Development of a Landing Algorithm for Autonomous Underwater Vehicles using Laser Profiling

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Abstract— **The autonomous underwater vehicle has proven to be a useful tool for ocean research. However detailed seafloor observations such as microscopic analysis of sand grain structure or study of microbial colonies require a platform with stable footing on the seafloor, which cannot be provided by a cruising type AUV. In this research the authors propose a new class of AUV, capable of landing to provide a stable, but mobile, platform with which to perform these observations. This paper proposes a sensing system and a software algorithm to enable the AUVs to perform landing. A light sectioning based method is used to scan the seafloor with high resolution. Since the seafloor can change abruptly and at short intervals, the reliability and functioning of such technology requires real-time seafloor classification and detection of suitable landing sites. A landing algorithm has been developed which uses three dimensional bathymetry data and calculates a landing vector coordinate in real-time. A microscope sensor payload developed to obtain magnified images of the seafloor after landing has also been tested. Data from sea experiments are presented, where the algorithm demonstrated real-time generation of landing vector coordinates for an ROV.**

I. Introduction

In recent years, the autonomous underwater vehicle (AUV) has established itself as an effective platform for seafloor observation. However, despite the advances in AUV technology, applications that require a stable, stationary platform for observing the seafloor have proved elusive. In order to provide such a platform the authors propose to develop an AUV capable of landing on the seafloor. The AUV would be capable of landing at points separated by a distance within the survey area and traverse at high speeds between landing sites. In order to perform landing the AUV needs an appropriate sensing system and a software algorithm. A negative buoyancy has been proposed for the AUV during operation to avoid use of its thrusters during landing and prevent the sand underneath from being disturbed. Negative buoyancy will however be a problem during forward motion. To compensate for this, a wing structure has been designed to generate lift. Landing skids have been introduced so that the vehicle can land on flat surfaces and provide a stable base once landed. Since the seafloor terrain may be uneven, the development of landing AUV technology relies on autonomous seafloor classification algorithms and hardware with which to make measurements and identify suitable landing sites. The authors propose a seafloor measurement system based on light sectioning to scan the seafloor with centimeter order resolution. Using this technique a landing algorithm has been developed that classifies the seafloor in real-time and finds a suitable landing site for the AUV to land.

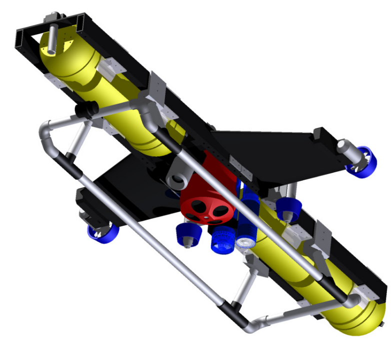

Fig. 1. Landing AUV hardware setup

The AUV mission scenario is divided into a series of three stages. In the first stage, the AUV covers a distance of about 100m at 1.5 knots speed maintaining an altitude of 5-10m before searching for a suitable landing site. While cruising the AUV uses its thrusters for forward propulsion and a forward looking sonar for obstacle avoidance. The wings generate lift to compensate for negative buoyancy during forward motion. In the second stage, it lowers altitude to about 2m and cruises at a lower speed of 0.1m/s to perform laser scanning of a patch of approximately 10x2m in area. Once scanning is complete the landing algorithm is used to compute if a landing area is available and identify a landing coordinate and heading angle. The AUV is then given a landing command. In order to get microscopic images of the seafloor an underwater microscope has been developed as a payload sensor. Once landed, the AUV uses the microscope to take seafloor images. These stages are performed in a cycle up to the end of the mission.

The proposed sensor system was deployed at sea using a ROV onboard the research ship R/V Kaiyo during the KY10-04 cruise. The landing algorithm was implemented in real-time to detect suitable landing sites where the ROV was made to land and microscopic images of the seafloor were taken. A landing AUV is currently under development at

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the Underwater Robotics and Applications Lab, University of Tokyo. The landing algorithm will be used to perform autonomous real-time seafloor landing.

II. Problem Formulation

The seafloor can adopt various different topologies as illustrated in figure 2. Furthermore the seafloor can change abruptly and at short intervals. Since it is not always safe for a vehicle to land, the development of landing AUV technology requires classification the seafloor in real-time to identify flat regions where the AUV can land safely.

