right). \qquad (3)$$

$$G_1 = l_2 f + l_3 f \cos a + (l_2 l_3 - l_3 f \cot f)\sin a, \qquad (4)$$

$$G_2 = l_2 l_3 + l_2 f \cot f + l_3 f \sin a - (l_2 l_3 - l_3 f \cot f)\cos a. \qquad (5)$$

2) 3 balls are visible :

From right side of SHR or left side, P4 or P3 is invisible in the camera image because of the opaque board. When P4 or P3 is invisible, q can be calculated as given in equation (6) or equation (7), respectively;

$$q = \cos^{-1}\frac{l_2 d}{Lf\sqrt{1+A^2}} + \sin^{-1}\frac{f\cot f - l_2}{f\sqrt{1+A^2}} - \frac{p+a}{2}, \qquad (6)$$

$$q = \cos^{-1}\frac{l_3 d}{Lf\sqrt{1+B^2}} - \sin^{-1}\frac{f\cot f - l_3}{f\sqrt{1+B^2}} - \frac{p+a}{2}, \qquad (7)$$

$$A = \cot f - \frac{l_2}{f}, \quad B = \cot f + \frac{l_3}{f}. \qquad (8)$$

where f is given by Eq.(2).

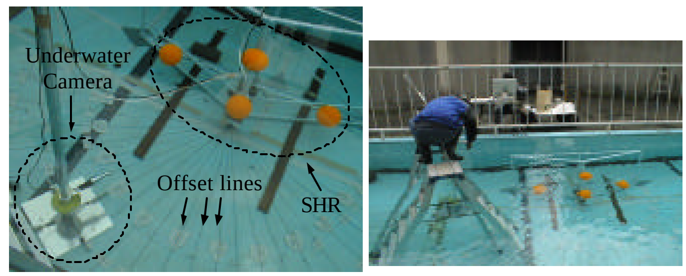
■ *EXPERIMENT*

Calibration of the SHR was carried out in the out-door pool at the Institute of Industrial Science as shown in Fig.14. The SHR and underwater camera were set at the same level at the bottom of the pool depth 1.5m. The camera was moved manually by measuring actual distance and heading angle on the predefined offset lines. Diameter of the colored ball D and the parameter L were determined as 17cm and 60cm, respectively. The colored balls were painted out in light orange considering environmental color noises. The angle f was fixed at $90°$, i.e. the center line of camera always oriented to P2 of SHR. Parameter *d* and q are changed in the following ranges;

d : 175 ~ 300 cm (25 cm intervals),

q : $-90° \sim +90°$ ($7.5°$ intervals).

Brightness on the surface was form 24500 Lux (when very cloudy) to 83000 Lux (when very shining) .



(a) (b)

