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Concept of Autonomous Underwater Vehicle Docking Using 3D Imaging Sonar

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In this paper, we propose the concept of underwater docking of an autonomous underwater vehicle (AUV) for power supply and data transfer to conduct the continuous operation of the AUV without launch and recovery operations. Our basic concept of docking involves the use of a 3D imaging sonar as the autonomous homing sensor for AUV and a remotely operated vehicle (ROV) as the docking station, which has maneuverability to compensate for the homing error of the AUV. On the basis of this concept, we use a 3D imaging sonar as a homing sensor during docking. The 3D imaging sonar has a potential for advanced AUV operation and will be the versatile "eye" of the AUV.

1. Introduction

Nowadays, a remotely operated vehicle (ROV) is used for many types of subsea operation by a human pilot on a surface ship through a tether cable. On the other hand, an autonomous underwater vehicle (AUV), which has no tether cables, is used for large-area subsea survey or bottom mapping. However, its operating time is limited because its power source is an internal battery, typically a lithium ion secondary battery, with limited energy. Although battery technology has recently been improved, the battery power for such survey and mapping operations remains limited. For this reason, launch and recovery, and power supply and data uploading on the surface ship need to be repeated for the continuous operation of the AUV. This operation is inefficient and costly in terms of the total operation. Furthermore, the recovery of the AUV is a troublesome and dangerous offshore operation.

For the improvement of the efficiency of AUV operation, many research studies on subsea docking stations for the AUV have been carried out for many years. The basic concept is that the AUV docks to the subsea docking station and power is supplied and data are transferred through subsea cables between the docking station and the surface ship.

Various types of underwater sensor have been developed or used for precise AUV navigation and homing to a docking station. Typical underwater acoustic sensors are used in addition to

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an electromagnetic sensor and an underwater camera. In particular, the underwater acoustic tracking sensor called ultra-short baseline (USBL) is used. The USBL consists of a transceiver and a transponder. The transceiver is installed at the nose of the AUV and the transponder at the docking position of the station. The USBL has sufficient tracking and AUV homing accuracies.

We apply the 3D imaging sonar developed by Coda Octopus Products Ltd. as the docking sensor. For our docking concept, the 3D imaging sonar can be used as a sensor for not only docking but also typical front avoidance and underwater monitoring. Furthermore, no signal sources for an AUV homing sensor, such as an acoustic transponder, an electromagnetic transceiver, or LED light, are necessary on the docking station because the 3D imaging sonar is an active sonar. In the future, this feature can lead to other applications that require approaching an arbitrary subsea object without a signal source.

2. Basic Docking Concept

As for the conventional AUV docking concept, the docking station, which has a cone-shaped dock to compensate for the error of AUV homing, is laid on the sea bed, and the AUV approaches the dock with homing sensor information. The disadvantage of this concept however is that the docking station requires maintenance of its operation and durability for long-term operation. Moreover, the advantage of the AUV, that is, its large-area surveillance capability, might be lost because the station is settled at a fixed position.

Here, we apply the concept of using an ROV as the docking station, which is operated from a surface ship, to improve the operability and flexibility of the docking station. In this concept, the operability of the docking station is improved, and the AUV capability of large-area surveillance can be expanded because docking points can be moved continuously.

All operations can be controlled from the surface ship using the USBL in a wide range because the USBL has very wide range capabilities. The ROV waits at the planned position and scheduled docking time, and after the AUV reaches the docking area and its signals are captured by the USBL, the surface ship sends waypoint commands to the AUV by underwater acoustic communication to form the appropriate approaching course and relative position between the AUV and the ROV docking station. After this preparation, the AUV begins homing to the ROV, and finally the AUV is docked to the ROV by adjusting the final position of the ROV.

3. Homing Using 3D Imaging Sonar Concept

3.1 Previous homing sensors for docking

In this section, we provide a brief summary about typical previous homing sensors for docking. Previously studied homing sensors are typically categorized into the following three types of underwater sensor: underwater acoustic, electromagnetic, and visual sensors such as an underwater camera.

As for the underwater acoustic sensor, the USBL is typically used . The transceiver is installed on the nose part of the AUV and the transponder on the docking station.[1] The USBL transceiver consists of transmitters and a receiver array, and can detect the range and bearing of the transponder with a delay time of the echo returned from the transponder and the phase difference between the array elements. The USBL has very wide range capabilities. In this research, a range of 2000 m was observed. However, the USBL can only detect the target position, so even if the directions of the dock and AUV do not coincide, the AUV has to enter the dock as it is. Therefore, the dock entrance has a conelike shape to compensate for this angle misalignment.

