Development of Autonomous Underwater Vehicle (AUV) with Robot Arm SPICE

In the offshore development business, including offshore oil and gas field development, as well as in other businesses, it is required to enhance operating efficiency and reduce environmental impact, and as a solution to it, there are increasing expectations for the commercialization of autonomous underwater vehicles (AUVs). In response to such expectations, we have developed SPICE, an AUV that is equipped with a subsea docking station and a robot arm for inspecting subsea pipelines.

Introduction

Recently, in the offshore development business, including offshore oil and gas field development and offshore mineral resource development, as well as in other businesses, it is required to enhance operating efficiency and reduce environmental impact [1].

1. Background and aim

In the offshore development business, including the development, construction, and maintenance of offshore oil and gas fields and exploration of offshore mineral resources, remotely operated vehicles (ROVs) have been used to explore the seabed, and construct, inspect, and maintain subsea structures. Because of the recent oil price drop and increasing interest in environmental impact, and thanks to the progress of technology in the field of autonomous underwater vehicles (AUVs), it is increasingly expected that operating efficiency will be enhanced by automating part of ROV operation with AUVs and CO_2 emissions will be reduced by reducing the operating time of the support vessel with the enhanced operating efficiency. AUVs, unlike ROVs, do not require operators with advanced skills and their movement is not restricted by wires. Also, ROVs require support vessels with advanced dynamic positioning capabilities to operate, but AUVs can be operated with simpler support vessels. We began the research and development of AUVs in 2013 by taking advantage of the underwater vehicle and equipment technologies we have accumulated for many years in building submarines and deep submergence rescue vehicles.

2. Product concept and technical challenges

In addition to our unique underwater docking technology, we developed underwater power transfer and underwater optical communication technologies, which are fundamental technologies to operate AUVs continuously without retrieving them. Also, aiming to enter the oil and gas industries, we developed technologies to enable close-range inspection that conventional AUVs cannot perform, including pipeline tracking systems and robot arms for inspection, and successfully commercialized SPICE (Subsea Precise Inspector with Close Eyes), which is an AUV for pipeline inspection [2].

Based on the results of comparison of advantages and disadvantages with ROVs, which are now commonly used in offshore exploration, and interviews with pipeline inspection companies, we set the following as technical challenges for commercialization.

- Because the operating time is restricted by the battery capacity, underwater station docking technologies are required, including underwater charging systems.
- Because real-time monitoring and instruction are

† System that is designed for the close-range inspection of subsea pipelines and other infrastructure and that consists mainly of autonomous underwater vehicles, support vessels, and stations

impossible, new technologies are required to autonomously search for and track pipelines and control robot arms.

3. Details of element technologies and problem-solving process

(1) Underwater station docking technology

Conventional AUVs are retrieved and charged on the vessel when they run out of battery. However, if AUVs can be docked to an underwater station for charging and data transfer, they can inspect subsea pipelines almost permanently without being retrieved, which provides enhanced safety in offshore operations. This technology can be applied to stations installed at the seabed. It can also be used for systems that periodically conduct patrol inspection in a certain area around a station with adequate power supply and communication. **Figure 1** shows how an AUV is docked to an underwater station.

(i) Underwater docking [3)]

The AUV performs a docking sequence in two steps. In the first step, the AUV catches the pole installed on the station. The AUV moves guided by the acoustic signals from the transponder mounted at the tip of the pole. When the AUV approaches the station, it detects the omni-directional light source mounted at the base of the pole. The AUV moves toward the light source and grabs the pole with the concave hardware mounted on the front of the AUV. In the second step, the AUV turns around the pole it has grabbed and moves up and aligns the convex mating hardware mounted on the top of the AUV with the mating device on the station to dock with the station. For this positioning process, a pair of optical communication devices mounted on the AUV and station are utilized.

(ii) Underwater charging and data transfer

The AUV starts charging the battery after it docks with the station. For underwater power transfer, both the AUV and station have a pair of wireless power transfer pads. During docking, these pads are kept a few centimeters apart, and power is transferred by electromagnetic induction with an efficiency of 90% or more.

While the battery is being charged, the inspection data acquired during subsea pipeline inspection, including videos and images, are transferred via the optical communication device used for docking.

(2) Pipeline search and tracking technology

The AUV recognizes its own location to approach a subsea pipeline, performs a pipeline search, and tracks and inspects the pipeline by tracing the pipeline with the body and arm.

