Design and Concept of a Biointeractive Autonomous Underwater Vehicle "BA-1"

Hayato Kondo*, Kenji Nakane**, Etsuro Shimizu*, Jin-Kyu Choi*,
Kenji Nagahashi**, Masakazu Matsushima**, Yasunori Nishida***, Takafumi Arimoto****,
Yoshinori Miyamoto****, Kazuo Amakasu****, Makoto Endo**** and Ryosuke Matsui***

*Faculty of Marine Technology, Tokyo University of Marine Science and Technology
2-1-6, Etchujima, Koto-ku, Tokyo, 135-8533, Japan
**Underwater & Defence Systems Engineering Dept., Mitsui Engineering & Shipbuilding Co., Ltd.
3-1-1, Tama, Tamano city, Okayama, 706-8651, Japan
***Mitsui Engineering & Shipbuilding Co., Ltd.
3-16, Nihonbashi 1-chome, Chuo-ku, Tokyo, 103-0027, Japan
**** Faculty of Marine Science, Tokyo University of Marine Science and Technology
4-5-7, Konan, Minato-ku, Tokyo, 108-8477, Japan

Abstract- **To keep the precious protein source, it is thus extremely important to conserve the biodiversity of the ocean and at the same time to make use of its limited space as much as possible without doing any environmental harm. With this broad objective in mind, Tokyo University of Marine Science and Technology (TUMSAT) and Mitsui Engineering & Shipbuilding Co., Ltd. have started a research and development project, "Pen-free Offshore Aquaculture System using Biointeractive Autonomous Underwater Vehicles." This project is part of a more comprehensive project, "Marine Biotechnology Innovation," which has been funded by the Japanese government since 2007. In this paper, we propose a concept of a biointeractive AUV that monitors and takes care of schools of fish just like a sheep dog in a ranch. In a future plan of this system, multiple biointeractive AUVs monitor the environment spatially and accurately, feed the fish, monitor the growth of the fish, guide them, and report the data through satellite to the land while charging their batteries by docking with buoys. A first model of the biointeractive AUV "BA-1" has launched in early 2009. The design of the biointeractive AUV "BA-1" is described in this paper. The basic test result of the interaction system for fish is also described briefly.**

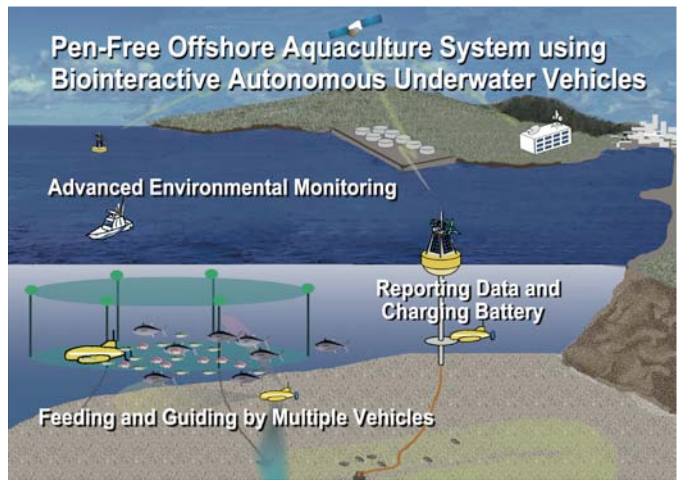

Figure 1. Conceptual drawing of biointeractive AUVs.

I. INTRODUCTION

In 2006, a shocking paper was published in *Science* that predicts that the fish will be extinct in 2048 if the current condition continues [1].

Considering the growing world population, we must prepare for the problem of world-wide famine in the near future. In this regard, the ocean is increasingly considered to be an important supplier of a protein source, since it is the ocean that cultivates one of the most important protein sources, i.e., fish. However, the fish population has been decreased not only by excessive hunting but by environmental pollution as well. To keep the precious protein source, it is thus extremely important to conserve the biodiversity of the ocean and at the same time to make use of its limited space as much as possible without doing any environmental harm.

With this broad objective in mind, Tokyo University of Marine Science and Technology (TUMSAT) and Mitsui Engineering & Shipbuilding Co., Ltd. have started a research and development project, "Pen-free Offshore Aquaculture System using Biointeractive Autonomous Underwater Vehicles." This project is part of a more comprehensive project, "Marine Biotechnology Innovation," which has been funded by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) since 2007. The pen-free offshore aquaculture system is designed specifically to operate in a relatively far off shore area. This enables us to utilize part of the ocean intensively minimizing environmental harm.

