Autonomous underwater vehicles and aviation robots

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Abstract: The author developed several advanced autonomous underwater vehicles and aviation robots. This paper describes AUV development for long cruising and high maneuverability, and multi-rotor flight robotics for a marine network system. AUV Urashima and the next generation AUVs are described in the paper.

Keywords: AUV, long distance cruising, high maneuverability, marine network, aviation robot

1. INTRODUCTION

The paper describes autonomous underwater vehicles (AUV) and aviation robots developed by the author. The first to be presented is the deep and long-distance cruising AUV Urashima powered by a fuel cell with the following specifications: 300 km cruising distance; 3500 m depth diving autonomously in the ocean; and it is used for seabed surveys in earthquake areas and for research on global warming. The second is the next generation AUV designed for higher maneuverability and longer distance cruising than Urashima. Thirdly, biomaneuvering robotic fish which are fish-like swimming robots used for various purposes in scientific research. Fourth, aviation robots for supporting AUVs and observation of marine structures. Finally, a marine system network based on AUVs is described with the additional use of multi-rotor flight robotics.

2. LONG-DISTANCE CRUISING AUV

2.1 AUV Urashima

The deep and long-distance cruising AUV Urashima, which can be used for oceanographic surveys such as seabed surveys in earthquake areas and the research of global warming (Fig. 1) [I.Yamamoto (2005)] has been developed by JAMSTEC, where the author was the leader of development. The principal specifications of the AUV Urashima are listed in Table 1. It is designed to have a maximum cruising range of 300 km and a maximum working depth of 3500 m, powered by a fuel cell.

Urashima is equipped with vertical thrusters, a horizontal thruster, horizontal rudders, and vertical rudders for motion control; a buoyancy adjustment system, an oil bladder, a trim adjustment system and ballast for buoyancy adjustment; and a high-performance lithium-ion battery as a secondary energy source that can be used alone for cruising to some extent. Furthermore, a digital camera and side-scan sonar are installed for precision seafloor exploration. Fig. 2 shows the general arrangement of Urashima.

As a main power source, the fuel cell system which has high energy density, is adapted for the AUV Urashima [I.Yamamoto (2004), S.Tsukioka (2004)]. The fuel cell for the AUV generates electricity by electro-chemical catalysis of hydrogen and oxygen. The hydrogen is stored safely within a metal hydride hydrogen-absorbing alloy.

In a February 2005 sea trial [I.Yamamoto (2004), S.Tsukioka (2004)], Urashima achieved an autonomous long-range cruise world record of 317 km for a fuel-cell powered AUV [Ikuo Yamamoto (2016)].

Fig. 1. Deep-sea cruising AUV Urashima

2.2 Next generation AUV

The author has started to develop the next generation AUV.

The key technologies are the optimization of vehicle configuration using computer fluid dynamics (CFD) and the

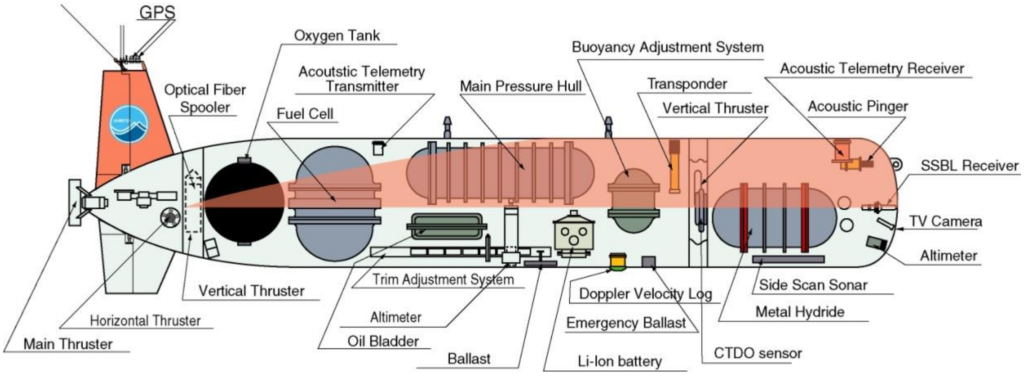

Fig. 2. General arrangement of Urashima

Table 1. Specifications of Urashima.

