Maritime Infrastructure Security Using Underwater Sonar Systems

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OVERVIEW: Hitachi has been developing and manufacturing sonar systems for use in the ships of the Japan Maritime Self-Defense Force since the 1950s. This technology, which at first was mainly developed as a means of finding submarines and underwater mines, is currently being used for the protection of public infrastructures located along the coast, and to contribute to the improvement of both efficiency and safety in underwater civil engineering work. Hitachi will continue aggressively working to achieve safety and security in each type of public marine infrastructure, with a focus on underwater acoustic system technology.

INTRODUCTION

JAPAN, which is comprised of islands, is a marine nation, and not only does it enjoy countless benefits from the ocean, it also relies on the ocean for more than 90% of its cargo shipments. Various types of marine security have been important topics in recent years due to problems such as a range of terroristic actions, piracy, and other issues.

In the 1950s, Hitachi began to work on the research and development of sonar systems that can search for various types of undersea objects using ultrasonic waves, and has delivered these systems for use on ships in the civil service.

This article provides an overview of sonar systems and discusses Hitachi's track record in participating in research related to marine infrastructure security.

OVERVIEW OF SONAR SYSTEM

Visible light, radio waves, and other electromagnetic waves attenuate quickly underwater, making it extremely difficult to locate objects using radar. A sonar system works in the same way as the method used by the dolphin, a type of marine mammal, to locate the positions of underwater objects with sound waves.

History of Development

In 1912, the luxury liner Titanic hit a gigantic iceberg during its maiden journey from the UK to New York, sinking and taking with it the lives of approximately 1,500 passengers. Spurred on by this tragedy, the USA developed a device that could detect icebergs by bouncing sound waves off their underwater parts and picking up the reflected sound, called "sound navigation and ranging," or "sonar." Sonar technology has been improved in various ways since then, and was used by the navies of Europe and the USA to detect submarines during the ship battles of the First World War.

Basic Principle

A sonar system uses a sensor that converts between electrical and acoustic signals to send ultrasonic waves underwater. The sound reflected off underwater objects and the seafloor is received and converted back into electrical signals, which are then turned into images through various types of signal processing. Sonar uses this basic principle to detect underwater objects, and similar ultrasonic wave technology is also used by fishing industry's fish detectors, and by the medical sector's ultrasonic imagers. Fig. 1 shows this basic principle in a system block.

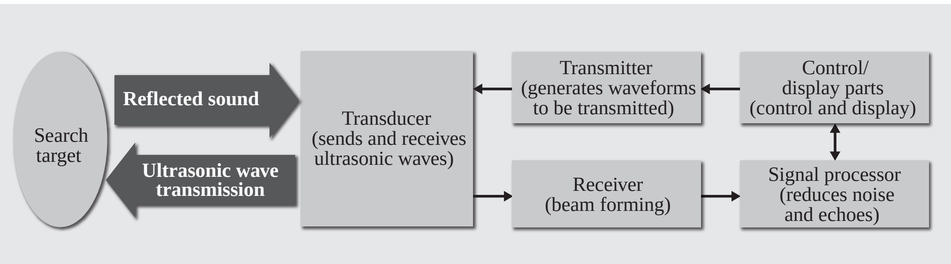

Fig. 1—Basic Principle of Sonar.
This system block shows the basic principle used by sonar to detect underwater objects.

OVERVIEW OF MINE HUNTING SONAR SYSTEM

Hitachi was the first company in Japan to develop sonar for detecting submarines and mines in the postwar era (based on the research conducted by Hitachi, Ltd.). This section provides an overview of the sonar-based mine hunting sonar systems used to search for and classify mines, as well as a description of the technologies that are applied to this task. Fig. 2 shows a minesweeper equipped with a mine hunting sonar system.

Target Objects

An underwater mine, which is the type of weapon mine hunting sonars attempt to find, works by exploding after it detects either the noise or fluctuations in geomagnetism or water pressure caused by ship movement, thereby damaging the hull of a passing ship. A mine's external form is a small spherical or cylindrical shape, and inside the mine is explosive material, multiple ship detection sensors, and detonators. Mines are covertly dispersed in shipping lanes throughout the vast sea, and since they are tiny objects that wait motionlessly underwater or on the seafloor for ships to ambush, they are extremely difficult to find.