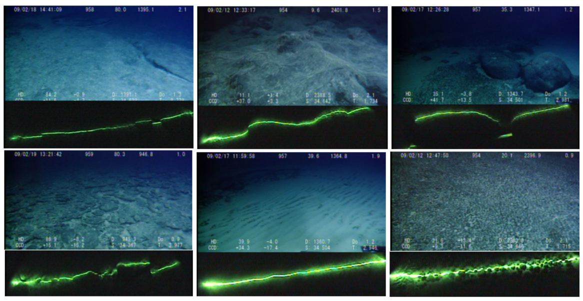


Fig. 2. Seafloor images and laser profiles taken during NT09-02 Leg2[1] using the ROV Hyper Dolphin

A landing algorithm capable of automatically detecting flat regions for the robot to land will be an essential part of the landing system. The landing algorithm should be capable of generating an autonomous landing command for the AUV and perform landing operations. A landing direction should also be identified in case the landing area is not oriented along the direction of travel of the vehicle. In this case the AUV will need to realign its heading before landing. However before a landing algorithm can be developed, a sensing system capable of scanning the seafloor with centimeter order resolution must be developed.

III. Profiling Hardware

To identify seafloor features it is essential to scan the seafloor with high resolution. A laser profiling system [2][3] is proposed to map the seafloor with centimeter order resolution. The hardware consists of a sheet laser and camera assembly to capture the seafloor profile and navigational sensor data to convert this profile into actual bathymetry coordinates. The laser used in this system is a sheet laser with an opening angle of 64.2° in water. The laser is mounted vertically and projects down onto the seafloor surface. The camera used has a horizontal opening angle of 61° and vertical opening angle of 50.3° in water, with a pixel resolution of 640x480. Underwater housings have been constructed for the camera and laser so that they can be used for depths of up to 3000m. As shown in Figure 3, camera and laser are mounted on a platform separated from each other with a baseline of 700mm. The camera is mounted at 77° angle with the horizontal plane.

During operation the sheet laser projects onto the seafloor surface below and this projection is captured by the camera to obtain an image as seen in figure 4. Position information, specifically depth and vehicle x, y, z, roll, pitch, yaw information in real world coordinates are obtained from the AUVs position system. These can be measured using a depth sensor and Doppler Velocity Log (DVL). This data is used to convert the laser pixels into actual three dimensional bathymetry coordinates based on triangulation. This system was tested at the tank facility available at the University of Tokyo. The setup was mounted on the AUV Tuna Sand and test runs were performed over objects of known size. Figure 5 shows a plastic cylinder and a metal weight being scanned by the sheet laser. This profile image was captured by the camera and from the AUVs position information, the pixels were assigned real world coordinates as shown in the figure 6.

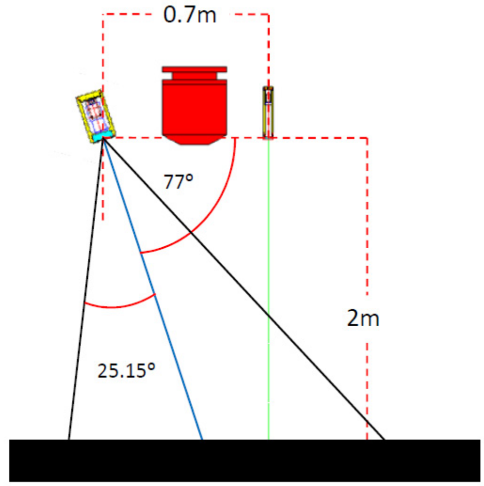


Fig. 3. Laser Profiling Hardware

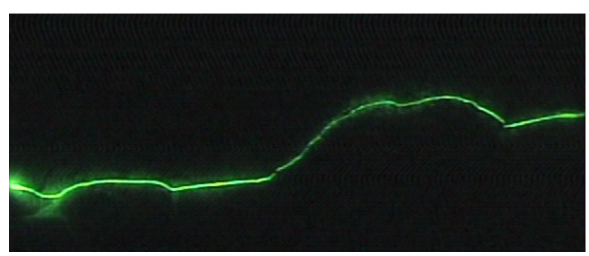


Fig. 4. Laser Profile of a boulder

The average height of the plastic cylinder measured by the system was 389mm, where actual height is 395mm. The height of the metal weight was measured as 187mm while its actual height was 200mm. The profiling system ideally operates at an altitude of 2m off the seafloor, with a vehicle surge velocity of 0.1m/s to provide sufficient vertical and horizontal resolution

