This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

Multi-robot multimodal deep sea surveys for detailed estimation of Manganese crust distribution

Umesh Neettiyath, *Member, IEEE,* Harumi Sugimatsu, *Senior Member, IEEE*, Tetsu Koike, *Non-Member, IEEE*,
Kazunori Nagano, *Non-Member, IEEE*, Tamaki Ura, *Fellow, IEEE*, and Blair Thornton, *Member, IEEE*

***Abstract*—This paper describes a multi-year survey of Cobalt-rich manganese crust (Mn-crust) deposits using multiple underwater robots. Using two autonomous underwater vehicles and one remotely operated vehicle, mounted with camera systems, multibeam sonar and sub-bottom sensors, large areas were surveyed by incorporating the advantages of each robot to create a comprehensive database of Mn-crust distribution estimates. The robots clocked in a total of 438 hours of seafloor observation, surveying about 589 km of seafloor in different locations. Specific use cases of the survey methodology and example results showing how each sensor contributes to the understanding of Mn-crust distribution are shown. The results from this survey can be combined with ship base multibeam data for seamount scale estimates of Mn-crust volumetric distribution with high accuracy.**

***Index Terms*—Mn-crust, AUV, Multi-robot, Deep-sea surveys, 3D mapping, Deep-sea mineral, ROV, Multi-AUV.**

I. INTRODUCTION

THE continuous advancement of technologies is driving the need for greater quantities of minerals to support innovation. Advancing technologies like electric vehicles, smartphones, and the global push for a carbon-neutral society have significantly increased the demand for batteries, which rely on essential metals such as cobalt and nickel. As conventional land-based mineral deposits struggle to meet this escalating demand, there is a growing interest in exploring and exploiting mineral resources located on the seabed [1]. This trend is particularly crucial for island nations like Japan, which lack significant land-based mineral reserves and hence prioritize the exploration and utilization of seabed mineral resources. Primary classes of mineral deposits on the seabed are Polymetallic Nodules, Cobalt-Rich Manganese Crusts (Mn-crust), and Polymetallic Massive Sulphides [2]. While there has been significant interest on exploring Polymetallic nodules, including trial mining exercises recently, Mn-crusts have not been explored as much [3]. The exploration and extraction of seabed mineral resources are regulated by International Seabed Authority (ISA), a subsidiary of the United Nations. ISA has allotted four contracts to agencies around the world for exploration of Mn-crust for 15 years [4]. The regulations dictate that one-third of the area has to be relinquished at the end of 8th year and 10th year each, and the final one-third of the area can be used for mineral extraction. The Japan contractor with ISA is Japan Organization for Metals and Energy Security (JOGMEC).

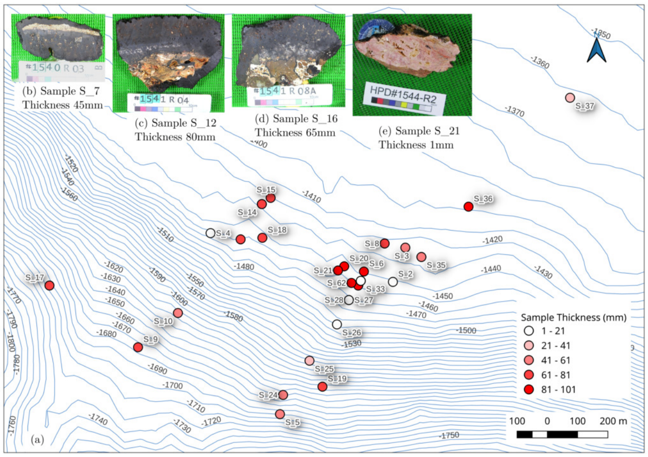

Fig. 1. (a) ROV collected Mn-crust samples in a 2km x 1.5km area in the Northwestern Pacific Ocean. 37 samples are shown with thickness varying from a few millimeters to 95 mm. (b), (c), (d), and (e) shows photos of selected samples. The structure of Mn-crust - with black top section being Mn-crust and below section being substrate rock, can be seen. This variability of thickness was later confirmed in surveys by AUV Boss-A. Data courtesy JAMSTEC/UTokyo

In order to estimate the resource potential of Mn-crusts, it is necessary to understand its formation, composition and distribution. Mn-crusts are hydrogenetically precipitated deposits formed on hard surfaces on the seafloor [5]. They occur on the slopes and shoulders of seamounts kept free of tectonic activities for millions of years, at depths ranging from 800m to 2400m, with some samples found as deep as 7000m. The thickness of Mn-crusts vary from a few millimeters up to 25 cm [2], although thicker Mn-crusts are very rare. The cross-sectional structure of several Mn-crust samples are shown in Fig. 1, with the black top section being the Mn-crust and the brown bottom section being the substrate rock on which the crust is formed. It can be seen that the thickness can vary from a few millimeters to about 95 mm within a range of a

Umesh Neettiyath and Harumi Sugimatsu are with the Institute of Industrial Science, The University of Tokyo, Japan (e-mail: umesh@iis.u-tokyo.ac.jp)

Tetsu Koike is with Kaiyo Engineering Co., Ltd. and is associated with the Institute of Industrial Science, The University of Tokyo, Japan (e-mail: koike@kaiyoeng.com)

Kazunori Nagano is with IDEA Consultants, Inc. and is associated with the Institute of Industrial Science, The University of Tokyo, Japan (e-mail: k-nagano@iis.u-tokyo.ac.jp)

Blair Thornton is Professor at the Maritime Robotics Laboratory, Southampton Marine and Maritime Institute, Faculty of Engineering and Physical Science, The University of Southampton, with an adjunct position at the Institute of Industrial Science, The University of Tokyo, Japan (e-mail: b.thornton@soton.ac.uk)

Tamaki Ura is Professor Emeritus at the Institute of Industrial Science, The University of Tokyo, Japan (e-mail: ura@iis.u-tokyo.ac.jp)

This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

few tens of meters. While this is a dense sampling scenario; in most practical applications, only one sample per several square kilometers is collected, which is largely insufficient to provide an accurate estimate of Mn-crust distribution.

II. RELATED RESEARCH

Survey of Mn-crust deposits are more difficult compared to Polymetallic nodules - the former requires both the thickness and the lateral coverage to be measured, whereas the latter requires only the lateral coverage in order to calculate the volumetric distribution [6]. Stakeholders and researchers around the world have attempted several methods for estimating the resource potential of Mn-crusts. Since they are distributed over seamounts spanning hundreds to thousands of square kilometers, accurate estimation is a challenging task. Typically shipboard multibeam backscatter and bathymetry data is used for estimation, combined with a near-bottom survey such as towed video [7], Remotely Operated Vehicle (ROV) video, ROV sidescan sonars [8], or sub-bottom profiler (SBP) [9]. Towed sensors and ROVs provide an output quality inferior to AUV surveys due to the effect of tether forces. SBP surveys can estimate sediment layer thickness, typically with resolution of several meters, but cannot detect Mn-crust thickness or lateral coverage. All of these methods rely heavily on the visual confirmation of the seabed in a small area; whose accuracy has a significant impact on the final estimates. It is therefore important to collect large ground truth datasets for more accurate resource estimation; this is one of the main themes addressed in the present work.

