Sensors and Materials, Vol. 35, No. 9 (2023) 3451–3460
MYU Tokyo

S & M 3404

Bathymetric Surveying Using Autonomous Surface Vehicle for Shallow-water Area with Exposed and Partially Exposed Rocks

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(Received April 28, 2023; accepted July 28, 2023)

Keywords: autonomous surface vehicle, bathymetric surveying, shallow water, exposed rocks

The rising sea levels caused by the climate crisis are causing significant changes in the coastal environment of the Korean Peninsula, leading to increased demand for coastal erosion protection. Accurate bathymetric information is crucial for implementing effective prevention measures. However, existing methods such as the airborne light detection and ranging (LiDAR) bathymetry (ALB) and multibeam echo sounder (MBES) are not cost-effective for small-scale regions, and the single-beam echo sounder (SBES) method using manned survey vessels is challenging to use in low-water-depth areas. In this study, we aimed to develop an autonomous surface vehicle (ASV) to conduct bathymetric surveying at a very small water depth of less than 2.0 m. The survey was conducted by connecting SBES and network real-time kinematic (N-RTK) positioning data to a small, self-developed ASV. The vessel was autonomously navigated using N-RTK positioning data during most measurement operations, allowing for precise sounding intervals using a simple waypoint setting for each planned sidetrack without direct steering. The bathymetric measurements of exposed or partially exposed rocks at average water depths of 2.0 m or less could be obtained from the bathymetric surveying using the unmanned vessel and devices applied in this study.

1. Introduction

The Korean Peninsula is a unique geographic location surrounded by the sea on three sides. With a high coastline occupation within South Korea's borders, coastal conditions are greatly affected by climatic changes.(1) Over the past 33 years, coastal sea levels have been rising by an average of 3.01 mm every year,(2) corresponding to 1.3 times the rate of rise of global sea levels.(3) This alarming trend of rising sea levels will make it increasingly more difficult to prevent coastal erosion. Additionally, the rising sea levels are expected to intensify coastal erosion,(4) as they cause coastal retreat and increase the frequency of storm surge. The coast, which is directly affected by rising sea levels, is a critical interface between the land and the ocean, an area that plays a vital role for humanity.

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https://doi.org/10.18494/SAM4478

ISSN 0914-4935 © MYU K.K.
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Along the coast, exposed, partially exposed, and submerged rocks exist, characterizing the bathymetry of the region. Exposed or partially exposed rocks become rocky islands where land appears above the surface of the water, becoming submerged during high tide, impacting offshore waves. Exposed rocks shield the coast from waves by acting as a seawall, blocking most incident waves, meaning that only waves of relatively low magnitude reach the shore. However, when exposed or partially exposed rocks become deeply submerged at high tide, high waves crash along the coastline and wave shoaling occurs.(5)

To design effective coastal erosion countermeasures, accurate geospatial information must be obtained for the exposed, partially exposed, and submerged rocks so that it can be used as design data for the protection of coastal erosion and offshore breakwaters. Current bathymetric surveying methods include airborne light detection and ranging (LiDAR) bathymetry (ALB) using an aircraft and multibeam echo sounder (MBES) methods that use vessels, but these are often economically inefficient for small-scale regions.

For ALB, it is difficult to rely on observed data owing to the effects of surface reflection and refraction in seawater, as well as the turbidity of the water, which affect the maximum measurable depth.(6) Additionally, there are hassles of verifying missing data after postprocessing and of conducting airborne depth measurements again in the future.(7)

Obtaining precise measurements can be challenging using a single-beam echo sounder (SBES) on a manned ship, such as a fishing boat with a displacement of 5–11 tons, as the draft of the vessel is very large, making approaching shallow rocky regions problematic. Additionally, such methods are not suitable for bathymetric surveying that can be greatly affected by the weather owing to licensing procedures such as vessel inspections for other purposes, making immediate deployment under observable weather conditions impossible.

