AUV Tri-TON 2: An intelligent platform for detailed survey of hydrothermal vent fields

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***Abstract*—The AUV Tri-TON 2 was built in 2013 under the governmental project to develop instruments to estimate ore reserves in underwater hydrothermal deposits, after the success of the prototype AUV Tri-TON [1]. The vehicle has two suites of imaging instruments looking forward and downward directions, in order to obtain dense, large-area 3D image of hydrothermal vent fields. The vehicle can follow rugged surface of hydrothermal vent fields at close range of less than 2.0 m. Although the vehicle is not equipped with an inertial navigation system (INS), the vehicle can estimate its position in real-time with a precision enough for rough photo-mosaicing, owing to the mutual acoustic positioning with a seafloor station. The vehicle has a strong ability of real-time path-planning to obtain a full-coverage 3D image of a rough, unknown seafloor in a single deployment [2].**

The performance of the vehicle was verified through a series of sea experiments. At the first experiment, the vehicle succeeded in imaging seafloor with the area of 14 $\times$ 10 m. Then, the vehicle was deployed to hydrothermal vent field at Irabu Knoll in Okinawa Trough with the depth of around 1,850m.

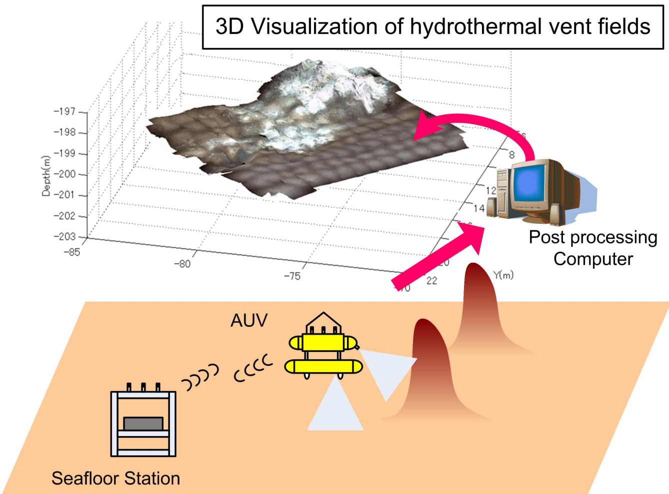

Fig. 1. Overview of the system for 3D visualization of hydrothermal vent fields.

I. Introduction

Hydrothermal vent fields are considered to be potential mineral resources. As current researches imply that there are a number of hydrothermal vent fields around Japan [3], [4], the Japanese government has started a series of programs to develop them. One of the programs aims at developing sensors those can be used to evaluate the amount of the mineral resources contained in existing vent fields, as well as to find new vent fields.

Under the program, the authors had proposed a system consisting of a hovering type AUV and a seafloor station to visualize a whole vent site in a 3D manner as shown in Fig. 1. The AUV Tri-TON had been developed as a prototype of the system in 2011 [1]. The vehicle's mission is to obtain dense, large-area 3D image of hydrothermal vent fields, in collaboration with a seafloor station. The vehicle has two suites of imaging instruments looking forward and downward directions in order to image whole surface of bumpy hydrothermal vent fields.

The AUV Tri-TON 2 is a practical vehicle developed in 2013, as a successor of the AUV Tri-TON. Although the general design is almost same with Tri-TON, the maximum operational depth has been extended from 800m to 2,000m, so as to cover almost all the existing vent fields around Japan.

This paper firstly explains the general design of the vehicle, then reports experimental results at shallow sea and deep sea vent field.

II. AUV Tri-TON 2

The general arrangement and specifications of the AUV Tri-TON 2 are shown in Fig. 2 and Table I, respectively. The vehicle consists of a three pressure hulls, where top one contains computers and sensors, and the bottom two contain batteries. Buoyancy material (syntactic form) is attached to the top hull. The vehicle acquires a high attitude stability, which is ideal for visual observation, by separating the center of buoyancy and gravity as far as possible. The vehicle can move in surge, sway, heave, and yaw directions by 5 thrusters. The high degrees of freedom of motion enables an effective view planning at complicated terrains.

A. Imaging Instruments

The vehicle has two identical set of imaging instruments consisting of a camera, a flash, and a sheet laser. One set is looking forward, while the other looking downward. The purpose of this arrangement is to obtain not only images but also bathymetry data of both flat seafloor and bumpy surfaces such as hydrothermal chimneys.