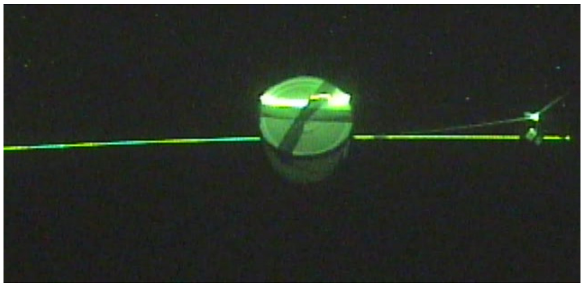


Fig. 5. Laser profile of a plastic cylinder and metal weight being scanned in test tank

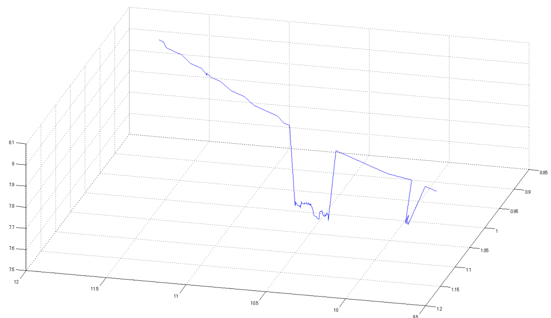


Fig. 6. Plastic cylinder and metal weight converted into actual 3D bathymetry data

in both x and y directions. Under these conditions the system has a swath of 2.5m, a vertical resolution of 6 to 10mm, a horizontal resolution of 4 to 6mm across the section, and a resolution of 6 to 10mm along the path taken by the vehicle. This provides sufficient resolution for the landing algorithm to work effectively.

IV. Landing Algorithm

The landing algorithm is applied when the AUV enters the second stage of operation, where a suitable flat region needs to be located for the AUV to land safely. The AUV performs laser profiling of the seafloor at a slow velocity of 0.1m/s at an altitude of 2m. After scanning for a distance of 10m, the laser profile images captured by the camera are processed and three dimensional bathymetry is generated. During this processing period the AUV maintains a fixed position. Since landing areas are defined on a local scale, the DVL's accumulation error in the position data does not pose any degradation in performance.

Once a 10x2m patch of seafloor bathymetry has been generated, spectral analysis is carried out. Different surfaces, flat or bumpy, exhibit different frequency components which can be used to distinguish between them. Surface classification information is used to determine automatically whether the seafloor is flat enough for the AUV to land. Different stages of the landing algorithm are illustrated in the form of a flowchart in figure 7.

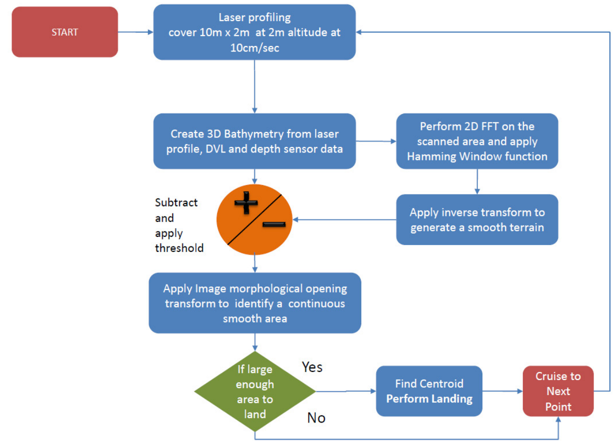


Fig. 7. The Landing Algorithm

A. Bathymetry Generation

The first stage involves scanning a 10x2m patch of seafloor, with the major axis in the direction of travel of the AUV, with high resolution using the laser profiling system as described earlier in Section III. The pixels from the laser profile are converted to actual 3D bathymetry coordinates using position information from the DVL and depth sensor. A complete three dimensional bathymetry mesh, with dimensions proportional to those of the region scanned, is generated of the area where the landing algorithm will be applied. Figure 8 shows the three dimensional bathymetry generated of an area observed during NT09-02 Leg2, scanned left to right and the images taken using a forward looking camera.

