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Primary Experimental Results of the Navigation Method of Multiple Autonomous Underwater Vehicles

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Abstract—We report the first experimental results of the navigation method of multiple Autonomous Underwater Vehicles (AUVs) for wide seafloor surveys proposed by us in our previous reports. The key idea of the proposed method is that moving AUVs estimate their states (horizontal position and heading angle) based on AUVs remaining stationary on the seafloor (landmark AUVs), alternating between these roles to expand the observational coverage. Moving AUVs land on the seafloor and transmit compressed information about their estimated states to the landmark AUVs when they change the roles. Sea trials were carried out using two AUVs to evaluate the performance of this method. One is the AUV Tri-Dog 1 (TD) which can move and estimate the states and the other is a Dummy AUV (DA) which cannot move but can estimate the states. In the experiments, TD and DA alternatively estimated the states. To evaluate the positioning accuracy of the proposed method, the states were recalculated based on sensor data obtained at sea trials in post processing. As a result, positioning errors of the proposed method were estimated to be smaller than dead reckoning. The Errors were found to be about 0.4 m in horizontal position and about 1.5 degree in heading angle. The method demonstrated to be successful in stable positioning with AUVs alternating between the moving role and the landmark role. Future works include the verification of the method using two AUVs in sea environment to realize wide seafloor survey.

I. Introduction

A number of navigation methods for a single Autonomous Underwater Vehicle (AUV) have been previously proposed in order to perform different kinds of missions [1-3]. There are many underwater tasks such as seafloor mapping, exploration of benthic resource, and monitoring colonies of underwater life periodically. It is necessary to estimate one's own state accurately to achieve these missions automatically. However, the coverage areas are usually limited because positioning accuracy becomes uncertain as the vehicle moves away from positioning references. Due to the limited coverage area, observation targets are also limited. Even when the position of the target is well-known, vehicles often fail to reach the target because of underwater currents, positioning errors, and so on. In order to overcome these problems, we have proposed a positioning method for multiple AUVs where moving AUVs estimate their states (horizontal position and heading angle) based on AUVs remaining stationary on the seafloor (landmark AUVs) [4]. The key idea in our proposed method is to alternate a moving and a landmark role between the AUVs.

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Many navigation methods of multiple vehicles in land, aerial, and marine environments have been previously proposed by various groups [5-7]. One such method involves decentralized state estimation in fixed topology formations of vehicles with applications to Autonomous Underwater Vehicles (AUVs) [8]. Cooperative positioning method using range-only measurements between two AUVs has also been proposed [9]. A method for Autonomous Surface Vehicles (ASVs) has also been developed [10]. In the field of land vehicles, one such study is the analysis of trade-offs between efficiency and accuracy in terms of the number of vehicles [11], and the other is CPS (Cooperative Positioning System) method [12]. In CPS method, one set of vehicles remains stationary and acts as landmarks for the moving set of vehicles, and the sets change roles every now and then. We have applied this technique to multiple AUVs for the first time, to the knowledge of the authors [4]. As all vehicles navigate near the seafloor and at least one landmark vehicle is always located within communication range of the moving vehicles, the proposed method is suitable for accurate survey near the seafloor such as seafloor mapping and sampling. The proposed method also takes advantage of the stochastic state estimation in order to suppress estimation errors caused by sensor errors and lack of measurements. Moving AUVs estimate their own states as well as those of the landmark AUVs. After completing observation around landmark AUVs, moving AUVs land on the seafloor and transmit the compressed information of the estimated states to the landmark AUVs [13].

In this paper, we addressed implementation of the proposed method on two underwater platforms and the performance analysis on the method. One is the AUV Tri-Dog 1 which can move and estimate the states and the other is a Dummy AUV which cannot move but can estimate the states. The proposed method is explained in section 2. The implementation of this method is explained in section 3. Section 4 explains the performance analysis on the proposed method through the sea trials. Section 5 provides our conclusion and future works.

II. Proposed method

In the proposed navigation method, two groups of AUVs alternate between the "Moving Role (MR)" and "Landmark

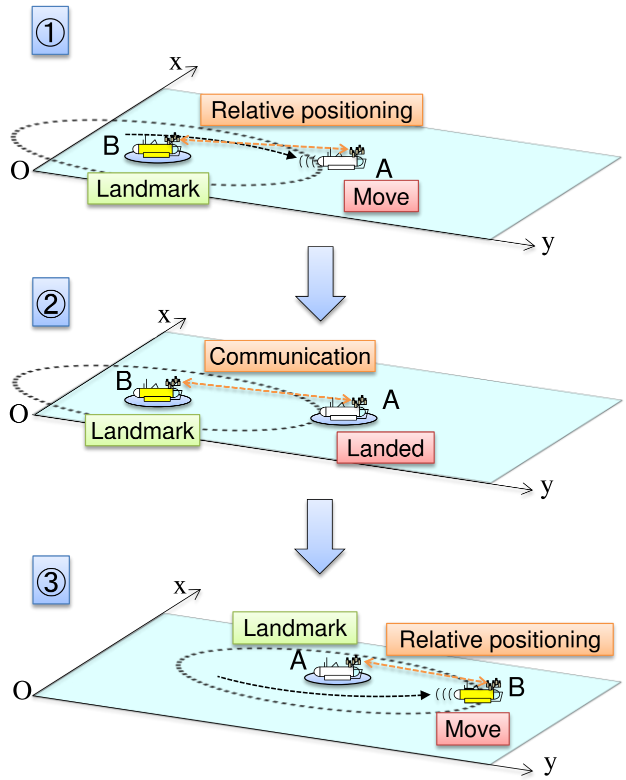

Fig. 1 The procedure of the proposed method.