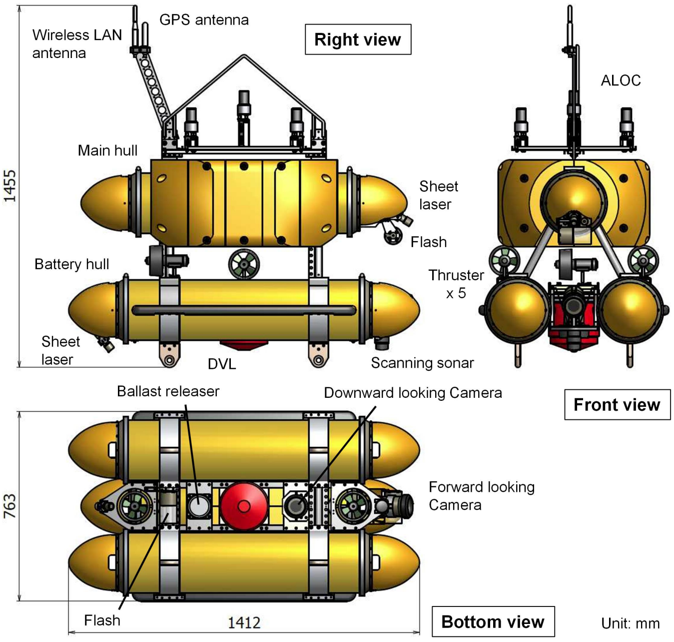

Fig. 2. General arrangement of Tri-TON 2.

TABLE I
SPECIFICATIONS OF THE AUV TRI-TON 2.

Vehicle	
Size	1.41m (L) × 1.46m (H) × 0.76m (W)
Mass	260 kg
Max. speed	0.5 m/s
Max. depth	2,000 m
Duration	8 hours
Actuators	100 W Thruster × 5
Power	Li-Ion 26.6 V 30 Ah × 4
Communication	Wireless LAN (in air), ALOC
CPU	Intel Core i5
OS	Microsoft Windows 7
Navigational Instruments	
Velocity & Altitude	Teledyne RDI Navigator 1200 kHz (DVL)
Depth	Mensor DPT6000
Roll & Pitch	OceanServer OS5000
Heading	JAE JG-35FD (FOG)
Obstacle detection	Tritech Micron
Position	GPS (in air), ALOC
Imaging Instruments	
Camera	Lumenera Lm165 (2M pixel) × 2
Flash	Morris Hikaru-komachi 6 × 2
Sheet laser	Custom made (445 nm, 500 mW) × 2

Bathymetry data is obtained using a camera and a sheet laser by light sectioning method [5], [6]. The resolution of the bathymetry measurements depends on camera performance, positional offset, and the distance to the target. The resolution of the downward-looking set is 5 mm at the range of 1.5 m, and 9 mm at the range of 2.0 m. Typically, images are taken at every second by both sets. Once an image was taken with flash, the following nine images are taken with sheet laser.

B. Navigation

Precise navigation is one of the most important requirements for wide-area seafloor imaging. Tri-TON 2 takes a sensor fusion approach to estimate relative position with regard to a seafloor station, which should be placed beforehand. Although the vehicle is not equipped with an inertial navigation system (INS), the vehicle can estimate its position in real-time with a precision enough for rough photo-mosaicing, owing to the mutual acoustic positioning with the station. Acoustic localization and communication device (ALOC) is used to obtain distance and direction to the station [7]. The position and heading of the vehicle is stochastically estimated by Particle filter [8], using Doppler Velocity Log (DVL) and Fyber Optical Gyro (FOG), as well as ALOC.

The vehicle firstly detects the seafloor station using ALOC. The maximum detectable range depends on the environment, typically 100m. The vehicle has a strong ability of real-time path-planning to obtain a full-coverage 3D image of a rough, unknown seafloor in a single deployment [2]. First, the AUV observes the seafloor by following a pre-given path defined relatively to the station. Second, the AUV calculates the following on-site based on the data obtained: 3D bathymetry map, unscanned areas on the map, and the next path that can be taken to image the unscanned areas effectively. Then, the AUV follows the new path to obtain better results.