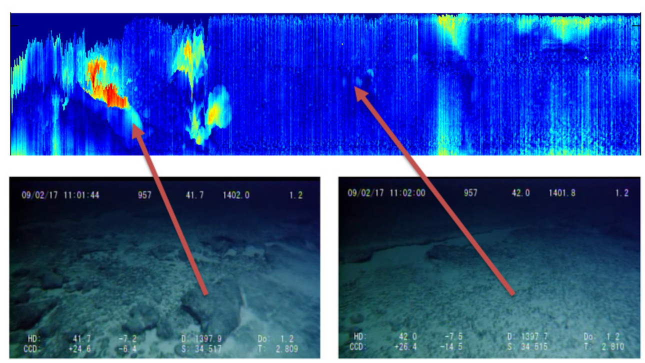


Fig. 8. (Top) Three dimensional bathymetry (Bottom) Seafloor images taken using a forward looking camera

B. Spectral Analysis

Different surfaces exhibit different frequency components depending on their shapes and dimensions. By considering the laser profile as a series shape data, we can perform spectral analysis to find bumpy areas and also identify flat landable areas. A 2D FFT is performed on the bathymetry data to determine its frequency components. The bathymetry data is converted into frequency domain data.

C. Identification of flat areas

A two dimensional Fourier transforms converts the bathymetry into frequency components. Extremely low frequency components represent the flat surfaces. We can then mask the high frequency components by using a two dimensional Hamming window function. The Hamming window can represented as:

$$w(u1,u2) = \begin{cases} [0.54 + 0.46\cos(\pi u1/U1)][0.54 + 0.46\cos(\pi u2/U2)] & \text{if} |u1| < U1 \text{ and } |u2| < U2 \\ 0 & \text{elsewhere} \end{cases}$$

where u1,u2 are the frequency components under analysis. U1 and U2 represent the cut-off frequencies along the two dimensions.

By multiplying the FFT data with the Hamming window, element by element, we can mask the high frequency components which represent the bumps and pebbles. An inverse 2D Fourier transform can then be applied to produce a smoothened out bathymetry. This can be subtracted from the original bathymetry to generate a map of the area which highlights the bumpy areas as seen in figure 9.

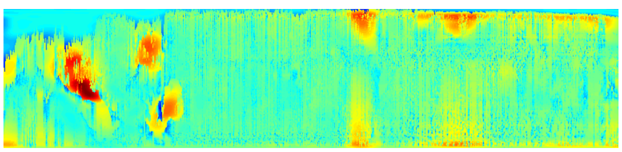


Fig. 9. Difference bathymetry

A threshold is used to separate the flat region from the bumpy non landable areas as shown in figure 10. The threshold to qualify a region suitable for landing remains fixed.

Fig. 10. Difference bathymetry after applying threshold, red - flat areas; blue - bumpy areas

Once the obstacles large enough to cause trouble for the AUV to land have been found, a continuous patch of land suitable for landing needs to be identified. For this operation the threshold bathymetry is considered as a binary scaled image and simple image processing operators are used.

D. Finding a suitable region to land

The final step in the algorithm involves finding a suitable continuous flat patch of land for the AUV to perform landing operations. The concept of finding a suitable landing site can be considered as fitting an object of a given size into a continuous red region of the image, which in this case corresponds to landable areas. The opening morphological image processing operator can be used to fit a structuring element into an image and find regions where it fits completely within a boundary. The structural element chosen here corresponds to the size of the robot which needs to land in the area. Considering the area scanned to be a set of points B containing only two types of elements, landable and non landable. The structural element R is a mask of the size of the robot which is trying to land. Opening operation is performed by an erosion process followed by a dilation process. This can be expressed as:

$$B \circ R = (B \ominus R) \oplus R$$

where $\ominus$ represents erosion and $\oplus$ represents dilation operation. By performing opening operation multiple times, we can find an area suitable for landing in which the AUV can fit. In our case the robot is considered to have a size of 1x2m. Figure 11 shows the results after opening is performed by orienting the mask in the direction of motion of the AUV.

