Hovering Type AUV "Tuna-Sand" and Its Surveys on Smith Caldera in Izu-Ogasawara Ocean Area

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***Abstract*—During the operation of and AUV in the ocean, it is necessary to monitor the vehicles position and the status in real time to prevent accidents that may occur abrupt changes in oceanic condition. Therefore a support ship should follow and monitor the AUV during survey. The ship operation costs are high and it is inefficient use if only one AUV dives during a survey. We developed a new survey method for multiple AUVs to make effective use of ship time. In our survey method, two cruising AUVs (AE2000a and AE2000f) pass through approximately the same route and observe the seafloor at a high altitude. One hovering type AUV (Tuna-Sand) navigates and takes pictures of seafloor at a low altitude. The ship follows the two cruising AUVs and sends the command by acoustic communication as necessary. Then an SSBL device on a moored buoy localizes Tuna-Sand and sends vehicle's position and status to the ship by satellite communications. To avoid sound wave interference, sufficient time gap is added between signal transmissions and the GPS time is used for synchronization. The Tuna-Sand AUV observed on Smith caldera in Izu-Ogasawara ocean area in two dives using our survey method. In first dive, the vehicle surveyed for about 2 hours and took 170 pictures of the seafloor. In second dive, we succeeded that AE2000a, AE2000f and Tuna-Sand dived and surveyed on the caldera at same time. The results obtained during the survey are described in detail in this paper.**

Keywords— multiple AUVs survey, image observation

I. INTRODUCTION

There are mineral, energy and living resource such as hydrothermal deposit, methane hydrate and fishes in Japanese exclusive economic zone. Many resources are in deep sea over a wide range. We have been working on AUVs which can survey resources over a wide range full-automatically without special deck equipment and high resolution image observation of seafloor [1,2]. However, we should monitor an AUV position and status in real time on a support ship to prevent the accident that may occur abrupt changes in oceanic condition, even if AUVs can survey on the seafloor full-automatically. Current survey methods are difficult to survey by multiple AUVs at the same time, because the ship follows a cruised AUV during the dive for monitoring. The ship operation costs are high and it is inefficient use if only one AUV dive during a survey.

Table I Specification of "Tuna-Sand"

Dimension	1.1m x 0.7m x 0.7m
Weight	278kg
Maximum velocity	1.7knot
Maximum depth	1500m
Duration	8.0h
Actuators	Thrusters 220W x 4, 100W x 2
Battery	Li-ion battery 50.4V, 18Ah x 4
Sensors	INS, GPS, DVL, Depth sensor, SSBL
Observation devices	Video camera, Digital camera, Profiling sonar

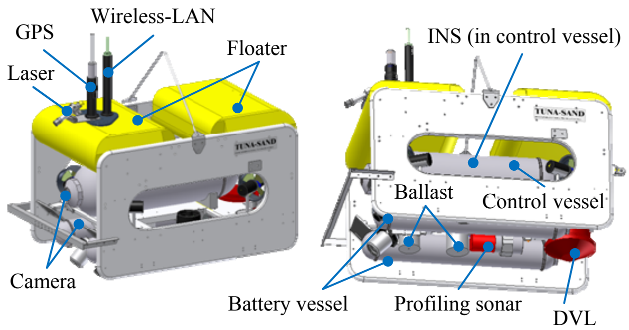

Fig.1 General arrangement of the "Tuna-Sand"

We developed new survey method which multiple AUVs observe ocean environment and seafloor at the same time to make effective use of the ship time. This paper describes our survey method used in research cruising (KY12-13) on Smith caldera in Izu-Ogasawara Ocean area and reports survey result of hovering type AUV Tuna-Sand. The vehicle dived two times in KY12-13 and total dive time was over six hours. 170 pictures of seafloor on the caldera are taken by the vehicle in first dive. We succeeded that two cruising AUVs and Tuna-Sand dived and surveyed on the caldera at the same time. This paper describes mainly first dive results.