In this study, we aimed to develop an autonomous surface vehicle (ASV) that is inexpensive and can operate freely to complement the disadvantages of the above-mentioned equipment. The catamaran-shaped ASV had a small draft, making it suitable for the bathymetric surveying of shallow coastal regions with exposed or partially exposed rocks. Autonomous sailing was possible, and the user could remotely monitor the seafloor depth. Additionally, it could be directly deployed without administrative burden under appropriate climate conditions for surveying, reducing costs even further owing to the shortening of the survey time scales.(8)

In Sect. 2, we describe the design of the ASV body and its system composition, whereas in Sect. 3, we discus autonomous sailing using the way-point function, the experimental process, and the postprocessed raw data. Finally, in Sect. 4, we summarize the conclusions of this research. Overall, the development of an ASV for bathymetric surveying provides a cost-effective and efficient way to obtain geospatial information for coastal erosion countermeasures, helping to protect the coast and the communities that depend on it.

2. Materials and Methods

2.1 ASV design and development

The development of the ASV was a crucial aspect of this research, and its design was carefully considered to ensure optimal performance.(9) The catamaran structure was chosen as the basic platform for the ASV owing to its inherent stability during sailing, which is a crucial factor for any marine vehicle.(11) Compared with a monohull ship, the ASV has a wider draft and a lower center of mass, which make it less prone to rolling and pitching. This is especially important during high-speed sailing, where stability can be a major challenge. Although two ships may have similar line widths, their buoyancy point of action can differ, making stability a critical design feature.(10)

Another advantage of the ASV is its submerged draft, which is just 8 cm, considerably smaller than that of a monohull ship.(11) This makes it ideal for bathymetric surveying in shallow coastal regions where the water depth may be limited. Additionally, the ASV's surface in contact with the water has low resistance, which enables efficient battery use and longer mission times.

The hull of the ASV is made of fiberglass reinforced plastics (FRPs), providing a long lifespan, high strength, and resistance to decay.(12) The ASV is powered by two motors and designed with an onboard jet pump propeller propulsion system to prevent entanglement with marine organisms and ensure mission success.(13) The H/W system operates using the Pixhawk Autopilot(14) and consists of power equipment, control facilities for the remote operation of the ASV, and communication devices.

The ASV's wireless communication system is capable of using two methods: radio frequency (RF) communication over a distance of 1 km and long-term evolution (LTE) communication over the entire area of coastal waters (excluding signal shadowing areas). This makes the remote monitoring of the ASV's position and real-time depth information possible. The ASV is also equipped with a gyroscope, an accelerometer, and magnetometer sensors, which can be used as a motion sensor to save positional data caused by wave motion, including roll, pitch, and yaw data, as a real-time log file. This log file can be used to correct depth information during postprocessing. In this study, the 3D design drawing and the exterior, interior status of the ASV and specifications of the produced ASV are presented in Fig. 1 and Table 1 below.

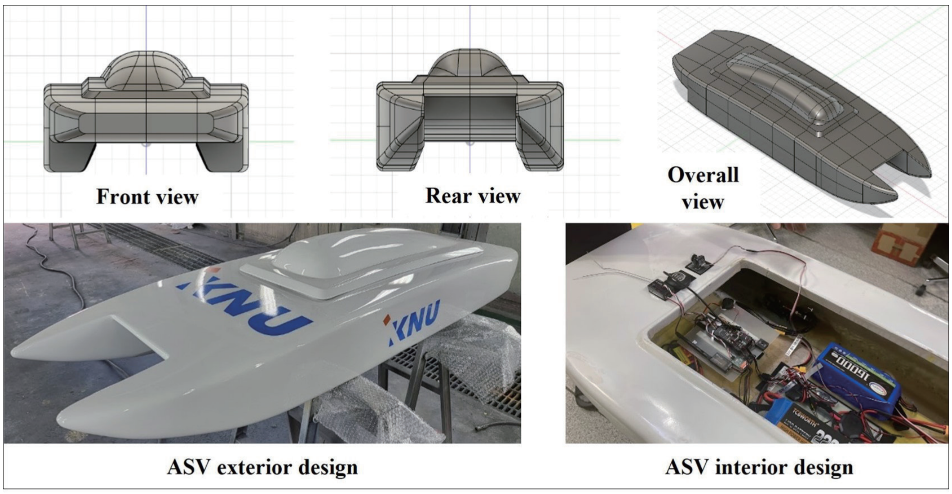

Fig. 1. (Color online) 3D design drawing, exterior, and interior of the ASV.