A robotic approach was used for Polymetallic nodules estimation combining Autonomous Underwater Vehicles (AUV) based multibeam and image surveys with ship-based multibeam surveys [10]. This survey used a single AUV over multiple dives. Multi-AUV approaches have been proposed for other applications, such as archaeological sites survey [11], although the field surveys was conducted using a single AUV. One of the motives of the present work is that by using multiple robots in tandem, we can collect more diverse multimodal data suitable for better estimation.

Thickness of Mn-crust and its variability are equally important to the estimation. While most researchers depend on physical samples collected by ROVs, dredges, or core drills for this purpose; it is expensive, time-consuming and provides a very low spatial resolution. For example, a typical Benthic Multi-core System (BMS), used by JOGMEC, collects a maximum of 5 samples during one day of operation from within a few square km of area. In order to measure the continuous variation of thickness, the authors developed an acoustic sub-bottom probe for in-situ measurements [12], and validated it in the area shown in Fig. 1. A similar device was developed a few years later by a research team from China for surveying areas allotted to China Ocean Mineral Resources Research and Development Association (COMRA) [13].

In addition to increasing the spatial resolution of thickness measurements, the authors were able to combine the thickness results with simultaneously collected visual mapping data in order to estimate volumetric distribution over hectare scale areas by using an underwater robot [14]. These results demonstrated the utility of underwater robots - mainly AUV and ROV - for getting high accuracy Mn-crust estimates. However, the robot should operate close to the seafloor (1~2 m) for the thickness measurements, thereby limiting the lateral area visually surveyed. Hence it is necessary to collect data from larger areas, albeit at lower resolution, which can intermediate between decameter resolution ship collected multibeam sonar maps with millimeter resolution AUV based measurements. The authors are attempting to bridge this gap by surveying using multiple robots and different sensors (multimodal) at varying resolutions, and combining the data in order to get higher accuracy estimates of Mn-crust distribution over seamount scale regions.

TABLE I
SPECIFICATIONS OF THE PLATFORM (AUV BOSS-A)

Dimensions	3.0 m x 1.15 m x 1.25 m
Mass	580 kg
Operating velocity	0.3 kn (0.15 m/s)
Operating altitude range	1.5 ± 0.5 m
Depth rating	3000 m
Endurance	7 h
Payloads	Acoustic thickness probe SeaXerocks1 mapping system

III. SYSTEM OVERVIEW

A multi-robot multimodal approach was used by the authors to survey Mn-crust deposits. Three robots - two AUVs and an ROV are brought together to take advantage of the different sensors and navigational capabilities of each as shown in Fig. 2.

A. Robots

1) AUV Boss-A: is a hovering type AUV built in 2014 by the University of Tokyo for surveying Mn-crusts using the acoustic thickness probe. Being a hovering type robot, it is designed to operate close to the seabed at altitudes around 1.5 m and moves slowly at 0.15m/s in order to avoid obstacles. In addition to measuring sub-surface reflections using the acoustic probe, it also creates a 3D reconstruction of the seabed using SeaXerocks1 system. The data analysis methodology is described in section IV-B.

2) AUV AE2000f: is a cruising type AUV developed by KDDI research labs in 2001 for seafloor cable surveys. It was transferred to the University of Tokyo in 2012, renovated, and was used for high altitude (10m) large area mapping of the seafloor using the SeaXerocks3 seafloor mapping system. Using the streamlined shape and higher altitude from the seabed, it can operate at relatively higher speeds up to $1m/s$. It can travel up to 20 km in a single dive and can therefore cover larger areas compared to the other robots.

3) ROV QUASAR9: is a work-class 3000m rated ROV owned and operated by Nippon Salvage Co. Ltd. In the payload section of the ROV, sensors for surveying the seafloor were attached as shown in Fig. 5. Since the ROV is manually operated, it could traverse more rugged terrain, such as cliffs

