"MARINE BIRD", A New Experimental AUV with Underwater Docking and Recharging System

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Abstract-**Autonomous Underwater Vehicles (AUVs), used by marine scientists mainly, have to refuel and download data regularly. Usually, AUVs resurface and are recovered for these routine tasks, but surfacing waste time and manpower for AUV's launch and recovery on a support ship. Especially, the cost of manpower on the support ship is in problem for long-term monitoring. To solve these problems, some concepts of underwater docking and recharging, that AUV docks with a fixed (or mobile) base, to recharge its batteries and download data, are suggested. When AUVs need no surfacing for routine tasks by this system, it will become a 'completely autonomous' underwater observation and monitoring system in the future.**

Some devices of underwater docking and recharging system for AUVs have been suggested and underwater-tested in U.S. and Europe, but we have developed a new experimental AUV, called "MARINE BIRD" with new underwater docking and recharging system. This system is based on an original, unique concept, different from previous ones. We have also carried out docking trials in the dock, the MARINE BIRD succeeded the docking test and demonstrated the excellence of its autonomous docking capability.

This paper introduces an overview of MARINE BIRD, docking and recharging system, and test results of docking test.

I. INTRODUCTION

Kawasaki Shipbuilding Corporation, a member of Kawasaki Heavy Industries group, has been one of the leading shipbuilders in Japan, with various type of shipbuilding, including submarine and submersible, and R&D of new marine technologies, also including underwater technologies.

To extend underwater duration is an important issue for autonomous underwater vehicles (AUVs.) Limited duration restricts the working ability of Autonomous Underwater Vehicles and needs frequent surface support. On the other hand, to enlarge power source capacity leads to the enlargement of the vehicle, that makes difficult to handle the vehicle and raises the cost.

One of the solutions to be free from such a problem is an underwater docking and recharging technology. Not only can we obtain a long duration by this technology, but downsize the AUV and save the manufacturing/running cost.

Fig.1. the AUV "MARINE BIRD"

To build up fundamental technologies, we developed the experimental AUV "MARINE BIRD" in October 2000. The docking and recharging technologies have already been tested in USA and European countries, i.e. are Odyssey [1][2][3], ABE [4], REMUS [5][6] of WHOI, Eurodocker [7] of a European consortium, etc., but newly developed docking system for the MARINE BIRD is different from such ones, based on our new original concepts. Through the trials in a dock after 2000, autonomous functions such as way-point tracing, underwater docking and electrical connection for battery recharging were demonstrated successfully [8][9][10]. In March 2003, we carried out the first sea trial in Wakayama pref. and got some practical knowledge.

II. THE EXPERIMENTAL AUV "MARINE BIRD"

The AUV "MARINE BIRD" (shown in Fig.1.) is the experimental AUV that has an underwater docking system based on our original "Landing-on-Base" concept.

Precise navigation and strict motion control are another features of the MARINE BIRD and they make the vehicle possible travelling around and returning to the base.

The general arrangement of the AUV is shown in Fig.2., and the vehicle specifications are shown in TABLE I. The