Table 1. ASV specifications.

Item	Description
Dimensions	2.0 × 0.65 × 0.35 ($L \times W \times H$) m^3
Platform weight	35 kg
Payload	Up to 43 kg
Batteries	LiPo 6S (22.2 VDC / 2.2 Ah) × 6
Propulsive power	3.5 HP × 2
Speed	Up to 5 knots
Endurance	6 h @ 3 knots
Wireless communication: RF, LTE	RF: 1 km, LTE: all possible ranges
Operating system	Pixhawk 2.4.8
Onboard motion sensors	ST Micro L3GD20 3-axis gyroscope ST Micro LSM30D 3-axis accelerometer magnetometer
Mapping sensors	SBES Echologer ETH D24U (200/450 KHz) GNSS Trimble R6

The global navigation satellite system (GNSS) is used as a positioning sensor, and the Trimble R6 receiver is used to record the real-time position with network real-time kinematic (N-RTK) positioning. The SBES, on the other hand, uses the 200 and 450 kHz frequencies of the Echologger ETH D24U to distinguish between marine vegetation and the ground line. The national marine electronics association (NMEA) packet data is then transferred from the SBES to a laptop PC to remotely identify and save data in real time.(15)

2.2 ASV bathymetric surveying

The use of ASVs for bathymetric surveying has been gaining attention owing to their ability to access shallow and rocky areas that may be difficult to reach with manned vessels. As shown in Fig. 2, the ASV-based SBES system used in this study was tested at the Geoil-ri, Uljin-gun, Gyeongsangbuk-do area, which was selected as the study site owing to its challenging features. The test site covered an area of 60000 m^2, with water depths ranging from 0.7 to 7.8 m and about 70% of the total water depth being less than 2.0 m in this site.

Bathymetric surveying using traditional manned vessels can be limited by various factors, such as exposed rocks and offshore breakwater exits. These factors make it difficult to conduct surveys in such areas, and the data obtained may not be accurate. The ASV-based SBES system overcomes these limitations by conducting an autonomous navigation bathymetric surveying using the way-point tracking function, which can accurately map the underwater terrain and provide high-quality data.

To determine the performance of the ASV-based SBES system, a 10 × 10 m grid map was constructed, and the water depth established using an existing bathymetric surveying method at the same point was compared with the data acquired by the ASV. The results of the study showed that the ASV-based SBES system was highly applicable in rocky and shallow-water regions, providing accurate and reliable data.

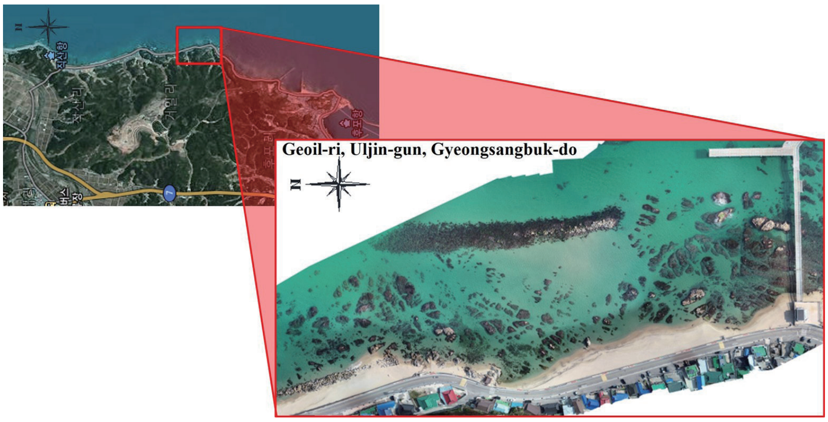

Fig. 2. (Color online) Test site for ASV bathymetric surveying.