Fig. 11. Opening the image

By orienting the structural element in a different direction we can find out if a landing site oriented along a different direction to that of travel is available. By using a mask with its major axis normal to the length of scanned area, i.e. the robot landing perpendicular to its direction of travel, we can find more candidate landing sites as shown in figure 12. This can be extended to other orientations.

Fig. 12. Opening the image with a different mask

The landing vector for the AUV can then be decided by computing the centroid of the continuous region which is found suitable for landing and passing direction information concerning the orientation of the mask to decide the AUVs heading. If more than one separated flat region is detected, the candidate region with the largest area is considered to be the landing site. In the example, this is shown in figure 11 by the filled triangle. The empty triangles in figure 12 were rejected in favor of that in figure 11, since they had a smaller flat area. Note that the heading is in the opposite direction to the scanning direction since the vehicle must return back to this point for landing.

V. Payload Sensor

In order to obtain magnified images of the seafloor, an underwater microscope has been developed. Microscopic images are useful for microbial and sand grain size analysis [4]. The microscope used has a fixed focus lens with 60mm focal length in water. In this study, the observed area was 3x4mm across with a pixel resolution of 6.25μm. An underwater housing has been made for the camera which was test rated to 3000m. In order to focus the microscope images, a linear stage has been constructed. Figure 13 shows the microscope assembly mounted on the linear stage.

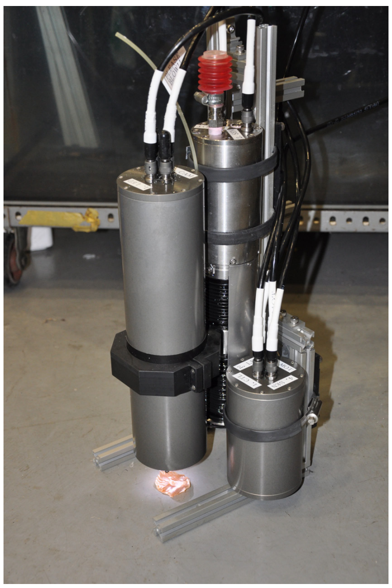


Fig. 13. Microscope and linear stage assembly

A sample underwater microscope image of a hydrothermal chimney rock sample can be seen in figure 14. Objects are illuminated by white light LEDs, also developed as part of the system. The linear stage can be used to focus on different layers of the rock and perform a 3D microstructure analysis of the target.

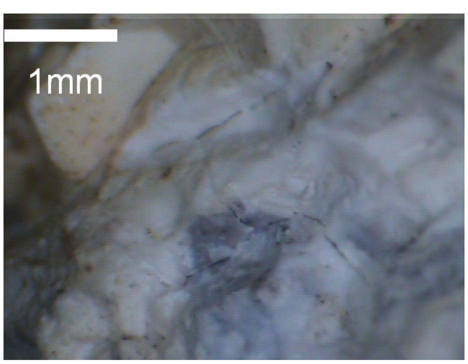


Fig. 14. Hydrothermal vent sample

VI. Experiments

Experiments were performed in March 2010 during the KY10-04 cruise of R/V Kaiyo at Teishi Knoll, Japan which erupted on July 13th, 1989. During this cruise the AUV Tuna Sand [5] was used as the test vehicle. The laser profiling hardware was mounted on the vehicle along with microscope payload sensor. Figure 15 shows the hardware setup mounted on the vehicle and some of its specifications. Four dives were performed in the region at different spots. During the survey, the vehicle was tethered and operated as a ROV.

Length	1.1 m
Width	0.7 m
Height	0.71 m
Weight	240 kg
Max. Depth	1,500 m
Max. Speed	1.7 knots
Duration	5 hours
Thruster	220W × 4 100W × 2
OS	VxWorks
Battery	50.4V NiMH 9Ah × 4

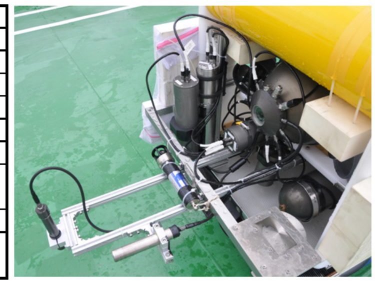


Fig. 15. Setup on AUV Tuna Sand

The landing algorithm was implemented in real-time at different locations. Real-time analysis was performed and suitable landing sites were found. The vehicle was made to land manually at the calculated landing spots and the underwater microscope was used to take microscopic images of the seafloor. Data from dives TS#34 and TS#35 are presented here (figure 16), since the two areas had different types of terrain. In this study we present the data from the second scan performed in TS#34 and the fourth scan performed in dive TS#35.