Main Functions of Applied Technologies

The development and manufacturing of mine hunting sonars requires technologies in a wide range of fields, including operational analysis, system engineering, marine acoustic engineering, piezoelectric materials, high-speed computing, optical transmission, signal image processing, and mechatronics control, as well as human-machine interfaces for the sake of operability, maintainability, and upgradeability. The key components and technologies applied to functions are described below.

Fig. 2—Minesweepers Equipped with Mine Hunting Sonars.
A minesweeper guards the safety of the ocean by removing mines laid underwater and on the seafloor.

(1) Transducers

A transducer is an electrical acoustic converter that is equipped at the bottom of the ship, transmits ultrasonic waves underwater, and receives the reflected sounds. A large number of broadband transmitting and receiving elements are in an array in the transducer module, which is included along with the electronic circuit module in a watertight stainless steel case. The transducer internally converts received signals to light and transmits them to the on-ship processor for front-end processing to reduce the effects of signal degradation and noise, in order to convert the received ultrasonic waves into high-definition images.

(2) Drive stabilizers

A minesweeper is a small ship with a standard displacement of approximately 500 t, and is easily destabilized by ocean waves. In order to deal with this problem, data from the motion sensors in the ship's hull is used to control multiple watertight hydraulic cylinders and rotation and elevation devices in a three-axis parallel link system. This makes it possible to correct for the oscillation of the transducer in realtime, so that mines can be searched for in a stable fashion even in rough seas.

(3) Signal processing and display

When ultrasonic waves are transmitted, other sounds are picked up as well, including the various noises caused by the moving ship, and underwater echoes from the seafloor, reefs, and other objects that are not mines. Noise/echo reduction signal processing and signal accumulation functions are used to accumulate multiple signals received and corrected based on the speed of the ship's own movement, thereby removing extraneous noise signals. This makes it possible to clearly display just the shape of the seafloor and other underwater objects, thereby improving the visibility of picked up images.

(4) Automatic support functions

An automatic detection function is used to automatically superimpose a detection marker over any signal that appears to be a mine in the underwater images shown on the display. Two algorithms are available for selection based on hydrographic conditions, the attributes of the ocean area, and other environmental characteristics. When the "multiping" signal detection process algorithm reaches a threshold after receiving and accumulating multiple signals that appear to be the search target from the same position, it determines that the search target has been detected. The phase-error variance process is an algorithm that quantifies the stability of phase differences, and detects a mine if the stability of the signal is less than the threshold. This algorithm was created to analyze the attributes of echo signals by taking data measurements of the actual ocean surface.

The automatic classification function extracts the image region from search target images that appear to indicate the detection of a mine, and applies image processing to automatically measure and display dimensions. The sonar crew then determines the type of mine based on these measurement results.

(5) Search target depth measurement function

Reflected sounds from the mine are used to automatically compute the depth of the search target based on the calculation of the vertical orientation of the phase difference between the transducer's upper and lower layers of reception elements. Since the propagation path taken by the sound waves is bent according to the temperature of the seawater, by automatically correcting based on sound speed data measured in advance at each depth, it is possible to calculate the correct depth. Based on this result, the sonar crew determines whether or not the mine moored under the water is a ground mine.

(6) Others

Defense systems exist in a "sword and shield" relationship. On the mine's side, development is aimed at preventing detection through research into shapes and materials with acoustic stealth capabilities. On the sonar side, research and development must continuously focus on how to detect signals with a weak reflection echo, and on sensors for unmanned underwater vehicles and other areas. The development and manufacturing of these systems in the field of defense involves specialized engineers, various types of specialized facilities such as large cisterns and fixtures, and secret maintenance engineering facilities that satisfy the standards of the Japan Ministry of Defense.

Track Record

The mine hunting sonars manufactured by Hitachi have helped contribute to international efforts such as minesweeping in the Persian Gulf after the war of 1991, in the search and rescue operations after the Great East Japan Earthquake of 2011, and in the various missions of the Japan Maritime Self-Defense Force. Minesweepers also include an acoustic minesweeping apparatus that imitates the sound of a moving ship in order to cause mines to explode through sympathetic detonation, a non-magnetic crane and capstan to deploy and recover this apparatus from the water, and a degausser and various electrical devices designed to prevent the mines from detonating due to the magnetism of the ship's hull. Many different products built by Hitachi are contributing to the safety of the ocean in this way.