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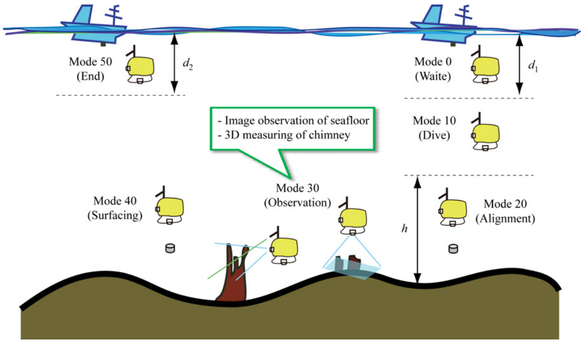

Fig.2 Dive flow of the "Tuna-Sand"

II. DIVE METHOD OF TUNA-SAND

A. Hoverlling AUV Tuna-Sand

The specification and general arrangement of Tuna-Sand are shown in Table I and Fig.1, respectively. Tuna-Sand has two floaters in the upper side, CPU board and inertial navigation system (INS) inside control vessel and lithium ion batteries inside two battery vessels in the bottom side. High-density polyethylene which specific gravity is 1.0 is used as constructional element. GPS and wireless antenna on front floater are used for alignment of INS and communication to support ship, respectively. Tuna-Sand is mounted with four 220W thrusters for horizontal movement and two 100W thrusters for vertical movement. Surge, sway, heave, roll and yaw directions are able to control by all thrusters and pitch and roll directions are stability. Horizontal thrusters are arranged for that surge thrust is larger than sway thrust. Tuna-Sand is realized to localize self-position with a high accuracy by using a combination of an INS and a doppler velocity log (DVL) [3,4]. Distance of Tuna-Sand and forward obstacle is calculated geometrically from the laser position in a camera image. The system also is used for measuring of subsea structure shape such as hydrothermal vent. As other device, Tuna-Sand has a strobe and a camera for taking seafloor pictures and a profiling sonar for measuring bathymetry and two ballasts for diving and surfacing.

B. Dive survey in Tuna-Sand

Survey flow of Tuna-Sand in real ocean area is separated into several modes which transit to next mode by achieving setup condition. Survey flow in the vehicle is shown in Fig.2. The vehicle with two ballasts dives by one's own weight at average velocity 0.4m/s after putting water, because its weight in sea water is about 8 kg (mode 0). Current mode transmits Mode 10 after reaching setup depth d_1. Devices such as DVL and thrusters are turned on in Mode 10. When the vehicle reaches altitude h_1, ballast for diving is released and the vehicle gets neutral buoyancy (Mode 20). h_1 is altitude that DVL can measure ground speed. INS obtains the vehicle velocity from DVL and is aligned again in Mode 20. After that, the vehicle navigates along setup route and observes seafloor (Mode 30). The vehicle controls its heading with the target setup direction during route tracking. When the vehicle gets away from line between current and next waypoints, target direction is changed in direction of its line. After passing through all waypoints, current mode transmits Mode 40 and the vehicle surface by releasing ballast. All thrusters are turned off and the vehicle finishes dive survey, after reaching depth d_2. The vehicle can navigate high accuracy and observe seafloor full-automatically with above dive survey flow. However, location accuracy is reduced when the vehicle dives at high altitude which DVL can't measure, because self-position is calculated from only the acceleration. Thus, support ship should localize and update the vehicle position during diving to navigate high accuracy. In multiple AUV survey, the vehicle position is measured by buoy.

