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Development of an autonomous surface vehicle for monitoring underwater vehicles

Takeshi Nakatani, Tadahiro Hyakudome, Takao Sawa, Yoshiyuki Nakano,
Yoshitaka Watanabe, Tatsuya Fukuda, Hiroshi Matsumoto, Ryotaro Suga, and Hiroshi Yoshida

Marine Technology and Engineering Center (MARITEC)
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
2-15 Natsushima-cho, Yokosuka 237-0061 Japan E-mail: tnakatani@jamstec.go.jp

***Abstract*— JAMSTEC has developed and operated several AUVs (Autonomous Underwater Vehicle) as platform for scientific investigation and explorations of seabed mineral resources [1-4]. Conventionally, a support vessel monitors only one AUV during its whole dive for safety and positioning. We propose an operation of multiple AUVs using an ASV (Autonomous Surface Vehicle) to improve survey efficiency. For this purpose, JAMSTEC has been developing an ASV "MAINAMI" with a length of 6 meters since 2013. It has a diesel engine, two thrusters and a rudder. The vehicle is equipped with an acoustic communication device and a satellite one, in order to relay information between an AUV and operators on a ship or on land.**

Keywords—ASV; AUV; multi-vehicle operation

I. Introduction

AUV is a powerful platform for scientific investigation and explorations of seabed mineral resources. JAMSTEC has developed and operated several AUVs; e.g., Urashima[1], Jinbei[2], and Yumeiruka[4].

Conventionally, a support vessel monitors only one AUV during its whole dive for safety and positioning. AUV cruises a predefined route autonomously. However, the AUV may make an emergency surfacing or lose its way according to a unexpected system failure. Furthermore, it is difficult to keep high-accuracy positioning on its own, because GPS is not available underwater. Therefore, the vessel tracks and communicates with the AUV to monitor the status and inform SSBL's positioning information.

ASV (Autonomous Surface Vehicle) is one of solutions to improve the survey efficiency (German, 2012) [5]. Instead of a vessel, an ASV tracks an AUV and relay information between the AUV and operators on a ship. We propose an operation system of multiple AUVs using an ASV[6]. Fig.2 shows our concept. In this paper, we explain a newly developed ASV "MAINAMI" and a tracking method based on a probabilistic positioning.

II. ASV "MAINAMI"

A. Vehicle

JAMSETEC has been developing an ASV "MAINAMI" with a length of 6 meters and a weight of 3 tons. The appearance, general arrangement, specification of the vehicle are shown in Fig.1, Fig.3, and Table 1, respectively. The vehicle has a keel along the bottom that keeps it steady.

The main purpose is tracking of an AUV. In the design, we assume that an AUV cruises at a speed of 2knots. And, its operation depth is from a few hundred to 3,000 meters. We plan to operate 3,000 m class AUV "Jinbei" or "Yumeiruka".

The ASV has a diesel engine, two electric thrusters and a rudder. The maximum speed is 5 knots so that the vehicle can track an AUV against a current. The capacity of the engine's output is 11.5kW with AC240V. The vehicle's endurance is 48hours at 2knots. The volume of oil tank is 100 litters.

As main navigation device, the vehicle has a GPS satellite compass, Furuno SC-50. The compass has 3 GPS antennas and calculates its heading based on phase difference of the GPS signals. The accuracy of heading is 0.5 degree RMS. Additionally, the vehicle has an anemovane and an ADCP to measure environmental disturbance.

Fig. 1. Autonoumos Surface Vehicle "MAINAMI".