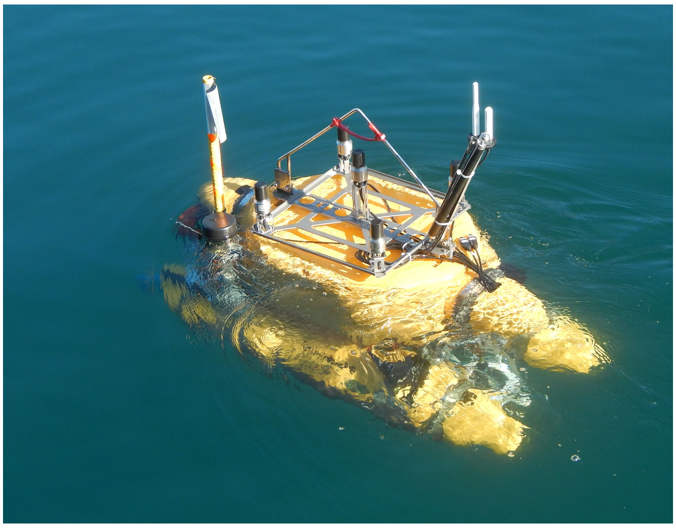

Fig. 3. Tri-TON 2 at the shallow sea experiment.

III. EXPERIMENTS

The performance of the vehicle was verified through a series of sea experiments. Here, results of the two important experiments are reported.

A. Seafloor imaging

The experiment was carried out at shallow area of Suruga Bay in November 2013. Fig. 3 shows the vehicle cruising to the starting point. Fig. 4 shows the horizontal trajectory of the vehicle during the experiment. After reaching the seafloor with the depth of around 35m, the vehicle quickly located itself based on the seafloor station (Fig. 4-1), and started seafloor observation by following the pre-given waypoints (2). After that the vehicle stopped and generated the new waypoints to

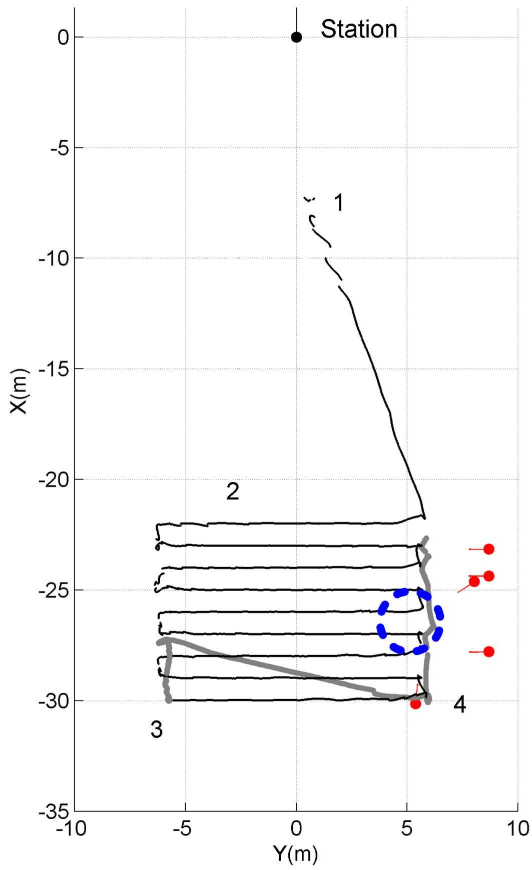

Fig. 4. Trajectory of Tri-TON 2 at the shallow sea experiment. Black line: Initial observation. Gray thick line: Second observation. Blue dotted circle: Estimated location of the target. Red dots: Automatically generated waypoints for the second observation.

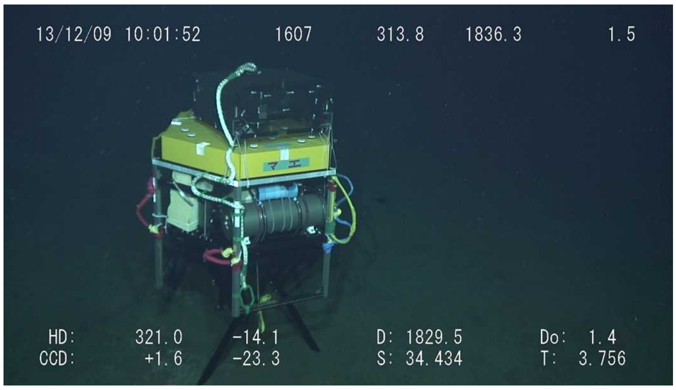

Fig. 6. Seafloor station set near the hydrothermal vent area of Irabu Knoll.