This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

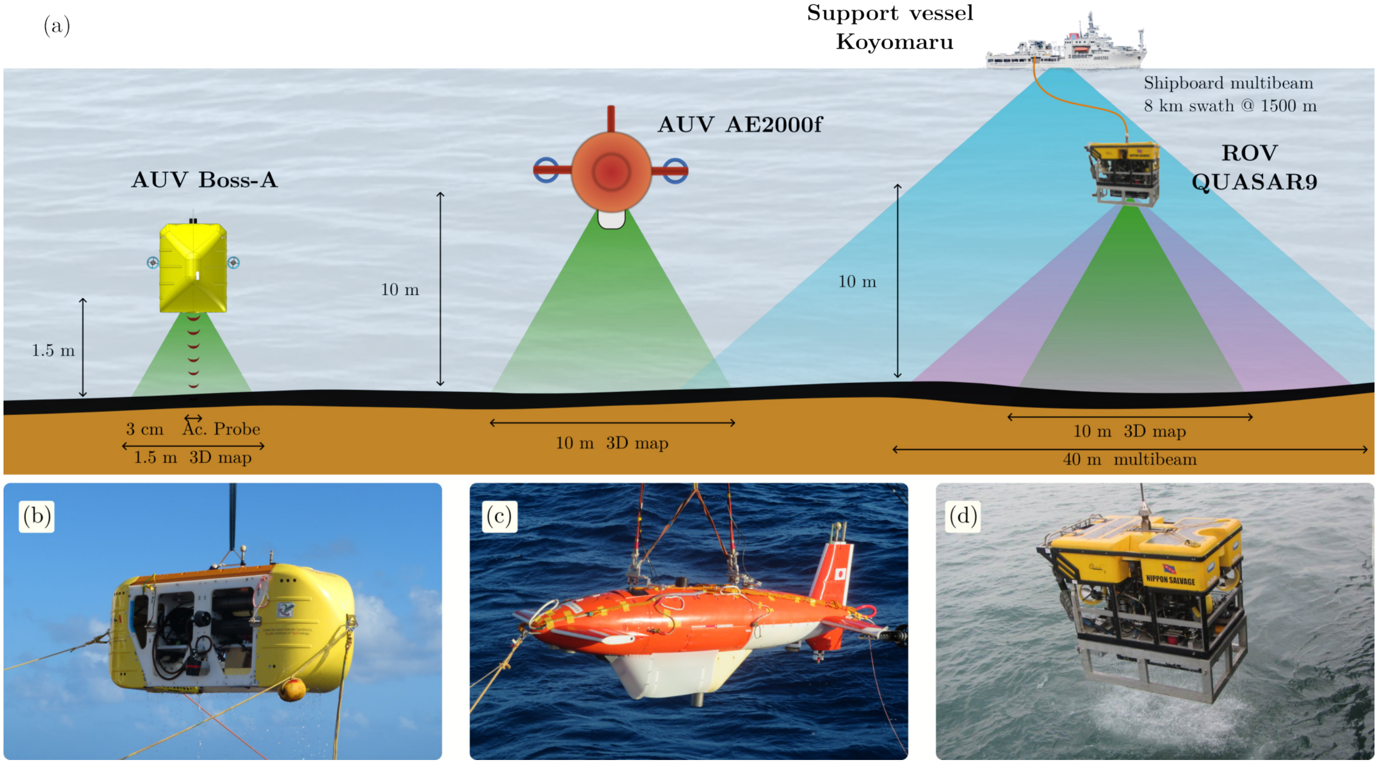

Fig. 2. (a) Conceptual overview of mapping scenario by different robots used in this survey (figure not to scale). Field deployment photos of each robot is shown below. (b) AUV Boss-A is used for Mn-crust thickness estimation and high-resolution survey. (c) AUV AE2000f is used for large area surveys. (d) ROV is used for surveying locations normally inaccessible using AUVs.

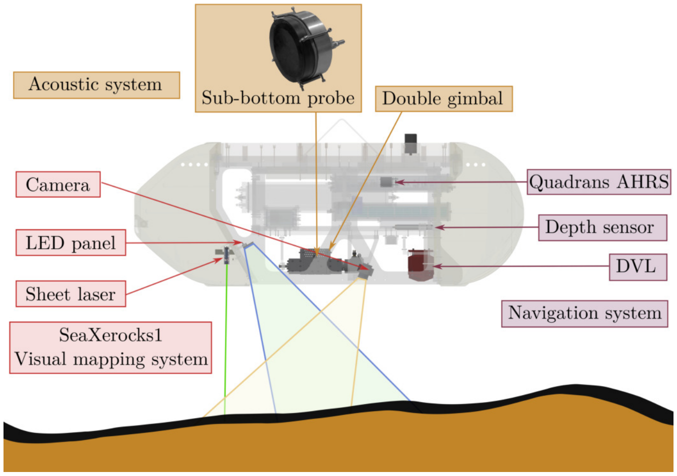

Fig. 3. Schematic representation of Boss-A showing sensor subsystems and their components. Specifications of the AUV are shown in Table I.

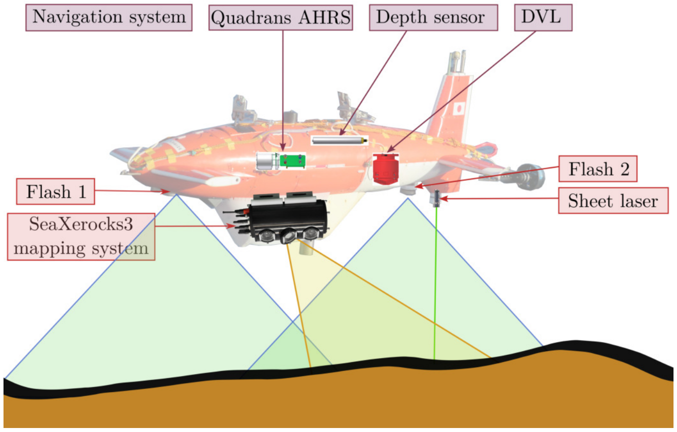

Fig. 4. Schematic representation of AE2000f showing sensor subsystems and their components. Specifications of the AUV are shown in Table II.

and steep sections of the seabed. Although existence of Mn-crust deposits in such regions is known, these areas are avoided by AUVs due to operational safety. The ROV operate at an altitude of about 10m from the seafloor generating 3D maps of centimeter order resolution using SeaXerocks3 system. The visual 3D mapping and navigational components are same as the ones installed in AE2000f. The power and communications are obtained through ROV tether cable. However, unlike the AUVs, the ROV data is monitored and adjustments made real-time using a visualization software from the shipboard control room.

B. *Sensor systems*

Specifications of the sensor systems used are provided in Table IV. These sensors are paired with a navigation system, which consists of the AUV's navigational sensors. These include an iXblue Quadrans Attitude Heading Reference System (AHRS) for pose estimation, Doppler Velocity Log (DVL)

This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

TABLE II
SPECIFICATIONS OF THE PLATFORM (AUV AE2000F)

Dimensions	3.0 m x 1.3 m x 0.9 m
Mass	370 kg
Operating velocity	2 kn (1 m/s)
Operating altitude range	10 ± 2 m
Depth rating	2000 m
Endurance	6 h
Payloads	SeaXerocks3 mapping system

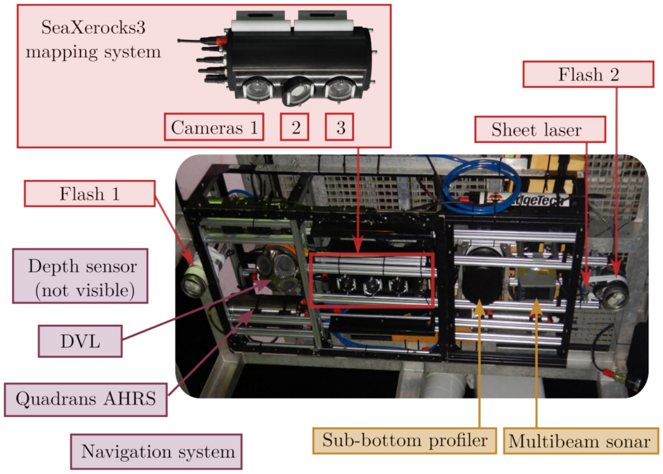

Fig. 5. For surveys using the ROV, the sensors were mounted on a payload skid installed at the bottom of the robot. The visual 3D mapping and navigational components are same as the ones installed in AE2000f. In addition, a multibeam sonar is installed for simultaneous wide area acoustic survey.

for self-localisation, Paroscientific pressure sensor for depth measurement, and an iXblue GAPS system for localisation from the support vessel.

1) Acoustic probe for thickness: is a parametric sonar that records subsurface reflections of the seafloor for estimating the Mn-crust thickness [12]. The probe consists of a five-channel annular array of 2-MHz piezoelectric transducers for transmission and a 200-kHz piezoelectric transducer to record reflections. It is dynamically focused on the seafloor at ranges from 0.5 to 2.5 m. Since optimal measurements require the probe to be orthogonal to the measured surface, the probe is mounted on a two axis gimbal. Using the SeaXerocks1 visual mapping system, the relative slope of the seafloor is calculated in real-time and the gimbals are oriented normal to the seafloor [15]. The signals are analyzed to remove noise, to find reflections from the crust-substrate boundary, to determine continuity of measurements, and to calculate the thickness values using the method described in [14].