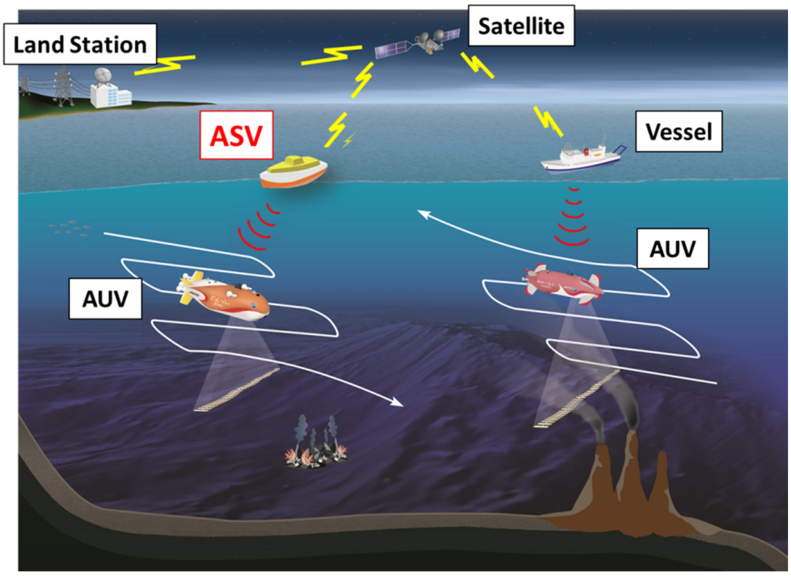

Fig. 2. A multi-vehicle operation system using an ASV and a satellite communication.

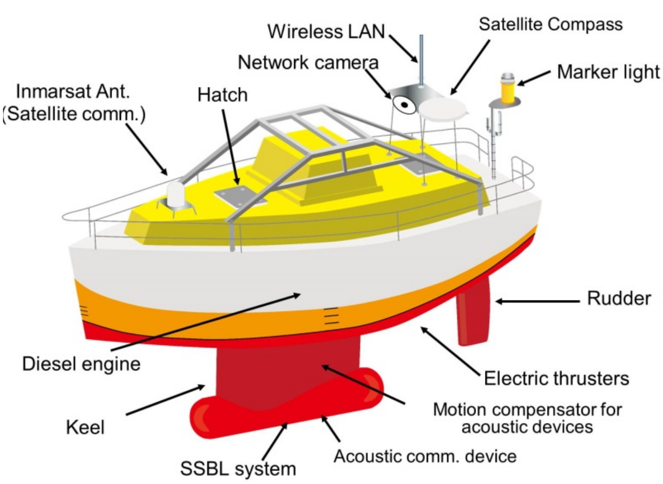

Fig. 3. General arrangement of the ASV "MAINAMI".

TABLE I. SPECIFICATION OF ASV "MAINAMI"

Size	6.0m(L)×2.6m(W)×3.2m(H)
Weight	3 ton
Max. Speed	5 knots (2knots@cruising speed)
Duration	48 hours
Actuators	Thrusters × 2 Rudder
Power	Diesel engine Lead battery
Communication	Acoustic comm., Satellite comm., Wireless LAN
Control unit	Distributed CPU system
OS	Linux

The vehicle has an acoustic device for communication with an AUV and a SSBL system for position measurement of the AUV. We arrange the devices in the keel to keep away from noise sources, i.e. the diesel engine and the thrusters. A motion compensator stabilizes attitude angles and heave motion of the acoustic devices[7].

Fig. 4. ASV "MAINAMI" on R/V KAIYO at Sagami-Bay.

For communication with an operator on support vessel or on land, the vehicle is equipped with wireless LAN, VHF, Iridium and Inmarsat. We use the different means according to the communication distance; wireless LAN up to 1-2 km, VHF up to 10km, and satellite any more. In operation, the communication helps safety operation of the vehicles. We can monitor their status and video image of a network camera mounted on the ASV in real-time. And, we can send a command to the AUV as well as the ASV.

B. Sea-trial at Sagami-Bay (Only ASV)

During KY15-E01 cruise in February 2015, we launched the ASV at Sagami bay. Fig.4 was taken on R/V KAIYO. The ASV was deployed by the A-frame crane. We succeeded in remote control of the ASV by a wireless LAN as well as by Inmarsat. The distance between R/V and the ASV was up to 1.5 km. Through the experiments, we verified the hardware / software systems of the vehicle, especially wireless communications and motion performances.

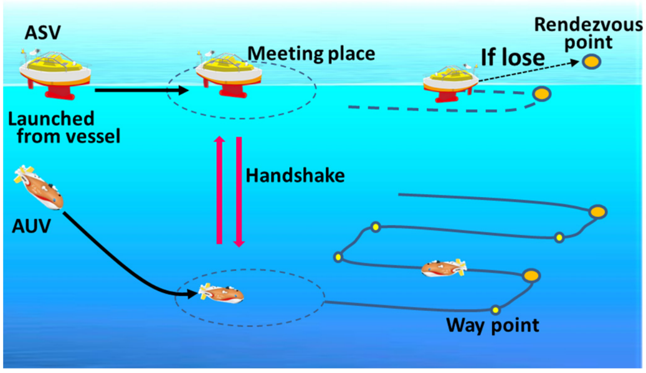

Fig. 5. A stratey of an AUV tracking.

