Autonomous detection and volume determination of tubeworm colonies from underwater robotic surveys

Toshihiro Maki*, Ayaka Kume*, Tamaki Ura*, Takashi Sakamaki*, Hideyuki Suzuki†
* The University of Tokyo
Meguro, Tokyo, 153-8505 Japan
{maki, kume, ura, sakamaki}@iis.u-tokyo.ac.jp
† The University of Tokyo
Hongo, Tokyo, 113-0033 Japan
suzukih@naoe.t.u-tokyo.ac.jp

Abstract— **Although the vast amount of information collected by AUVs brings significant benefit to oceanographic research, it is necessary to develop methods to analyze the large volumes of data, in order to avoid accumulation of unused information. Automatic data processing and analysis are key technologies necessary to cope with this problem. We propose a robust, automated method for detection and volume determination of tubeworm colonies using visual and geometric features obtained during underwater robotic surveys, on the condition that the position of the sensors are provided. The tubeworm is a characteristic benthos of hydrothermal vent fields. The proposed method achieves robustness against sensor noise by using both geometric and visual features for identification. First, the tubeworm candidates are obtained as a three-dimensional region between the measured bathymetry of the region and an estimation of the seafloor topology without tubeworms. Next, the tubeworm candidates are verified through frequency analysis of corresponding images. The performance of this method was verified using a data set obtained by the AUV Tri-Dog 1 at Tagiri vent field, Kagoshima bay in Japan.**

I. Introduction

Wide range underwater image observation is greatly complicated by the attenuation and scattering of light. In order to achieve large area visual observations, it is necessary to take many images of the seafloor from close range. Autonomous underwater vehicles (AUVs) form ideal platforms with which to achieve this task, since automation allows observations to be made over long periods of time without human intervention, and visual observation using AUVs has been the subject of much research to date. As underwater robotic technologies grow, an increasing number of AUVs capable of following the seafloor at close range to obtain imagery and bathymetry are being developed [1]. Although the vast amount of information provided by these AUVs brings significant benefits to both science and industry, it is necessary to develop methods to analyze this data in order to avoid accumulation of unused information. Automatic data processing and analysis are key technologies necessary to cope with this problem.

In this paper, we propose a robust, automated method for detection and volume determination of colonies of *Lamellibrachia satsuma* using visual and geometric features obtained during underwater robotic surveys, on the condition that the position and attitude of the sensors are precisely estimated.

Lamellibrachia satsuma is a species of shallow water tubeworm discovered at Tagiri vent field, Kagoshima bay in Japan [2]. Tubeworms play an important role in the ecosystem of hydrothermal vent fields. The shape of an individual tubeworm is shown in Fig. 1. Fig. 2 shows a typical tubeworm colony. Since tubeworms are typically found at depths greater than the euphotic zone, *Lamellibrachia satsuma*, which was found in the euphotic zone, is an important species to study the mechanism of tubeworm speciation and dispersion due to its accessibility. Surveying their distribution in both spatial and temporal manner is very important in understanding not only their ecology but also scale and distribution of vent fields.

The performance of the proposed method was verified using a data set obtained by an AUV at Tagiri vent field. Fig. 3 shows the experimental location. The depth is around 100 meters.

II. Data set

The data set was obtained by the AUV Tri-Dog 1 [3] shown in Fig. 4. Since 2006, the AUV has observed the site for 73.2 hours through 41 dives, to create photo mosaics of the site with an area of 3,000 square meters. The vehicle is a hovering type AUV equipped with a downward looking camera and flash light for imagery . The vehicle also has a light-section ranging system consisting of a camera and a sheet laser to profile seafloor with sub-centimeter resolution [4], [5]. The sensor pose (three-dimensional position and orientation) at each moment of data acquisition is cashed in the memory of the vehicle. The vehicle estimates its position in real-time with the horizontal uncertainty of around 0.5 meters using a SLAM based algorithm [3]. The positioning scheme uses a profiling sonar mounted on the AUV and two passive acoustic landmarks as shown in Fig. 5, as well as Doppler Velocity Log (DVL) and yaw rate gyro. The profiling sonar scans a 2D plane with a pencil beam in order to detect the landmarks. The landmarks are defined as pole-like acoustic reflectors set vertically on the seafloor. The stochastic estimation is based on Particle Filter, which is a random-sampling based implementation of Bayesian filtering that is suitable for non-linear, non-Gaussian state estimations [6].

