FULLY AUTONOMOUS OBSERVATION OF BREAKWATERS BY AN AUV AT KAMAISHI BAY

Hayato Kondo\textsuperscript{1}, Toshihiro Maki\textsuperscript{2}, Tamaki Ura\textsuperscript{2}, Takashi Sakamaki\textsuperscript{2}, Masaaki Inaishi\textsuperscript{1}

\textsuperscript{1}Tokyo University of Marine Science and Technology  
2-1-6, Etchujima, Koto, Tokyo, 135-8533, Japan  
{hkondo, inaishi}@e.kaiyodai.ac.jp

\textsuperscript{2}Institute of Industrial Science, The University of Tokyo  
4-6-1, Komaba, Meguro, Tokyo, 153-8505, Japan  
{maki, ura, sakamaki}@iis.u-tokyo.ac.jp

Abstract- This paper proposes a robust navigation method for Autonomous Underwater Vehicles (AUVs) operating around structures such as harbors and breakwaters. This method consists of a state estimator and a motion controller, enabling localization in the configuration map as well as following pre-given waypoints without any external help. The state estimator is based on a “particle filter” where the vehicle’s state, horizontal position and heading, is stochastically updated in real time using multi-sensor data. This method was actually implemented to a testbed AUV “Tri-Dog 1” and a series of sea trials were carried out around breakwater caissons at the mouth of Kamaishi bay in Japan. This is the first time an AUV has succeeded in fully autonomous observation around breakwater caissons. Mosaics of the foot protection blocks, rock mound and caisson’s surface are made from the observed images based on the estimated state of the AUV, to verify the performance of the method.

I. INTRODUCTION

Condition survey of artificial underwater structures such as harbor constructions, installations of offshore oilfields and ship hulls is very important for maintenance, search-and-rescue, scientific investigation and counterterrorism. Although divers and ROVs (Remotely Operated Vehicles) are playing an important role on this work [1 - 3], they have some inherent shortcomings. Divers work is a dangerous condition and can not reach great depth. ROVs require an umbilical cable that restricts their range and mobility.

AUVs can operate without an umbilical cable and the demand for AUVs that can undertake such missions is increasing. The most challenging hurdle to overcome is localization. GPS cannot be used underwater as transmissibility of radio waves is limited, so acoustic method such as Long Base Line (LBL), Short Base Line (SBL) and Super Short Base Line (SSBL) is often used. However, acoustic localization requires external landmarks and is not suitable for operations around structures, where problems such as multipath and acoustic shadow are unavoidable. At the same time, there is no comprehensive applicable solution to error accumulation when dead reckoning using DVL (Doppler Velocity Log) and INS (Inertial Navigation System). Structure based localization methods are proposed for some applications [4, 5]. Although they need no external help like acoustic transponders, they are not robust against noise since they are single-sensor systems. An oceangoing AUV must cope with various types of unexpected conditions under which single-sensor systems easily fail. The need of multi-sen-
Sor fusion is highlighted and some attempts are made with limited success [6 - 8].

We proposed a fusion based localization scheme to develop a practical navigation method for an AUV working around artificial structures, and the performance of the method was verified through tank trials [9], using a testbed AUV “Tri-Dog 1” [10]. The method utilizes a probabilistic approach called “particle filter” [11, 12] and enables an AUV to localize itself in real time and follow pre-set waypoints without any external help, referring to sensory data and the map of the environment where the AUV is deployed. Although application of the particle filter for AUV navigation has already been proposed [13], there seems to be no reported example of an AUV using a particle filter.

To verify practical availability of the method, sea trials were carried out around breakwater caissons of Kamaishi bay, Iwate Prefecture in Japan (see Fig. 1). Condition surveys of the caisson’s surface, foot protection blocks and rock mound are important for construction, maintenance and disaster-relief. The AUV “Tri-Dog 1” carried out practical observations. This paper reports the results of the sea trials, to evaluate the practical performance of the method.