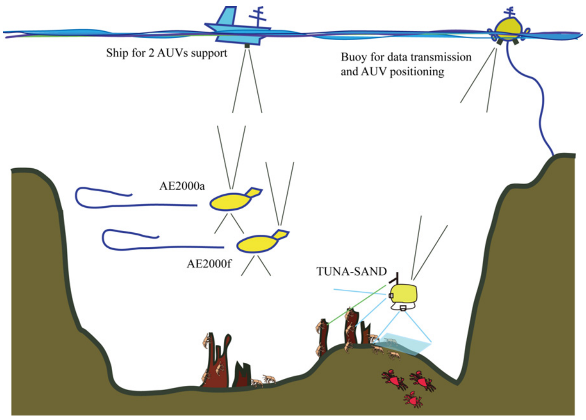

Fig.3 Image of three AUVs simultaneously survey

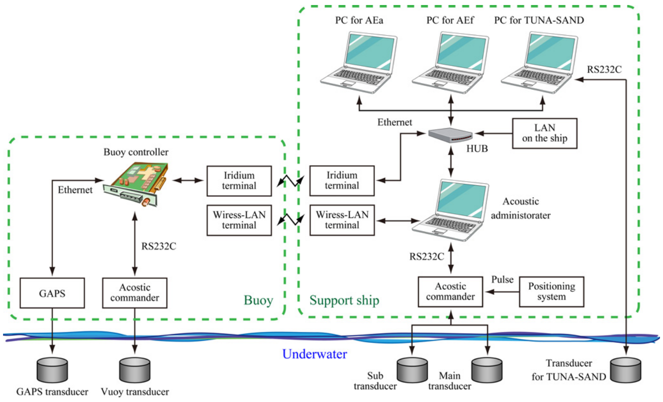

Fig.4 System for three AUVs

C. Three AUVs simultaneously survey

Our cruising type AUVs AE2000a and AE2000f and Tuna-Sand simultaneously dive for survey on smith caldera in KY12-13. AE2000a equips interferometry sonar for obtaining acoustic image of seafloor. AE2000f equips CTD sensor for measuring the salt level and three-axis geomagnetism sensor. Tuna-Sand equips camera and strobe for taking picture of seafloor. We developed survey method and system shown in Figure 3 and 4 for Three AUVs survey. Mooring buoy has SSBL and INS for localizing Tuna-Sand with high accuracy, acoustic communication device for communicating to Tuan-Sand and iridium communication for communicating support ship.

After three AUVs ready, the ship moves to Tuna-Sand dive point and Tuna-Sand starts to dive. Tuna-Sand is localized by SSBL of the ship and is monitored. The ship moves to the dive

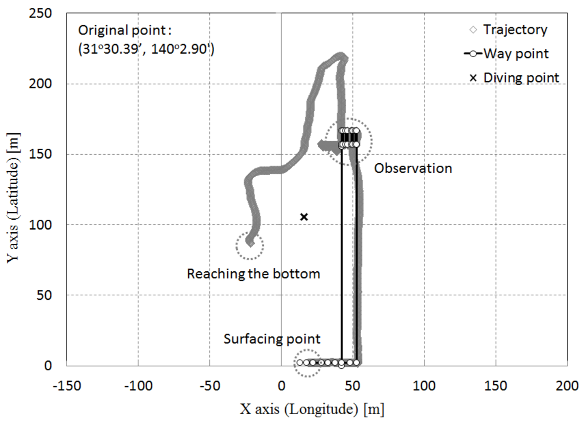

Fig.5 Total trajectory in first dive

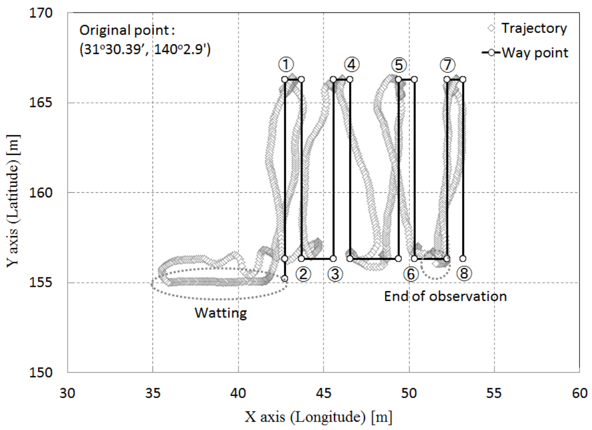

Fig.6 Trajectory duration observation in first dive

point of AE2000a and AE2000f after reaching the bottom of Tuna-Sand, and two AUVs start to dive. Two AUVs navigate along approximately same route at high altitude and observe ocean environment and seafloor. Then, Tuna-Sand navigates at low altitude close to the bottom and takes picture of seafloor. The Ship follows and localizes AE2000a and AE2000f during 3 AUVs coinstantaneous survey. Operators on the ship send the commands to AUVs as necessary. Our survey method has the risk for sound wave interference because there are many devices which emit sound wave. Sending time of sound wave is scheduled using GPS time.