TABLE III
SPECIFICATIONS OF THE PLATFORM (ROV QUASAR9)

Dimensions	3.2 m x 1.8 m x 1.8 m
Mass	3500 kg
Payload Mass	250 kg
Operating velocity	0.2 kn (0.1 m/s)
Operating altitude range	10 ± 2 m
Depth rating	3000 m
Umbilical Cable Length	3200 m
Manipulators	5-axis & 7-axis
Payloads	High vision camera Multibeam sonar Sub-bottom profiler SeaXerocks3 mapping system

TABLE IV
SPECIFICATIONS OF THE SENSORS USED

Acoustic thickness probe:	
Type	Parametric sub-bottom sonar
Frequency	2 MHz (carrier), 200 kHz (signal)
-3 dB footprint	<2 cm (dynamic focusing)
Mounting	2-axis gimbal
Gimbal roll, pitch range	±15°, ±45°
Ping rate	20 Hz
SeaXerocks1 3D visual mapping system:	
Type	Monocular vision and Structured light using sheet laser
Illumination	2 x LED panels (20,000 lm/panel)
Laser power, wavelength	120 mW, 532 nm
Camera resolution, FOV	1328 x 1048, 65° x 53°
Camera frame rate	15 fps
Laser to camera baseline	1.22 m
Swath, resolution	1.5 m, 1.4 mm
Bathymetry resolution (at 1.5 m)	1.4 mm (cross-transect) 6.7 mm (along-transect) 3.0 mm (depth)
SeaXerocks3 3D visual mapping system:	
Type	Stereo vision and Structured light using sheet laser
Illumination	2 x Xenon flash lamps
Laser power, wavelength	120 mW, 532 nm
Camera resolution, FOV	1280 x 1024, 68° x 57°
Camera frame rate	0.2 fps (Stereo) 10 fps (Bathymetry)
Swath, resolution	10 m, 9 mm
Bathymetry resolution (at 10 m)	9 mm (cross-transect) 20 mm (along-transect) 87 mm (depth)
Imagenex Delta-T 837B sonar:	
Type	Multibeam sonar bathymetry and backscatter
Frequency	260 kHz
Transducer Beam Width	120° × 3°
Number of beams	120
Beam resolution	1°
Horizontal opening angle	120°
Min. Range	0.5 m
Range resolution	0.02 % of range
Frame rate	12 Hz
Swath (at 10 m altitude)	40 m
Bathymetry resolution (at 10 m)	333 mm (cross-transect) 20 mm (along-transect) 20 mm (depth)

2) SeaXerocks1 mapping system: is used for low-altitude (1.5 m) survey in this project; and is integrated into the AUV Boss-A for simultaneous mapping of the seafloor together with the acoustic probe. This system is a light-sectioning based seafloor 3D mapping system consisting of a sheet laser, LEDs for illumination, and a camera which records the laser projection on the seafloor and generate visual color reconstructions of the seafloor.

3) SeaXerocks 3 mapping system: is used for high altitude (10 m) surveys in this project [16]. It consists of three cameras - a stereo pair for color imaging of the seafloor and a monochrome camera for recording the laser projection on the seafloor. The system can produce 3D reconstructions of the seafloor in two methods. First method is similar to SeaXerocks1, with the exception of using separate cameras for laser bathymetry and color detection. Second method uses feature matching from the stereo camera images.

4) Multibeam sonar: is used for wide area acoustic observation of the seafloor from the ROV. The authors used an Imagenex Model 837B Delta T multibeam imaging sonar with 120 beams resolved digitally. It was controlled from a dedicated beamforming software running over an ethernet link. Recorded data is post-processed to generate bathymetry and backscatter maps of the surveyed seafloor. The difference in backscatter intensity between hard and soft surfaces can be used to identify Mn-crust covered areas from sediment covered areas.

IV. FIELD SURVEYS

Several surveys were conducted over 5 years using the described systems to estimate the distribution of Mn-crust resources in the Northwest Pacific Ocean, offshore of Minami Torishima island at depths ranging from 1000 m to 2000 m below sea level. A summary of the dives by each robot is given in Table V.

A. Survey Methodology

Target survey locations were decided based on shipboard multibeam maps and previous surveys. Depending on the location, one or more robots were chosen to conduct the survey. Visual confirmation of Mn-crust was conducted mostly using AE2000f; with ROV being used for more rugged areas. Close-up high resolution surveys and thickness measurements were done using Boss-A in areas where Mn-crust is confirmed or highly probable. Multi-resolution surveys were conducted in the same area using multiple robots for correlating multimodal data.

The robots surveyed the seafloor by following predefined waypoints by keeping a constant altitude. The waypoints were arranged in different modes of survey - line transect, dense grids, or sparse grids. With a wide swath of 10 m, dense grid surveys are better realized with AE2000f. While it is possible to do dense grid surveys Boss-A with a narrow swath of 1.5 m, the area covered is of the order of only a few hundred square meters. Sparse grids can be done with either AUVs. ROVs are manually operated and therefore produce undulations in the positioning, causing a mapping output of a lower quality. Therefore, the ROV transects were generally connected straight line segments.

All robots were tracked during operation using an Ultra Short BaseLine (USBL) system on the survey vessel. Real-time navigation of AUVs is based on ded.-reckoning based self localisation using a DVL, combined with the AHRS. The ROV was operated by pilots monitoring the USBL real-time position. Both AUVs are equipped with an acoustic modem for communicating with the survey ship. Due to the low bandwidth, it is only used for telemetry and emergency signalling. In order to optimize the use of valuable ship time and resources, operations were conducted round the clock by several teams of researchers.

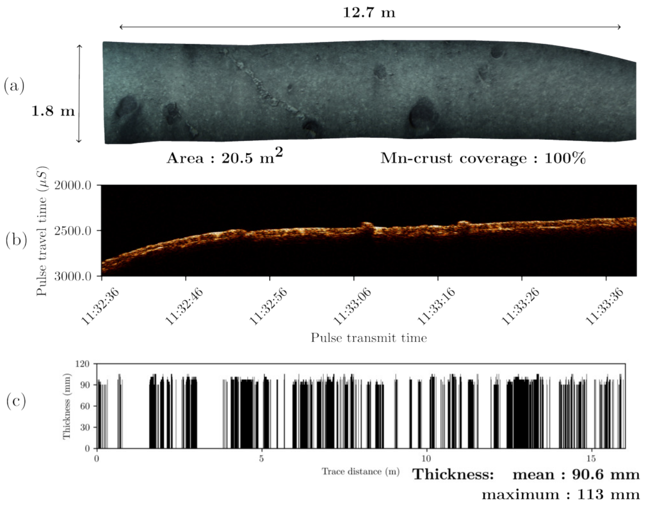

Fig. 6. Thickness estimations by Boss-A. (a) Seafloor reconstruction showing a flat Mn-crust area. (b) Acoustic reflections. Primary and secondary reflections are sharper than most places, albeit discontinuous (c) Estimated thickness values. The gaps denote areas where the thickness calculation is not performed due to data inconsistency or absence of Mn-crust.