The electromagnetic sensor system consists of a transmitter located at the dock and a receiver located at the AUV.[2] The transmitter generates two orthogonal oscillatory magnetic dipole fields from two 64-cm-diameter coils. The receiver in the nose of the AUV consists of three orthogonal coils of 9 cm diameter. The range of this system is estimated to be around 25–30 m.

Optical sensor research has been conducted since 1997.[3] A recent example of a system used in this research consists of four LED lights located at the inlet of the cone of the dock in the shape of a cross and a stereo camera located at the nose of the AUV.[4] Optical sensors are used as terminal guidance sensors because their range is limited in seawater.

3.2 Homing using 3D imaging sonar

The 3D imaging sonar developed by Coda Octopus Products Ltd. consists of transmitters and a receiver array. An example of their product is shown in Fig. 1.

The transmitter transmits a wide-angle acoustic pulse to the target and the receiver receives the echo reflected from the target with a planar array, which forms horizontal and vertical receiving multibeams by array signal processing. The acoustic frequencies are 365 and 630 kHz (software-switchable). Each beam is very sharp and the sonar has a fine resolution around the horizontal and vertical angles. In the case of Echoscope C500, which is the most compact product, the beam number is 128 × 64 and the beam spacing is 0.19° × 0.39° (finest). In addition to this bearing information, each beam has range information obtained from the delay time between transmitting and receiving. The resolution range is 2–3 cm. This acoustical

Fig. 1. 3D imaging sonar.[5]

signal is processed inside the sonar body and translated to fully 3D volumetric information of X, Y, Z in real time and at a high update rate. The update rate is up to 20 Hz. An example of a 3D image is shown in Fig. 2.

This sonar is suspended from a surface ship and mainly used for monitoring offshore constructions. Recently, it has been used as a navigation sensor installed at the ROV or AUV because it has a sufficient range for front avoidance. Furthermore, it can detect complex subsea structures for future advanced AUV operation beyond simple surveys, such as the combination of large-area survey and the identification or acquisition of a searched object.

We use this 3D imaging sonar as the front homing sensor on the AUV. The 3D imaging sonar can be a multipurpose sensor; thus, dedicated docking sensors such as those mentioned above are not necessary. Moreover, it can detect not only the position of the ROV docking station in a wide range, but also the attitude in the near range by recognizing the outline shape of the ROV. The conventional USBL homer can only detect the position of the docking station. However, the 3D imaging sonar can detect the attitude of the docking station and this can lead to an optimal approach and attitude of the AUV to dock. Moreover, it can make the final capturing maneuver of the ROV easy.

3.3 Docking sequence

The docking sequence is roughly divided into four phases. The conceptual schematics are shown in Fig. 3.

(1) Meeting phase
(2) Waypoint guidance initial phase
(3) Simple tracking intermediate phase
(4) Optimal routing terminal phase

In the meeting phase, the AUV moves to the docking region where the mother ship and ROV docking station wait for the AUV. Basically, in the mission plan, the docking schedule and area are determined in advance. The mother ship monitors the position of the ROV docking

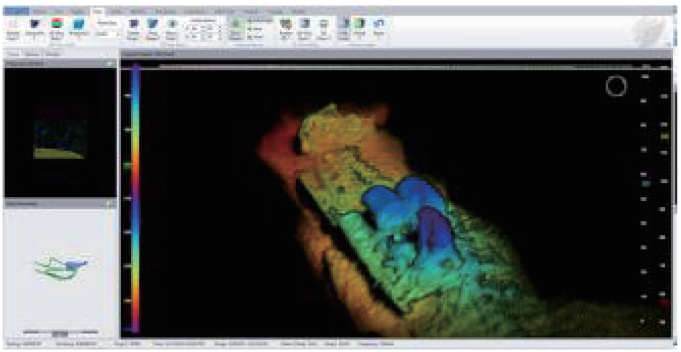

Fig. 2. (Color online) Example of 3D imaging sonar output.[6]