(i) Subsea self-location recognition

Some subsea pipelines are installed at a water depth of more than 3,000m. To inspect such deepwater pipelines, AUVs are required to constantly recognize their own location while in the water, and the inertial navigation system (INS) carries out this function. The INS estimates the location of the vessel based on the acceleration and attitude acquired from sensors, but errors are accumulated because AUVs operate underwater for several hours. In the water, unlike on land, the location of the vessel cannot be measured with GPS or the like, and therefore, correction is made from the support vessel by using acoustic positioning and acoustic communication.

(ii) Pipeline search

After the AUV reaches the seabed, it moves toward the estimated location of a pipeline, from the side of the pipeline, and from a location some distance from the

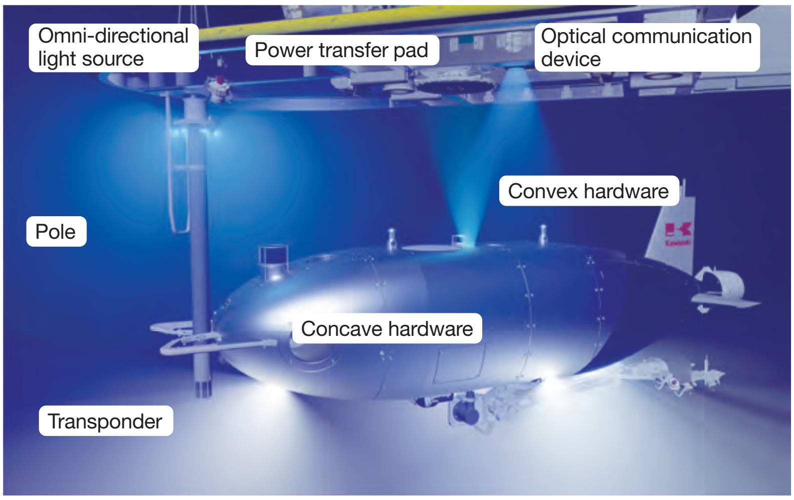

Fig. 1 Docking between AUV and underwater station

pipeline. The AUV performs seabed mapping with a multi-beam sonar. A linear gradation pattern is observed when the AUV passes over a pipeline, which is processed by image processing technology to identify the exact location of the pipeline.

(iii) Pipeline tracking

After identifying the location of the pipeline, the AUV starts pipeline tracking from a few meters above the pipeline in the predetermined direction. In pipeline tracking, as shown in **Fig. 2**, the multi-beam sonar used to search for pipelines is used to detect the cross section of the pipeline and the seabed as a semicylindrical shape. This semicylindrical shape is followed to track the pipeline. At the same time, the robot arm is controlled in consideration of the position, speed, and altitude of the AUV to guide the tip of the robot arm precisely to the proximity of the pipeline [4].

(3) Robot arm control technology

As a technology to precisely locate the sensors, including the cameras, close to the pipeline for underwater close-range inspection, we developed a robot arm specially designed to be installed at the bottom of the AUV.

(i) Structure

The structural members must be lightweight and able to be used for subsea operation in order to be installed on the AUV, and therefore, they are made mainly of corrosion-resistant aluminum alloy. In addition, bearings and actuators have been adopted that can withstand use in the sea.

The robot arm is designed to have six degrees of freedom with six axes so that the sensors can be located close to the pipeline with the robot arm tip in any position or posture as shown in **Fig. 3.** Three axes at the AUV side are controlled actively, and the other three axes at the tip of the arm have a passively controlled link structure, which allows the sensors to smoothly track the pipeline to be inspected. This simplified structure has provided a reduced weight and control load.

(ii) Control

Unlike the robot arms secured to the ground, this robot arm is installed onto an AUV, which is constantly moving. Therefore, we developed a logic to control the tip of the robot arm in consideration of the position coordinates detected by the moving AUV and the future position and attitude of the AUV so that the tip of the robot arm is always directed toward the pipeline and stays over the pipeline even if the AUV moves away from the pipeline as shown in **Fig. 4.**

(iii) ITU (Inspection Tool Unit)

We developed an ITU for enabling the sensors mounted at the tip of the robot arm to track the pipeline safely and reliably. The ITU has stabilizing fins for generating a pushing force against the pipeline by using the water stream generated during operation and sensors and damping mechanisms for preventing excessing pushing and mitigating damage caused by collision with obstacles and other objects. The ITU is installed at the tip of the robot arm so that the sensors installed on the ITU can be kept close to the pipeline in a stable posture while the AUV is moving over the pipeline. This provides accurate and precise inspection data that conventional AUVs cannot achieve [5].