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

Fig. 1. A tubeworm specimen (scale;mm)[2]

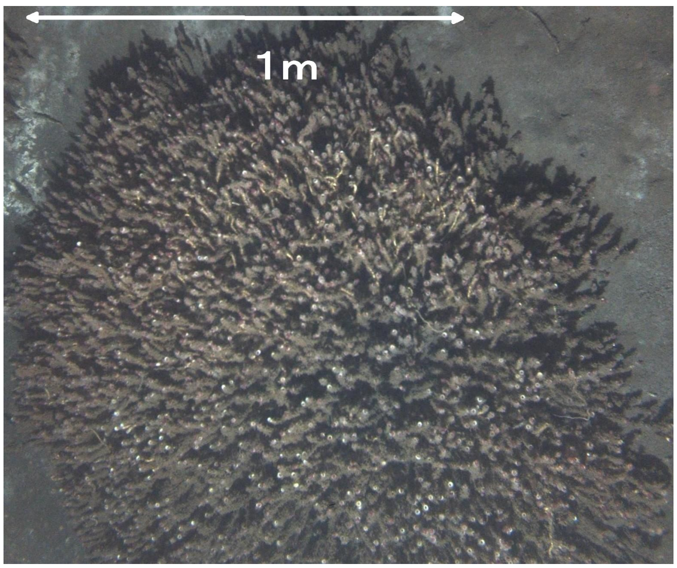

Fig. 2. A Colony of *Lamellibrachia satsuma* photographed by Tri-Dog1

Table I gives an outline of the data set. The trajectory of the vehicle in the experiment is shown in Fig. 6.

Fig. 7 describes the experimental site, Tagiri vent field. The photo mosaic on the upper right was created based on the real-time pose estimation, with the aid of feature based matching [7]. As the photo mosaic indicates, there exist not only tubeworm colonies but also white bacteria mats and other objects such as driftwood. The illustration in the lower left is a cross section of the seafloor, showing tubeworms and bubbles on a smooth seafloor.

TABLE I
DESCRIPTION OF THE DATA SET

Date	2009-9-25
Speed of AUV	0.12 m/s
Number of seafloor images	519
Number of laser images	3478
Altitude	2.0 m
Shooting interval(seafloor)	7 sec
Shooting interval(laser)	1 sec
Image size(seafloor)	2448 $\times$ 2088 pixels

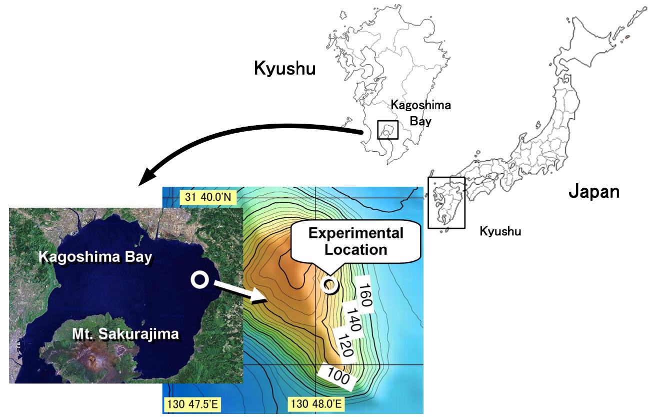

Fig. 3. Experimental site

Fig. 4. AUV Tri-Dog1

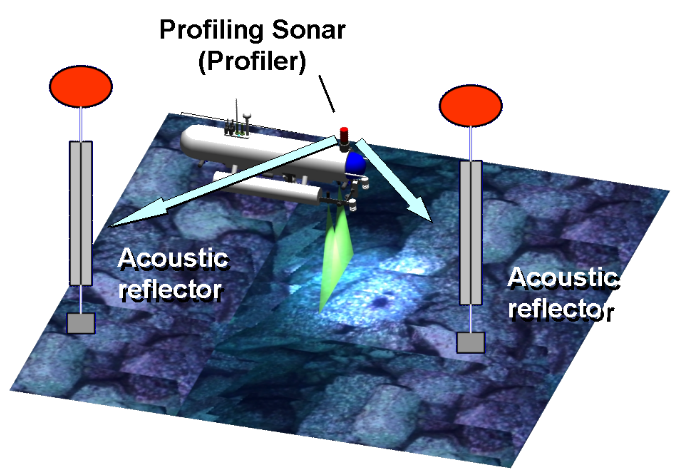

Fig. 5. Positioning method of Tri-Dog1

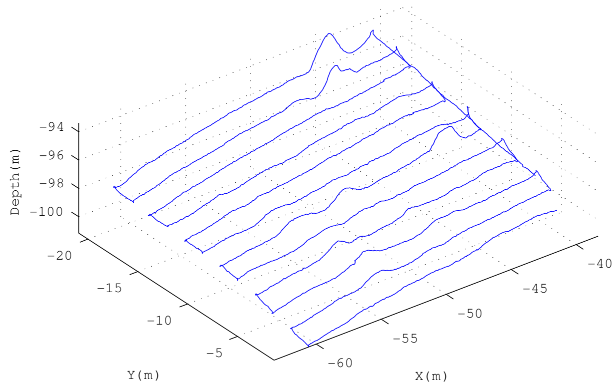

Fig. 6. Trajectory of Tri-Dog1 during the dive used for the data set.