The postprocessing correction of the SBES *.NMEA, GNSS *.CSV, and Pixhawk *.LOG files was a critical step in obtaining accurate bathymetric data. This correction process ensured that the data collected by the ASV-based SBES system were reliable and could be used for further analysis. However, owing to the larger volume of data generated by the ASV-based SBES system compared to traditional manned vessels, the analysis process is more time-consuming and labor-intensive.[6] Despite this, the ASV-based SBES system provided an efficient solution for conducting surveys in rocky, shallow-water regions, where traditional vessels or aircraft may not be able to access or operate safely. The quality of the data obtained from the ASV-based SBES system was high, enabling researchers to obtain detailed bathymetric information rapidly and accurately. Overall, the ASV-based SBES system proved to be an effective tool for surveying shallow coastal regions, where traditional methods may not be suitable.

2.3 Autonomous navigation implementation

As shown in Fig. 3, to obtain accurate bathymetric data in the study area using the ASV-based SBES system, autonomous navigation using the way-point function was implemented. This method involved the use of a mission planner software based on Google Maps, which allowed the automatic control of the ASV's route. The software enabled the predetermination of the way points, route, area, and navigation speed to maintain precise sounding intervals and constant speed, thereby improving the measurement accuracy. However, the autonomous navigation was not entirely free from manual intervention as some manual steering was required to avoid obstacles such as offshore breakwaters and exposed rocks. With the predetermined route and navigation speed, the ASV-based SBES system was able to navigate autonomously and efficiently in the study area, ensuring that the data obtained were of good quality.

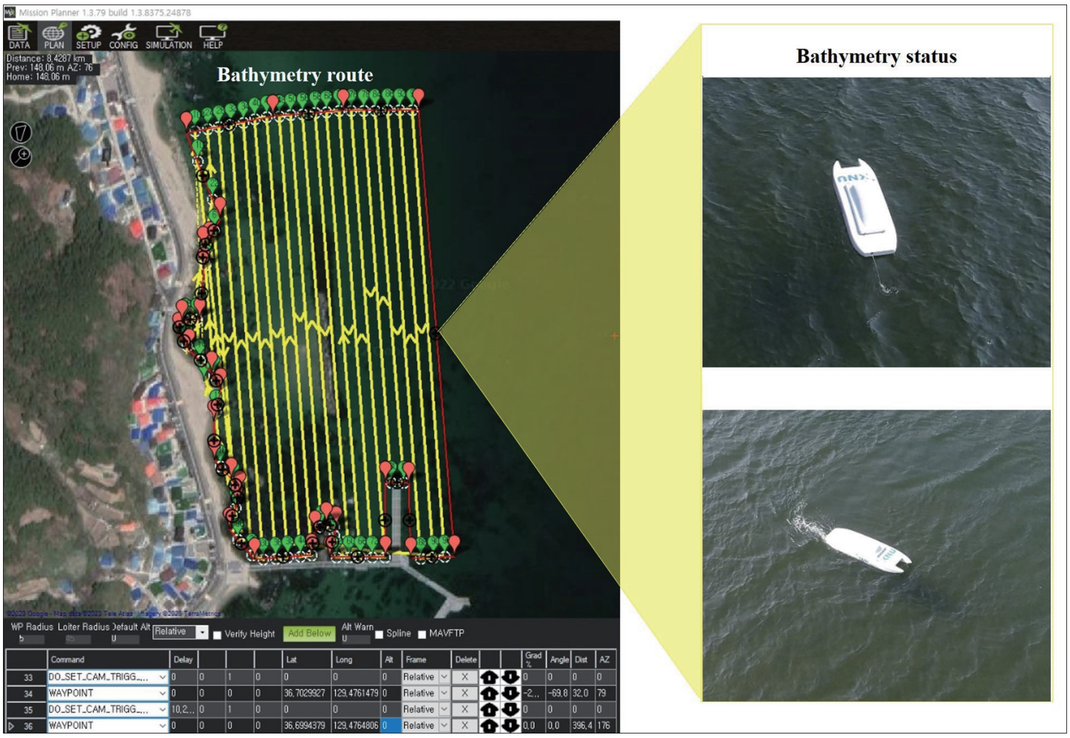

Fig. 3. (Color online) ASV surveying with autonomous navigation.