B. Data Analysis

The data collected by each robot is analysed post-dive. The navigational systems used have two types of uncertainties - drift and bias, both highly dependent on the environmental conditions. Inertial navigation sensors (DVL and AHRS) drift over time causing the robot to move away from the desired trajectory and is typically less than 2% of traveled distance. The bias occurs in the USBL tracking system for global positioning, is random in nature, and can be up to 1% of slant range (straight line distance from the ship to the robot). In case of a survey at 1500m depth, this amounts to about 15m, more than the width of high altitude visual surveys. We have used an Extended Kalman Filter (EKF) in post-processing to combine the inertial navigation sensors with the USBL system to minimize the error; and this position estimate is used for map generation.

In the case of Boss-A, the 3D maps generated by Boss-A is classified by using a Support Vector Machine classifier (SVM) into continuous Mn-crust deposits, Mn-nodules and sediments; and an estimate of the percentage cover of exposed Mn-crust is calculated [14]. In areas identified as Mn-crust, the acoustic sub-surface reflections were analysed to calculate thickness values, as shown in Fig.6. By extrapolating the thickness results to the entire 3D map, volumetric estimates are generated. Using the density of Mn-crust calculated from samples collected in the past, estimates are made for the mass coverage per unit area; for example, the area shown in Fig.6 has a mass coverage of $174\,kg/m^2$.

In case of AE2000f and ROV using the SeaXerocks3 system, the 3D reconstruction is generated using one of the two methods mentioned in section III-B3. Simultaneously, the images were classified using a semi-supervised location guided autoencoder in order to classify the seafloor and generate percentage cover estimates [18].

This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

TABLE V
SUMMARY OF DIVES CONDUCTED OVER 5 YEARS. BY ALTERNATIVELY OPERATING ROVS AND AUVS, MULTI-RESOLUTION, MULTI-MODAL DATA COULD BE COLLECTED OVER LARGE AREAS OF MN-CRUST DEPOSITS IN A VARIETY OF LANDSCAPES.

Robot		2018	2019	2020	2021	2022	Total	Average (per dive)
AE2000f	No. of dives	5	5	4	9	5	28	-
	Total length (km)	71.8	55.6	53.8	105.3	92.3	378.8	13.5
	Total duration (hh:mm)	19:54	27:15	21:15	42:17	7:21	141:50	5:03
Boss-A	No. of dives	6	1	3	2	1	13	-
	Total length (km)	18.3	3.1	8.1	3.8	2.5	35.8	2.8
	Total duration (hh:mm)	25:50	4:43	11:53	5:56	3:28	51:50	3:59
ROV	No. of dives	11	7	5	12	6	41	-
	Total length (km)	47.9	33.7	16.0	58.9	18.3	174.8	4.3
	Total duration (hh:mm)	59:54	48:39	28:39	69:22	38:30	245:04	5:58

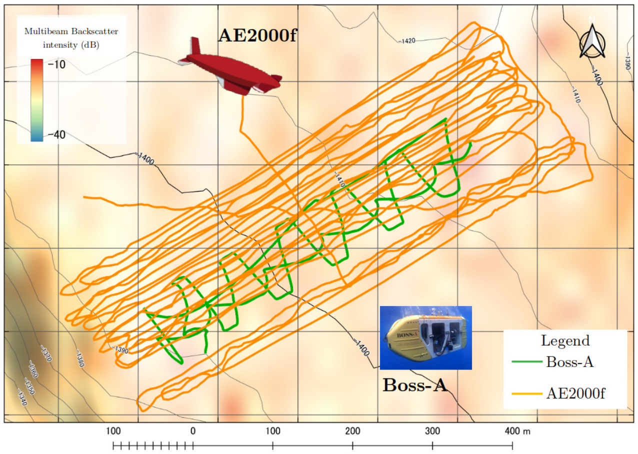

Fig. 7. Navigation tracks of the AUVs (orange) AE2000f (green) Boss-A at one of the surveyed locations. The survey results are shown in Fig. 8 and Fig. 9.

C. Results

Figure 7 shows a case study which shows the benefits of the proposed methodology. Initially, AE2000f conducted a dense grid survey of the area, 210 m x 620 m, in a lawnmower pattern with a total length of 17.7 km in 4:40 hrs. Since large Mn-crust deposits were identified in camera images, Boss-A was deployed in the subsequent dive to conduct a sparse grid survey, 462 m x 82 m, with a total length of 2.3 km in 3:30hrs. The navigation transects are shown in Fig. 7 and the 3D reconstructions generated are shown in Fig. 8. Different types seafloor including Flat Mn-crusts, Pillowy Mn-crusts and nodules are visible in this area, with co-located maps from the two robots showing similar landscapes. Fig. 8(b) and (c) show zoomed views highlighting the trade-off between swath and resolution.

Further analysis of Boss-A data is done to generate highly accurate volumetric estimates of Mn-crust in the surveyed area, as shown in Fig. 9. The results showed a thickness of $74 \pm 27\,mm$. 80% of the $2779\,m^2$ area surveyed is covered with Mn-crust with a unit mass coverage of $120\,kg/m^2$.

Figure 10 shows a section of the data collected by the ROV, consisting of alternating sections of rocky Mn-crust and sediment deposits. It can be seen that the multibeam backscatter can identify areas containing Mn-crusts for an area 3x that of the visually surveyed area. The seafloor matches between the visual and sonar surveys. However, low acoustic backscatter intensity alone is not always a good indicator of the absence of Mn-crust due to the presence of buried Mn-crust layers in some areas.

V. DISCUSSION AND FUTURE WORK

The authors faced several challenges while collecting and analyzing this large dataset. Excluding the operational challenges such as bad weather conditions, instrument failures, and human errors, some of the technical challenges are discussed below.

Localization between multiple surveys is difficult and an exact match of position is not obtained because the map width (1.5 m or 10 m) is much lower than the positioning error of the USBL system (about 15 m or 1% of slant range), making the same point having an offset up to 30 m between surveys. EKF can create navigation solutions suitable for 3D mapping purposes, but the results from different days of survey will have an unknown offset. Currently, these are adjusted manually; localisation solutions based on image matching, by adapting a stereo matching solution [17] for multi-robot surveys, is a potential solution.

Multibeam reflection is strongly affected by the beam geometry with the central beams having stronger backscatter intensities. It is possible to minimise this by reducing the transmitted signal power, but this has the effect of weaker reflections from the outer beams and limiting the effective coverage. This was compensated by beam correction using an angle dependant attenuation function; nevertheless, some artifacts remain.

In SeaXerocks1 and SeaXerocks3, the images are preprocessed individually to correct the lens distortion and light attenuation in the seawater. Mathematical models for light transmission and attenuation in seawater for each color channels is used to correct the color of images. Another method is to balance the grey levels for each pixel in the image across the entire image dataset, assuming a uniform illumination scenario. These models still need to be tuned for each dataset, for the best results.