D. *Estimation of flow velocity and direction*

Frontal projected area of hovering type AUVs like Tuna-Sand is larger than cruising type AUVs. Thus, their velocity depends largely on flow generated by tide and other. Hovering type AUVs is difficult to control self-position and can't observe everywhere for target area under flow environment. They navigate along route if flow velocity is measured. However, acoustic doppler current profiler (ADCP) equipped in support ship can't measure flow close to the bottom same as cruising altitude of Tuna-Sand. And Tuna-Sand doesn't have special sensor for flow velocity. In this research, flow velocity and direction are estimated from DVL data and motion equation to analyze Tuna-Sand motion in more detail.

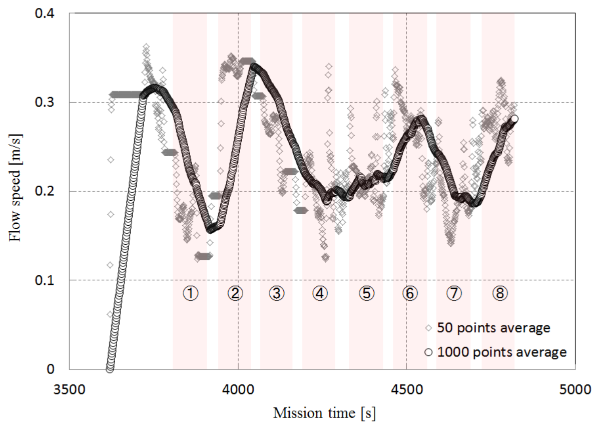

Fig.7 Estimated absolute flow velocity

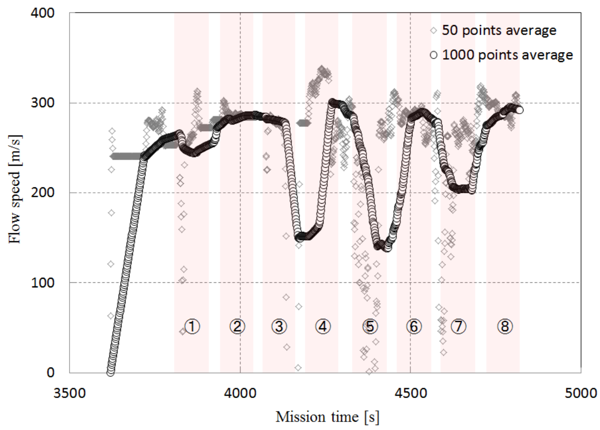

Fig.8 Estimated absolute flow direction

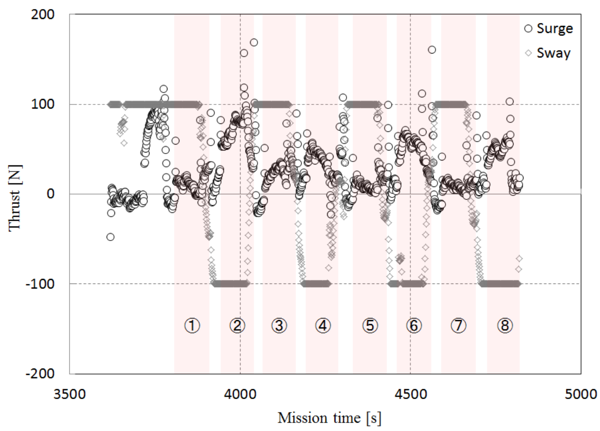

Fig.9 Surge and sway thrust

Let Tuna-Sand cruise in the direction of surge by its thrusters. With flow velocity denoted by u_{srg}, ground speed denoted by v_{srg} and vehicle thrust denoted by F_{srg}, motion equation of the vehicle is expressed by following equation.

$$M_{srg}(\dot{v}_{srg}-\dot{u}_{srg})+D_{srg}\,|v_{srg}-u_{srg}|\,(v_{srg}-u_{srg})=F_{srg} \qquad (1)$$

M_{srg}, D_{srg}, $\dot{v}_{srg}$ and $\dot{u}_{srg}$ in (1) denote weight of vehicle in air and additional mass, fluid drag coefficient, flow acceleration, and vehicle acceleration, respectively. Equation