II. AUTONOMOUS NAVIGATION METHOD

The method consists of two parts, the State Estimator and the Motion Controller as shown in Fig. 2. The State Estimator estimates the state of the AUV;

\[ x = \{ r, \psi \} \]  

(1)

using onboard sensors and environmental map \( M \), where \( r \) and \( \psi \) represent the horizontal position \( [x, y]^T \) and heading angle respectively. There is no need to estimate roll angle \( \theta \), pitch angle \( \phi \) and depth \( z \) as they can be precisely measured by onboard sensors. The Motion Controller outputs the control reference \( R \) to follow the observation path \( W \), using the estimated state \( x \) and the map \( M \).

The map \( M \) is given as a set of segments \( \{ m_1, m_2, ..., m_n \} \) and the observation path \( W \) is defined as a set of waypoints \( \{ w_1, w_2, ..., w_n \} \) as shown in Fig. 3. The control reference \( R \) consists of surge velocity \( u \), sway velocity \( v \), heading angular velocity \( \omega \) and depth \( z \).

A. State Estimator

Localization of an AUV should be treated as a stochastic state estimation problem, for every sensor measurement has random error. The particle filter is a powerful method that determines the probability density function of AUV’s state \( p(x) \), described by \( N \) samples

\[ S = \{ s^1, s^2, ..., s^N \} \]  

(2)

which are assumed to be randomly drawn from \( p(x) \).

The state at the time \( t \) is described by an average of the samples:

\[ x_t = \frac{\sum_{j=1}^{N} s^j_t}{N} \]  

(3)

The samples are updated recursively for each successive time step through the prediction phase and the observation phase.

1) Prediction Phase: During the prediction phase, the sample set \( S_{t-1} \) is moved to \( S'_t \) in accordance with the action
where \( A_2 \) is a two-dimensional rotating matrix.

The samples diffuse in time and this diffusion represents dead reckoning error. The standard deviation \( \sigma_r \) and \( \sigma_\psi \) are estimated with due consideration to the sensor specifications.

2) Observation Phase: The set \( S_t \) is obtained from \( S_t' \) by referring to the observation \( O_t \), which is a set of positions of detected objects in the vehicle coordinates as shown in Fig. 4.

Each sample \( s_t'^i \) of the set \( S_t' \) is weighted and re-sampled so that they are distributed in proportion to the likelihood \( L(O_t | s_t'^i, M) \). The re-sampled set results in \( S_t \) that indicates the probability distribution function \( p(x_t | x_{t-1}, a_{t-1}, O_t, M) \).

Now we consider the specific sample \( s_t'^k \), omitting suffixes \( k \) and \( t \). Assuming that the observation \( O \) consists of \( n \) points \( o^1, o^2, \ldots, o^n \),

\[
L(O) = L(o^1) L(o^2) \ldots L(o^n) \tag{9}
\]

is derived for each point is regarded as independent. As sensor error can be described as Gaussian distributions in general, the likelihood of the point \( o^i \) can be determined as follows using the shortest distance \( d \) between \( o^i \) and the map \( M \) as shown in Fig. 4:

\[
L(o^i | s_t'^i, M) = f(d, \sigma) \tag{10}
\]

where \( f(x, \sigma) \) is distribution function:

\[
f(x, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{x^2}{2\sigma^2}} \tag{11}
\]

There are concerns about serious error that result in a non-Gaussian distribution. For example, floating particles, debris and underwater creatures may disturb sensor measurements. Acoustic noise such as multipath, as well as large angle of incident, interferes measurement by sonar. To treat these errors correctly, the error coefficient \( e \) is introduced and Eq.10 is applied only when all of the following conditions were satisfied,

i) The segments of the map \( M \) must be measured from correct side.
ii) There must be no segments between the measured point and the sensor.
iii) The shortest distance \( d \) must be explained by a Gaussian, i.e. \( d < e \sigma \).

iv) The incident angle must be less than certain threshold (for sonar).