Fig. 14 Underwater experiment to estimate the accuracy of SHR

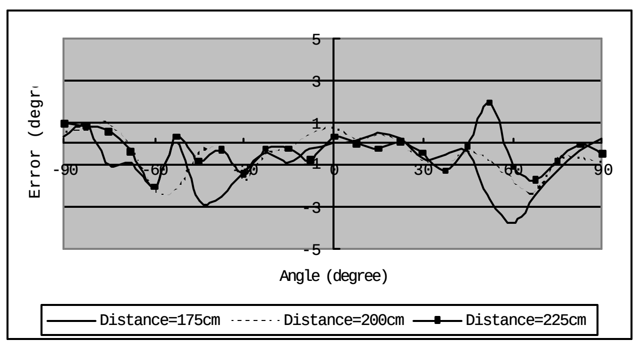


Fig.15 SHR orientation error A

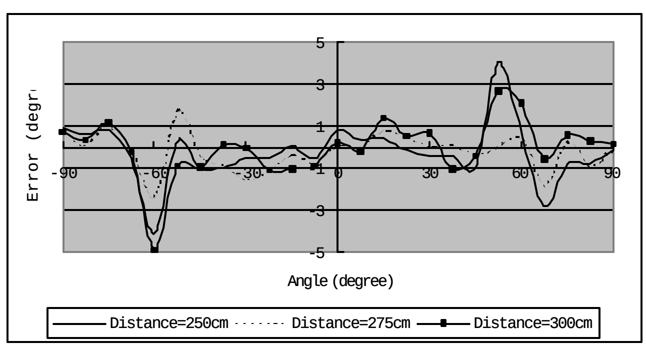


Fig.16 SHR orientation error B

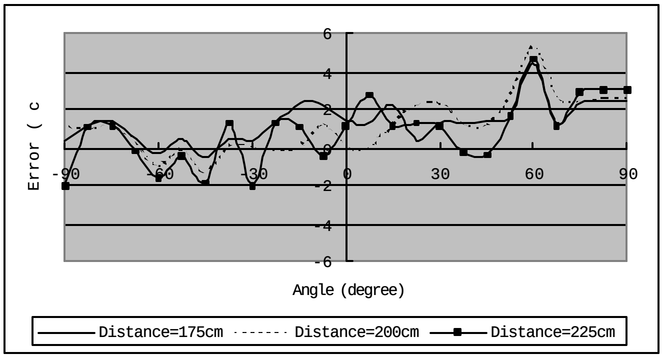


Fig.17 SHR distance error A

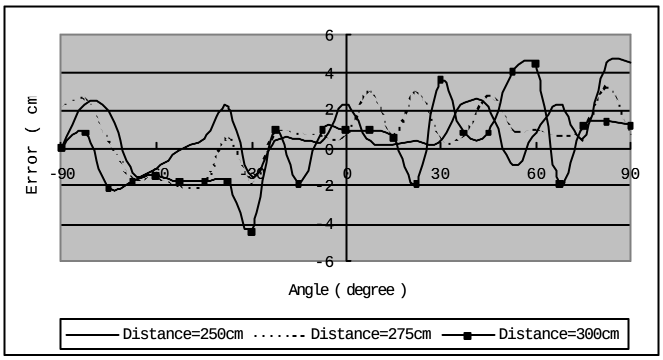


Fig.18 SHR distance error B

■ *RESULTS*

Figures 15 and 16 shows orientation error of SHR on the offset line, Fig.17 and 18 shows distance error .

Maximum error in q which was calculated by the AUL was 4.9° and maximum error in d was 5.4 cm. The proposed SHR showed reasonable accuracy as a tool for heading angle reference.

From the results, it can be seen that near to the $\pm 52.5^\circ$,

orientation error increased quickly due to overlapping of the farmost ball and P2. It is recommended that the AUV should be navigated keeping q small, where the orientation error can be minimized. The error can be reduced up to 1°.

C. Information Tool

After reset the deadreckoing error,the AUV can obtain the necessary information by the infomation tool which is installed in center part of the AUL as shown in Fig.8.

The information tool should be designed to recognize the information data correctly even if there are many noises in underwater. We proposed 1D and 2D bar code type underwater information tool[14][28].

Since 2D bar code has a self-error correction funtion which modifies noisy and damaged image to correct image,it can be correctly recognized even if underwater noises and shading are existed in the image. 2D bar code's density of information per an area is sores or a hundred times higher than 1D bar code.Considering that visible range of an AUV is very narrow,2D bar code can provide amounts of information to an AUV efficiently.

5. EXPERIMENT

A. Experiment

Experiment for deadreckoning error correction was carried out in an outdoor pool. The AUV "Tri-Dog1"(refer to Fig.20 and Table 1) starts with 1.5 m′s deadreckoning error. This means that the AUV has traveled more than 300m based on deadreckoning traveling. The AUV ′s sensors are not work properly close to the bottom of the pool and experimental pool was too shallow so that we changed the SHR′s shape upside down as shown in Fig.19. This kind of change does not affects on calculation of the SHR. Yellow and orange was decided of the color for the cable and the SHR based on the result of analysis, respectively(refer chapter 3). Assume that the AUV has traveled more than 300m and it has 1.5m's cross-track error, the start point of the AUL is apart 1.5m from the center of the AUL(refer to Fig.21).