Analyzing the large amounts of data collected is also a daunting task. Automated analysis methods utilizing machine learning tools can significantly reduce the workload and reduce the time taken, while increasing the output quality [14], [18]. However, training and validating the systems needs ground truth data which is difficult to obtain in deep sea environments.

This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

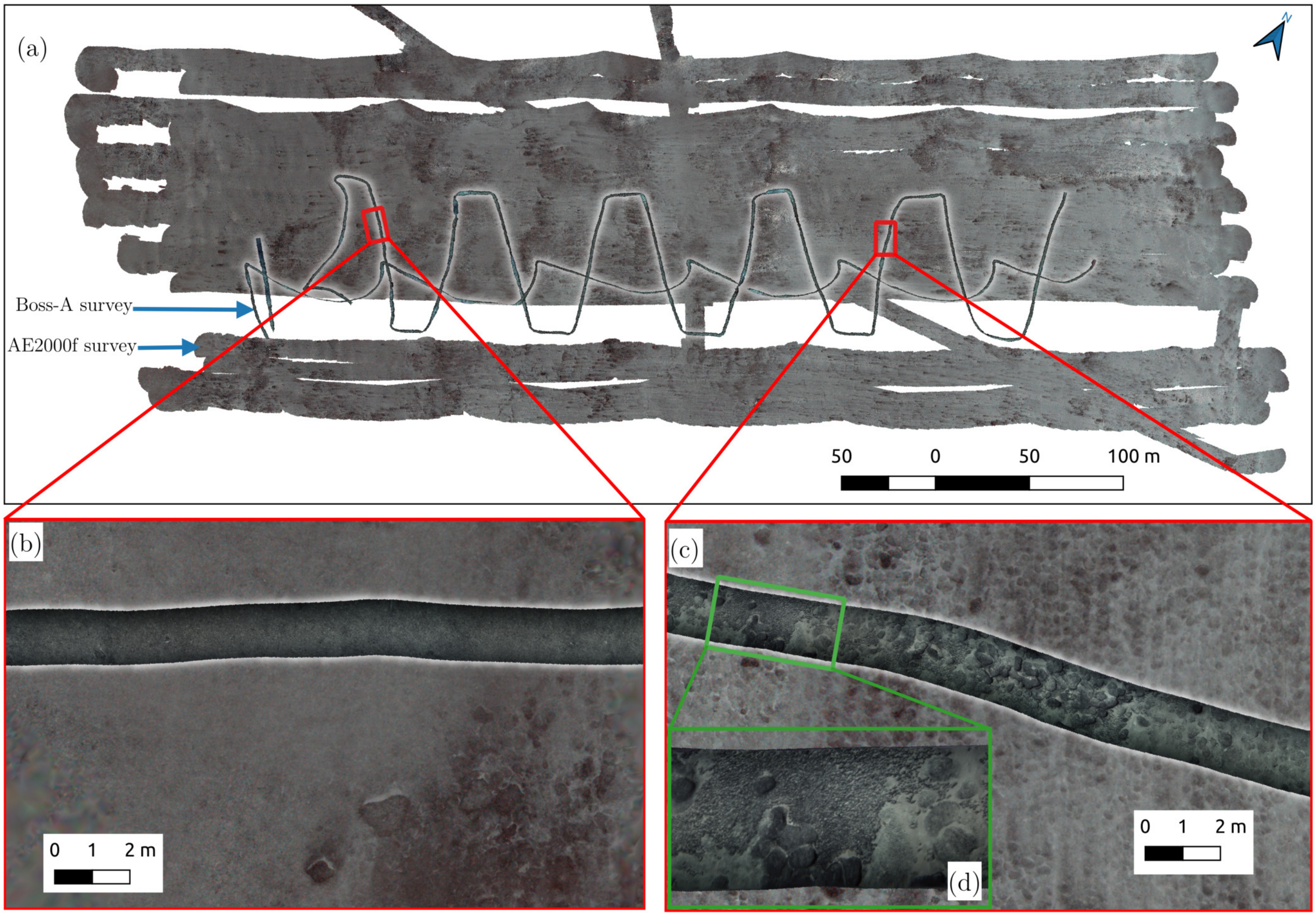

Fig. 8. (a) Top view of 3D maps of a Mn-crust covered area generated by AE2000f (outer image) and Boss-A (inner image, highlighted for better visibility) (b) Close-up view of a flat Mn-crust area (c) Close-up view of a flat Mn-crust area with pillowy sections. (d) Further close-up view of the Boss-A map show small nodules, almost invisible in AE maps. With narrow swath millimeter resolution Boss-A maps, small features can be seen; whereas with wide swath, centimeter resolution AE maps, larger areas can be studied. In addition, Boss-A can study the sub-surface structure of Mn-crust and measure its thickness and volumetric coverage, as shown in Fig.9.

Therefore, multimodal sensor data is compared to each other for better understanding and validation.

AI models tuned to regions from one area may not work as efficiently in other areas due to changing conditions. Increasing the robustness of these models is a potential research problem. New methods for synergistically combining multimodal, multi-resolution data for seamount scale (hundreds to thousands of sq. km) areas is another research theme being actively pursued. Sensor-agnostic methods of correlating multimodal data are being considered for this task.

One of the highlights of this survey was the ability to identify Mn-crust deposits buried under thin layers of sediment (<30 cm thick), using Boss-A's acoustic probe. While sonar and visual mapping surveys notice only sediment, Boss-A could identify buried layers, which were assumed to be Mn-crust, based on surrounding areas. These results were later validated using BMS sampling [19].

The authors could study the variability of Mn-crust distribution both within the same seamount and across different seamounts. It was observed that the variability depends on the choice of location and general trends can be deceptive, further reinforcing the need of similar surveys.

Although the system proposed is used for Mn-crust surveys, they can be used for other seafloor surveys as well by changing the sensor suite. For example, Polymetallic nodules can be surveyed without using the acoustic thickness probe. By adding methane or other chemical sensors, methane seeps and hydrothermal vents can be surveyed. The number and choice of robots was made by considering features of the Mn-crust deposits. While reducing the number of robots will negatively impact the results, increasing the number of robots with other sensors can have a positive impact. In particular, collecting high altitude sidescan sonar, and/or multibeam surveys from a cruising AUV at 30-60m altitude can provide wider area survey results, adding an additional resolution level to improve the prediction accuracy. Efforts in this direction are ongoing.

Although this study used multiple robots, they were not operating simultaneously or as a coordinated multi agent system. While this is a future direction of underwater robotics, several challenges including localisation and communication needs to be addressed before it can be realized in the deep sea field surveys.