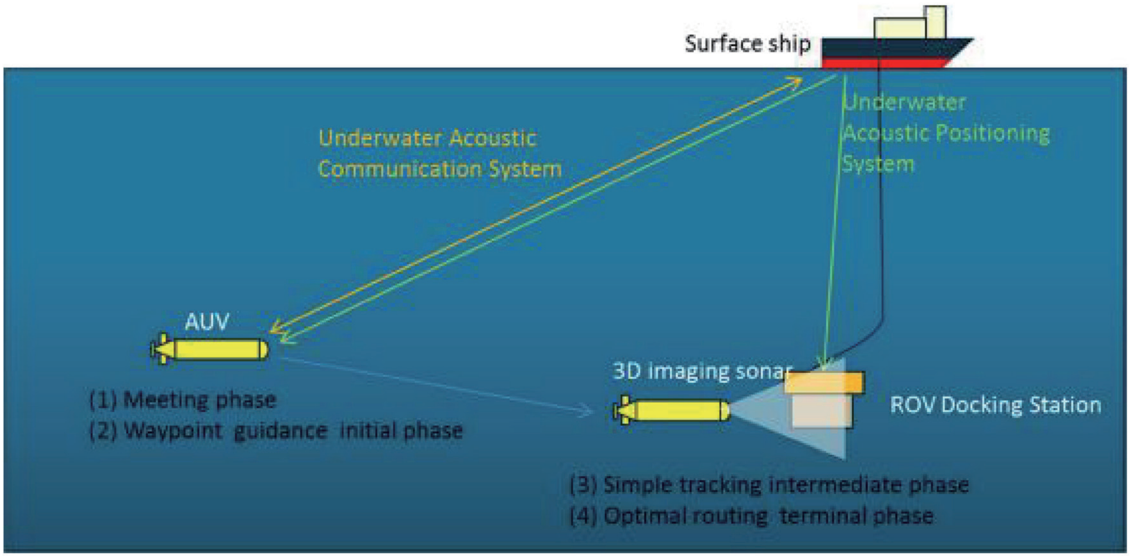

Fig. 3. (Color online) Conceptual docking schematics.

station using the underwater acoustic positioning system (USBL). When the AUV enters the meeting point, communication with the mother ship is established by the underwater acoustic communication system, and the position of the AUV is monitored by the USBL.

On the basis of the results of positioning the AUV, the mother ship plans a waypoint route to rendezvous with the AUV in a straight line to the ROV docking station, and the waypoint route is transmitted to the AUV by underwater communication. This waypoint route consists of the following two waypoints: the target point of the ROV (WP1) and the beginning point of WP2.

WP2 is set under the following two conditions: The orientation of the line of WP2 to WP1 is the same as the tidal current such that the lateral current is eliminated as much as possible when docked. The distance between WP1 and WP2 is greater than or equal to the sonar detection distance such that the 3D imaging sonar can detect ROV docking stations after passing WP2. The AUV navigates autonomously from its current position to WP1 via WP2. After passing WP2, the AUV starts 3D imaging sonar searching. This phase is called the waypoint guidance initial phase.

After the AUV passes the detection distance of the ROV docking station, the 3D imaging sonar provides detection information as a point cloud. During this time, although there is a possibility of false detection, WP1 is used to eliminate the false detection. The average position of the obtained point group is set as a new waypoint SWP1, and the AUV performs autonomous navigation so as to direct its course to this SWP1. This is called the simple tracking intermediate phase.

As the AUV further approaches the ROV docking station, the number of points detected by the 3D imaging sonar increases, and the point cloud more accurately represents the shape of the ROV docking station. From the obtained 3D cloud shape, it is possible to recognize not only the position of the ROV docking station but also its attitude, that is, the docking axis.

Although the ROV is controlled to direct the docking axis to the AUV from the initial phase, the course of the AUV does not necessarily coincide with the actual docking axis owing to errors in the underwater acoustic positioning system and the initial guidance error of the AUV. For this reason, the AUV plans its final proximity path so as to simultaneously carry out the position control to the docking position SWP1 and the attitude control to make the docking axis on the ROV side and the docking axis on the AUV side coincide with each other. The AUV controls its own position and attitude in accordance with this path plan. This phase is called the optimum routing terminal phase.

3.4 Configuration of ROV docking station

In an international project, Nagasaki University is in charge of developing the prototype of the ROV docking station, and it is important to make the shape recognition of the 3D imaging sonar easier. The ROV has a frame structure in which components such as thrusters, a docking device, and buoyancy bodies are attached to the frame. This configuration results in a complicated shape as an acoustic reflection body.

Thus, we planned the ROV docking station to have acoustic reflector panels on the surface on the AUV side. The planned ROV docking station is shown in Fig. 4.

Furthermore, to improve the *S*/*N* ratio with respect to the 3D imaging sonar, it is preferable that the acoustic reflection panel is made of a material having a high reflectance against underwater ultrasonic waves. The acoustic reflectance at the boundary between two mediums is generally determined as follows using the acoustic impedances of the mediums passing through.

$$R = (Z_2 - Z_1)/(Z_2 + Z_1) \tag{1}$$

Here, Z_1 is the acoustic impedance of seawater and Z_2 is one of the materials of the acoustic reflector panel.