Figure 22 shows high-level controller. At the beginning, the AUV moves dreadreckoning mode from waiting mode by the trigger and continue the cruising until the stripe cable is detected. When the stripe cable is detected, the AUV moves cable tracking mode and following the cable until the SHR is founded. When the SHR is founded, the AUV moves positioning & information update mode and change the position of the AUV until the SHR is located in the proper region of robot's image. After that, the AUV modifies the deadreckoning error by the SHR and starts recognition of the information tool; an upper arrow sign.

If an upper arrow sign is recognized correctly by pattern matching method, the AUV moves ascend mode and ascend to the surface of water and moves waiting mode. When the AUV lost the AUL in the image, the AUV moves searching mode and searches the AUL. If AUL cannot be founded longer than the limited time, the AUV ascend and waiting for the trigger.

B. Results

Fig.23 is inner camera's image of the AUV. As shown in Fig.24, the AUV found out the cable at 3m apart from the start point and moves the center point of the SHR. When the SHR is detected, the AUV reset the deadreckoning error as shown in Fig.23(b).The reset point was the 326cm apart from the SHR, counter clockwise 4 degrees angled spot.Fig.25 shows mission mode changes. From 50 to 90 seconds, mode was vibrated because the high-level controller rejected the mode changing until the AUV located the proper position to modify the deadreckoning error. Fig.26 shows heading angle changes during the mission. About 90sec, the AUV reset the orientation +3.32 degree by the SHR.

Table 1 Dimensions and Instruments of Tri-Dog1

Length over all	1.85m
Breadth over all	0.58m
Depth	0.53m (0.90m include antennas)
Dry weight	170kg
Operating depth	100m max
Maximum speed	2knots
Duration	More than 2hours
Structures	Aluminum Pressure Hulls (Main Cylinder x1, Battery Cylinder x2)
Actuators	100W Thrusters x6 (Rotation, Amp. Feed back)
Processors	Intel Pentium MMX 233MHz x3 (High Level, Low Level, Vision)
Sensors	Attitude and Heading Reference System Doppler Velocity Log Electromagnetic Flow Meter Pressure Sensor (Depth Sensor) Real Time Kinematics GPS Acoustic Ranging Sensor x8 CCD Camera with Pan & Tilt Mechanism
Communications	Acoustic Command Link, Wireless LAN 430MHz Wireless Modem for RTK-GPS
Lights	24W Arc Lamp x2
Batteries	25.2V Ni-Cd Battery 20Ah x4

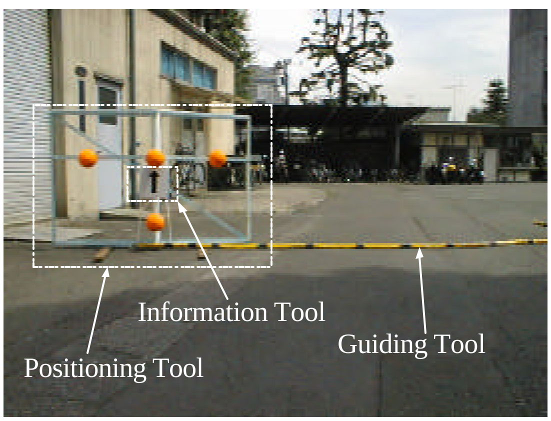


Fig.19 Experimental AUL

Fig.20 Intelligent AUV “Tri-Dog1”