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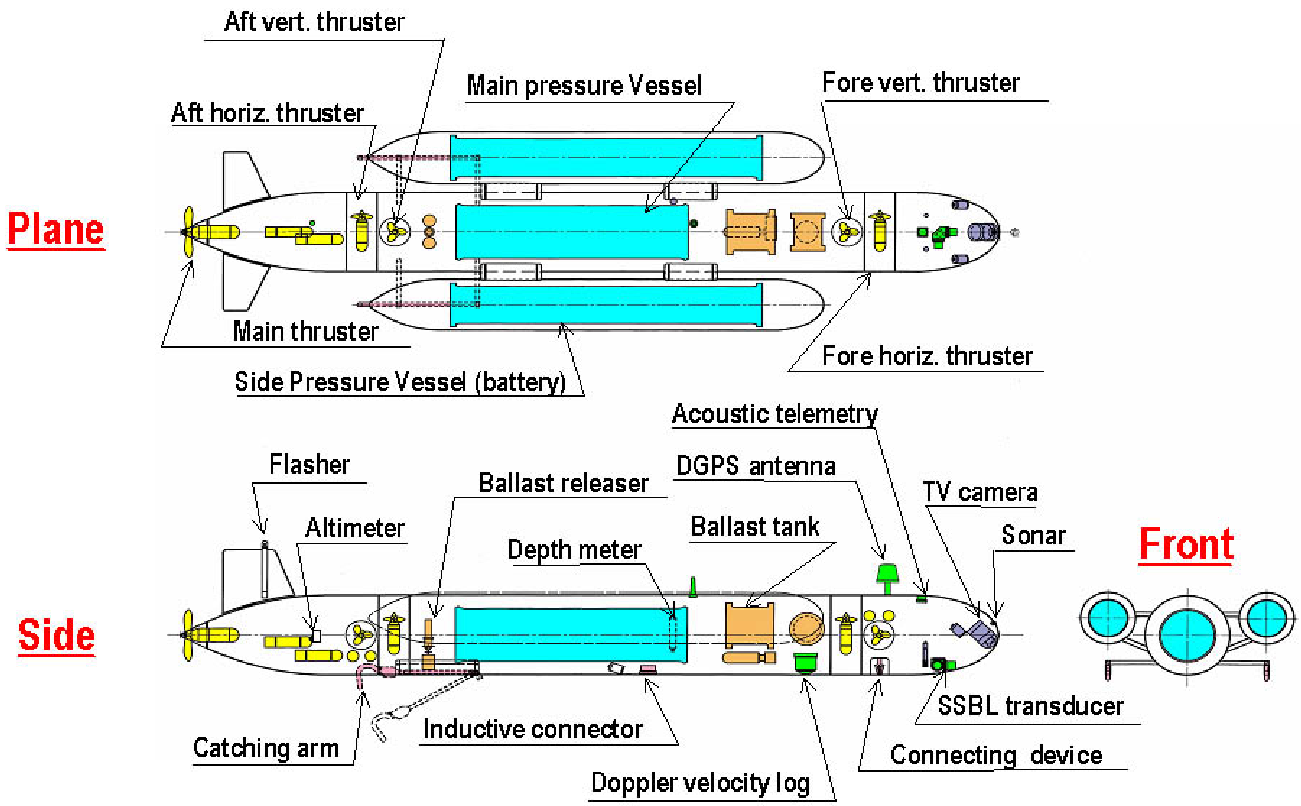

Fig. 2. General Arrangement of The AUV "MARINE BIRD"

TABLE I
VEHICLE SPECIFICATIONS

Item	Value
Dimensions	6.7m(L) x 1.8m(B) x 1.1m(H) 0.7m(Main hull), 0.45m(Side hull)
Wait in air	1,300kg
Cruising speed	2.5 knots
Operation depth	100m
Power source	Lithium-ion rechargeable battery
Effectors	5 Thrusters(main, horizontal x 2, vertical x 2) Control surface (rudder, elevator)
Duration & range	5 hr/battery charge at cruising speed 23 km/battery charge at cruising speed (can be extended by underwater recharging)

vehicle consists of torpedo-shaped main hull and two side hulls for batteries. This form enables easy maintenance for high-energy batteries. Five thrusters (main x 1, horizontal x 2, vertical x 2) and control surfaces (rudder, elevator) for motion control are equipped in the main hull. With these effectors, the MARINE BIRD can control five of six degree of freedom of motion (except rolling).

The main pressure vessel that houses many electrical hardware such as the main control unit and an inertial navigation system (INS) is in the center of the main hull. The buoyancy adjustment equipment is in front of the main pressure vessel. Other devices such as acoustic sensors, a TV camera and docking devices except catching arms are also equipped in the main hull.

In each side hull, there is only a long cylindrical pressure vessel (side pressure vessel). It houses lithium-ion rechargeable batteries and the battery management device. Under each side hull, there is a catching arm for docking. They are used in combination with other devices in a docking process.

The main control unit of the Marine Bird is based on a CompactPCI bus system (CPU : MOTOROLA MCP-750 PowerPC processor) and the real-time operating system for software is VxWorks.

The navigation system is made up of an INS with a monolithic ring laser gyro, a doppler velocity log (DVL), a differential global positioning system (DGPS) and a depth sensor. A super short base line (SSBL) is also equipped for the acoustic navigation.