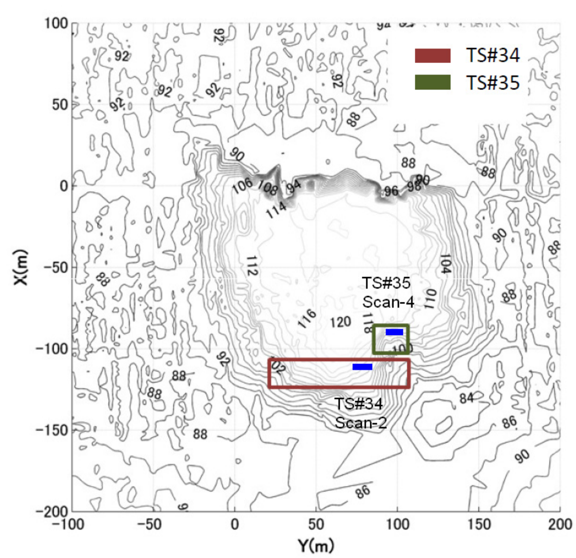
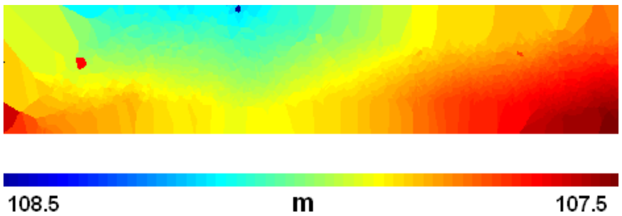


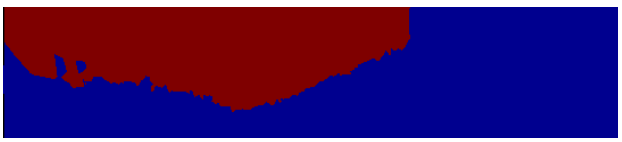
Fig. 16. Dive Area

A. *Dive: TS#34 Scan-2*

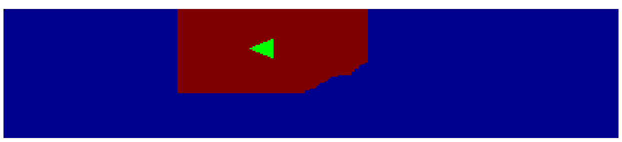
A 10x2m patch of land was scanned and bathymetry was generated from an altitude of 2m. Figure 17 shows the result of the analysis.



(a) Bathymetry Contour



(b) Detected flat region



(c) Detected landing site

Fig. 17. Analysis of Scan-2

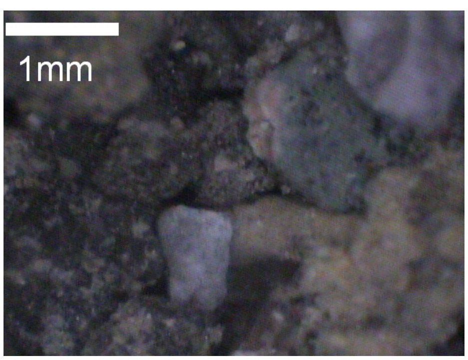


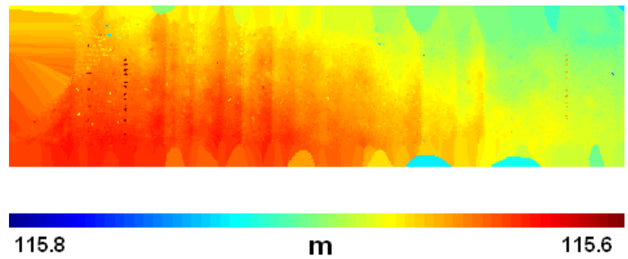
Fig. 18. Coarse grain sand structure

The area was scanned left to right and the landing algorithm was implemented. The terrain observed was generally bumpy, but a site in the centre of a flat area was defined as the landing site with the robot heading in the direction opposite to the direction of the travel since the vehicle has to come back to this landing spot. Successful landing was performed and microscopic images of the seafloor were taken. The sand grain structure observed was coarse as seen in figure 18.