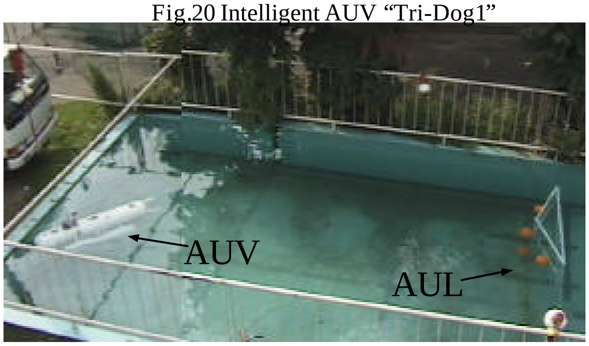


Fig.21 Underwater Experimental Environment

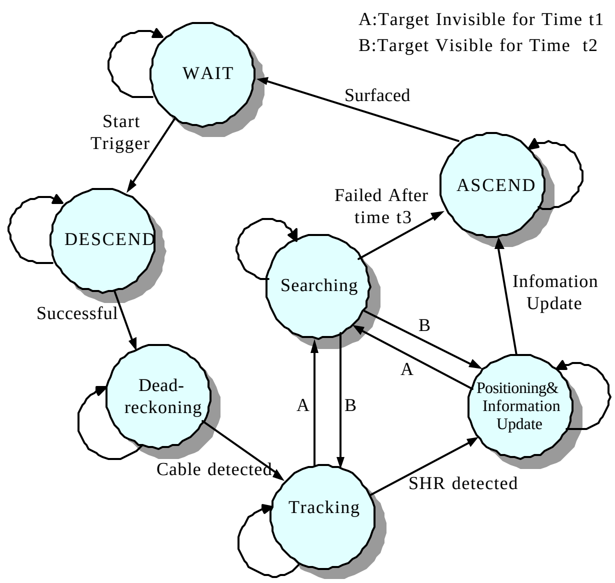
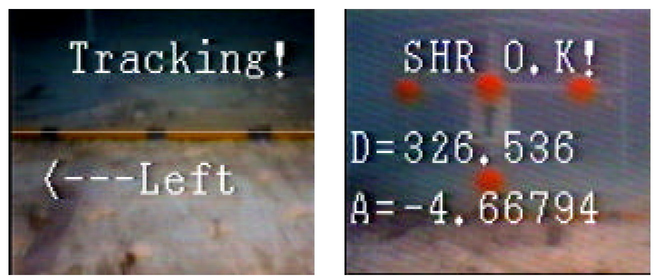


Fig.22 High Level Controller Strategy



(a) (b)

Fig.23 Experimental Result (Images by Tri-Dog1)

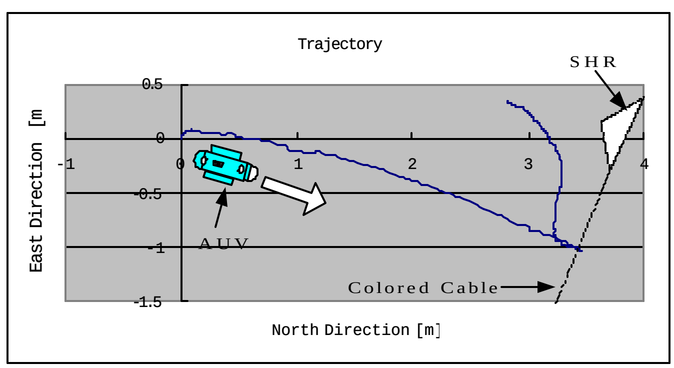
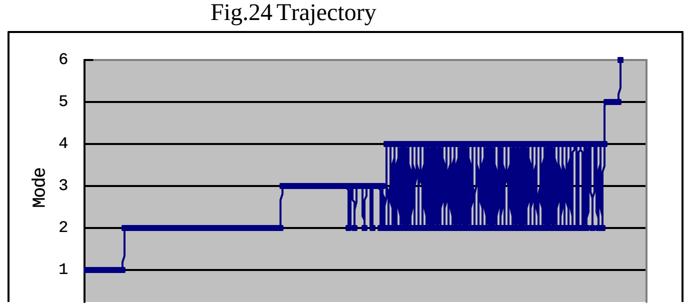


Fig.24 Trajectory



Mode 1: Descend Mode2:Deadreckoning Mode3:Cable Tracking Mode4:Positioing by SHR Mode5:Correction by SHR Mode6:Information ***Update***