About the underwater docking and recharging system, a detailed description is to be in section III.

Although the MARINE BIRD executes its mission autonomously in usual activities, it can communicate with the on-board operator when needed using three types of communication unit. A wireless LAN when the MARINE BIRD is on surface, an acoustic link when in underwater and fiber-optic links when the vehicle is connected by a fiber-optic cable at untethered remotely operated vehicle (UROV) mode.

The software of the MARINE BIRD consists of five systems described below.

A. Main control system

The main control system creates a mission execution plan according to a loaded mission file and the vehicle status (Mission Management), and determines the action to be carried out and issues the navigation command by navigation data from the INS, the depth sensor, sonar, and the SSBL (Navigation Control).

B. Obstacle avoidance system

When the MARINE BIRD detects a risk of collision with a forward obstacle or the seafloor, the obstacle avoidance system creates and issues an obstacle avoidance command.

C. Failure supervision system

When the MARINE BIRD detects failure of the hardware or impracticality of the mission (by obstacle, water current larger than the vehicle's motion control capability), the failure supervision system creates a counter-measure plan and issues the failure countermeasure command.

D. Competition resolving system

Each command mentioned above has a priority depend on its urgency and the competition resolving system selects the suitable command for the motion control system.

E. Motion control system

The motion control system receives the command from the competition resolving system and drives effectors according to the command.

In March 2003, we carried out the first sea trials in Wakayama. A photograph of the trials is shown in Fig.3.. The main purpose of these trials is to check the hardware/software performances under a practical environment and to build up the know-how for developing practical AUVs in the future. And we got practical know-how and data for the terms (launch and recovery, hardware performances, remote control by operator via fiber-optic link, autonomous way-point tracing, and etc.).

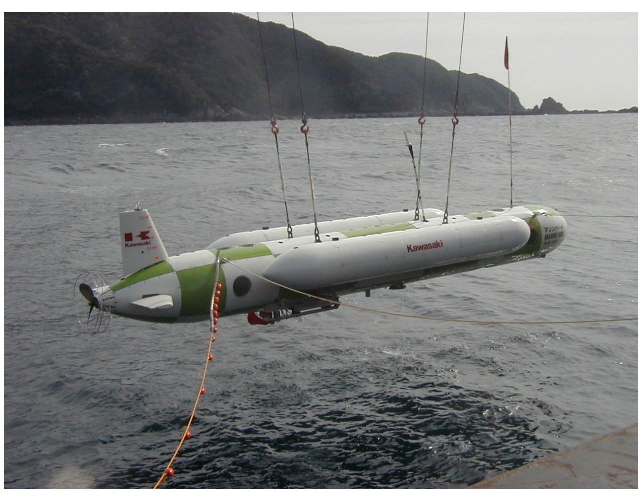

Fig. 3. Photograph of Sea Trials in Wakayama

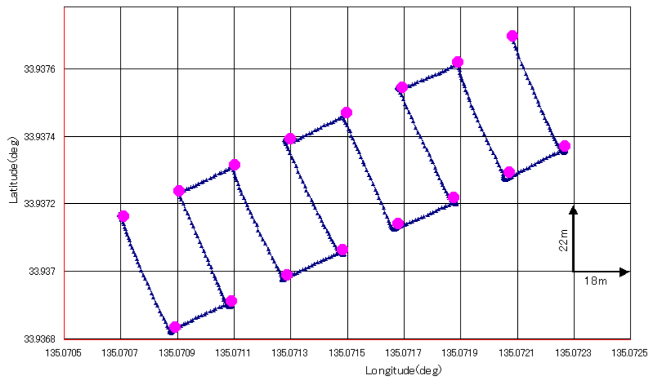

Fig. 4. Example of Sea Trial Results

For a sample of the trials, a trail of the way-point tracing test is shown in Fig.4..

III. Underwater Docking and Recharging System

A conceptual view of the underwater docking to an underwater base by the MARINE BIRD is shown in Fig.5.. The MARINE BIRD docks with an underwater base placed on the sea floor. This method is similar to the landing of an aircraft to the aircraft carrier. That is, running slowly over the base, the vehicle catches the V-shaped guide on the base by its catching arms and joins the connecting device. A merit of this method is that the structure of the underwater base is quite simple and it has no mechanical moving part, therefore the necessity for maintenance of the underwater base is to be reduced greatly.