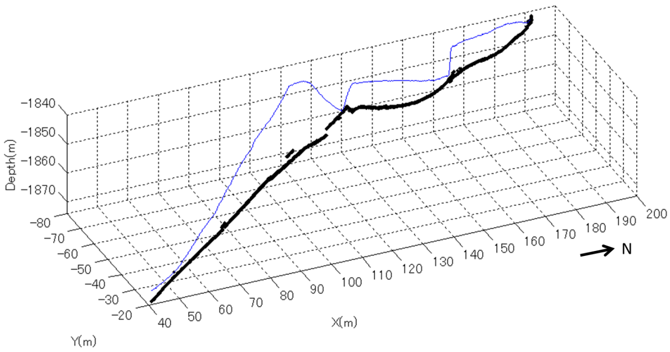

Fig. 7. Trajectory of Tri-TON 2 during the trial at Irabu Knoll (Blue line). The black bold line indicates the seafloor beneath the vehicle measured by the DVL.

observe the target(3). Then the vehicle followed the new waypoints (4). The actual trajectory at this time was about 3m inside than the generated waypoints. This is because the operational area of the vehicle was limited due to safety issue.

Fig. 5 shows the resultant seafloor photomosaic, which was obtained by post processing based on the alignment method [9]. The area is about 14 × 10m. The pictures were taken from the altitude of 1.7m. The blue box shown in the right is the observation target set on the seafloor. White ropes are attached to the target and laid on the seafloor for quality evaluation of the photomosaic.

B. Deep sea vent field

The vehicle was deployed to Irabu Knoll, a deep sea hydrothermal vent field in Okinawa Trough, Japan. The experiments was held during NT13-25 cruise by R/V Natsushima with ROV HyperDolphin from Dec.4 to 11, 2013. Irabu-knoll is a relatively deep hydrothermal vent field located north of Miyako Island, with the depth of 1,800 to 2,000m. Since the discovery of the two hydrothermal vent areas in 2000, Irabu-knoll has been extensively surveyed to study its hydrothermal activities [10].

The seafloor station was installed near the hydrothermal vent area at the depth of 1,840m by the ROV. The station automatically keeps itself horizontal by controlling its three legs as shown in Fig. 6. Due to the bad weather, Tri-TON 2 was deployed only one day, towed near the seafloor. Fig. 7 shows the trajectory of the vehicle estimated by dead reckoning. Some of the seafloor pictures taken by the vehicle are shown in Fig. 8.

IV. Conclusions

This paper explained the AUV Tri-TON 2, which is a hovering type AUV developed for 3D imaging of hydrothermal vent fields. The vehicle has been built in 2013 under the governmental project to develop instruments to estimate ore reserves in underwater hydrothermal deposits. The vehicle has two suites of imaging instruments looking forward and downward directions, in order to obtain dense, large-area 3D image of hydrothermal vent fields. Although the vehicle is not equipped with an inertial navigation system (INS), the vehicle can estimate its position in real-time with a precision enough for rough photo-mosaicing, owing to the mutual acoustic positioning with a seafloor station.

The performance of the system was verified through the shallow sea trials held at Suruga Bay. Although further experiments are necessary, the basic feasibility of the system at deep sea hydrothermal vent fields was confirmed through the trials at Irabu Knoll, Okinawa Trough in Japan. Future plan includes improvements of both software and hardware to