Role (LR)". AUVs in the MR move based on AUVs in the LR. On the other hand, AUVs in the LR remain stationary on the seafloor to act as landmarks for the moving AUVs. Although one set of vehicles must remain stationary while the others move, moving vehicles can perform stable state estimation owning to landmark vehicles. The two groups of AUVs can expand the observational range by alternating between these roles. This method is the application of CPS method [12].

Fig.1 shows the proposed method in case of two AUVs A and B. Assuming that AUV A is in the MR, and AUV B is in the LR, the procedure is as follows.

1. Firstly, the moving AUV A performs the observation tasks based on AUV B remaining stationary on the seafloor.
2. After completing the tasks around B, A lands on the seafloor and transmits compressed information about the estimated states to B. Data compression and communication is performed only when the vehicles change their roles.
3. B starts the observation around A using the information about the states received from A.

An AUV's state consists of six parameters; 3D position (x, y, and z) and 3 axis rotation (roll, pitch, and yaw). The depth (z) can be precisely measured by a pressure sensor. The roll angle and the pitch angle are measured by an on-board attitude sensor without substantial drift. The parameters that need to be estimated accurately are horizontal position (x, y) and yaw angle (ψ). State estimation is performed only by the moving AUV. The moving AUV estimates own state as well as that of the landmark AUV based on its own sensor measurements and

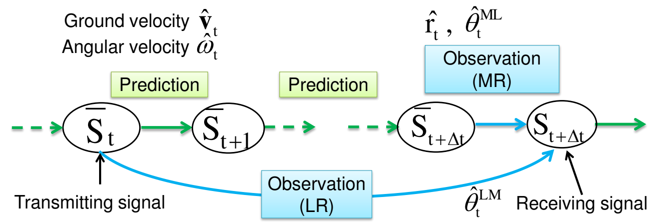

Fig. 2 The process timeline of state estimation.

relative position measurements between them, assuming that the landmark AUV is stationary on the seafloor.

A stochastic approach is used for state estimation [14]. There are many algorithms. One algorithm is a particle filter where the probability density of the states are expressed by a set of particles. Another algorithm is Extended Kalman Filter (EKF) which is nonlinear version of the Kalman filter. Comparing these two algorithm, as the states in particle filter are expressed by a set of particles, it can express multimodal distributions of the states and perform state estimation robustly against sensor noises and lack of measurements. Hence, we selected particle filter for state estimation.

The states at time t can be represented as $S_t = \{\mathbf{s}_t^i \mid i = 1, \cdots, n\}$. n is the number of particles. The i-th particle is expressed by $\mathbf{s}_t^i = \left[x_t^{Mi}\ y_t^{Mi}\ \psi_t^{Mi}\ x_t^{Li}\ y_t^{Li}\ \psi_t^{Li}\right]^T$, where M and L represent the moving AUV and landmark AUV, respectively.

The process timeline of state estimation is shown in Fig. 2. The particles are updated through two phases of prediction and observation by the moving AUV. In the prediction phase, the states $\bar{S}$ is updated by measurements data from on-board sensors mounted on the moving AUV such as a ground velocity sensor and a heading rate gyro. In the observation phase, the states are updated by relative positioning measurements where the moving AUV starts by interrogating the landmark AUV acoustically and measures $\hat{r}_t$, the slant range between the two AUVs, as well as $\hat{\theta}_t^{ML}$, the relative direction from the moving AUV to the landmark one, and then, the landmark AUV also computes $\hat{\theta}_t^{LM}$, the relative direction from the landmark AUV to the moving one, and transmits this information back to the moving AUV using a similar acoustical device [4, 15]. When no relative positioning measurements between the AUVs are available, the observation phase is skipped. Fig. 2 assumes that the moving AUV transmits a interrogating signal at time t, and receives a response from the landmark AUV at time $t + \Delta T$. This delay is taken into account while updating the particles by positioning measurements.

When the AUVs change the roles, the moving AUV lands on the seafloor and compresses the estimated states to share efficiently. In the compression method, the original particles are divided into some groups by a clustering method and then are approximated based on the clustering result. The moving AUV transmits only the optimal clustering result to the next moving AUV after a few tries of the clustering. Please see the following paper for details of the compression method [13].