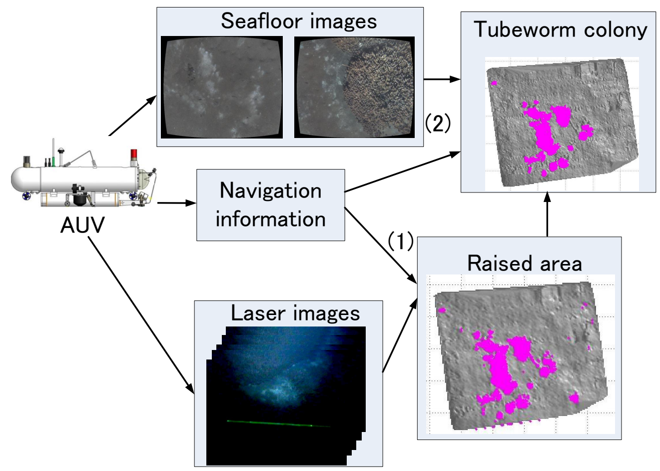

Fig. 8. Outline of classification of tubeworm colonies

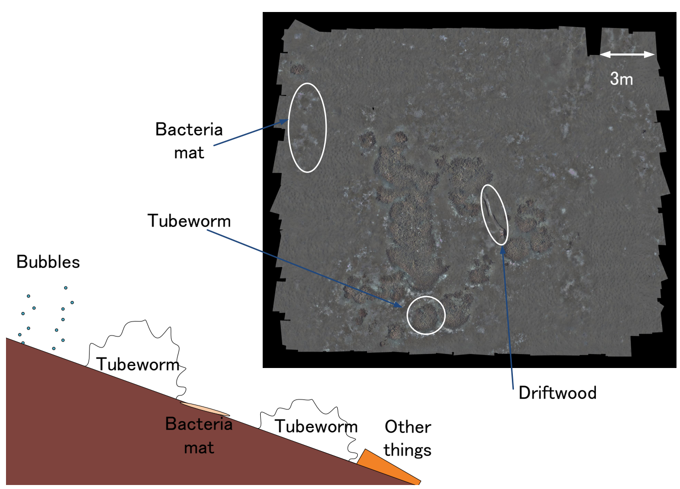

Fig. 7. Experimental site (Left: Vertical cross section Right:Photo mosaic)

III. Method

Differentiating tubeworm colonies and protrusions such as rocks geometrically is complicated due to the similarity in shape. Conversely, image of tubeworms and bacteria mats can have similar spatial frequency signatures.

The method achieves robustness against sensor noise by utilizing different kinds of characteristics, imagery and geometry. The method is applicable to a data set obtained by any platform as long as the data set contains the following information;

- Seafloor pictures with the resolution higher than the diameter of tubeworms (around 15mm)
- Bathymetry as a set of swaths, with the resolution of each swath higher enough to detect tubeworms
- Sensor poses (tree-dimensional position and orientation) at each moment of data acquisition.

Fig. 8 gives an outline of the proposed method. The AUV takes both seafloor image for imagery information and laser profile image for geometric information. First, geometry based estimation is carried out, where bathymetry is created directly using laser profile images and the provided sensor poses (1). Raised area is the area which protrudes from the new generated bathymetry of the area. Second, the raised area is split up into separate regions, and then each region is verified through frequency analysis of corresponding images (2).

A. Geometry based estimation

Fig. 9 gives an outline of the geometry based estimation. The bathymetry map is first constructed from the laser images (a).

In order to extract geometric information from the laser images, each laser image is first binarized. Next, detected laser positions are transformed from pixel coordinate to the sensor coordinate system by light-sectioning, where the coordinates of the projection are calculated as the intersection of laser plane with the viewing vector of the camera. Finally, the points are transformed from sensor coordinate system to the world coordinate system based on the navigation information.

The raised area is detected by comparing the bathymetry map and that of estimated bare seafloor without protrusions.

If we attempt to estimate the bare seafloor by filtering the original bathymetry map, it is very difficult to eliminate all the effect of protrusions. Furthermore, mapping artifacts might be detected as raised area since they are also smoothed by filtering. For example, Fig. 10 shows a bathymetry map to which a median filter has been applied, where effects of protrusions are remaining.

In order to avoid this problem, the individual laser images are filtered directly. All the bathymetry swaths are classified into two groups of, A: tubeworm candidates and B: others, based on their linearity ((b) in Fig. 9). Since tubeworms form compact, knoll-like colonies on seafloor, a jagged swath is assumed to contain profile of a tubeworm colony.

The image in the top left of Fig. 9 contains the profile of a tubeworm colony. The image in the top right is of the bare seafloor. The blue points plotted in the graphs