CONTRIBUTION TO MARINE PUBLIC INFRASTRUCTURES

A description of Hitachi's track record of using sonar technology to participate in the security of public marine infrastructures follows.

The demand for strengthened security against various types of terrorism has been increasing in recent years, starting with the September 11, 2001 terrorist attacks in the USA. In addition, a large number of crucial social infrastructures are located along Japan's seafront and in the coastal region, including various types of power plants, oil reserve facilities, and offshore airports. If these facilities are hit by a terrorist attack, Japan's society and economy may suffer damage.

Terrorist acts aimed at essential facilities based on covert infiltration from the sea are envisioned in the design of the various advanced security systems in the geographical environment of the seafront and coast, and there have been kidnapping problems and cases of suspicious vessels in the past as well. During an incident that occurred in the marine area off the southwestern coast of Kyushu in 2001, a covert operation vessel was sunk in a gun battle with the Japan Coast Guard, and a large number of weapons were discovered in the vessel along with equipment used in underwater infiltration including small boats, rafts, diving gear, and underwater scooters.

Underwater Infiltration Monitoring: Research into Underwater Security Sonar Systems

Together with the Underwater Technology Research Center, Institute of Industrial Science, The University of Tokyo, Hitachi participated in joint research into an underwater security sonar system between 2005 and 2007. The objective of this research is to build a monitoring system that can prevent acts of terrorism against all types of coastal public infrastructure facilities, and to contribute to the achievement of a safe and secure society by establishing various technologies based on operation and evaluation in an actual harbor. A conceptual diagram of these operations is shown in Fig. 3.

The system is built around an integrated monitoring system, and is comprised of fixed location sonar

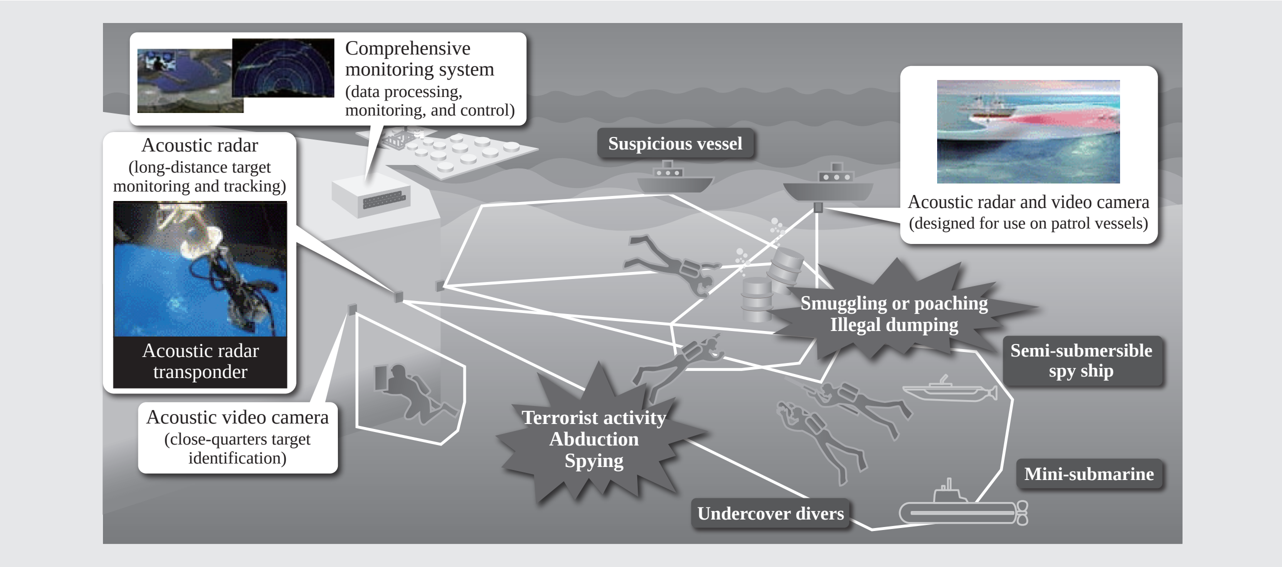

Fig. 3—Conceptual Diagram of Underwater Security Sonar System Operation.
This diagram illustrates the concepts behind the underwater security sonar system.

devices installed on quays and the seafloor, as well as sonar devices installed on ships. Of this research, Hitachi was responsible for general consideration and support of the research project as a whole, the integrated monitoring subsystem that is central to operation, sonar signal processing, and the rotation and elevation mechanism installed on the ships. In addition, Hitachi provided technologies in a wide range of fields, including system engineering, sonar signal processing software, mechatronics, and others.