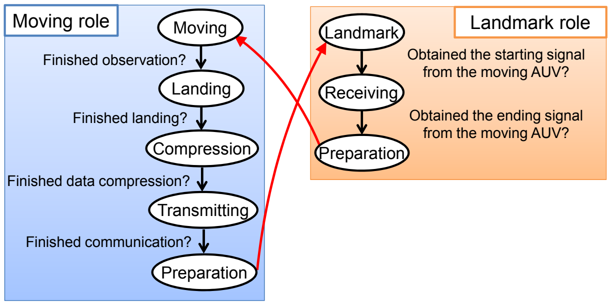

Fig. 3 The mode transition diagram.

III. IMPLEMENTATION

In this section, the implementation of the proposed method using two AUVs is explained.

A. Mode Transition

Each AUV takes one of the navigation modes described below. The mode transition diagram is shown in Fig. 3.

1. Moving
   The AUV performs assigned observation tasks, moving around the AUV in the landmark role. It also estimates the states of all the AUVs.
2. Landmark
   The AUV remains stationary on the seafloor to act as a landmark for the moving AUV.
3. Landing
   The moving AUV descends vertically to land on the seafloor to change the landmark role.
4. Compression
   The moving AUV reduces the data size of the estimated states to share the states after landing on the seafloor.
5. Transmitting
   The moving AUV transmits the compressed information of the estimated states to the next moving AUV.
6. Receiving
   The landmark AUV receives the information of the estimated states from the moving AUV.
7. Preparation for landmark
   This mode is to identify the next role (the landmark role).
8. Preparation for moving
   The landmark AUV reconstructs the estimated states based on the received data.

The moving AUV navigates around the landmark AUV and lands on the seafloor after making observations. After landing, data compression is performed. The moving AUV then transmits the starting communication signal to the landmark AUV. The landmark AUV starts receiving the compressed information about the estimated states after receiving the start signal. When the communication is completed, the ending communication signal is transmitted from the moving AUV to the landmark AUV, and the roles are interchanged.

B. Positioning and Communication Device

The authors developed an acoustic positioning and communication system named "ALOC (Acoustic Localization and Communication)" as shown in Fig. 4 in order to implement the proposed method [15]. The specifications of the system are shown in Table 1. ALOC has one transmitter and four receivers. The relative distance between ALOCs is calculated from round-trip time and the relative direction is measured by arrival time differences between receivers (SBL: Short Base Line method). The speed of sound used for positioning is calculated based on depth, water temperature, and salinity. A chirp signal is used for relative positioning. Communication protocol is multiple-value FSK and the data rate is 100 bit per second with packet size of 8 bytes. The time interval between pings needs to be more than 4 seconds. Table 2 shows the performance of ALOC, the relations between standard deviations of measurements and the distance between ALOCs.

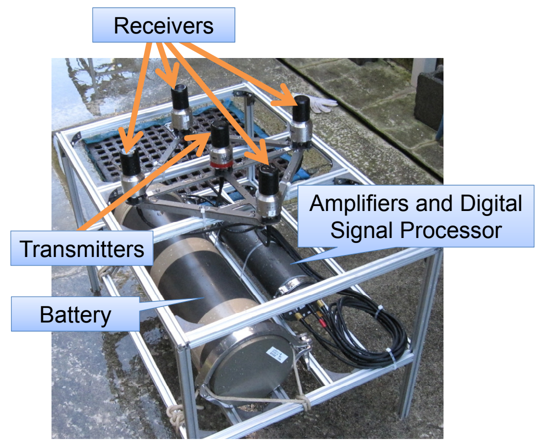

Fig. 4 Positioning and Communication device ALOC [15].

TABLE I
SPECIFICATIONS OF ALOC

Positioning	Chirp pulses (22-28kHz) SBL(Short Base Line) Positioning range (100 m)
Communication	Multiple-value FSK (23-26kHz) Data rate: 100 bps

TABLE II
PERFORMANCE OF ACOUSTIC POSITIONING

Standard deviations (direction & distance)	0.69 + 0.029 r * [deg](moving) 0.63 + 0.0009 r * [deg](landmark) 0.04 + 0.0002 r * [m]

*r means the distance between ALOCs [m]

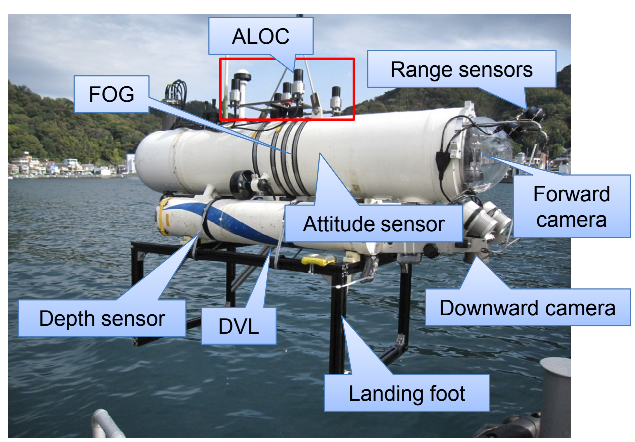

Fig. 5 AUV No. 1: Tri-Dog 1 (TD).