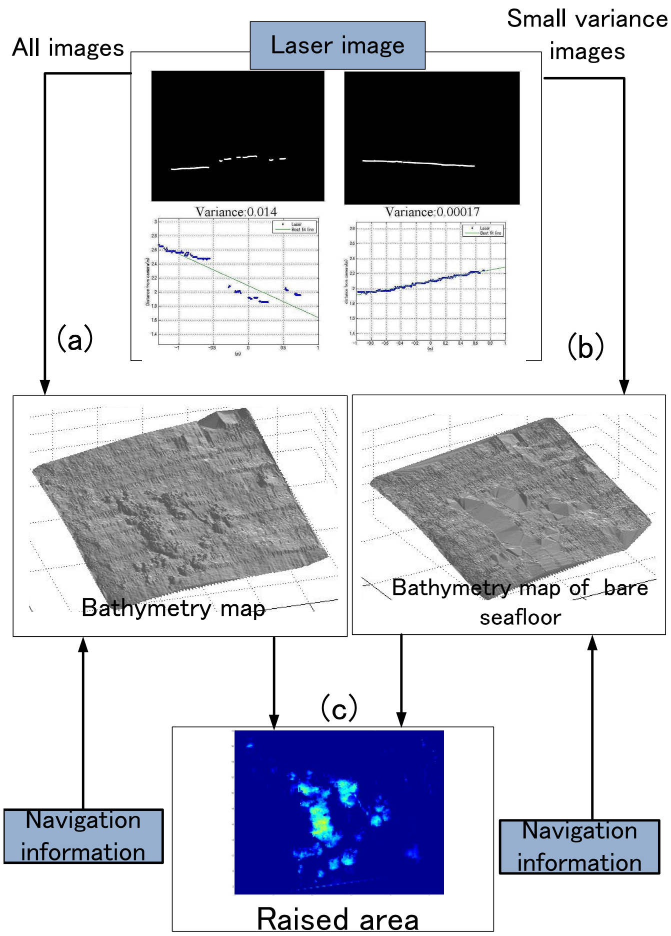

Fig. 9. Outline of geometry based estimation

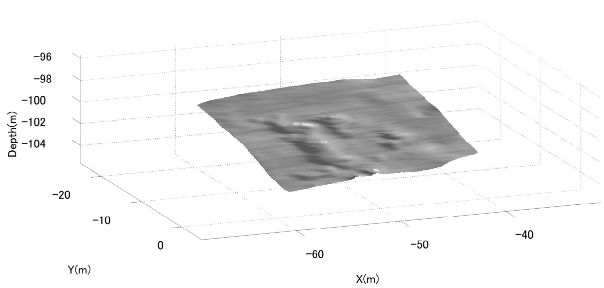

Fig. 10. Bathymetry map after median filtering

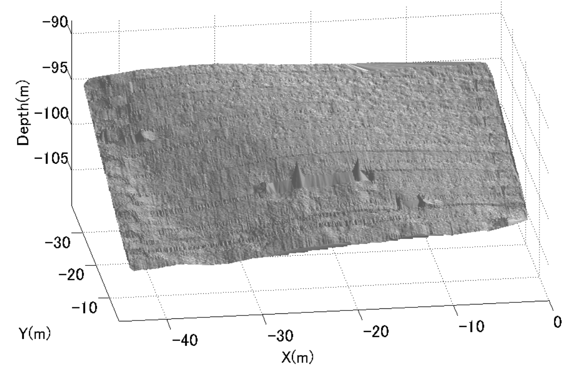

Fig. 11. Bathymetry map without tubeworm colonies used to threshold determination

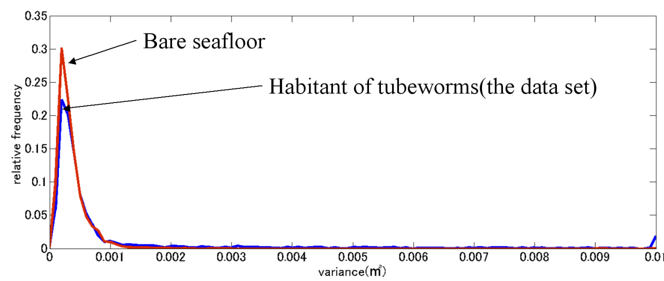

Fig. 12. Histogram of variances of the two data sets

symbolize the swaths in sensor coordinate. The width of each swath is around 2 meters. The green lines are the straight-line approximation of the blue points. Each swath is classified by its variance from the straight-line approximation. A swath is categorized as belonging to group A if it has a large variance, where the threshold is decided by comparison between swaths of habitats of tubeworms and of the bare seafloor. The data set shown in Fig. 9 is used as the habitats of tubeworms. Fig. 11 shows another data set taken at different area without tubeworm colonies, which is used as the bare seafloor to determine threshold. The histogram of variances are indicated in Figs.12 and 13. These figures show that bare seafloor is smooth compared to tubeworms which have a large variance. Fig 13 indicates that there is a clear separation of relative occurrence at more than 0.001 square meters. So, the threshold is decided as 0.001 square meters.

Then, a bathymetry is created using only swaths classified as group B (bathymetry of the bare seafloor). The areas where there is no seafloor information are linearly interpolated to construct an estimated seafloor without tubeworms. Finally, the raised area is obtained as a three-dimensional region that is:

- above the estimated seafloor without tubeworms by more than a certain threshold.
- below the original bathymetry containing tubeworms.