Otherwise,

\[
L(o', s, M) = f(e \sigma, \sigma)
\]

(12)

is applied. \( \sigma \) is determined considering sensor accuracy \( \sigma_s \) and uncertainty of the map \( \sigma_m \).

B. Motion Controller

Motion Controller generates control reference to follow the observation path, as well as managing the entire mission. When the sample set \( S' \) is well concentrated, the estimated \( \hat{x} \) is regarded as an actual state and the Motion Controller orders AUV to move. The aim of motion control is to zero the error \( dx, dy \) and \( d\psi \) shown in Fig. 5. Reference \( R = \{u, v, \omega, z\} \) is calculated using the following equations where \( \psi_{\text{max}} \) is a threshold value to switch both surge and sway control modes.

\[
g(x, a, b) = \begin{cases} 
  b & (\frac{b}{a} < x) \\
  ax & (-\frac{b}{a} \leq x \leq \frac{b}{a}) \\
  -b & (x < -\frac{b}{a}) 
\end{cases}
\]

(13)

\[
\text{if} \quad |d\psi| > \psi_{\text{max}}
\]

\[
R = \{0, 0, g(d\psi, a_y, b_y), z_i\}
\]

(14)

\[
\text{else}
\]

\[
R = \{g(dx, a_x, b_x), g(dy, a_y, b_y), g(d\psi, a_\psi, b_\psi), z_i\}
\]

(15)

The AUV surfaces upon passing all the waypoints.

III. IMPLEMENTATION

The proposed method is implemented in the test bed AUV “Tri-Dog 1” (see Fig. 6). The specifications of the vehicle are shown in Table 1. Six thrusters independently control surge, sway, heave and yaw motion.

A. State Sensors

Two state sensors are used to calculate the action \( a \) in Eq.4. The Fiber Optical Gyro (FOG) measures heading angle and rate, and the Doppler Velocity Log (DVL) reads ground speed. The AUV also has Attitude Heading Reference System (AHRS) and depth meter for motion compensation and navigation.
B. Perception Sensors

The AUV has four obstacle avoidance sonars (OA1 to OA4), one profiling sonar (PS) and one light-section ranging system (LS) to acquire observation $O$, as shown in Fig. 7.

Directivity of the obstacle avoidance sonars is about 20deg and its resolution is 0.01m. Coverage is set to be 5m for the experiment. Frequency of sampling is 4Hz.

The profiling sonar has directivity of about 2deg with a resolution of 0.01m. It mechanically scans 360deg on a horizontal plane with a step size of 2.4deg. Coverage is set to be 40m and rotation period is about 17sec.

The light-section profiling system consists of a TV camera and a sheet laser device, providing continuous shape of target structures by light-sectioning. The authors proposed this system for AUV navigation and bathymetry mapping, and the performance has been verified though tank trials [14, 15]. The resolution within a 2m range is of millimeter order. It can provide simultaneously range data on a horizontal plane within 40deg at once with a frequency 5Hz. Coverage is set to be 3m.

C. Observation Instruments

There are three TV cameras (Cam1, Cam2, Cam3) onboard. Cam1 is mounted on AUV’s nose directing forward, Cam2 is on its left. Cam3 is mounted on its bottom looking forward with 55deg depression. As well as being an observation tool Cam2 is also a component of LS and to enhance its performance it is mounted with 20deg elevation. There is another sheet laser device on AUV’s nose, looking downward with the laser plane orthogonal to surge direction for bathymetry mapping. Its footprints are extracted from images of Cam3 by post processing.

IV. EXPERIMENTS

Experiments were carried out at the breakwaters of Kamaishi Bay, Iwate Prefecture in Japan. The experimental zone is shown in Fig. 8. Concrete caissons have a length of 30m and are mounted on the rock mound. The depth of rock mound is about 20m and there are foot protection blocks with a horizontal face $5m \times 2.5m$ laid along with the caissons as shown in Fig. 9.