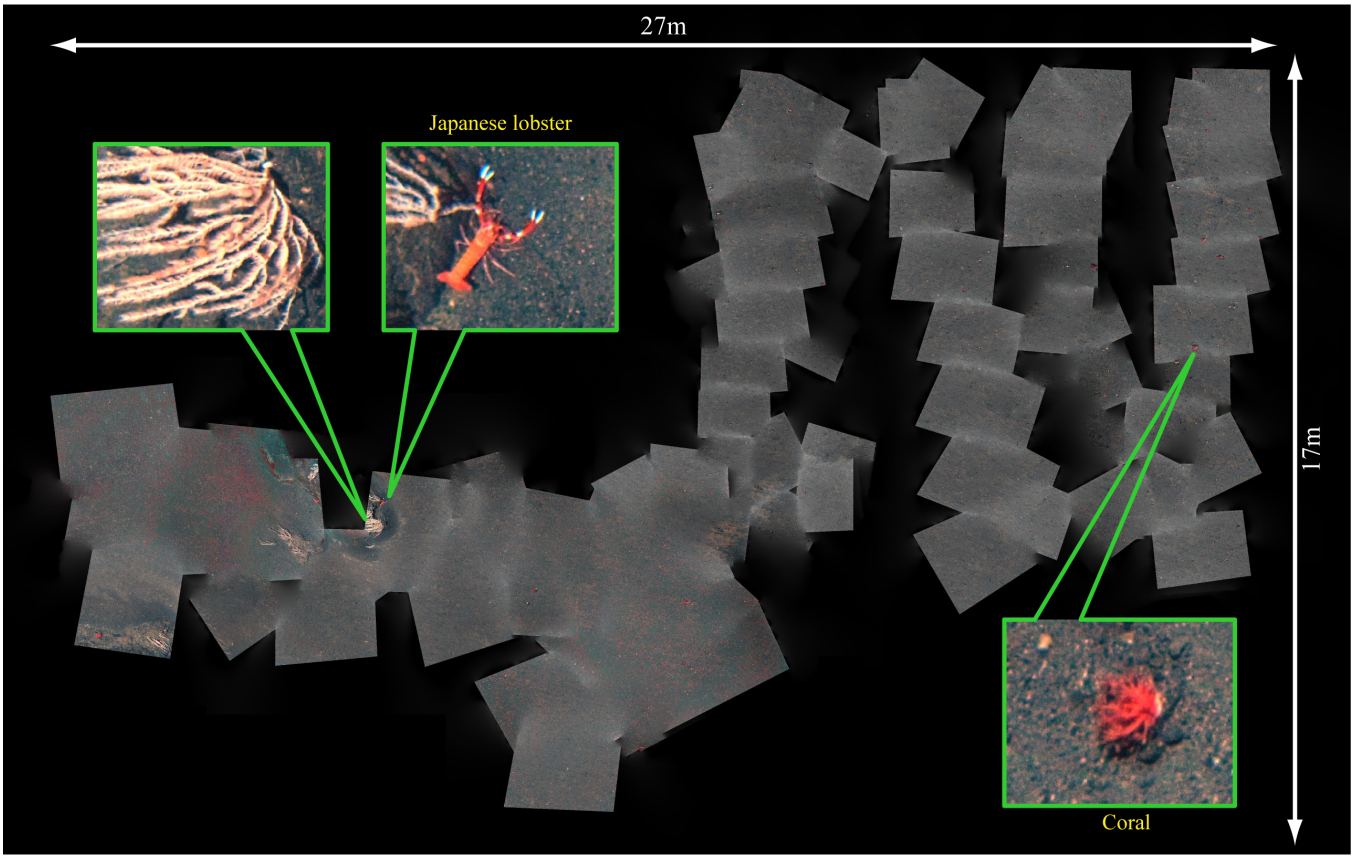

Fig.2 Dive flow of the "Tuna-Sand"

(1) is approximated by following equation if flow velocity is assumed to remain static.

$$M_{srg}\dot{v}_{srg} + D_{srg}\,|\,v_{srg} - u_{srg}\,|\,(v_{srg} - u_{srg}) \cong F_{srg} \tag{2}$$

u_{srg} in (2) is resolved as follows in (3).

$$u_{srg} = v_{srg} \pm \frac{1}{D_{srg}}\sqrt{M_{srg}\dot{v}_{srg} - F_{srg}} \tag{3}$$