During this three-year research project, after numerous test evaluations conducted on the actual ocean surface, integrated operations were tested over a period of approximately 10 days in November 2007. These tests showed that the system resulting from this research and development is effective in the monitoring of actual underwater infiltration. Fig. 4 shows an example of how the various types of data are integrated, with ship sonar images superimposed over geographical data.

Underwater Construction

In 2009 fiscal year, Hitachi participated in the development of an ultrasonic three-dimensional image acquisition device aimed at underwater surveying and the verification of construction for the Port and Airport Research Institute. The purpose of this device is the verification of the state of the underwater bridge supports of Haneda Airport's runway D, and it is contributing to the streamlining of construction verification for underwater civil engineering work in an environment affected by Tama River's tidal currents and poor underwater visibility, as well as to improvements in safety for underwater operations. This device is also being used to verify the underwater state of harbors affected by the Great East Japan Earthquake.

CONCLUSIONS

This article provided an overview of sonar systems and applied technologies, and described Hitachi's track record of participating in research regarding marine infrastructure security.

The relative merits of a defense system are determined by its balance between the need for operators and the viability of its engineering. The sensor technology used to search for enemies is the most important technology, and research institutions in Europe and the USA are fiercely competing in the research and development of this technology.

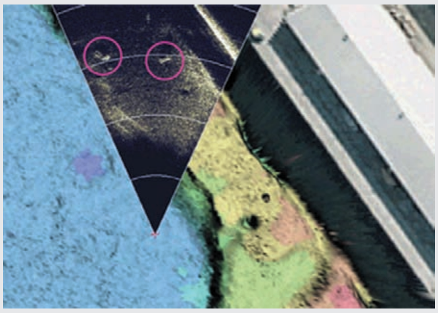

Fig. 4—Example of Superimposition of Acoustic Sensor Images.
This example shows ship sonar images superimposed over geographical data.

At present, Hitachi has begun considering an integrated sonar system for use on next-generation minesweepers, and is starting development on an acoustic imaging sonar system that can acquire video at an even higher resolution in a small and lightweight form (see Fig. 5).

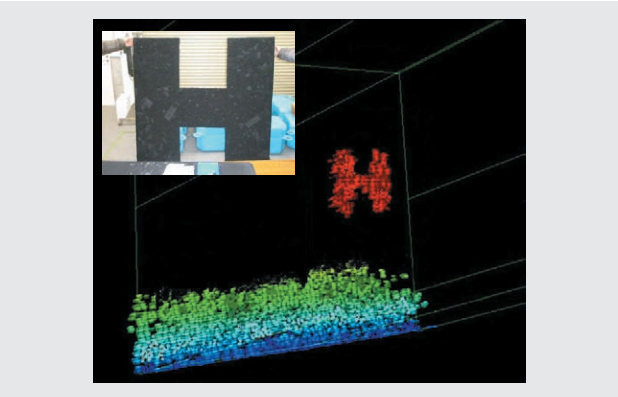

Fig. 5—Example of Acoustic Imaging Sonar Images.
An acoustic imaging sonar system is being developed that is expected to have applications in public marine infrastructures, including ocean exploration, search and rescue operations, underwater civil engineering, harbor restoration, and other areas.

In the future, Hitachi will continue to work aggressively to contribute to the safety and security of public marine infrastructures and society, including not just defense and security, but also applications in ocean exploration, search and rescue operations, underwater civil engineering, harbor restoration, and underwater unmanned vehicles.

REFERENCES

(1) Marine Acoustics Society of Japan Ed., "Fundamentals and Applications of Marine Acoustics," Seizando-Shoten Publishing Co., Ltd. (May 2004) in Japanese.

(2) R. J. Urick, "Principles of Underwater Sound," McGraw-Hill (1967).

(3) A. Asada et al., "Development of an Underwater Security Sonar System," Marine Acoustics Society of Japan conference debate collection (2006) in Japanese.

(4) "Underwater Security Sonar System," Asada Lab., Underwater Technology Research Center, Institute of Industrial Science, The University of Tokyo, http://unac.iis.u-tokyo.ac.jp/index.html in Japanese.

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