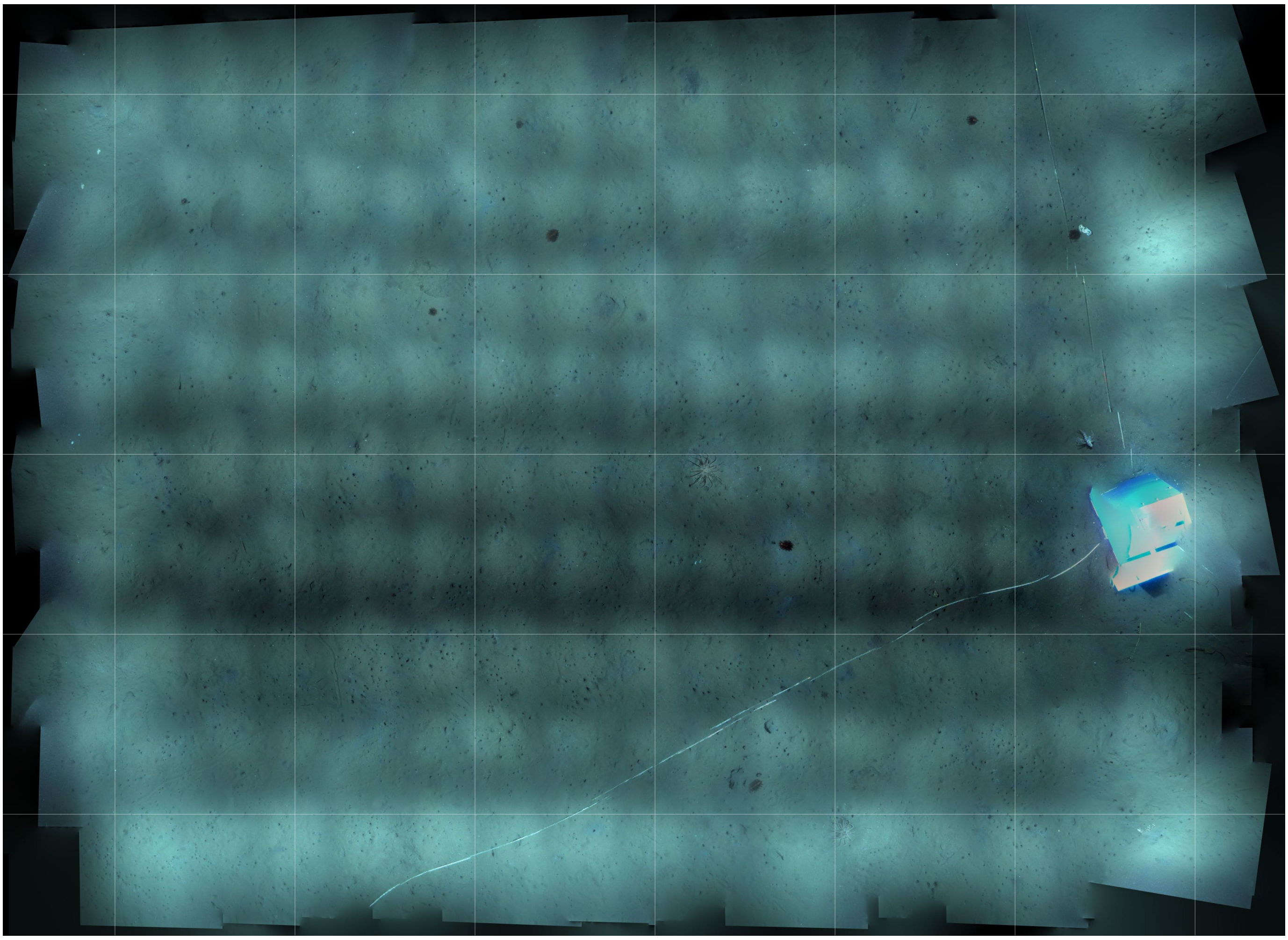

Fig. 5. Photomosaic of the seafloor obtained by Tri-TON2. Grid size is 2m. The blue box on the right is the target.

increase feasibility and robustness to the harsh environments of vent fields, as well as performing full missions at actual vent fields.

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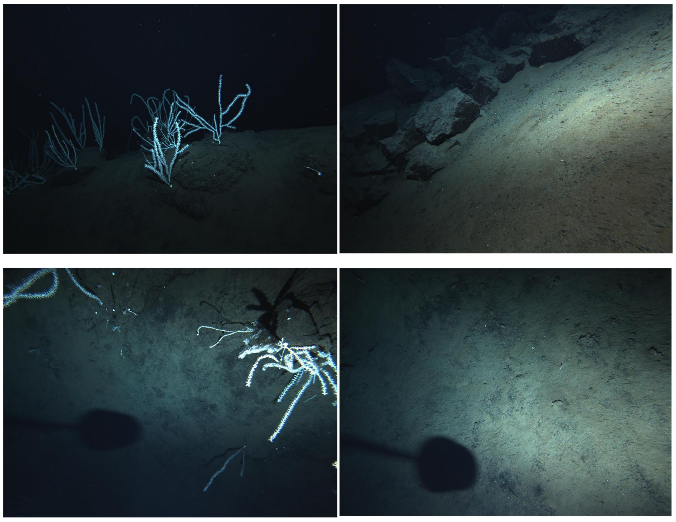

Fig. 8. Seafloor images taken by the vehicle. Top: taken by the forward looking camera. Bottom: taken by the downward looking camera.

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