3. Results

In this section, we describe the use of the ASV-based SBES and its autonomous navigation function in a shallow coastal region with exposed and partially exposed rocks and installed offshore breakwaters. The bathymetric surveying data were acquired using the SBES and monitored remotely in real time. The acquired data were postprocessed to extract the bathymetric grid map. This involved several steps such as data correction, filtering, and interpolation to obtain accurate and reliable bathymetric data. The resulting bathymetric grid map provided a detailed representation of the seafloor topography, water depths, and rock formations in the study area. The accuracy of the bathymetric data was evaluated by comparing the data obtained using the ASV-based SBES with those from existing manned vessels in the same area. The results showed that the ASV-based SBES system provided accurate and reliable bathymetric data, especially in areas where traditional manned vessels or aircraft may have difficulty in accessing. The use of the autonomous navigation function also helped to maintain precise sounding intervals and constant speed, which improved the measurement accuracy. Overall, the results demonstrate the potential of the ASV-based SBES system for efficient and effective bathymetric surveying in shallow-water areas with complex seafloor topography. For bathymetric surveying in a shallow-water area, the ASV-based SBES and its autonomous navigation function were used in a shallow coastal region with exposed and partially exposed rocks, and installed offshore breakwaters. Moreover, the location and bathymetric data were remotely monitored in real time. The acquired measurement data were postprocessed step by step to extract the bathymetric grid map, the process being outlined below.

3.1 Raw data analysis

We have provided detailed information on the data acquisition process during the bathymetric surveying using the ASV-based SBES system. The system was programmed to follow a preplanned log-line with a 10 m interval and maintain a constant speed of 5 m/s using autonomous navigation. However, the effect of tidal changes resulted in a deviation of ±2 m from the log-line, which necessitated manual steering to avoid obstacles such as offshore breakwaters and exposed rocks.

To ensure the accuracy of the measurements, the GNSS system's N-RTK signal quality was closely monitored, and calibration was performed at a base level point installed by KHOA. This calibration allowed the system to provide real-time responses to tidal changes and ensure the accuracy of the measurements. The left-hand side of Fig. 4 shows the depth record sheet obtained from the SBES system during the survey, whereas the right-hand side shows the NMEA *.LOG file. These files provide valuable information about the measured depths, location, and other relevant data, which can be further analyzed and processed to obtain accurate bathymetric maps of the survey area. Overall, we have provided a detailed description of the raw data analysis process, which is essential for accurately interpreting the results obtained from the bathymetric surveying.

3.2 Postprocessing data analysis

In the postprocessing data analysis, the raw bathymetric surveying data collected from the ASV-based SBES system were analyzed. The data included the real-time X, Y, and DL data of the GNSS and the roll, pitch, and water depth data of the SBES. These two types of data were time-synchronized, and using this time-synchronized data, ΔX and ΔY data were obtained for a certain time in the X- and Y-coordinates while considering the roll, pitch, and water depth. Additionally, the roll and pitch data were used to correct the water depth. By doing so, accurate seafloor X, Y, and DL values were obtained, and a bathymetric map was created. The map was constructed by interpolation to create a 10×10 m^2 canonical lattice network.

The resulting final bathymetric map clearly shows the location and shape of various underwater features, including artificial offshore breakwaters, exposed and partially exposed rocks, and underwater reefs in shallow-water areas with depths of less than 2.0 m. From the accuracy of the map, it was concluded that the bathymetric surveying using the ASV-based SBES system developed in this study was successfully conducted. Figure 5 is an illustration of the final bathymetric map constructed after the postprocessing of the ASV surveying data.