Positive and negative of second member on the right in (3) is discern from equation in square root. The second member is positive if inertial force of the vehicle is larger than vehicle thrust ($M_{srg}\dot{v}_{srg} - F_{srg} > 0$). The second member is negative if the inertial force is smaller than the thrust ($M_{srg}\dot{v}_{srg} - F_{srg} < 0$). Flow velocity of sway direction denoted by u_{swy} is derived the same way. Absolute velocity of denoted by U and absolute direction of flow denoted by φ are given in following equation using estimated u_{srg} and u_{swy}.

$$U = \sqrt{u_{srg}^2 + u_{swy}^2} \tag{4}$$

$$\varphi = \mathrm{atan}(\frac{u_{swy}}{u_{srg}}) + \theta_{yaw} \tag{5}$$

θ_{yaw} in (5) denotes the vehicle heading. Absolute flow velocity and direction is estimated from only onboard sensors in the vehicle.

III. Dive Survey on Smith Caldera

A. Overview of dive survey

We surveyed on Smith caldera enclosed by latitude and longitude line of 31°27.00'N, 31°32.00'N, 140°00.00'E and 140°06.00'E using the system described in second chapter. The Shape of edge, size and depth in the caldera are near-circular, 5.0 x 6.2km and 800 to 900m, respectively. Buoy for localizing Tuna-Sand is moored in 280m depth located in 31°30.00'N and 140°02.40'E.

Tuna-Sand surveyed three times on the caldera in KY12-13. The vehicle dived on one's own in first and second dive and three AUVs such as AEa, AEf and Tuna-Sand were deployed simultaneously. Dive points and target observation points in all dives are shown in Table II. Measurement of ADCP equipped in support ship showed that Sea water flowed to northern cliff before diving. All dive points was decided on south of target observation points because DVL was possible to be equipped in Tuna-Sand can't measure ground velocity on steep cliff.

Tuna-Sand dived for about 2 hours and took pictures of seafloor in first dive. Three AUVs simultaneously survey is succeeded although the Tuna-Sand surfaced by electrical accident before observation in second dive. There is no enough time for survey in third dive because ocean condition was worsened by low-pressure. Thus, Tuna-Sand surfaced before observation.

B. Dive results of first dive

Trajectory and waypoints which the origin is the point of 31°30.39'E and 140°2.80'E in first dive is shown in Fig.5. Tuna-Sand moved to 20m south and 40m west by water flow from taking water to reaching bottom, and navigated to target observation point. Trajectory and waypoints during observation is shown in Fig.6. The vehicle moved to 6m west by water flow although it kept heading and position constant for 100 seconds to calibrate profiling sonar before observation. The vehicle controlled self-position with an uncertainty of 4m although position error of the east-west direction was wide. U and φ estimated by section 2.4 are shown in Figure 7, 8, respectively. Vehicle trust of surge and sway direction is shown in Fig. 9. The number (1 to 8) in these graphs is as the number of north-south line in Fig.5. U is about 0.2m/s and φ is south direction around 156m y-axis. U is about 0.3m/s and φ is west direction at around 166m y-axis. Figure 7 and 8 shows that water flows to west direction at over 0.2m/s averagely. And Fig.9 shows that the vehicle kept maximum thrust in sway direction during north-south movement. Thus, force applied by water flow around target observation point to the vehicle was stronger than maximum thrust of sway direction in the vehicle. Different between trajectory and setup route shown in Fig.5 was caused by the strong water flow. Mosaic image from 170 pictures taken in first dive is shown in Fig.10 and its size is 27m x 17m. We can find a Japanese lobster in the mosaic image. Some read points in the mosaic image are corals.

IV. CONCLUSION

This paper described survey method of Tuna-Sand and survey method for three AUVs, and shown survey result in KY12-13. In first dive, Tuna-Sand navigated along setup route with an uncertainty of 4m although there was water flow to west direction at over 0.2m/s around observation point. 170 pictures of seafloor were taken in first dive for about two hours. Mosaic image from their pictures showed the appearance of seafloor and creatures with high resolution. Successes of three AUVs simultaneous survey suggested a possibility for effective use of limited ship time.

We will improve position controlled performance under flow environment by that flow velocity estimated by our method is built to control law. And Self-propelled buoy will be developed to realize effective survey for multiple AUVs.

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