B. *Dive: TS35 Scan-4*

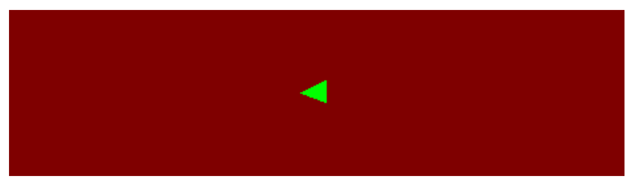
A 10x2m patch of land was scanned from left to right and processed in real time to identify potential landing sites.

Figure 19 shows the bathymetry of the scanned surface. The surface was flat as compared to the scan presented for TS#34. The landing algorithm was implemented and it identified the entire patch as landable. In this case the algorithm defines the centre of the scanned area as the landing site with the robot heading opposite to the direction of travel.



(a) Bathymetry Contour

(b) Detected flat region



(c) Detected landing site

Fig. 19. Analysis of Scan-4

Microscope images of the seafloor were taken. The sand structure was found to be fine in this flat region as seen in figure 20.

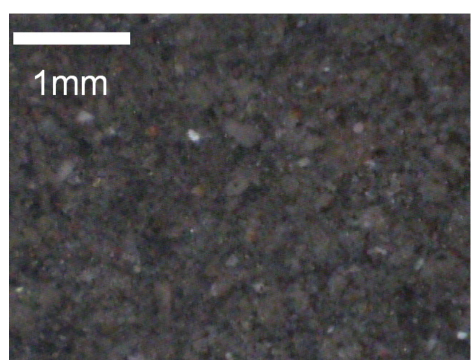


Fig. 20. Fine grain sand structure

VII. Conclusion

This research has proposed a system to allow AUVs to land on the seafloor. The necessary hardware and mission scenario have been discussed. To obtain high resolution seafloor bathymetry a scanning system based on laser profiling has been implemented and tested. A landing algorithm has been developed which uses this bathymetry data and identifies a suitable landing site for an AUV in real-time. An underwater microscope was developed as a payload and microscopic images of the seafloor were taken. The system was implemented at sea and the results showed that the landing algorithm can be used on an AUV to generate a landing vector coordinate. In future work we aim to extend the algorithm to perform real-time seafloor classification and mapping of different seafloor topologies.

Acknowledgment

The authors would like to thank the crew of the R/V Natsushima and the Hyper-Dolphin ROV team during the NT-09-02 Leg2 research cruise and the crew of R/V Kaiyo during the KY10-04 cruise and the members of JAMSTEC for their support during the ROV operations and experiments at sea.

References

[1] Blair Thornton, Akira Asada, Tamaki Ura, Mehul Sangekar, Katsumi Ohira, *A Case study to demonstrate remote acoustic measurement of Ferro manganese crust thickness* 21st Ocean Engineering Symposium.

[2] Chu-Chang Wang, Dajun Tang. *Seafloor Roughness Measured by a Laser Line Scanner and a Conductivity Probe* IEEE Journal of Oceanic Engineering, October 2009

[3] Hayato Kondo, Tamaki Ura. *Navigation of an AUV for investigation of underwater structures* Control Engineering Practice 12 (2004) 1551-1559, December 2003

[4] David M. Rubin, Henry Chezar, Jodi N. Harney, David J. Topping , Theodore S. Melis, Christopher R. Sherwood. *Underwater microscope for measuring spatial and temporal changes in bed-sediment grain size* Sedimentary Geology 202 (2007) 402-408

[5] Takeshi Nakatani, Tamaki Ura, Takashi Sakamaki, Junichi Kojima, *Terrain based localization for pinpoint observation of seafloor* IEEE Oceans'09, Bremen, Germany, May 2009.