TABLE III
SPECIFICATIONS OF TD

Length	2.0 m
Width	0.6 m
Height	1.4 m (with the landing foot)
Weight	200 kg (In air) -1.5 kg(In water)
Max. depth	110 m
Endurance	4 hours
Thrusters	100 W × 6
Sensors	Doppler Velocity Log (DVL) One-axis Fiber Optic Gyro (FOG) Attitude sensor Pressure sensor Acoustic range sensor × 6 Forward camera Downward camera ALOC

TABLE IV
PERFORMANCE OF NAVIGATION SENSORS

Std of velocity sensor	0.01 [m/s] (moving @ 0.15 [m/s]) 0.0[m/s] (landmark @ 0.0 [m/s])
Std of angular velocity sensor	0.033 [deg/s] (moving) 0.0 [deg/s] (landmark)

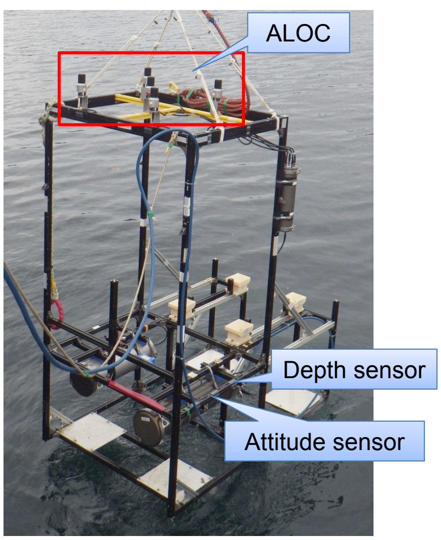

Fig. 6 AUV No. 2: Dummy AUV (DA).

TABLE V
SPECIFICATIONS OF DA

Length	1.6 m
Width	1.0 m
Height	2.0 m
Max. depth	1,500 m
Weight	130 kg (In air) 20 kg(In water)
Endurance	48 hours
Sensors	Attitude sensor Pressure sensor ALOC

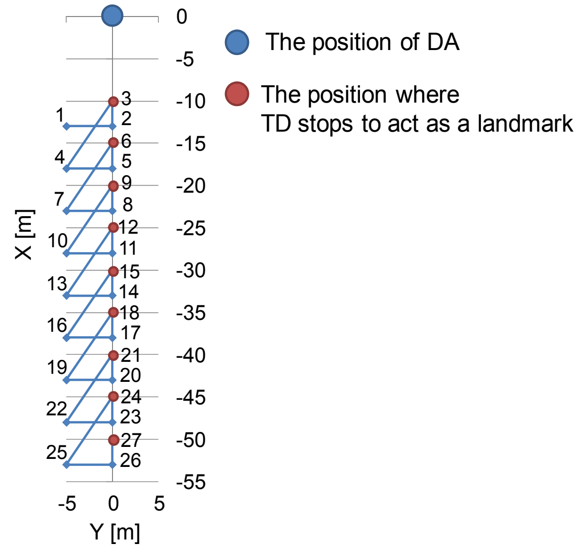

Fig. 7 Pre-given waypoints of TD based on DA. TD stops to act as a landmark at each red point. Waypoint numbers are shown around each waypoint.

C. *AUV No. 1: Tri-Dog 1(TD)*

Tri-Dog 1 (TD) is a hovering type AUV with six thrusters that can independently control surge, sway, heave and yaw motion [16]. A hovering type AUV can keep its position at constant altitude from the seafloor and is therefore suitable for detailed seafloor observation. A photograph and specifications of the vehicle are shown in Fig. 5 and Table 3, respectively. Ground speed is measured by a Doppler Velocity Log (DVL) and yaw angular velocity is measured by a one-axis Fiber Optic Gyro (FOG). Six acoustic range sensors are mounted for obstacle detection and terrain tracking. ALOC is mounted on the top center of the vehicle. The vehicle is also equipped with a landing foot to land on the seafloor. Table 4 shows the performance of navigation sensors (DVL & FOG).

D. *AUV No. 2: Dummy AUV (DA)*

Dummy AUV (DA) is a seafloor station that always remains stationary on the seafloor. It is equipped with ALOC and computers to simulate an AUV. DA does not move but estimates the states by a particle filter. The other on-board equipment includes a depth sensor, an attitude sensor, and two lithium-ion batteries (29.4V each). A photograph and specifications of the platform are shown in Fig. 6 and Table 5, respectively.

IV. PERFORMANCE ANALYSIS

Sea trials were conducted in November 2012 using the AUV Tri-Dog 1 (TD) and the Dummy AUV (DA) at Suruga Bay in Japan. This experiment is the first step in evaluating the two AUV navigation method. To evaluate the performance of the proposed method, the states of the two AUVs are recalculated based on the data obtained during the experiments in post-processing. Data consists of measurements from DVL, FOG, and positioning by ALOC.