The obtained raised area is shown as (c) in Fig. 9. The raised area contains not only tubeworm colonies but also other

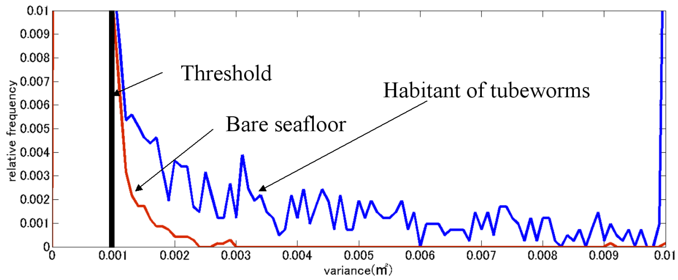

Fig. 13. The enlarged view of the histogram shown in Fig. 12

artifacts like bubbles and litter.

B. Image based verification

After the geometric estimation, the raised area is verified visually using the seafloor images. Fig. 14 shows the outline of image based verification.

First, the raised area is split into separate regions (a). The corresponding images are assessed according to each region (b). The location of the images is decided by the sensor pose at each moment of data acquisition. Fig. 15 shows location of the images. Only the central 600 pixels $\times$ 600 pixels of images (around 60 cm $\times$ 60 cm at an altitude of 2.0 meter) is used during the verification. If the location of an image is in a region, the image is referred as corresponding image of the region. When a region has more than one corresponding images, it is judged as tubeworm colony if more than one images are judged to be tubeworms. This is because the threshold of verification is sufficient to make false-negative judgments but no false-positive judgments. If there is no image whose center point exist in a certain region, the classification of the region is done using the corresponding area of the nearest image, which is sought based on the three-dimensional relationship between the candidate region and the camera.

Since the tubeworms have similar diameters (around 15 mm to 20 mm), their images contain higher spectrum at the corresponding frequency band than other images. Therefore the image is judged by a two-dimensional Fourier transformation; if the spatial frequency of the pixels corresponding 15 mm to 20 mm at an acquisition altitude of 2.0 meters is above a threshold or not. In this case, the range of the pixels are between 15 pixels and 20 pixels. The graph (c) in Fig.14 shows the seafloor images and their power spectrum. The threshold is defined in terms of the sum of the power spectrums of spatial frequency of diameter of tubeworms, S. Assuming $F(u, v)$ is frequency domain of an image and the Fourier spectrum is denoted by $|F(u, v)|$, the sum of the power spectrums of spatial frequency between 15 pixels and 20 pixels is calculated as follows:

$$S = \sum_u \sum_v \log |F(u, v)|_A, \tag{1}$$

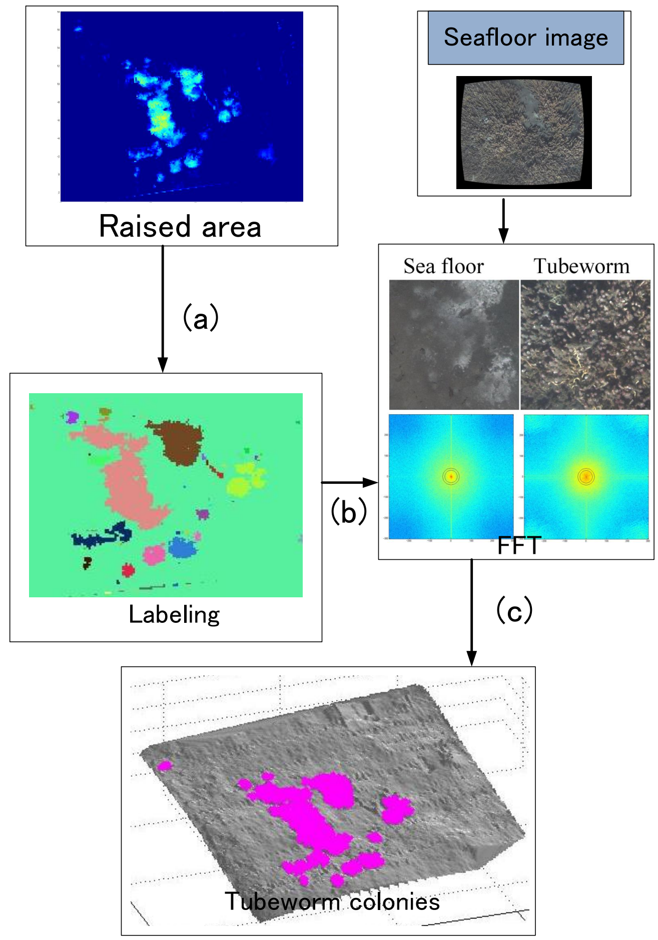

Fig. 14. Outline of image based validation

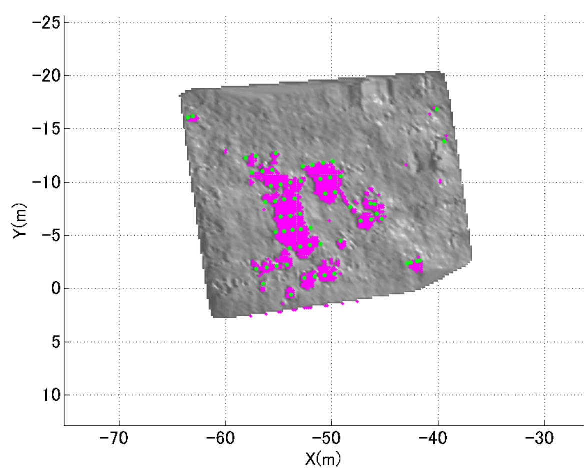

Fig. 15. The location of the images on the raised area (pointed as green dots)