Length Overall	10 m	**Power Source:** Fuel cell (PEFC) and lithium-ion rechargeable battery
Width Overall	2.5 m	
Height Overall	2.4 m	
Width (Shell)	1.3 m	**Navigation Instruments:** Inertial navigation system, acoustic doppler, current profiler, acoustic homing sonar, obstacle avoidance sonar
Height (Shell)	1.5 m	
Weight in the Air	10 tons	
Maximum Working Depth	3500 m	
Maximum Cruising Range	300 km	**Observation and Exploration Instruments:** Color TV camera, CTDO sensor, side-scan sonar, automatic water sampler, digital camera
Cruising Speed	3 kt	
Maximum Speed	4 kt	

control system to ensure fail-safe operation. The vehicle has an X-shaped wing (tail). The X-shaped wing allows for a larger wing surface, compared with a cross shaped wing. This configuration also reduces the storage area required for shipping the vehicle. It features high capacity lift, high lateral force, high manoeuvrability, smooth berthing reduced storage requirements, and easy system recovery in case of a wing failure. The X-shaped tail of the developed model can be converted to a conventional cross-shaped tail. The control of the X-shaped tail is based on wing force distribution method by non-linear programming of the penalty function law for consideration of wing angle limitation and the semi-Newton law to minimize the energy function total forces and moments in 6 degrees of freedom. This wing arrangement and new control system allows the wings to provide full force and total moment for stable control, even when one wing is damaged during operation.

This low resistance underwater vehicle configuration was simulated using CFD based on Reynolds-averaged Navier-Stokes equations. The simulation results are shown in Fig. 3 on the left. In Fig. 3 on the left is a conventional cylinder shaped vehicle, while on the right is the new configuration designed to provide uniform surface pressure distribution indicated by the same colour. Small pressure fluctuation will result in reduced flow turbulence and hence minimum drag force. Fig. 4 shows the appearance of the model constructed from the simulation results. The model is 2.6 m in length, 0.5 m in maximum width, and 0.4 m in maximum height. It is equipped with a lithium battery, ballast tank, motion sensor and control system to operate autonomously without cables. The control software was developed in the C language. Measurement data was collected to confirm the minimization of the squared sum of the total wing forces.

A design method by the above-mentioned CFD method was also developed to design a vehicle from computer-aided design data used for the model construction. Fig. 5 shows the model designed by the design method to have hydrofoils for higher lift. The underwater vehicle can cruise like a glider in the water. The manoeuvrability of the conventional cylinder-shaped model and the lower resistance underwater vehicle configuration model (with/without hydrofoils) were verified by water tank testing.

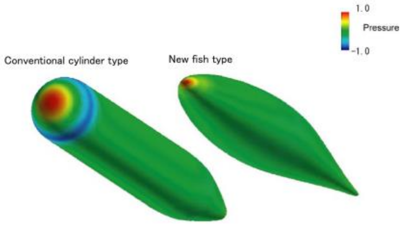

Fig.3 Optimum vehicle configuration from CFD simulation

Fig.4 The model of optimum vehicle configuration

The water tank testing and analysis indicates that the next-generation model has a considerably longer cruising distance than the conventional (cylinder-shaped) type because of the glider effect of hydrofoils and less drag force (20% reduction), which is evaluated at constant body length and energy.

Fig. 5 Model with hydrofoils

Also, the system allows stable control with despite one wing failure. The other wings can compensate for cruising of the vehicle by software control. The glider cruising has the advantage of extending the cruising distance, especially by using its own lift forces. Also, if the vehicle is used in deeper sea, it can cruise further depending on the depth.

Also, the X-shaped tail was tested and noted to be particularly effective for zig-zag cruising test shown in Fig. 6. Higher maneuverability was verified by the tank test.

Fig. 6 Zig-zag cruising test

2.3 Bio maneuvering robotic fish

The author began to develop an oscillating fin propulsion system as an alternative propulsion actuator to propellers in the 1980s. The flexible oscillating fin propulsion system was created to realise fishlike fin movement. It was found that the flexure like fish fin was produced by variously changing elastic modules of the flexible oscillating fin. In addition, it was found that the swimming motion of fish varied with the environment, so that the body structure and propulsion method evolved uniquely so as to suit the swimming motion. That is why the author's interest shifted to the creation of robotic fish. The development of robotic fish was promoted through scientific approaches, such as fluid mechanics, materials engineering, vibrational science, tribology, electrical engineering, and control engineering.

A seabream robotic fish was developed in 1995 as shown in Fig. 7. The weight is 2.6 kg and length is 0.6 m. It has an internal battery and conducts 3-D movement without cables. The surface is made of silicone resin. It cruises at 2 km/h autonomously and/or by remote operation. In addition, 1 hour cruising was acheived in 1995.

Also, the author has developed the robotic dolphin shown in Fig. 8. The length is 1.03 m, and the propulsion is produced by motors. In the robotic dolphin, eight servo motors are used for the tail fin and two servo motors are used for the breast fin. The author and his colleagues also developed a robotic whale in 1998, with a length of 4.50 m and powered by hydraulics. The robotic dolphin is the first large robotic fish operated by a vertical tail fin and motors. The cruising speed is approximately 10 km/h.