A. Experimental Procedures

The experimental procedure is as follows.

1. The experimental field is a flat seafloor area at a depth of about 30 m. At first, DA is deployed on the seafloor and acts as the landmark AUV.
2. TD is manually guided to about 10 m ahead of DA on the sea surface, and then made to start diving.
3. After reaching the reference altitude of 3 m, TD starts searching for DA by use of the ALOC system.
4. After finding the DA, TD starts seafloor observation based on DA. The reference surge velocity is kept at 0.15 m/s. Sampling frequency of navigation sensors is 5 Hz and positioning interval is 15 seconds. The observation route is pre-planned based on DA as shown in Fig. 7. TD takes a picture of the seafloor by a downward camera every 7 seconds.
5. When TD reaches the red point in Fig. 7, it stops moving to act as the landmark. TD remains stationary at an altitude of 3 m based on the ground velocity. TD does not perform landing in this experiment when it acts as a landmark.
6. TD transmits the compressed information of the estimated states to DA using ALOC.
7. DA starts estimating the states using the information received from TD to act as the moving AUV.
8. DA stops estimating the states after 1.5 minutes and transmits compressed information of the states back to TD. While DA is in the moving role, DA performs positioning about 5 times.
9. The procedures 4 to 8 are repeated until TD completes the planned waypoints

B. Comparison cases

To discuss the positioning accuracy of the proposed method, the states of the two AUVs were recalculated in the following cases based on the data obtained from sea trials.

1. <u>Proposed method</u>
   TD estimates the states based on measurements from DVL, FOG, and ALOC. DA estimates the states based on measurements of ALOC.
2. <u>Dead reckoning</u>
   The state estimation is carried out only by prediction phase. Hence, TD estimates the states based on measurements from DVL and FOG. DA does not estimate the states in the MR because both TD and DA remain stationary when DA acts as the moving AUV.

C. Results: Standard deviations

Fig. 8 shows standard deviations of the estimated states (particles) of the proposed method (lines) and dead reckoning (dotted lines). The elapsed time indicates the time from the discovery of DA by TD (hereafter, time). The blue shows the standard deviation of the X position of TD. The red shows the standard deviation of the Y position of TD. The green shows the standard deviation of the heading of TD. The time period when TD is the moving AUV is indicated by gray. It is light green when DA acts as the moving AUV. The standard deviation of the states of DA is considered to be 0 because DA remains stationary.

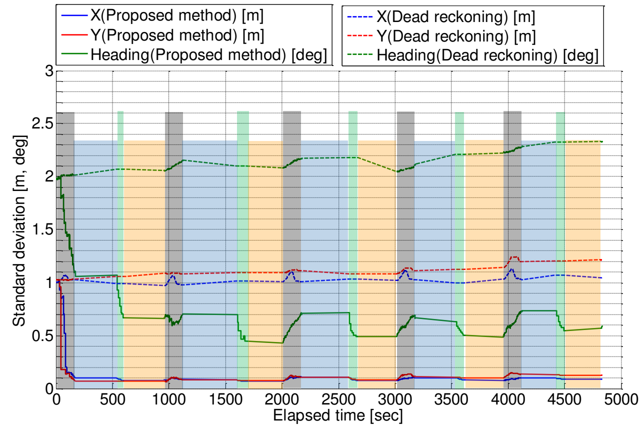

Fig. 8 The standard deviations of the estimated states of TD (Proposed method & Dead reckoning).

The blue boxes indicate the time period needed to transmit the compressed data from TD to DA before changing the roles. The orange boxes show the time period needed to transmit the compressed data from DA to TD before changing the roles. Almost all time periods were found to be between 5 and 7 minutes. Since the optimal time period to communicate all compressed data was expected to be about 4 minutes, it can be considered that the communications were successfully performed.

The initial standard deviations of X and Y are set to be 1.0 m, and that of the heading angle is set to be 2.0 deg. In the proposed method, the standard deviations converged during the mission, because positioning measurements were obtained both by TD and DA. The standard deviation of the horizontal position was decreased to be about 0.2 m and that of the heading angle was decreased to be around 1.0 deg. The standard deviations in heading angle increased when TD estimated the states. As the direction measurements by TD are less stable than those by DA, heading estimation by TD is poorly converged compared to that by DA.

In the dead reckoning case, the uncertainty of the states increased in time as there is no positioning measurements based on the landmark vehicle.

D. Results: Estimation errors –Positioning measurements–

Figs. 9-11 show the results of the horizontal trajectories of TD estimated by the proposed method. The results are shown every 5 m from 10 m to 30 m which are the distances between TD and DA when they changed the roles.

Fig. 9 shows the positioning measurements by TD. Black lines show the positioning measurements. The blue line shows the estimated horizontal trajectory of TD. The yellow star shows the position of DA. From these results, it can be seen that the positioning measurements roughly correspond to the actual position of DA and the deviations in positioning measurements increase as the distance of TD from DA increases. The black dots in the figure indicate particles at the time when TD reached each waypoint. As the standard deviations of the proposed method in Fig. 8 converged when TD estimated the states, particles also converged.