A. Mission

Considering the practical application, two missions were planned. The observation path of each mission is shown in Figs. 10 and 11 by the circles 1 to 20 with the radius 0.5m. The environmental map $M$ is given as the surface of the caissons No.22 to 24 as shown in Fig. 10.

Fig. 8. Breakwaters at the mouth of Kamaishi bay.

Fig. 9. Configuration of the breakwaters.

Fig. 10. Way points for the Mission 1: Bottom survey.

Fig. 11. Way points for the Mission 2: Wall survey.
by the circles M1 to M10. The map coordinate is also shown in Fig. 10.

1) Mission 1 (Bottom Survey): The AUV observes the foot protection blocks and rock mound, maintaining a constant depth of 17.5m. The entire length of the path is about 211m. Mosaic and bathymetry map are made from images of Cam3 by post processing.

2) Mission 2 (Wall Survey): The AUV observes the surface of caisson No. 23. The AUV takes images of the surface by Cam2, traveling along with runs at multiple depth (18m, 15m, 12m, 9m). The entire length of the path is about 298m.

B. Procedure

The AUV starts descending after being guided to the start area via wireless LAN. Upon reaching a depth of 2m, she initializes the particle filter and waits for the samples to concentrate. She then starts to track the observation path. The entire mission is carried out in full autonomy and there is no underwater communication. A diver follows her to take pictures of her and to restrain her in case she goes out of control. She surfaces and exits from autonomous mode after passing all the waypoints or if she decides it is impossible to continue the mission.

The number of samples N is 500 with the update frequency 5Hz. The maximum surge speed \( \dot{b}_s \) at Eq.15 is 0.2m/s.

C. Results

1) Mission 1: The AUV succeeded in fully autonomous operation of 1049sec, with a distance traveled of 166m although she terminated the mission just after passing w12 because of low altitude (less than 0.5m). Fig. 12 shows the estimated trajectory and Fig. 1 is her picture during the mission.

The mosaic of the bottom is shown in Fig.13 with a 5m × 5m grid superimposed. The distributions, shape and color of each rock and foot protection block can be observed. The mosaic is made considering not pictorial correlation but the estimated state and sensory data. It follows that the estimated state has enough quality for practical application.

2) Mission 2: The AUV passed the final waypoint w20 in 1423sec and completed the mission. Fig. 14 shows the estimated trajectory. The mosaic of the caisson’s surface was made with the images of Cam2 as shown in Fig. 15. This mosaic was also made in the same way for Fig. 13. The distribution of attached organism and surface condition can be seen over the entire wall. The leftmost white...
line indicates the edge of the caisson (Y = 0), so position error in Y direction is found to be between 10cm and 20cm, compared to the mosaic.

V. CONCLUSIONS

This paper proposed a fusion based navigation method for an AUV operating around artificial structures. It realizes independent and robust navigation with environmental map and waypoints given. The method was implemented to the AUV “Tri-Dog 1” and experiments were carried out around breakwater caissons of Kamaishi Bay, Iwate Prefecture in Japan. The AUV succeeded in fully autonomous, independent operation, taking detailed images of the bottom and the caisson’s surface. Mosaics of bottom features and caisson’s surface were made over the entire covered area forming a detailed map of them. Thus, it can be concluded that this method is practically available.

ACKNOWLEDGMENT

This project is supported by The Service Center of Port Engineering (SCOPE) and Japan Society for the Promotion of Science (JSPS). The experiments were done as a part of joint project with The Port and Airport Research Institute (PARI). The authors would like to thank Kamaishi Port Construction Office -Tohoku Regional Development Bureau -Ministry of Land, Infrastructure and Transport, TOA CORPORATION, Kamaishi Ocean Development Ltd., and International Coastal Research Center -Ocean Research Institute -The University of Tokyo for providing us an opportunity and support of the sea trials. The authors would also like to thank Dr. Arjuna Balasuriya and Mr. Bharath Kalyan of Nanyang Technological University for their cooperation.

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