The docking procedure is executed when the preprogrammed docking mission is called or when the low-level signal for a battery voltage is detected. If the docking procedure is called, the MARINE BIRD starts the primary sequence of docking described below (also shown in Fig.6..)

A. Searching the base

When the docking procedure is called, the vehicle, firstly, moves inside the service area of the transponder on the base by inertial navigation. And it starts calling

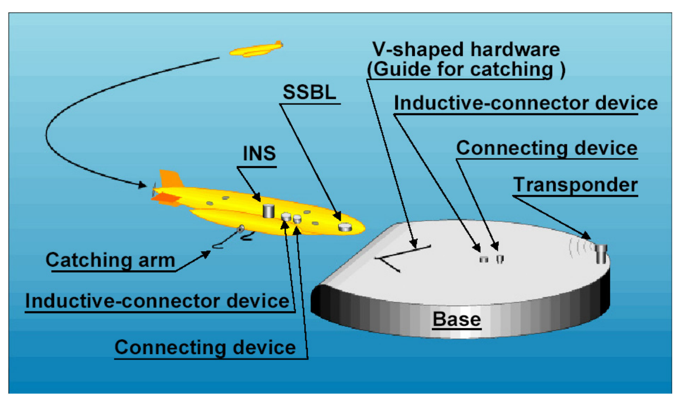

Fig. 5. Conceptual View of Underwater Docking and Recharging

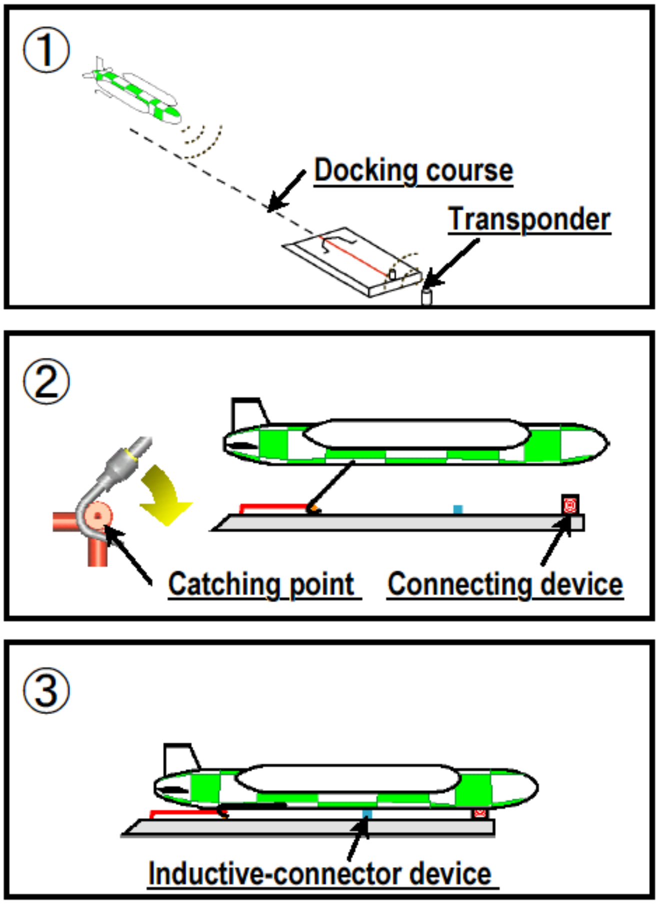

Fig. 6. Primary Sequence of Docking

transponder to search and detect the position of the base by SSBL.

B. Approaching the base

After the Vehicle detects the underwater base, it moves to around the point where the approaching run for docking is to be started. Next, the location of the vehicle is adjusted on the point after directing its azimuth to the transponder on the base. Then the vehicle advances to the base at a low speed, keeping its altitude, azimuth and pitch to a predefined value and keeping its course on the approaching line.

C. Holding the guide

When the vehicle comes near to the catching point, it releases the hooks of the two catching arms, drags them, catches the V-shaped guide (a position adjustment device) on the base with the catching arms. The advancing motion of the vehicle is stopped when the catching arms reaches the both ends of the guide and holds firmly.