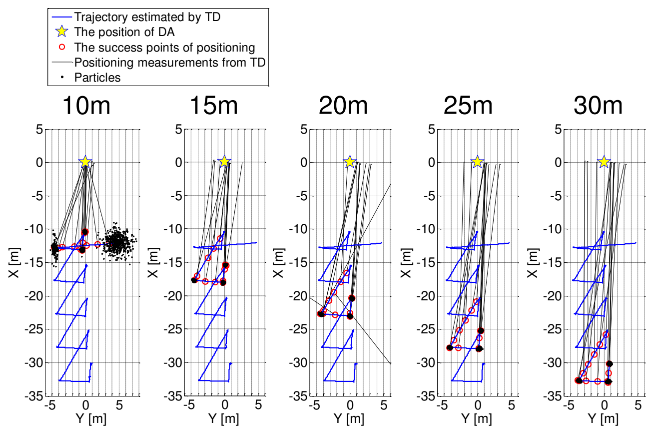

Fig. 9 Positioning measurements by TD obtained when TD is the moving AUV.

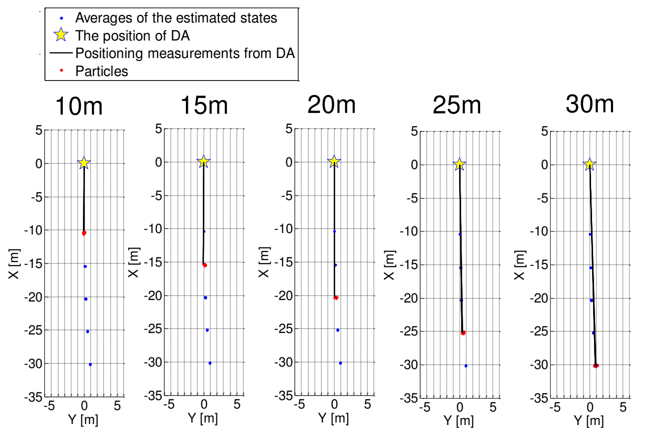

Fig. 10 Positioning measurements by DA obtained when DA acts as the moving AUV.

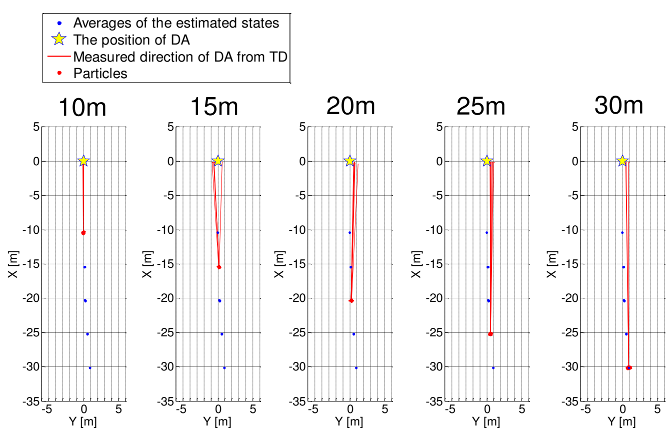

Fig. 11 Measured direction of DA from TD obtained when DA acts as the moving AUV.

TABLE VI STANDARD DEVIATIONS OF POSITIONING

	10m	15m	20m	25m	30m
distance(DA)[m]	0.022	0.013	0.014	0.018	0.018
direction(DA)[deg]	0.090	0.047	0.050	0.037	0.064
direction(TD)[deg]	0.219	1.882	0.234	0.143	0.202

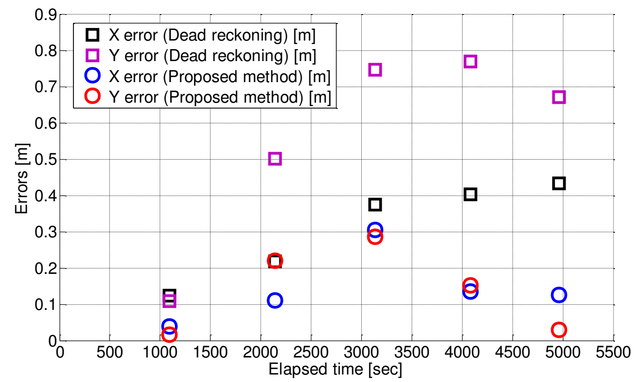

Fig. 12 Errors in horizontal position of TD.

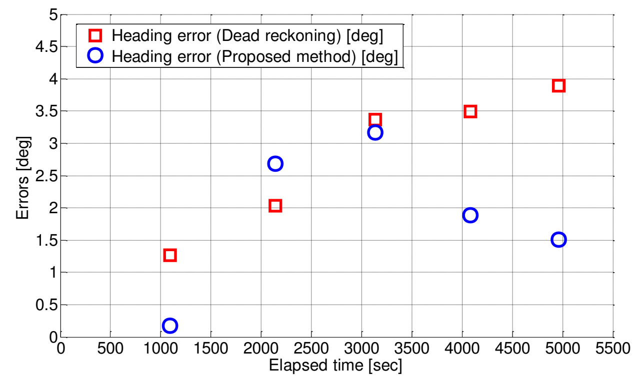

Fig. 13 Errors in heading angle of TD.