Resin materials, such as polyvinyl chloride (PVC), are light and easy to handle, but are not highly reflective. On the other hand, metals such as aluminum have high reflectivity but are heavy. Although the reflectance of air is extremely high, when an air layer is provided

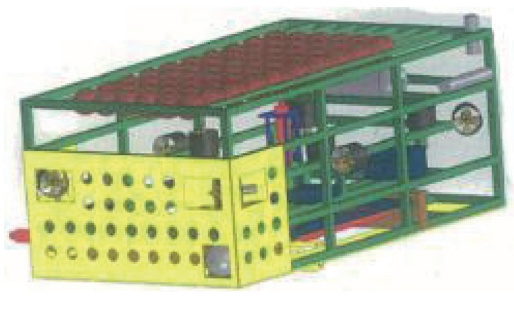

Fig. 4. (Color online) Planned ROV docking station.

Table 1
Acoustic reflectance in water.

Material	Sound velocity (m/s)	Acoustic impedance (MPa s/m)	*R* (%)
Water	1500	1.5	—
Aluminum	6380	17.2	83.6
PVC	2390	3.3	37.0
Air	340	0.0004	−99.9

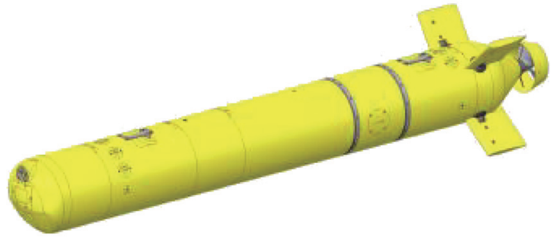

Fig. 5. (Color online) AUV technical demonstrator "Naminow".

in a pressure container, the weight of the container itself is expected to increase. As buoyant bodies generally used in ROVs, foaming resin materials and syntactic foams made of glass microbeads having macroscopic air bubbles inside are well known. These materials may have high reflectivity owing to their internal air bubbles and are very light, so they are expected to be good reflectors.

4. Conclusions and Future Work

We propose the AUV and ROV docking concept, and the 3D imaging sonar has practical benefit as a homing sensor for docking. Furthermore, it has potential for the future advanced operation of the AUV.

We have just begun the international joint development of a docking system in accordance with our concept. Mitsubishi Heavy Industries Ltd. takes part in the AUV and system integration and Nagasaki University takes part in the ROV on the Japan side. Coda Octopus Product Ltd. is developing the ROV recognition software on the Scotland side.

For this program, we will develop a technical demonstrator AUV based on the "Naminow" AUV shown in Fig. 5. The 3D imaging sonar will be installed at the front end of the body (there is no illustration yet).

The main technical development items are as follows; this research is being conducted within the framework of an international collaboration between Japan and Scotland, with (1), (3), and (4) on the Japan side and (2) on the Scotland side.

In this paper, we mainly described the concept developed on the Japan side.

(1) Total system integration
(2) ROV docking station tracking and attitude recognition technology with 3D imaging sonar
(3) AUV docking sequence and control

(4) ROV docking station tracked by acoustic sonar

With regard to (2) and (4), 3D imaging sonar evaluation tests using physical dummies of ROV were conducted in September 2019 to acquire basic data using several materials as acoustic reflectors and to fix the outer shape design of ROVs.

At the same time, the guidance and control logic of the AUV (3) are being studied, and the entire integration (1) will be carried out on the Japan side.

Acknowledgments

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References

1 B. W. Hobson, R. S. McEwen, J. Erickson, T. Hoover, L. Mcbride, F. Shane, and J. G. Bellingham: Proc. OCEANS 2007 (IEEE, 2007)
2 M. D. Feezor, F. Y. Sorrell, P. R. Blankinship, and J. G. Bellingham: Proc. OCEANS ’97 (MTS/IEEE, 1997).
3 S. Cowen, S. Briest, and J. Dombrowski: Proc. OCEANS ’97 (MTS/IEEE, 1997).
4 Y. Li, Y. Jiang, J. Cao, B. Wang, and Y. Li: Ocean Eng. **110** (2015) 163.
5 Echoscope4G® C500: https://www.codaoctopus.com/products/3d/echoscope-4G-c500 (accessed September 2019)
6 Obstacle Avoidance for Unmanned Missions: https://www.codaoctopus.com/defense/applications/auvasv-navigation (accessed September 2019)