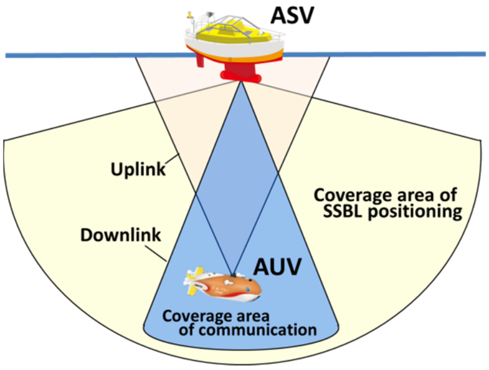

Fig. 6. Coverage areas of acoustic communication and SSBL positioning

III. AUV Tracking Method

Our concept is tracking control rather than cooperative control. AUV cruises its route independently and ASV tracks the AUV, except at start and in case of emergency. The relationship of ASV-AUV is similar to conventional one of support vessel - AUV. In order to realize autonomous tracking, ASV have to understand environmental situation, estimate AUV's position, and take action in real-time.

A. Strategy

The tracking strategy consists of several steps as shown in Fig.5. Firstly, ASV and AUV are launched from a vessel at survey area. Secondly, the vehicles reach to a meeting place and wait respectively. Then ASV confirms the state of SSBL positioning, acoustic communication, and AUV's navigation. And ASV sends commands of position update and the start of a cruise. Next, AUV cruises a pre-defined route and ASV tracks the AUV based on its estimated position.

In the pre-defined route, there are some rendezvous points. When ASV loses AUV's position for a certain period, ASV goes to a next rendezvous point and waits for AUV. On the other, AUV continues the cruise as scheduled before the vehicle reaches to the rendezvous point. At the rendezvous points, ASV and AUV confirm the existence each other. The vehicles don't restart unless without the confirmation.

Coverage areas of SSBL and communication are illustrated in Fig.6. In this paper, the communication from AUV to ASV

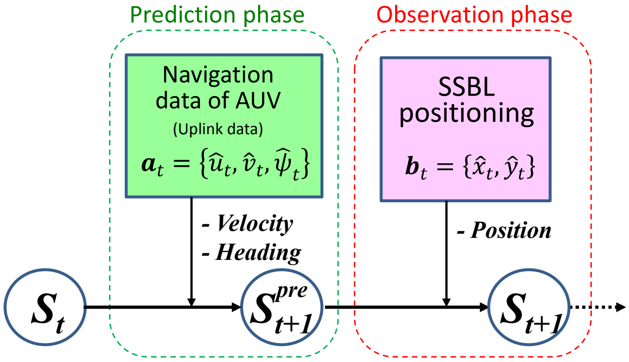

Fig. 7. Computation flow of particle filter. The state of AUV is updated recursively through the prediction phase and observation phase.

is defined as uplink. One from ASV to AUV is defined as downlink. Normally, an acoustic communication device has directionality to ensure S/N ratio. The coverage area is proportionate to the depth of AUV. Therefore, condition of tracking is more difficult with smaller coverage area when AUV cruises more shallowly.

B. Localization of AUV position

For tracking, ASV should estimate AUV's state in real-time. ASV obtains information of AUV's state through SSBL system and uplink communication. AUV position is measured by SSBL positioning system. Navigation data of AUV, e.g. attitude, speed and depth, are measured by on-board sensors such as INS, DVL and depth sensor. And ASV receives the AUV navigation data through acoustic uplink communication.

Our method is based on a stochastic approach called the Particle Filter [8]. The measurements are fused by particle filter, in order to realize stable estimation robust against sensor noises and lack of measurements.