Fig. 10 shows the results of positioning measurements by DA. Blue points show the averages of the TD's state estimated by DA at each time. Positioning is performed about 5 times at each point. Positioning measurements (black lines) roughly correspond to the estimated position of TD. Measurements by DA are more stable than those by TD because DA does not have noise inducing devices such as thrusters which are likely to affect positioning measurements. The red points indicate particles at the time when DA performed relative positioning. As the standard deviations of the proposed method in Fig. 8 converged when DA estimated the states, particles also converged.

Fig. 11 shows measured direction of DA received from TD obtained when DA acts as the moving AUV. The measurements (red lines) are more stable as compared to those in Fig. 9 because TD was stationary as the landmark AUV.

Table 6 shows the standard deviations of positioning measurements from Figs. 10-11. The standard deviations are stable because both AUVs remained stationary at this time.

Fig. 12 shows errors in horizontal position of TD which are the averages of the differences between positioning measurements by DA and the estimated positions of TD (Fig. 10). Errors are shown each time DA acts as the moving AUV. Errors in X position are estimated to be about 0.1 m in the proposed method and 0.4 m in the dead reckoning case. Errors in Y position are estimated to be about 0.05 m in the proposed method and 0.7 m in the dead reckoning case.

Fig. 13 shows errors in heading angle of TD which are the averages of the differences between measured direction of DA from TD and the direction from the estimated position of TD

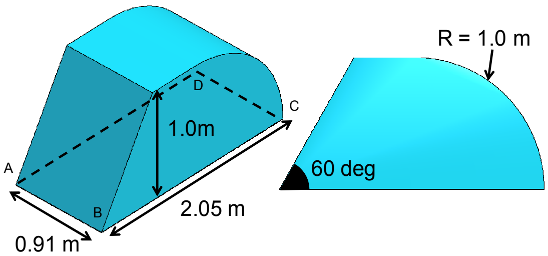

Fig. 14 The target

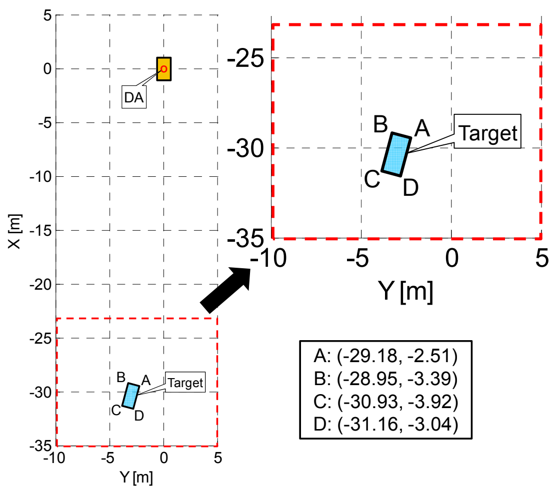

Fig. 15 The estimated position of the target in the DA-based coordinate system. These positions are considered as ground truth.

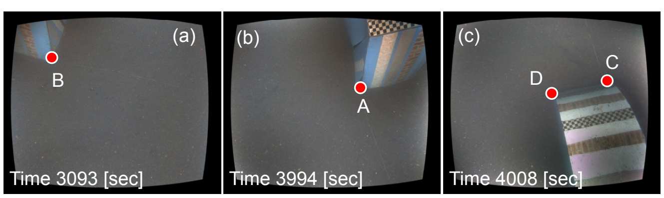

Fig. 16 Pictures of the target taken by the downward looking camera of TD.

to the position of DA plus estimated heading angle of TD (Fig. 11). Errors are shown each time DA acts as the moving AUV. Errors are estimated to be about 1.5 deg in the proposed method and 4.0 deg in the dead reckoning case.

The results show that the proposed method achieved more precise positioning compared with dead reckoning case.

E. Results: Estimation errors –Static target–

In order to evaluate positioning errors more precisely, image based analysis was performed based on a static target deployed on the seafloor. Fig. 14 shows the appearance and the size of the target. The bottom corners of the target are called A, B, C, and D respectively, as shown in the figure. The estimated positions of the corners are shown in Fig. 15. These positions are considered as ground truth, calculated by the following steps. TD took pictures of the targets at the time shown in Fig. 16.