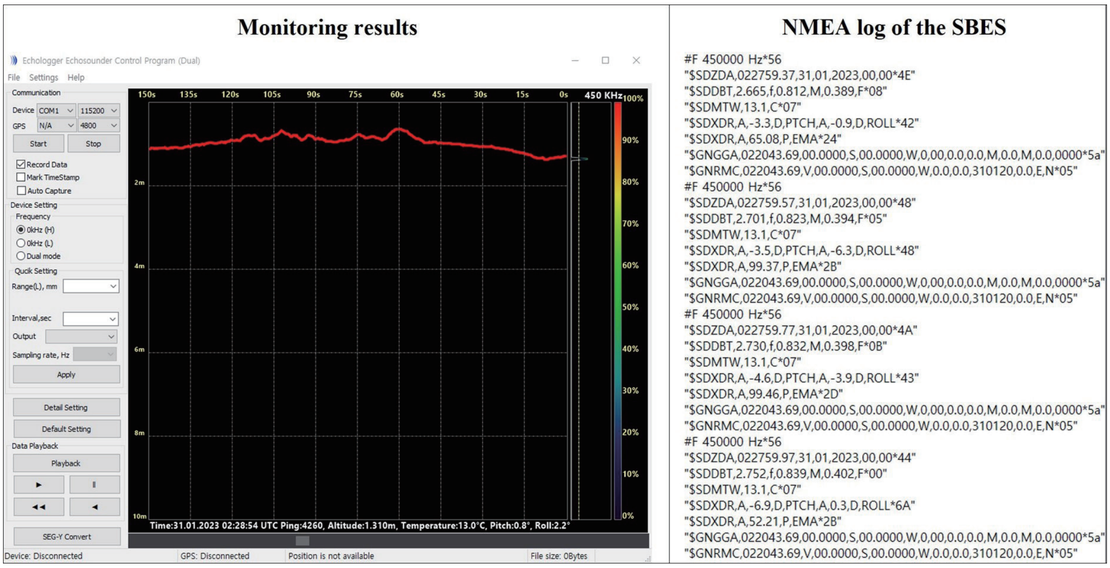

Fig. 4. (Color online) ASV surveying on-site monitoring results (left) and NMEA log of the SBES (right).