D. Connecting to the base

After holding the guide, the vehicle moves downward to push its connecting device to the corresponding connecting device on the base and completes the docking process by connecting them. The vehicle's transition is shown in Fig.7..

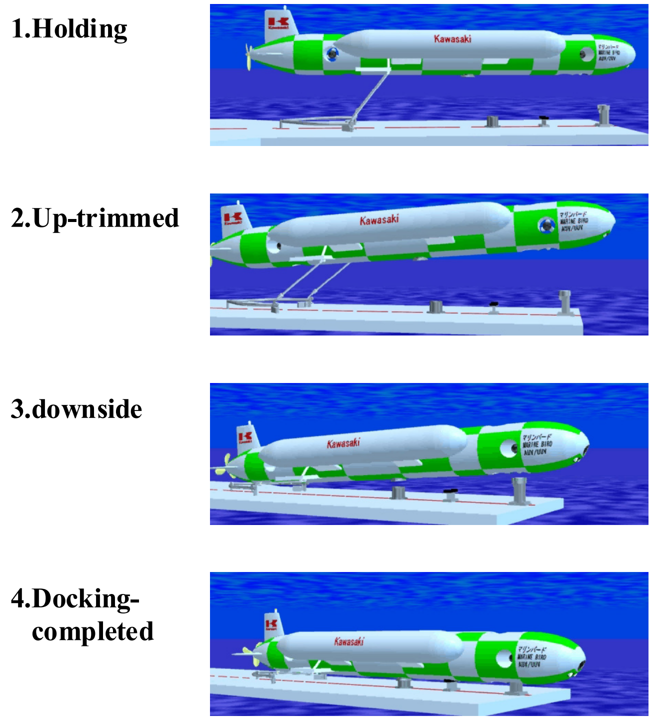

Fig. 7. The Vehicle's transition when it connects to the Base

E. Recharging batteries

After completing the docking, internal batteries of the vehicle are recharged via a couple of inductive connector. This connector is connected by electromagnetic coupling. It transfers energy from the underwater base to the vehicle by electromagnetic induction of an alternating current. This recharging system also has an electromagnetic signal transfer unit to transfer the vehicle's status (status of docking, recharging). The overview of recharging system is shown in Fig.8..

F. Launching

After finishing the battery charging, the vehicle launches from the base and leaves it to carry out the next mission. The procedure of launching is almost composed of the reverse sequences of the connecting.

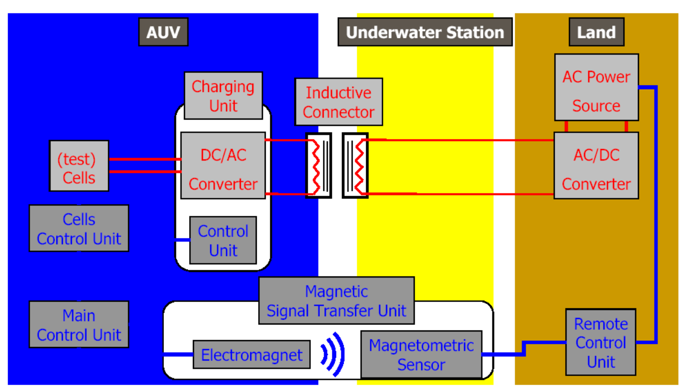

Fig. 8. Recharging System for Test

Fig. 9. Photograph of Docking Test in Dock

IV. Test Results

Through the trials in a dock and the sea after 2000, fundamental vehicle characteristics and the autonomous functions such as way-point tracing, underwater docking and electrical connection for battery recharging were demonstrated successfully.

The summary of the docking tests in 2001-2002 and the sea trials in 2002 are described as examples.

During the period from 2001 to 2002, we carried out the autonomous docking trials in a dock in Kobe. A photograph of a docking trial in the dock is shown in Fig.9..

The principal results are described below.

A The course tracking performance

The deviation for the course tracing on the docking route using the SSBL positioning data confirmed to be under the required value.

B Catching and connecting performance

The catching arms and the connecting device functioned correctly in catching V-shaped guide and in connecting to the base. Catching and connecting under the bad conditions such as a certain swaying of the vehicle, a certain error of the approaching angle and a certain deviation of the approaching route are also performed successfully.