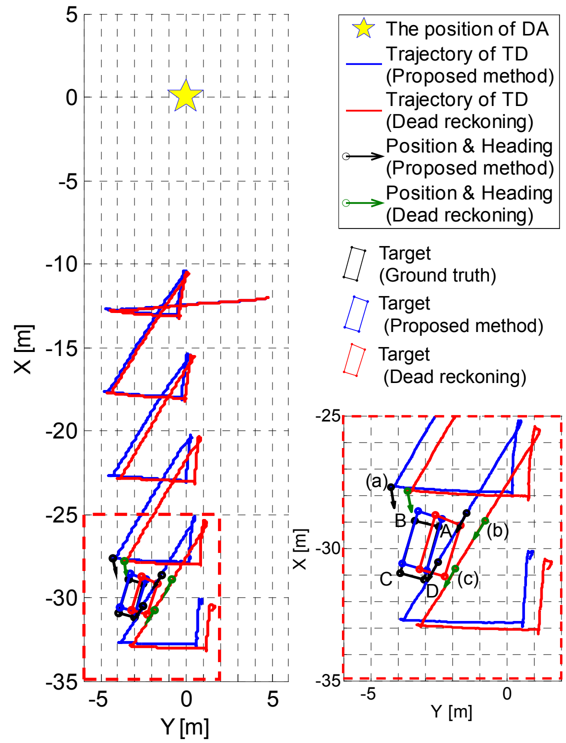

Fig. 17 Trajectories of TD in each case and the enlarged area. The blue line shows the trajectory estimated by proposed method. The red line shows the trajectory estimated by dead reckoning. Black points and arrows show the states of TD when TD took the pictures shown in Fig. 16 estimated by the proposed method. Green points and arrows show those estimated by dead reckoning. The alphabets (a), (b), and (c) in the enlarged figure show the points where the pictures were taken. Each rectangle indicates the target's position estimated by each case.

1. The positions of A and D in DA-based coordinate system are calculated from the following data.
   I. Positioning measurements by DA
      Positioning measurements by DA are obtained around the time when TD took the pictures of A and D (the images (b) and (c) in Fig. 16). From table 6, it is assumed that the positioning by DA is quite stable. The accurate position of TD when it took the picture is calculated from these positioning measurements (distance and direction from DA). In case there is a time difference between obtaining positioning measurements and taking pictures, the displacement of TD's position during this time is also taken into account.
   II. The position of the camera in the vehicle coordinate system.
   III. The position of the corners of the target in the image. Camera parameters are also required.
   IV. Heading and attitude of TD (roll, pitch, and yaw).
2. The positions of B and C in the DA-based coordinate system are calculated from the positions of A and D estimated in the previous step, and the known dimensions of the target.

TABLE VII ERRROS IN THE ESTIMATED POSITION OF THE CORNERS (A TO D) OF THE TARGET

A	Proposed method		Dead reckoning	
	X[m]	Y[m]	X[m]	Y[m]
Ground truth	-29.18	-2.51	-29.18	-2.51
Estimated position	-28.89	-2.37	-29.13	-1.69
Difference	0.29	0.14	0.05	0.82
Slant range	0.33		0.82	
Std. of the particles	0.09	0.12	1.08	1.18

B	Proposed method		Dead reckoning	
	X[m]	Y[m]	X[m]	Y[m]
Ground truth	-28.95	-3.39	-28.95	-3.39
Estimated position	-28.58	-3.25	-28.73	-2.63
Difference	0.37	0.14	0.22	0.76
Slant range	0.39		0.79	
Std. of the particles	0.10	0.13	1.11	1.14

C	Proposed method		Dead reckoning	
	X[m]	Y[m]	X[m]	Y[m]
Ground truth	-30.93	-3.92	-30.93	-3.92
Estimated position	-30.55	-3.85	-30.77	-3.20
Difference	0.38	0.07	0.16	0.72
Slant range	0.38		0.74	
Std. of the particles	0.08	0.13	1.10	1.20

D	Proposed method		Dead reckoning	
	X[m]	Y[m]	X[m]	Y[m]
Ground truth	-31.16	-3.04	-31.16	-3.04
Estimated position	-30.82	-2.94	-31.05	-2.29
Difference	0.34	0.10	0.11	0.75
Slant range	0.36		0.76	
Std. of the particles	0.08	0.13	1.10	1.20

Fig. 17 shows the results. Based on the results, the differences between the ground truth and the estimation are calculated. Table 7 shows the results. Errors in the proposed method are smaller than those in dead reckoning case for all the four corners of the target. The average of errors in the proposed method (0.37 m) is smaller than that in dead reckoning case (0.78 m). From these results, it can be said that the proposed method achieved better performance compared to the dead reckoning case.

V. CONCLUSION

In this paper, we implemented the method for multiple AUV navigation in which the AUVs alternate between moving and landmark roles we had proposed to verify the performance of the method. The AUV Tri-Dog 1 (TD) along with the Dummy AUV (DA) were deployed to shallow sea as a first step in evaluating the two AUV navigation method. They succeeded in alternatively estimating the states through acoustically communicating the states. TD and DA alternated the landmark role for 10 times. Compared to the dead reckoning case, errors in the proposed method were found to be smaller (0.4 m in the horizontal position, 1.5 deg in heading angle). Our future works include the implementation of this method on a second AUV to realize two AUV navigation to realize wide seafloor survey.

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