It is important to note that both projects are being carried out in a truly unique interdisciplinary environment by a number of engineering, fisheries, and biotechnology researchers from TUMSAT. This is possible because TUMSAT was established in 2003 by combining two universities in Japan, one of them specializing in marine engineering, the other specializing in fisheries and biotechnology. In this paper, we propose a concept of a biointeractive AUV that monitors and takes care of schools of

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

Figure 2. The biointeractive AUV "BA-1."

fish just like a sheep dog in a ranch. In a future plan of this system, multiple biointeractive AUVs monitor the environment spatially and accurately, feed the fish, monitor the growth of the fish, guide them, and report the data through satellite to the land while charging their batteries by docking with buoys (Fig. 1). To study the behavior of fish, it is important to monitor fish not only in tanks but also in a real sea where fish is living. However, many previous studies on fish behavior have been done in tanks. Thus AUVs might be very unique and useful method to monitor fish behaviors.

A first model of the biointeractive AUV "BA-1" has launched in early 2009 (Fig. 2). The length of the vehicle is 3m, the weight in air is about 430kg and the depth rating is 1,000m. The vehicle has not only navigation systems, but also interaction system using light, sound, bait for the fish, acoustic and video cameras to monitor their behaviors. It has an INS, a GPS, a DVL, a depth sensor, and an acoustic communication system with networking capability to be able to operate in the sea. It also has multiple sonar systems and hovering capability to operate in a test tank and in an aquaculture pen for testing its ability to interact with fish. The design of the biointeractive AUV "BA-1" is described in this paper. The basic test result of the interaction system for fish is also described briefly.

II. CONCEPT OF BIOINTERACTIVE AUV

A. Hovering Capability

Cruising AUVs are widely known and used for seawater, seabed and under seabed surveys. Typically they have one thruster on aft and hydro-efficient body like torpedoes. The thruster is pan and tilt movable or they have control surfaces to control pitch, yaw and roll motions.

On the other hand, hovering AUVs are increasingly known with their performance of hovering capability. They can hover around some special targets to take their visual images or intervene with them [2-7]. Typically they have multiple thrusters to control surge, sway, heave, (roll, pitch) and yaw motions to perform helicopter-like motions. They move relatively slow than cruising AUVs and can move close to

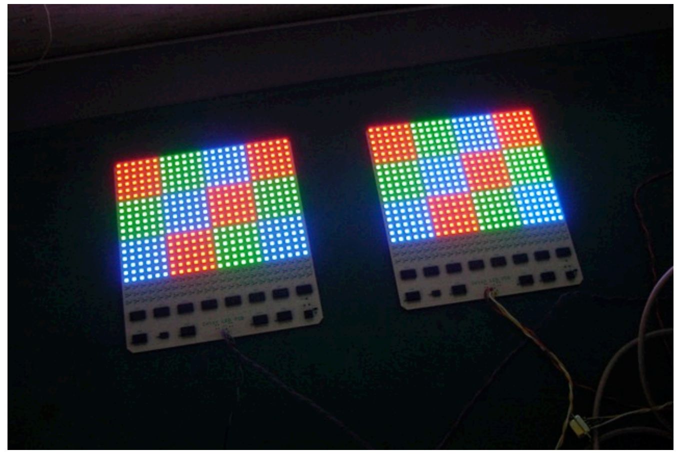

Figure 3. Color matrix LED lighting system (inner parts).

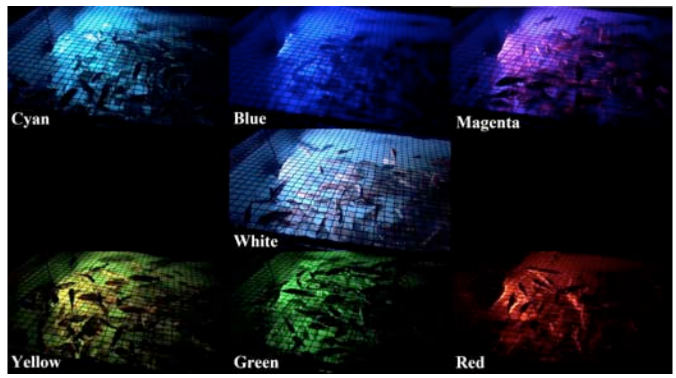

Figure 4. Tilapias color light response test.

targets such as seabed and underwater artificial structures. To accomplish such behaviors like tracing target's shape, they usually have range measurement systems.

To test interaction functionality with fish, a prototype biointeractive AUV is designed as a hovering AUV because it will be tested not only in the sea but also in an aquaculture pen and tank.

B. Biointeractive Functionality

It is demanded that the biointeractive AUV monitors fish without giving them stress. It is also expected to provide the viewpoint of fish while staying in the same environment where the fish is living in.