C Autonomous docking sequence

A sequence of procedure of the autonomous docking from approaching to undocking was demonstrated successfully.

D Battery recharging

The autonomous power feeding from the base to a battery in the vehicle through inductive connectors was demonstrated successfully. The downsizing of the inductive connector and the improvement of its efficiency are the future subjects.

As a sample for the result of a docking trial, the trail of the MARINE BIRD and the outline of the underwater base are shown in Fig.10.. The route plan for the docking trial is also illustrated in it.

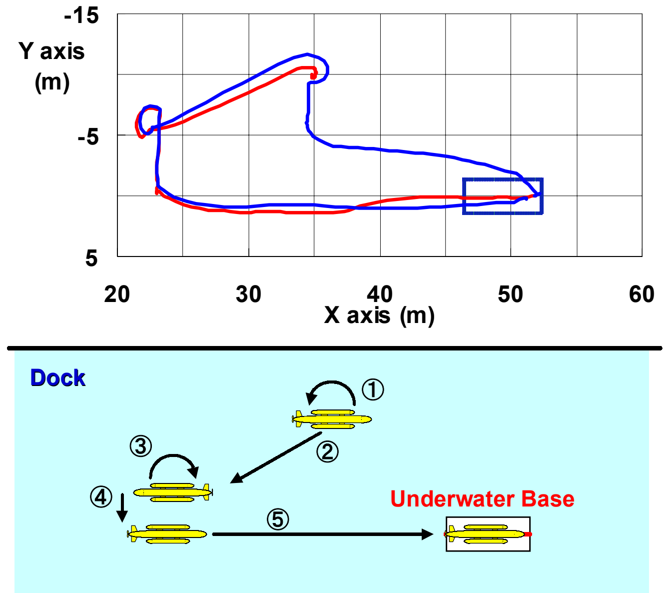

Fig. 10. Route Plan of Docking and Measured Trail

We have a plan to carry out the docking test at the sea in the end of 2003.

V. CONCLUSION

We developed the MARINE BIRD in 2000. The most conspicuous function of the vehicle is the docking and recharging using our original Landing-on-Base method. The performances of the vehicle are demonstrated successfully through the trials in a dock and the sea as described in this paper.

The MARINE BIRD can be a more useful tool when it is used in combination with scientific submarine cable network such as ARENA [11][12] (Advanced Real-Time Earth monitoring Network in the Area) of the Committee of IEEE OES Japan. That is, using the MARINE BIRD as a

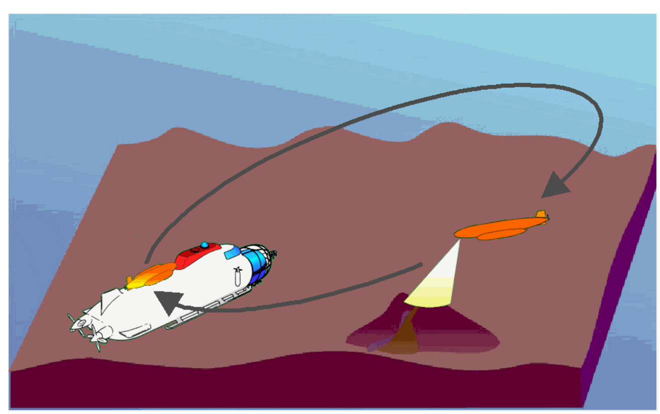

Fig. 11. A Concept of AUV-Submerged Hybrid System Using Docking-Recharging System

maneuverable observation unit, underwater observation systems connected to the scientific cable network can extend its observation area. The MARINE BIRD can also be used as a messenger between a local (closed) cable network system and other network systems. On the other hand, the MARINE BIRD can extend its duration and observation capabilities by using the underwater observation cable network system as an energy station and data trading terminal.

And furthermore, new usage of AUVs shown in Fig.11., AUV's hybrid operating with a mother submersible, and diver-less launch and recovery system to use docking-recharging technology.

The main goal of our AUV project is to develop the practical AUVs after the MARINE BIRD and contribute to the progress of various kinds of research. And the construction of the underwater infrastructures is to be one of the key points for it.

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