(iv) Verification

SPICE is the world's first AUV equipped with a robot arm, and we had many challenges with how to verify the robot arm in the processes from design, production, and

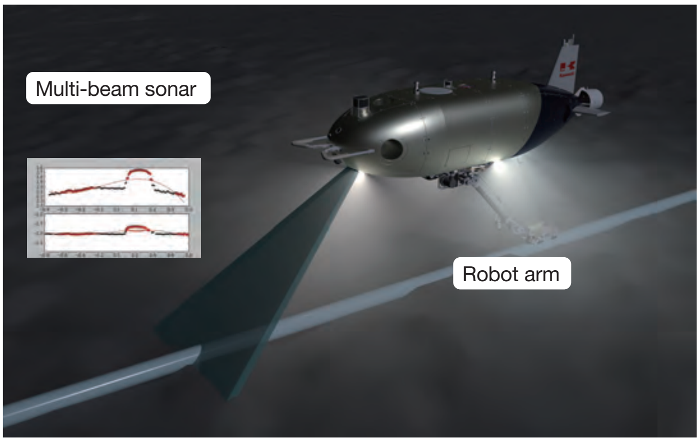

Fig. 2 Pipeline tracking

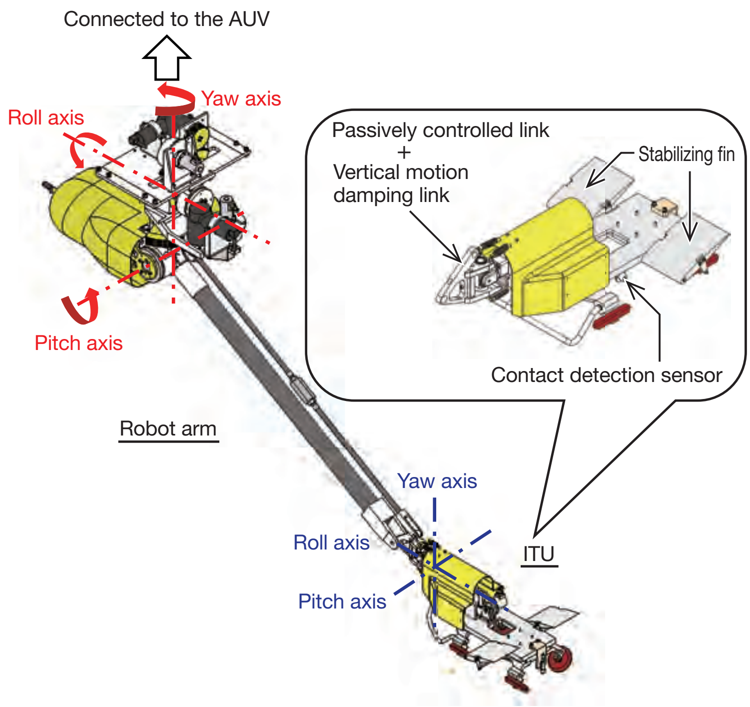

Fig.3 Structure of robot arm

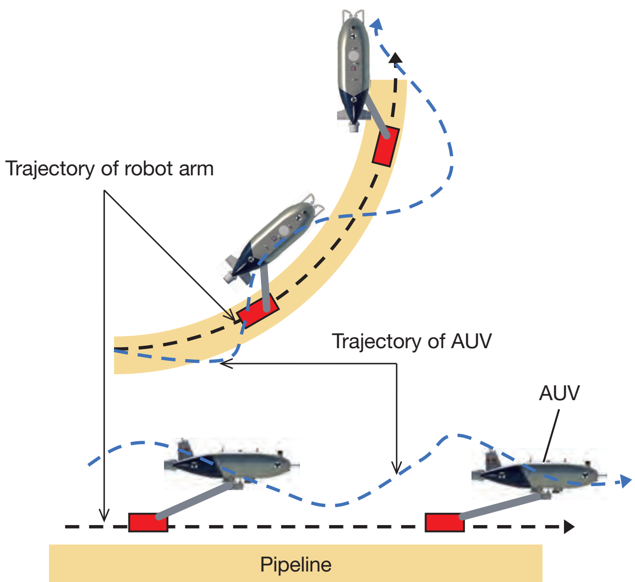

Fig. 4 Pipeline tracking by AUV [2)]

testing to installation on the AUV. Using the robot technologies we have accumulated, as shown in **Fig. 5**, we installed the robot arm designed for AUVs onto the tip of an industrial robot and verified the motion of the robot arm following the motion simulating an AUV, which allowed us to conduct element tests efficiently and reach operational verification testing earlier than anticipated.