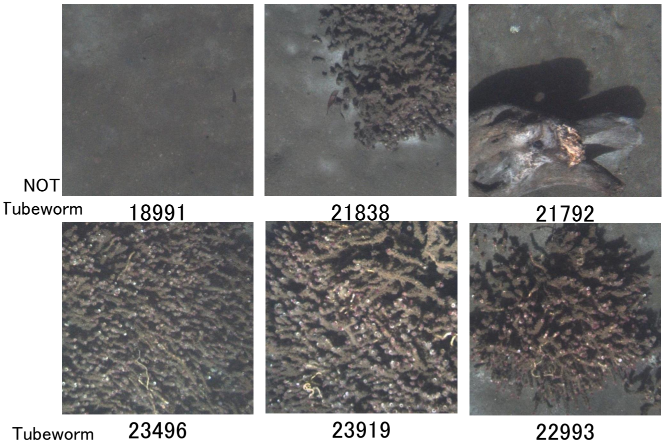

Fig. 16. Seafloor images and their S values

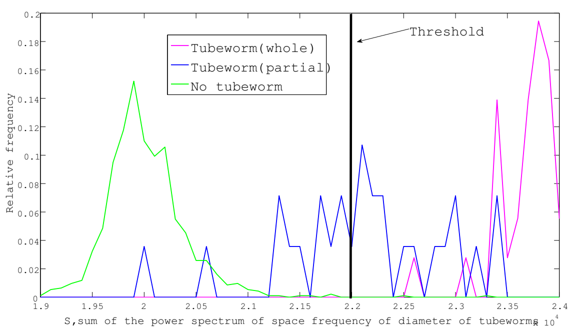

Fig. 17. Histogram of S, sum of the power spectrum in the frequency space for the observed diameter of tubeworms

$$A = \left\{ u, v; \sqrt{u^2+v^2} > \frac{600}{20} \bigcap \sqrt{u^2+v^2} < \frac{600}{15} \right\}. \quad (2)$$

An example of some images and their values of S are shown in Fig. 16. Fig. 17 shows the histogram of S for the three groups of images which were categorized manually. On this occasion, the threshold is 22000 which is the lowest S of the images which are filled by tubeworms. The images of the lower stage in Fig. 16 are judged as tubeworms, while images of upper stage are judged as not tubeworm. Some of images which partially contain tubeworms are judged as not tubeworms. This is because the threshold is set high enough to prevent false positive errors.

IV. Results

A. Comparison with mosaic images

The tubeworm colonies in Fig.14 are the results of the proposed method. Fig. 18 shows the comparison of the results with the photo mosaic shown in Fig.7. The photo mosaic is regarded as ground truth. The pink regions on the left indicate the detected tubeworm colonies and the blue regions are the raised areas that were rejected in the image based verification.

TABLE II
Volume estimation of two data sets(whole)

Year	2009	2007
Volume (m^3)	10.23	8.46
Footprint (m^2)	35.06	27.39
Average height (m)	0.29	0.31

TABLE III
Volume estimation of colony B

Year	2009	2007
Volume (m^3)	2.06	1.76
Footprint (m^2)	7.00	5.76
Average height (m)	0.29	0.30

Comparing the results with the mosaic, there are some small false-negative detections (indicated by the rectangles). There are two reasons for this. One is that an edge of a tubeworm colony is divided at labeling, and so corresponding image is only partially filled by tubeworms. The way of creating and labeling the raised area should be improved to solve this problem. The second is that a tubeworm colony is too small to be correctly judged. The problem would be solved if the size of reference image is suitably changed. There is no false-positive detection in the results. For example, the driftwood (indicated as A in Fig.18) is correctly detected as not tubeworm.

A major advantage of this method is that it enables quantitive measurement of tubeworm colonies. The volume of the tubeworm colonies in Fig.18 is measured as 10.23 cubic meters and the average height is 0.29 meters off the seafloor.

The variance of the height measurements was calculated to be around 2 centimeters according to two data sets of the same area taken in the same cruise. The growth rate of *Lamellibrachia satsuma* is 7 millimeter per year [8], so this error corresponds to about three-year growth. It can be concluded that the method enables discussion of the growth of tubeworm colonies over long periods of time.

B. Comparison with past data set

Fig. 19 indicates the result with a data set, obtained by the same vehicle in 2007. As Fig. 19 shows, the same tubeworm colonies were partially observed. Table II shows the volume of the entire observed tubeworm colonies. As the observed areas are different between the two data sets, their volumes are different. However, the difference of average height is only 2 centimeters, corresponding to 7% of the average height. The volume of one tubeworm colony indicated as B in Figs. 18 and 19 is shown in Table III. Fig. 20 shows the comparison of the results of colony B detected from the two data sets. Since the average height is almost same, it is clear that the volume difference is caused by the footprint difference. Fig. 20 shows that there is a narrow region without tubeworms indicated as C. The results of 2009 detected the region as tubeworms by error. The cause is due to the linear approximation and data blanks when constructing the bathymetry.