Fig.25 Operation mode

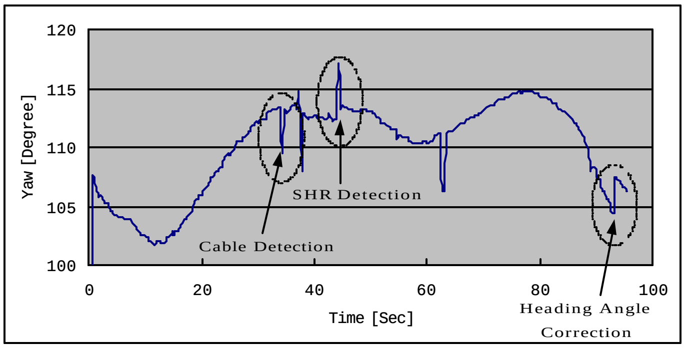


Fig.26 Heading Angle

6.CONCLUSION

This paper proposed the new navigation method for an AUV to investigate underwater structure or environment of shallow water. The AUV needs to make full use of the available sensor which has not utilized enough, to overcome the problems come from the limitation of the specific sensor.

The proposed navigation method refers two kinds of sensor; the position data from deadreckoning and the image data from CCD camera, for decision making of an AUV. It is important to integrate information of sensors for reliable decision policy of AUVs.

The proposed image processing strategy can reduce amounts of calculations for image processing such as, pre-processing an image to remove special underwater noises or enhancing stable edges to detect a target object. This strategy makes it possible to process underwater images in real-time with low computing power of small AUVs. limitations of small AUVs shuch as restricted computing power and lighting source should be considered to develope a practical vision system for AUVs.

Many factors affects on the reliability of vision system for AUVs. Not only improvement of image processing methods, but also improvement of the other factors such as the optimized design of target object, correct analysis of environment, efficient lighting method can encourage the reliability of vision system.

When the AUV need to modify the deadreckoning error by an AUL, it was carried out by 3 simple processes which use guiding tool, positioning tool and information tool. The proper combination of the simple and reliable processes enables the achievment of complex mission with high reliabliy to an AUV

Visual information is one of the most human-friendly information. Taking advantage of excellent compatiblity of visual AULs, they can provide various information for divers and ROV's pilots as well as an AUV.

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8.REFERENCE

[1]Japan Society of Naval Architecture Underwater System Division; "Underwater Technology", Seisandou -shoten Press, 1999.(in Japanese)

[2]Kazuo Aakuchi, Masahiro Tabata; "Fundamental of Oceanic Observation", Seisandoushoten Press, 1997.(in Japanese)

[3]H.Kondo, T.Ura S-C.Yu and Y.Nose; "Design of Autonomous Underwater Vehicles "Tri-Dog1"and Tank Tests", Proc.of Techno-Ocean2000 Int.Symp, Kobe, Japan, Nov.2000, pp.343-344.

[4] M. Kumagai, T. Ura, Y. Kuroda and R.Walker: "New AUV Design for Lake Environment Monitoring", Proc. of the 2000 Int. Symp. on Underwater Technology, Tokyo, pp.78 – 83, May. 2000.

[5]K.Asakawa, J,Kojima, Y.Kato and S.Matsumoto; "Autonomous Underwater Vehicle AQUA EXPLORER2 for Inspection of Underwater Cable", Proc.of Underwater Technology 2000, Tokyo, Japan, 2000, pp.242-247.

[6]B.A.A.P Balasuriya: "Computer Vision for Autonomous Underwater Vehicle Navigation", Doctoral Thesis, the University of Tokyo, Apr. 1998.

[7]K.Inoue; "Global Static Analysis System for Mega-Float ", Proceedings of 16th Int. Conf. on Offshore Mechanics and Arctic Eng.97, Vol.1A,pp.77-84,1997.

[8]Japan Acoustic Society;"Accoustic Handbook",Maruzen Press, 1999.(in Japanese)

[9]Josko. A. Catipovic; "Performance Limitaions in Underwater Acoustic Telemetry",IEEE J.of Oceanic Eng.Vol.15, No.3, July,1990,pp.205-216.