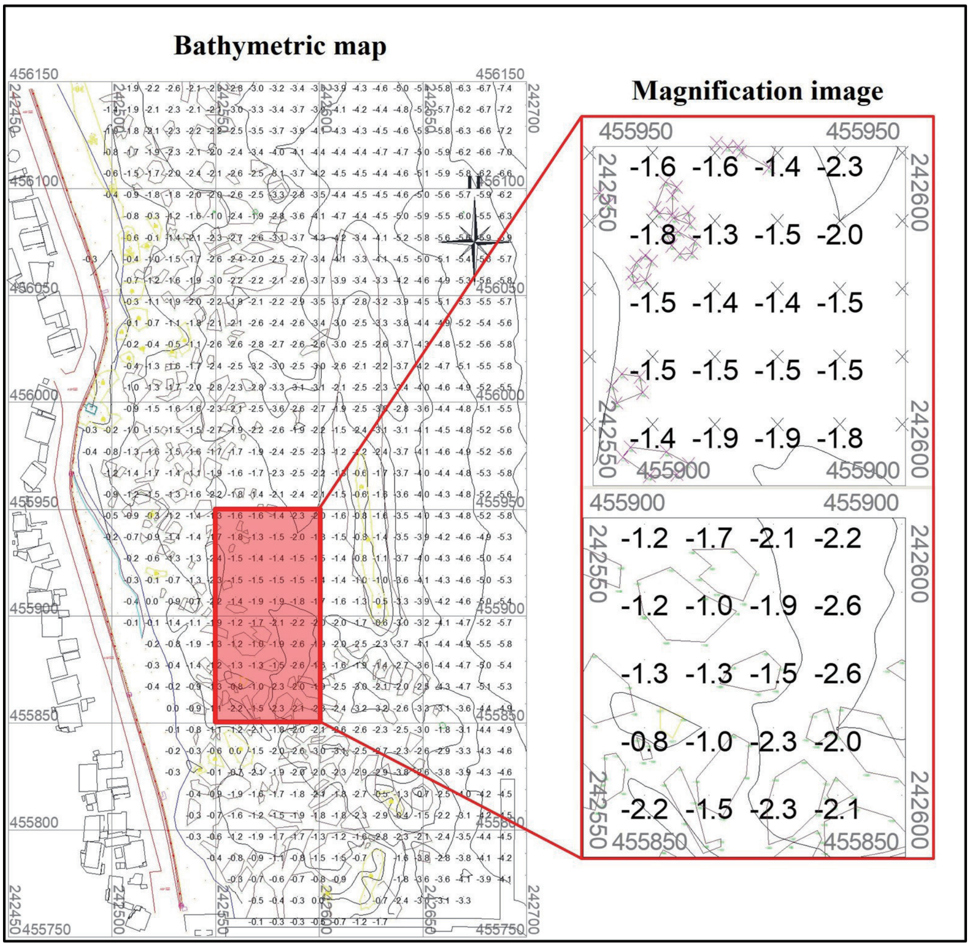

Fig. 5. (Color online) Bathymetric map from ASV-based SBES surveying.

4. Conclusions

In this study, we developed an ASV that is inexpensive and can operate freely to complement the disadvantages of the existing surveying methods, namely, ALB, MBES, and SBES with a manned vehicle, in order to determine whether bathymetric surveying could be conducted at very small water depths of less than 2.0 m.

The ASV is specifically designed to have a small draft and to be suitable for shallow-water bathymetric surveying in coastal areas by utilizing SBES and N-RTK positioning technologies.

To validate the ASV bathymetric surveying in a shallow-water area, we selected a region where rock formations were alternately covered or exposed in a shallow area as the test site. For the test, an autonomous navigation bathymetric surveying using the ASV way-point function and a manually controlled bathymetric surveying were conducted.

After postprocessing the surveying data, the bathymetric grid map in the test site was constructed to determine the ASV bathymetric surveying performance in a shallow-water area with a depth of less than 2.0 m. In the final map, the locations and shapes of artificial offshore breakwater structures, exposed and partially exposed rocks, and underwater reefs were accurately identified. Therefore, it was judged that the ASV-based SBES enabled bathymetric surveying to be successfully conducted in shallow-water areas at depths of 0.7 to 2.0 m where existing methods could not be used.

Consequently, the use of the ASV-based SBES proved to be advantageous for surveying previously inaccessible coastal areas such as shallow-water areas. Moreover, the gathered data could be used as preliminary data for coastal erosion control measures that consider the impact of tidal waves on exposed and partially exposed rocky areas and underwater reefs owing to rising sea levels.

The use of the ASV-based SBES has ultimately led to achieving bathymetric surveying results that comply with IHO Order 1a. Through this, the maneuvering capabilities and remote sensing performance of the ASV were validated in this study, allowing for immediate application. Furthermore, the ASV-based SBES offers the advantage of reducing labor costs, survey time, and overall expenses compared with traditional manned surveys, thereby creating significant value in the maritime survey industry. The utilization of the ASV-based SBES has proven to be advantageous for surveying previously inaccessible coastal areas, including shallow-water regions. Additionally, it serves as valuable preliminary data for coastal erosion control measures by considering the impact of tidal changes on exposed and partially exposed rocky areas and underwater reefs. This contribution helps protect coastal areas and the communities that depend on them.

Acknowledgments

This research was supported by the "Regional Innovation Strategy (RIS)" through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (MOE) (Grant No. 2022RIS-005).

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