Fig. 7 Seabream robotic fish

Fig. 8 robotic dolphin

3. MULTI-ROTOR FLIGHT ROBOTICS AND APPLICATIONS

3.1 Development of multi-rotor flight robotics

Aviation robotics for AUV exploration is important to give update commands and receive seabed data. Particularly, dynamic positioning and robustness against disturbance are important characteristics for the robot. The mechanism for a traditional single-rotor helicopter is mechanically dangerous, therefore the author has considered using a multi-rotor mechanism that is mechanically safer.

A quadrotor [R.Mahony et al. (2012)] is a typical arrangement using independently powered in line rotors. Fig. 9 shows a multi-rotor disk type flight robot which has been designed and prototyped by the authors [I.Yamamoto et al. (2011)]. As shown in Fig. 10 the fundamental configuration has been altered to optimize aerodynamics while also providing increased protection of the propellers against collision [T.Matsuzaki, I.Yamamoto et al. (2010)].

The feedback control is optimized for application to tracking precision. This resulted in the successful tracking of a reference trajectory while providing robustness against environmental disturbance.

Fig. 9. Disk-type flying robot

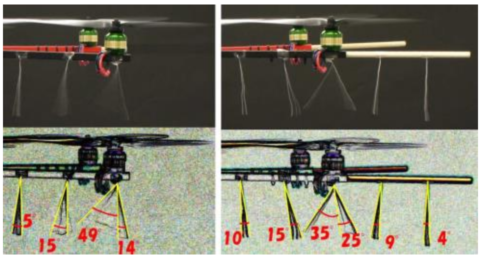

Fig. 10. Flow around the motor

3.2 Application of hybrid flight robotics for monitoring

The author developed hybrid flying robotic mechanisms to provide solutions tailored to specific needs. Such examples include a hybrid lighter-than-air (LTA) balloon (to remotely check tunnels) and tethered kite controlled by multi-rotors, and a wheeled vehicle also controlled by multi-rotors for efficiently checking bridge cables despite windy conditions - shown in Fig. 11.

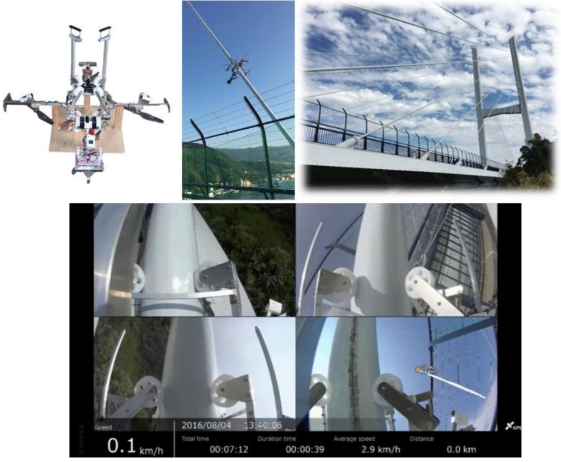

Fig. 11. Multi-rotor flight robot for bridge crack monitoring

4. CONCLUSION

Advanced AUV and aviation robots have been developed by the author. The author considers a marine system network shown in Fig. 12 by using the developed robotics. The marine network is now used for underwater cable monitoring of offshore wind generators and red tide monitoring of a fish farm.

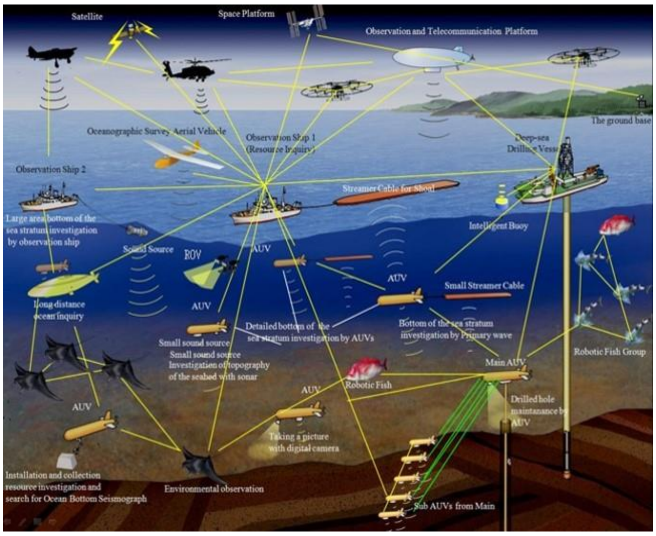

Fig. 12 Marine system network

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