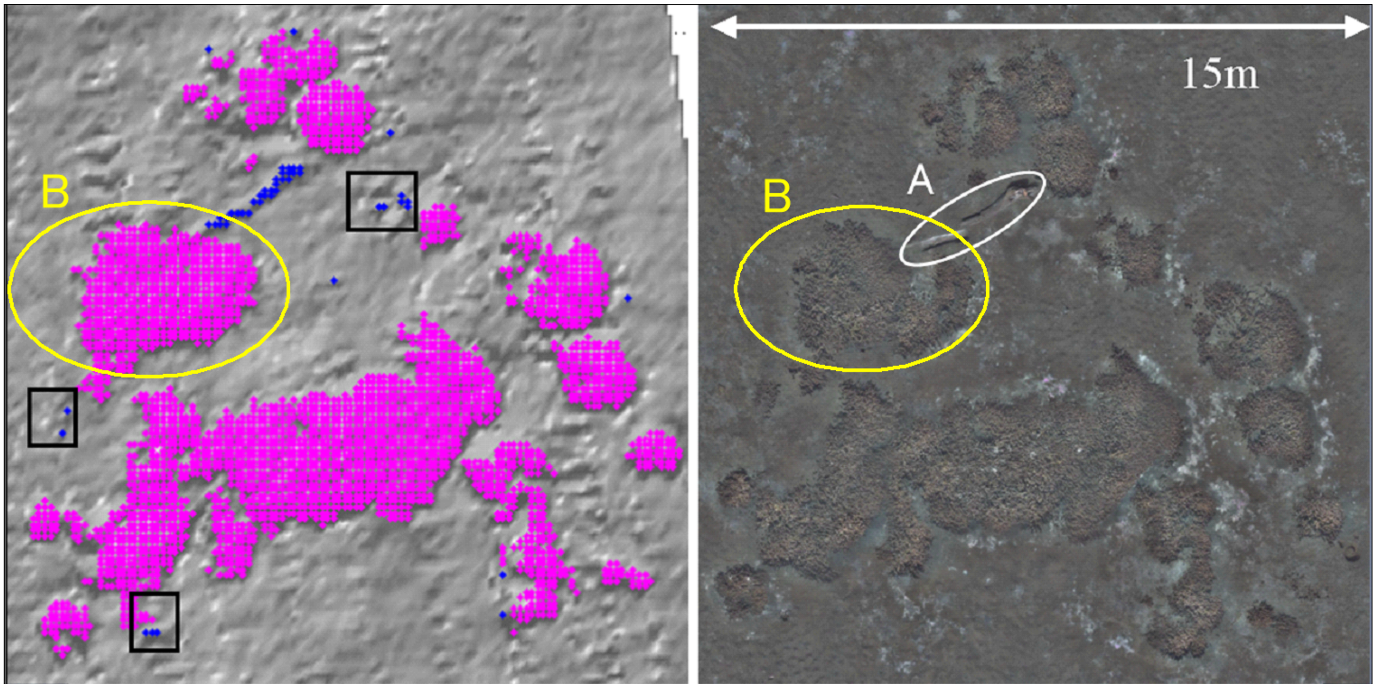

Fig. 18. Comparison of the result with the photo mosaic

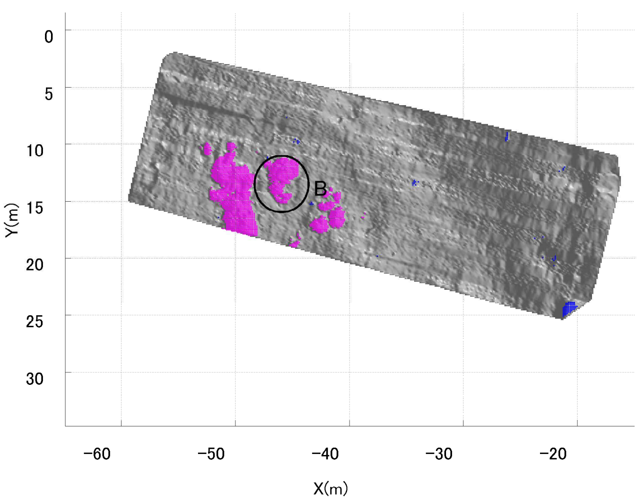

Fig. 19. Bathymetry map of the same region taken in 2007

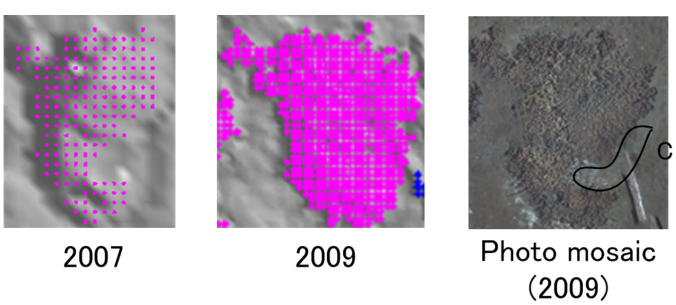

Fig. 20. Comparison of the tubeworm colony B

V. Discussion

The cause of measurement error of the volume is considered as two factors, assuming positioning error of the AUV is neglected. The first factor is error caused by discretization. When a bathymetry mesh is made, profiles are averaged. Each point of the bathymetry is classified as either the raised area or the plain area even if the point is a border between a tubeworm colony and seafloor. Therefore, a bathymetry map and its raised area are affected by scope and resolution of bathymetry. The second factor is the threshold to obtain the raised area. Even if a bathymetry is only slightly lower than the threshold, it is is not included to raised area.

The total bathymetry error was assessed by repeated determination of the depth of a particular region of seafloor, but which is not a habitat of tubeworms. The AUV measured the same region for nine times. The standard deviation of the depth measurement is shown in Fig. 21. It can be explained by the error in the horizontal position estimation of the AUV. The error of horizontal position is around 0.5 meters [3]. Since the slope of the region is about 25 degrees, this error causes up to 0.5 meters $\times \tan(25) = 0.25$ meters of the altitudinal error which exceeds the maximum error shown in Fig. 21.

VI. Conclusion

A method for automatic detection of tubeworm colonies based on 3D reconstructions and images of the seafloor has been developed. The performance of the method was verified using real data sets obtained by an AUV. The method makes a quantitative discussion about the size of natural tubeworm colonies possible. This method will reveal the long term

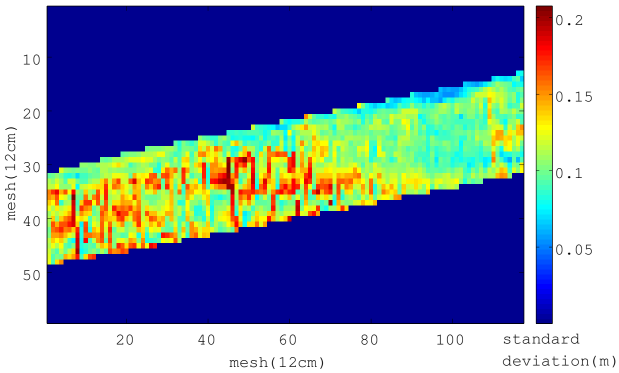

Fig. 21. Standard deviation of depth measurements