Also, through various tests, our AUV exhibited stable pipeline tracking capabilities and a high potential as a platform for subsea pipeline close-range inspection, attracting attention in the oil and gas field. In September 2022, we conducted offshore testing using SPICE as part of joint research with TotalEnergies SE, which is a French energy supermajor, on protective potential measurement in subsea pipeline close-range inspection, which ended in success (**Fig. 6**) and demonstrated SPICE's usability [6)].

Fig. 5 Simulation of robot arm tracking operation using an industrial robot

Fig. 6 Successful offshore testing jointly with TotalEnergies

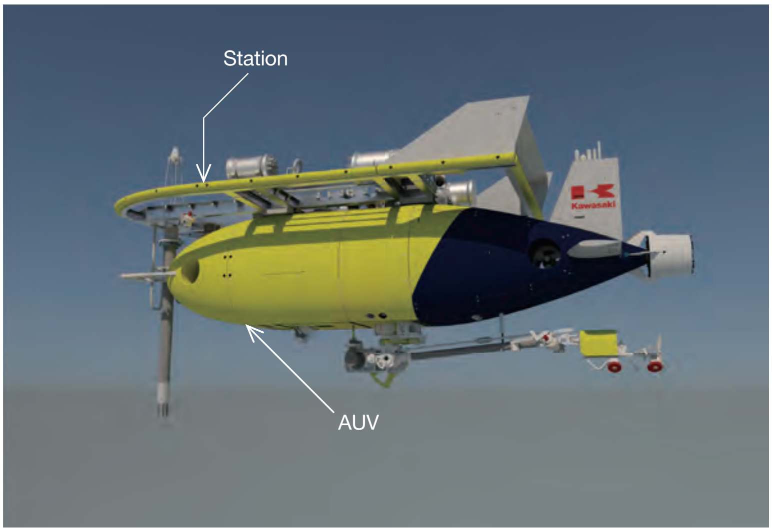

Fig. 7 First commercial AUV

Table 1 Principal particulars of first commercial model

	AUV	Station
Total length [m]	5. 6	5. 6
Total width [m]	1. 3	2. 0
Total height [m]	1. 5	2. 6
Weight in air [tons]	Approx. 2. 5	Approx. 1. 2
Operational water depth [m]	3, 000 (max)	500 (max.)
Battery	Lithium polymer battery	–
Speed [knots]	4. 0 (max.)	–
Operation time [hours]	10 (inspection work)	–
Charging time [hours]	3 (underwater)	
Wireless charging system [kW]	10	
Optical wireless communication [Mbps]	100	

4. Delivery and introduction examples

In 2020, we received an order for the first commercial model of SPICE (**Fig. 7**), which incorporates these technologies, from a British pipeline inspection company [7]. **Table 1** shows the principal particulars of this model. This commercial model can operate at a water depth of up to 3,000 m and perform pipeline inspection at a speed of 2 knots for 10 hours. The station can operate at a water depth of up to 500 m, which helps reduce battery power consumption while the AUV is operating. In addition, the underwater charging system has a capacity of 10 kW and can charge the AUV in only three hours.

Conclusion

We developed technologies aimed at automating pipeline inspection using AUVs and in the pipeline tracking verification test, received a high evaluation from an oil major. We are about to reach the commercialization stage.

Expanding their applications to floating offshore wind farms and other facilities, we will develop AUVs and inspection methods that meet the needs of the facilities to be inspected, by taking advantage of the AUV and robot arm control technologies we have accumulated with AUVs for pipeline inspection. Also, we will aim to develop AUVs that can be operated safely while satisfying the body requirements and operational requirements given in the "Guidelines for Safe Operation of AUVs," issued by the Ministry of Land, Infrastructure, Transport and Tourism.

Finally, we would likely to thank The Nippon Foundation, which provided subsidies to develop a robot arm for inspection and conduct demonstration experiments for pipeline tracking, and the Ministry of Land, Infrastructure, Transport and Tourism, which provided subsidies to develop inspection sensors and their data processing.

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Noriyuki Okaya
AUV Department, Kobe Shipyard,
Ship & Offshore Structure Business Division,
Energy Solution & Marine Engineering Company


Koichi Fukui
AUV Department, Kobe Shipyard,
Ship & Offshore Structure Business Division,
Energy Solution & Marine Engineering Company


Manabu Matsui
AUV Department, Kobe Shipyard,
Ship & Offshore Structure Business Division,
Energy Solution & Marine Engineering Company


Kosuke Masuda
AUV Department, Kobe Shipyard,
Ship & Offshore Structure Business Division,
Energy Solution & Marine Engineering Company


Kaoru Koyano
Integration System Department,
System Technology Development Center,
Corporate Technology Division


Kazuyuki Nakamura
Control System Department,
System Technology Development Center,
Corporate Technology Division