The filter is an implementation of the Bayesian filter. The probability density of a state by a set of samples(particles). The filter has the following advantages;

- suitable for non-liner, non-Gaussian state estimation problems.
- capable of concentrating the computational load on areas with high probability density.
- capable of adjusting the computational complexity by varying the number of particles.

Some navigation algorithms based on particle filter for underwater vehicles have been proposed and implemented[9-11]. This section describes our implementation of the particle filter.

The filter represents probability density function of the AUV's state at time t through the particles as follows;

$$p(\boldsymbol{s}_t) \cong S_t = \{\boldsymbol{s}_t^i | i = 1, \cdots n\}, \quad (1)$$

$$\boldsymbol{s}_t^i = \{\boldsymbol{x}_t^i, \boldsymbol{v}_t^i, \psi_t^i\}, \quad (2)$$

$$\boldsymbol{x}_t^i = \{x_t^i, y_t^i\}, \quad (3)$$

$$\boldsymbol{v}_t^i = \{u_t^i, v_t^i\}, \quad (4)$$

TABLE II. EXPERIMENTAL PARMETERS OF SIMULATION

AUV		
Surge velocity	u_{ref}	1.0 m/sec
Depth		3,000 m
Paticle Filter SETTING		
Time step		1 sec
Number of samples	n	500
Initial state ($\mathbf{x}$)		(-42.4, -42.4) m
Initial state (1σ)		60 m
Interval time of SSBL		8 sec
Interval time of uplink		8 sec
Mesurement error model(1σ)		
- Speed (u, v)	σ_{a1}	0.05 m/sec
- Heading (Ψ)	σ_{a2}	0.3 deg
- SSBL (x,y)	σ_b	60 m

where $\boldsymbol{s}_t^i$ is i -th particle and n is the number of particles. The state is updated recursively through the prediction phase and observation phase as shown in Fig.7. When there is no observation data, the observation phase is skipped.

1) Prediction phase

The particles are moved based on navigation data $\boldsymbol{a}_t$, in accordance with vehicle's motion as follows:

$$\boldsymbol{s}^{pre}{}_{t+1}^{i} = F\left(\boldsymbol{s}_t^i, \boldsymbol{a}_t, N(0,\sigma_a^2)\right), \tag{5}$$

$$\boldsymbol{a}_t = \{\hat{u}_t, \hat{v}_t, \hat{\psi}_t\}, \tag{6}$$

where function F represents the vehicle motion model and $N(\mu,\sigma^2)$ is Gaussian noise with mean μ and variance σ^2. A symbol ^ means a sensor measurement. The new state S_{t+1}^{pre} is obtained by applying Eq. 5 to each of particles independently.

ASV receives AUV data through uplink communication. Therefore, the navigation data of AUV is available at intervals on-site. When there is no navigation data at a time step, the vehicle motion is calculated with no aiding in accordance with a simple motion dynamics.

2) Observation phase

A particle likelihood $L(\boldsymbol{s}^i)$ is calculated as follows:

$$L(\boldsymbol{s}^i) = \frac{1}{\sqrt{2\pi}\sigma_b} exp\left(-\frac{{d^i}^2}{2\sigma_b^2}\right), \tag{7}$$

$$d^i = \left|\boldsymbol{x}^i - \hat{\boldsymbol{x}}\right|, \tag{8}$$

where σ_b is standard deviation of SSBL measurement error and d^i is Euclidean distance between points of i -th particle and SSBL measurement.

According to the likelihood obtained by eq.7, each particle is resampled to form S_{t+1}.

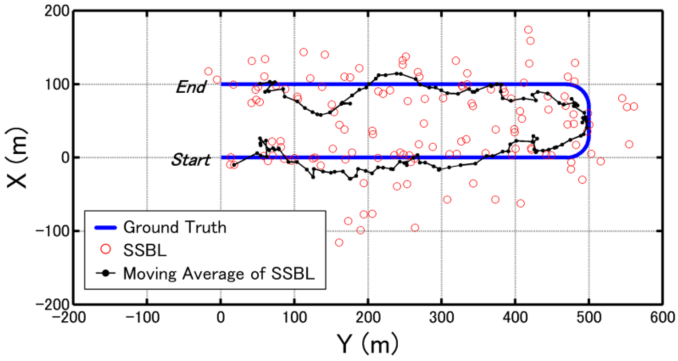

Fig. 8. Estimated trajectory by moving average of SSBL. Each mearement of SSBL is shown by a red cricle. The black line shows the moving average of 10 SSBL measuments. The blue line shows the ground truth of AUV trajectory.