variation in the volume and height of tubeworm colonies. This information is significantly important to understand tubeworm colonies and hydrothermal vent area ecology. Furthermore, the method can be extended for detection of other objects by changing the mesh size, spatial frequency and threshold of raised area.

However, in order to perform such studies, it is necessary to first verify the quantitive effect and sensitivity to the choice of threshold value for the raised area and the bathymetry resolution. The method should be verified using a data set of the area whose distribution and volume is known.

By using this method, automatic data processing can be achieved to make optimal use of the large volume of data obtained by AUVs.

VII. Acknowledgement

The authors thank Prof. K. Kubokawa, Prof. T. Yamanaka, Dr. T. Nakatani, Ms. X. Wang and all the staff of the R/V Tansei-Maru for their help (Cruise No. KT-09-19). The authors also thank Dr. H. Singh for his advice on photo mosaicing.

References

[1] S. B. Williams, O. Pizarro, M. Johnson-Roberson, I. Mahon, J. Webster, R. Beaman and T. Bridge, "AUV-assisted surveying of relic reef sites", Proc. IEEE OCEANS'08 Quebec, 2008.

[2] J. Hashimoto, K. Fujikura, T. Miura and J. Ossaka, "Discovery of vestimentiferan tube-worms in the euphotic zone", Proc. JAMSTEC symposium on deep sea research,1993.

[3] T. Maki, H. Kondo, T. Ura and T. Sakamaki, "Imaging vent fields: SLAM based navigation scheme for an AUV toward large-area seafloor imaging", Proc. IEEE/OES AUV2008, 2008.

[4] S. Tetlow and R. Allwood, "Development and applications of a novel underwater laser illumination system", Underwater Technology, 21(2), pp.13-20, 1995.

[5] H. Kondo, T. Maki, T. Ura, Y. Noe, T. Sakamaki and M. Inaishi, "Relative navigation of an autonomous underwater vehicle using a light-section profiling system", Proc. IEEE/RSJ IROS'04, pp.1103-1108, 2004.

[6] S. Thrun, W. Burgard and D. Fox, "Probabilistic Robotics", MIT Press, 2005.

[7] H. Singh, J. Howland and O. Pizzarro, "Advances in large-area photo-mosaicking underwater", IEEE J.Oceanic Engineering, 2004.

[8] T. Miura, M. Nedachi, J. Tsukahara, H. Suzuki and J. Hashimoto, "Nutrition and growth of shallow water vestimentiferan tubeworms Lamellibrachia satsuma", Proc. Zoological science, 2002.