To monitor fish behaviors the vehicle should have imaging systems; such as video cameras, still cameras and imaging sonars. It should also have environmental monitoring systems; such as thermometers, dissolved oxygen sensors and side scan sonars. Sonars are useful to monitor the fish behaviors and to know the bottom materials even the water is turbid.

To stimulate fish it will have lighting, sounding and feeding systems. Regarding to a prototype system, it will have a color matrix LED lighting system, an underwater speaker and an underwater demand feeding system.

For mounting on the BA-1, we develop a color matrix LED lighting system, which has 432 color LEDs in one unit. As shown in Fig. 3, they constitute 3 x 4 matrix segments, and

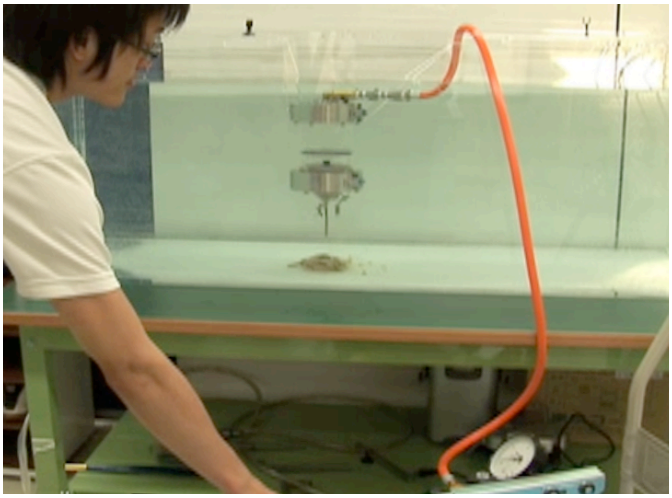

Figure 5. Bait pumping test.

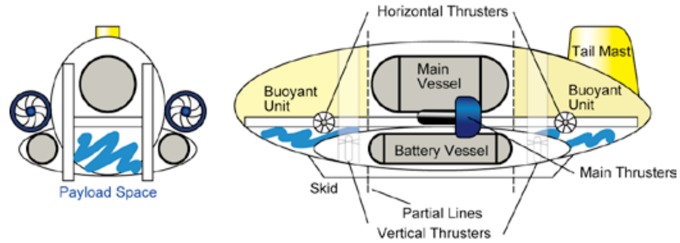

Figure 6. General arrangement of the BA-1.

TABLE I
SPECIFICATIONS OF THE BA-1

Length	3.0 m
Breadth	1.0 m
Height (Exclude antennas)	0.9 m
Weight (in air) approximately	430 kg
Depth rating	1,000 m

each segment is consisted of 6 x 6 LEDs. Each segment can be controlled individually to produce colors by giving RGB intensity data. It can shine uniformly or with motion like flashing. Series of color response test using Tilapias have executed to examine the effectiveness of the system as shown in Fig. 4. In this case, Tilapias swarmed well around yellow and green lights.

About feeding system, we develop an underwater demand feeding system. It consists of a lure, a demand feeding sensor, a bait syringe and an underwater pump. When a fish picks at the lure tied by fishing leader to the rod, the demand feeding sensor detects it and activates the water pump to push out the bait in the syringe. This system is specially developed for underwater use, thus it is designed as a pressure-balanced system. To design the structure of the syringe, a series of bait pumping tests have done as shown in Fig. 5. It is expected that fish will learn that function and follow the vehicle to obtain their food. The demand feeding system is tested and evaluated in a tank. This kind of system is used and known to reduce the waste of dry pellets in aquaculture pens. Dry pellets are difficult to be used for pressure-balanced system. So fish bait has been chosen.

C. *AUV Functionality*

The biointeractive AUV has also concepts as AUVs. As shown in Fig. 1, it is expected that multiple vehicles will be operated simultaneously to cover wide area. For this purpose the vehicle should have communication systems. Since the vehicles are expected to join and leave the group at any time, the communication system should have ad hoc underwater network capability. It is also desirable that they can know their relative positions with each other by using this communication system.

The first model "BA-1" should have capabilities to be a testbed vehicle to test under developing software systems. It is necessary to reduce cost to build multiple vehicles. The vehicle should have redundant sensors to develop cost efficient navigation software using relatively cheap sensors, referencing the ocean-going level sensors.

Once a computer system is selected and software system is developed, it is desirable to use the same systems to reduce the cost to build multiple vehicles. With this objective in mind, a custom computer system with multi-i/o ports for AUVs is developed.