This article has been accepted for publication in IEEE Robotics & Automation Magazine. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/MRA.2023.3348304

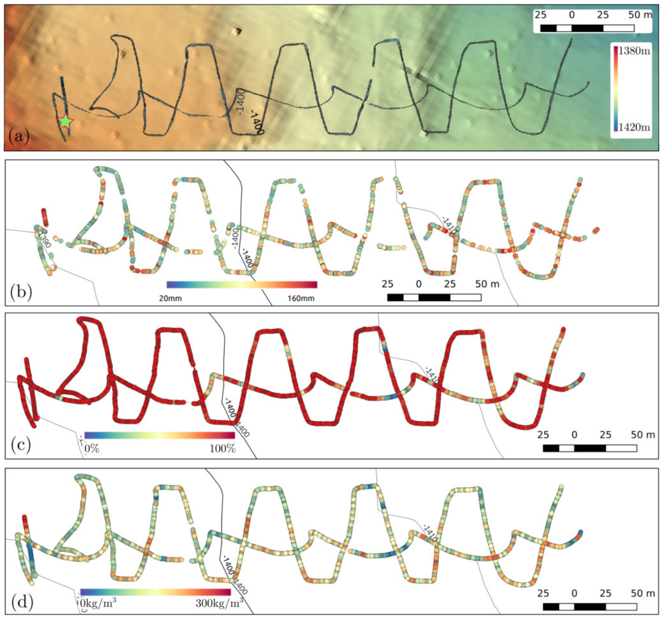

Fig. 9. Volumetric estimates of Mn-crust calculated from the data collected by Boss-A. (a) top view of the 3D mosaic generated, with the bathymetric map generated by AE2000f in the background. (b) calculated thickness values. (c) percentage cover of exposed Mn-crust deposits. Since the area shown is a large flat Mn-crust deposit, the coverage is close to 100% in most areas. (d) unit mass coverage. The star indicates the location of the patch shown in Fig. 6.

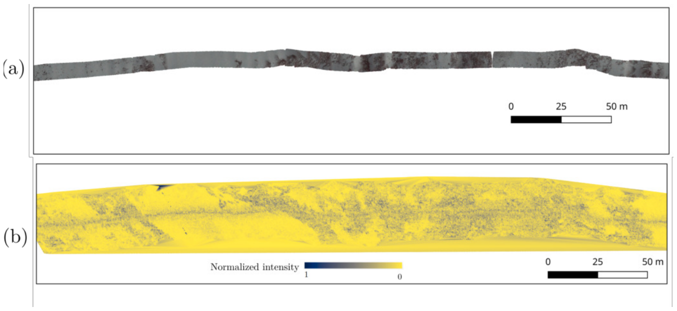

Fig. 10. Example of data collected by the ROV. (a) top view of 3D reconstruction (b) multibeam backscatter data. It can be clearly seen that albeit at a lower resolution, the multibeam can distinguish between Mn-crust and sediment covered areas for a larger area surrounding the visual 3D map.

VI. CONCLUSION

The authors have conducted a multi-robot multimodal survey of deep sea Mn-crust resources over a period of 5 years and have presented a portion of the results. By utilising the advantages of each system, a variety of data regarding the thickness, exposure coverage and mass coverage of Mn-crust was collected. Description of systems used, survey strategies, data analysis methodologies and considerations for future work are discussed.

Mn-crust exploitation is still technologically not feasible and economically not viable [20]. While technology improves the feasibility, other issues such as the effect on the ecosystem, pollution, and effect on marine animals must be addressed. These studies have not yet picked up. Nevertheless, robotic surveys such as the present work are important both in terms of technology development, the dataset collected, and scientific relevance for studying these deep sea environments.

ACKNOWLEDGMENTS

The data in this paper have been collected as a part of sponsored projects by Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI), Japan Organization for Metals and Energy Security (JOGMEC). The authors also thank the teams of Nippon Salvage Co., Ltd., the ship Koyomaru, and the ROV QUASAR9 for their support. The authors also would like to thank the team members from IDEA Consultants Inc., Jose Cappelletto from the University of Southampton and Nippon Marine Enterprise (NME) who contributed to data collection and analysis.

REFERENCES

[1] J. R. Hein, K. Mizell, A. Koschinsky, and T. A. Conrad, "Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources," *Ore Geology Reviews*, vol. 51, pp. 1–14, Jun. 2013.

[2] P. A. J. Lusty and B. J. Murton, "Deep-Ocean Mineral Deposits: Metal Resources and Windows into Earth Processes," *Elements*, vol. 14, no. 5, pp. 301–306, Oct. 2018.

[3] E. Baker and Y. Beaudoin, Eds.,*Deep Sea Minerals: Cobalt-rich Ferromanganese Crusts, a physical, biological, environmental, and technical review*. Secretariat of the Pacific Community, 2013.

[4] International Seabed Authority, "Regulations on Prospecting and Exploration for Cobalt-rich Ferromanganese Crusts in the Area," Oct. 2012.

[5] A. Usui, K. Nishi, H. Sato, Y. Nakasato, B. Thornton, T. Kashiwabara, A. Tokumaru, A. Sakaguchi, K. Yamaoka, S. Kato, S. Nitahara, K. Suzuki, K. Iijima, and T. Urabe, "Continuous growth of hydrogenetic ferromanganese crusts since 17 Myr ago on Takuyo-Daigo Seamount, NW Pacific, at water depths of 800–5500 m," *Ore Geology Reviews*, vol. 87, pp. 71–87, Jul. 2017.

[6] M. M. P. Weydert, "Measurements of the acoustic backscatter of selected areas of the deep seafloor and some implications for the assessment of manganese nodule resources," *The Journal of the Acoustical Society of America*, vol. 88, no. 1, pp. 350–366, Jul. 1990.

[7] J. Joo, S. S. Kim, J. W. Choi, S. J. Pak, Y. Ko, S. K. Son, J. W. Moon, and J. Kim, "Seabed mapping using shipboard multibeam acoustic data for assessing the spatial distribution of ferromanganese crusts on seamounts in the western pacific," *Minerals*, vol. 10, no. 2, pp. 1–20, 2020.

[8] J. Kim, Y.-T. Ko, K. Hyeong, and J.-W. Moon, "Geophysical and Geological Exploration of Cobalt-rich Ferromanganese Crusts on a Seamount in the Western Pacific," *Economic and Environmental Geology*, vol. 46, no. 6, pp. 569–580, 2013.

[9] B. Zhao, Y. Yang, X. Zhang, G. He, W. Lü, Y. Liu, Z. Wei, Y. Deng, and N. Huang, "Sedimentary characteristics based on sub-bottom profiling and the implications for mineralization of cobalt-rich ferromanganese crusts at Weijia Guyot, Western Pacific Ocean," *Deep Sea Research Part I: Oceanographic Research Papers*, vol. 158, p. 103223, Apr. 2020.