[10]J.M.Thorleifson,LCdr.T.C.Davies,M.R.Black,D.A.Hop

kin and R.I.Verrall;"The Theseus Autonomous Underwater Vehicle A Canadian Success Story",Proc. of MTS/IEEE OCEANS 97,Canada,1997, pp.1001-1006.
[11]Mikael Bliksted Larsen; "High Performance Doppler-Inertial Navigation-Experimental Results" Proc. of MTS/IEEE OCEANS 2000, Providence, Sep. 2000, pp.1449-1455.
[12] T.Ura, T. Obara, K. Nagahashi, K. Nakane, S. Sakai, Y. Oyabu, T. Sakamaki, S.Takagawa,H. Kawano, T. Gamo, M.Takano, T.Doi; "Exploration of Teisi Knoll by Autonomous Underwater Vehicle "R-One Robot" Marine Observation Technology ,To be appeared .(in Japanese).
[13]Son-Cheol Yu, Tamaki Ura and Teruo Fujii:"Utilization of Artificial Signboard Landmarks for Navigation of Advanced Autonomous Underwater Vehicle", Int.Conf. of Robot. ,Contr. And Vision 2000, , invited section, Singapore,Dec. 2000. CD-ROM 459.
[14]Son-Cheol YU: "Navigation of Autonomous Underwater Vehicles by Artificial Underwater Landmarks", Master Thesis ,Dept.of Environmental and Ocean Eng. Univ. of Tokyo,Sep.2000.(in Japanese)
[15]Jules S.Jaffe,:"Computer Modeling and the Design of Optimal Underwater Imaging System",IEEE J. of Oceanic Eng. Vol.15,No.2,1990,pp.101-111.
[16] Nuno Gracias and Jose Santos-Victor;"Underwater Video Mosaic as Visual Navigation Maps",J.of Computer Vision and Image Understanding, No.79, 2000, pp.66-91.
[17]A.Wettergreen,C.Gaskett,A.Zelinsky;"Development of a Visually-Guided Autonomous Underwater Vehicle ",Proc. of IEEE/MTS OCEANS'98,Nice,France,Sep.1998.pp.1200-1204.
[18]Jose.F.Zelasco;"Computer Vision in AUV's:Automatic Roto-Rectification of Streo Images",MTS/IEEE OCEANS 2000,Providence,Sep. 2000,pp.2169-2176.
[19]E. Trucco, Y. Petillot, I. Tena Ruiz, C. Plakas, D. M. Lane;"Feature Tracking in Video and Sonar Subsea Sequences with Applications",Computer Vision and Image Understanding,Issue 79,2000,pp.92-122.
[20]G.L.Foresti,S.Gentili and M.Zampato;"A Vision-Based System for Autonomous Underwater Vehicle Navigation" ,Proc.of IEEE/MTS OCEANS98, Nice, France, Sep.1998,pp.195-199.
[21]B.A.A.P Balauriya, Tamaki Ura:"Vision Based Object Following for Underwater Vehicles (Part2: collaborative control with pan and tilt camera mechanism)", Journal of the Society of Naval Architects of Japan,Vol.182,Dec. 1998.
[22]B.A.A.P. Balasuriya, Tamaki Ura:"Multi-Sensor Fusion for Autonomous Underwater Cable Tracking",Proc. of OCEANS99 IEEE/MTS, Seattle , pp.209-215, Sep. 1999.
[23]Tamaki Ura Shinichi Takagawa;"Underwater Robotics", Seisandoushoten Press,1994.pp.310.(in Japanese)
[24]Yasumasa Kobayashi;"Underwater Photo Handbooks", Tokai University Press,1996.(in Japanese)
[25]David Sisman;"The professional diver's handbook", submex,U.K,1982.
[26]T.Arai, H.Kirara, K.Maeta, J.Ota and K.Umehara, "Development of Real-time Position / Orientation Measuring System for Multiple Mobile Robot System", Journal of Robotics Society of Japan Vol. 12 No.3,1994,pp.472-478. (in Japanese)
[27] J.Ota,M.Yamato,K.Ikeda,Y.Aiyama and T.Arai; "Evironmental Support Method for Mobil Manipulators using Visual Marks with Memory Storage", Journal of Robotics Society of Japan ,Vol.17 No.5 pp.66-72,1999.(in Japanese)
[28]S-C Yu,T. Ura and T.Fujii:"Underwater Navigation using Artificial Underwater Landmark",Proc.of 15th Ocean Eng. Symp.,Tokyo,2000, pp.317-324. (in Japanese)