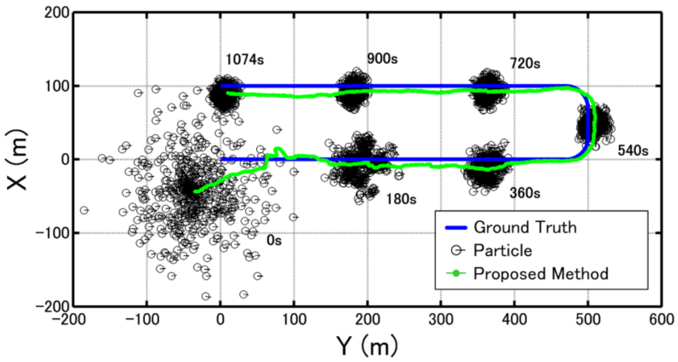

Fig. 9. Estimated trajectory by proposed method . The green line shows the result of the particle filter. Particles are shown by black circles at every 180 seconds. The arrow of the black circle corresponds the heading of the particle.

IV. PERFORMANCE ANALYSIS

A. Condition

The performance of the proposed method is verified through simulations. Table II shows an experimental parameter of a simulation. We assumed that an AUV cruises on a route at 2knots and at a depth of 3,000m. The route consists of two 500m survey lines.

The accuracy of SSBL positioning is 2 % of depth, or 60m. The intervals of SSBL and uplink communication are 8 seconds respectively.

The number of particles is 500. At the beginning of the localization, a 60m error was added to the estimated position of the AUV, to simulate the positioning inaccuracy.

B. Result and Discussion

Figs. 8-9 show results of a typical simulation. The trajectory estimated by proposed method is more smooth and higher accuracy than one by moving average of SSBL.

Fig. 10 shows the positioning accuracy and the standard deviations of the particles. Although the filter was initialized with a 60m error, the positioning accuracy improves to 15m of

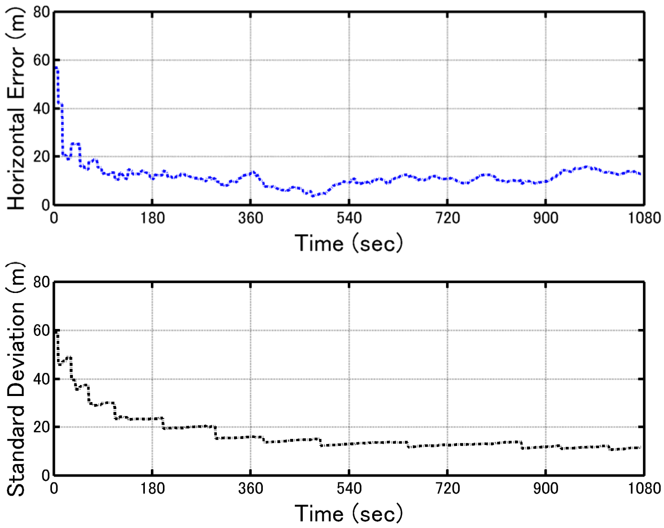

Fig. 10. The positioning accuracy of proposed method. The error and standard deciation are the result of the simulation shown in Fig.9.

the true position, in 100m distance travelled at 2knots, or 100 sec. The accuracy corresponds 0.5% of the 3000m depth.

V. Conclusion

In this paper, we proposed an operation of multiple AUVs using an ASV to improve survey efficiency. And, we explained a newly developed ASV "MAINAMI" and a AUV tracking method. One of key technology is a positioning method using a particle filter to estimate AUV's position in real-time. The method integrates navigation data of AUV and SSBL positioning as input data stochastically. The performance of the method was verified through simulations.

The tracking method will be implemented on ASV "MAINAMI". In near future, we will complete the implementation and carry sea trials that the ASV tracks an AUV.

Acknowledgment

This work was supported by Cross-ministerial Strategic Innovation Promotion Program (SIP) of Government of Japan. The authors would like to thank crew of R/V KAIYO for their help during the cruise.

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