[10] E. Alevizos, T. Schoening, K. Koeser, M. Snellen, and J. Greinert, "Quantification of the fine-scale distribution of Mn-nodules: insights from AUV multi-beam and optical imagery data fusion," *Biogeosciences Discussions*, pp. 1–29, Feb. 2018. [Online]. Available:https://bg.copernicus.org/preprints/bg-2018-60/. [Accessed Oct. 30, 2023].

[11] J. Wu, R. C. Bingham, S. Ting, K. Yager, Z. J. Wood, T. Gambin, and C. M. Clark, "Multi-AUV motion planning for archeological site mapping and photogrammetric reconstruction," *Journal of Field Robotics*, vol. 36, no. 7, pp. 1250–1269, Oct. 2019.

[12] B. Thornton, A. Asada, A. Bodenmann, M. Sangekar, and T. Ura, "Instruments and methods for acoustic and visual survey of manganese crusts," *IEEE Journal of Oceanic Engineering*, vol. 38, no. 1, pp. 186–203, Jan. 2013.

[13] Hong, Feng, Huang, Wang, and Xia, "China's First Demonstration of Cobalt-rich Manganese Crust Thickness Measurement in the Western Pacific with a Parametric Acoustic Probe," *Sensors*, vol. 19, no. 19, p. 4300, 2019.

[14] U. Neettiyath, B. Thornton, M. Sangekar, Y. Nishida, K. Ishii, A. Bodenmann, T. Sato, T. Ura, and A. Asada, "Deep-Sea Robotic Survey and Data Processing Methods for Regional-Scale Estimation of Manganese Crust Distribution," *IEEE Journal of Oceanic Engineering*, vol. 46, no. 1, pp. 102–114, Jan. 2021.

[15] T. Sato, B. Thornton, A. Bodenmann, A. Asada, and T. Ura, "Towards real-time control of a double gimbaled acoustic probe for measurement of manganese crusts thickness," In Proc. IEEE International Underwater Technology Symposium (UT)'2013, pp. 1–5, Mar. 2013.

[16] B. Thornton, A. Bodenmann, O. Pizarro, S. B. Williams, A. Friedman, R. Nakajima, K. Takai, K. Motoki, T. o. Watsuji, H. Hirayama, Y. Matsui, H. Watanabe, and T. Ura, "Biometric assessment of deep-sea vent megabenthic communities using multi-resolution 3D image reconstructions," *Deep-Sea Research Part I: Oceanographic Research Papers*, vol. 116, pp. 200–219, 2016.

[17] M. Johnson-Roberson, O. Pizarro, S. B. Williams, and I. Mahon, "Generation and visualization of large-scale three-dimensional reconstructions from underwater robotic surveys," *Journal of Field Robotics*, vol. 27, no. 1, pp. 21–51, Jan. 2010.

[18] T. Yamada, A. Prügel-Bennett, and B. Thornton, "Learning features from georeferenced seafloor imagery with location guided autoencoders," *Journal of Field Robotics*, pp. 1–16, 2020.

[19] U. Neettiyath, B. Thornton, H. Sugimatsu, T. Sunaga, J. Sakamoto, and H. Hino, "Automatic Detection of Buried Mn-crust Layers Using a Sub-bottom Acoustic Probe from AUV Based Surveys," In Proc. IEEE/MTS Oceans '22, Chennai, 2022.

[20] T. Yamazaki, N. Nakatani, and R. Arai, "An Economic Feasibility Analysis for Combined Mining of Cobalt-rich Crusts and Phosphorous Ores in North-west Pacific," In Proc. IEEE Underwater Technology (UT)'23, Tokyo, pp. 1–4, Mar. 2023.

VII. BIOGRAPHY SECTION

Umesh Neettiyath (M'16) received his B.Tech degree in Electronics and Communication from the University of Calicut (2008), his M.S. by Research in Engineering Design from Indian Institute of Technology Madras (2013), and his PhD from Kyushu Institute of Technology (2020). He is currently a Project Researcher at the Institute of Industrial Science at The University of Tokyo. His research interests include the design and development of field robotics systems for environmental observation. He is currently working on large scale data collection and analysis of manganese crust deposits using underwater robots.

Tetsu Koike graduated from Tokyo University of Fisheries (now Tokyo University of Marine Science and Technology) in 1998 and obtained a fisheries bachelor degree. Originally his specialty was fish classification and ecology. He is a technician of Kaiyo Engineering Co., Ltd. and a cooperative researcher of the Institute of Industrial Science, University of Tokyo. His work includes undersea survey using multi beam sonar, programming data analysis, and machine maintenance. For the reconstruction assistance of the East Japan great earthquake disaster, he started working on marine surveys. He frequently participates in cruises doing fishery surveys, ocean bottom topography surveys, and seabed resource surveys.

Kazunori Nagano graduated from the Electrical and Electronic Information Engineering, Toyohashi University of Technology, Japan in 2011 and received the degree of Master of Engineering from the same university in 2013. He is at present a Project Researcher at the University of Tokyo and also working Chief Researcher at IDEA Consultants,Inc. His research interests are underwater robotics, underwater image processing and the development of data processing techniques for environmental monitoring. He is devoted to the operation of underwater robotics, the analysis of the acquired data, and the analysis of image data using AI.

Harumi Sugimatsu (AM'04-M'08-SM'12) earned a Master's degree from the Graduate School of Humanities, Gakushuin University, Japan. She is a Research Fellow at the Institute of Industrial Science of the University of Tokyo, Japan, specializing in whale and dolphin echolocation with application to cetacean observation systems, and deep-sea resources survey systems by multiple AUVs.

Tamaki Ura (M'91-SM'02-F'07) graduated from the Faculty of Engineering, The University of Tokyo, Japan, in 1972 and received the degree of Doctor of Engineering from the same university in 1977. He retired as Professor emeritus of The University of Tokyo and has held positions as the Director and Distinguished Professor of Center for Socio-Robotic Synthesis, Kyushu Institute of Technology, and Director of Underwater Technology Center of National Maritime Research Institute. He has developed various types of Autonomous Underwater Vehicles (AUVs) and related application technologies including navigation methods, a new sensing method using a chemical sensor, precise seafloor mapping methods, a precise seabed positioning system with a resolution of a few centimeters, a new sensing system of the thickness of cobalt-rich crust, etc. Finally, he exemplified using these technologies that AUVs are practicable and valuable tools for deep-sea exploration.

Blair Thornton (M'07) received the B.Eng. degree in ship science and the Ph.D. degree in underwater robotics from The University of Southampton, Southampton, U.K., in 2002 and 2006, respectively. He is Professor of Marine Autonomy at the the University of Southampton and has a cross-appointment at the Institute of Industrial Science, The University of Tokyo. His research interests involve the development of in-situ sensors and data processing techniques for integrated acoustic, visual, and chemical survey of marine minerals and environment monitoring. He is dedicated to fielding real systems in real environments and overcoming bottlenecks in the flow of information from data collection to human interpretation.