III. DESIGN OF THE BIOINTERACTIVE AUV "BA-1"

A. *Basic Design*

With above-mentioned concept, the vehicle should be ocean going one, and at the same time it can be used in test tanks, aquaculture pens and aquarium tanks. Thus it should be free from special support vessels, and can be operated on a small boat only with crane. It should also have payload capacity for biointeractive functionality. Therefore, we set the design goal as the vehicle's length should be less than 3 meters, and the weight should be less than 500 kg.

It also should be able to be separated into few parts less than 1 meter and the weight should be the amount that few people can carry without crane for transportation.

The depth rating should be more than 1,000 meters.

B. *Structures and Pressure Vessels*

Pressure vessels are made of aluminum anodized and titanium alloy. Main vessel contains computer, electric circuits and equipments that have no pressure bottles. Two battery vessels contain battery stacks and power monitor and switching board.

Buoyant units are made of syntactic form that can resist until 2,400 meters depth pressure. Structures and fairings are made of High Density Poly Ethylene (HDPE) to minimize their weight especially in water.

Fig. 6 shows the general arrangement of the BA-1. Buoyant units and the main vessel are located in higher part and the most heavy battery vessels are located in lower part to make buoyant and gravity centers keep separation to stabilize in roll and pitch motion statically.

Structural members are arranged like "H" character. Two vertical structures are penetrating the fairings to be skids for standing without any support on a flat surface. This provides

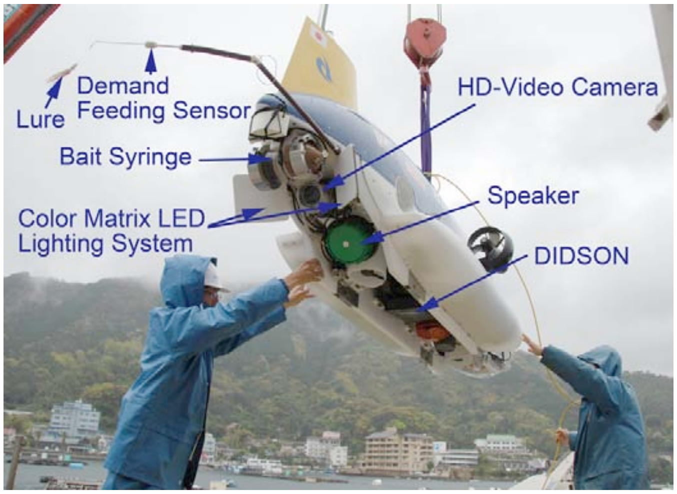

Figure 7. Payload equipments for fish interaction.

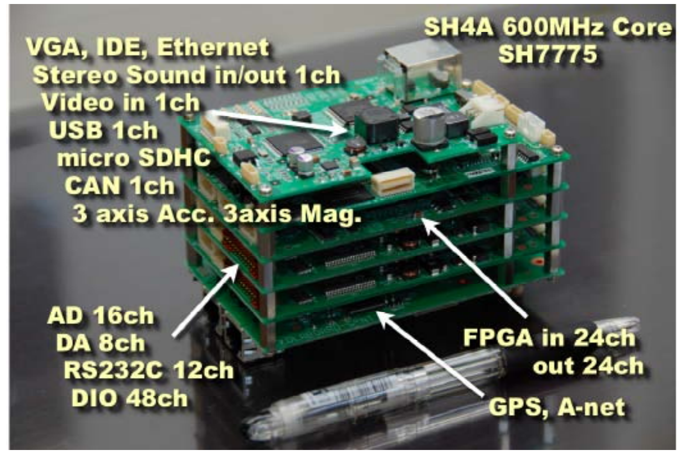

Figure 8. AUV controller "KOLABOARD."

easy maintenance ability on a small boat. The vehicle length is 3 meters and can be separated into 3 parts. Each length is 1 meter. Partial lines are shown in Fig. 6.

Most of the payload sensors are likely to be mounted on the centerline and fixed as its direction to look forward and the bottom. Thus the central under part from fore to aft is secured for payload equipments. The aft part is especially secured for interaction payload.

Vertical and wing-shaped tail mast is designed to stabilize the yaw motion in high surge speed or when the vehicle is towed by boats.

C. Thrusters

Two 2.7kW direct drive brushless DC thrusters are mounted on the side of the vehicle in parallel to the stem/stern line. These are the main thrusters to control surge and yaw motions. Four 450W geared blushless DC thrusters are mounted in fore and aft tunnels. Two are mounted in direction to lateral horizontally to control sway and yaw motions, and other two are vertically mounted to control heave and pitch motions.

D. Sensors

The BA-1 has four kinds of sensors; navigation, collision avoidance and localization, self-status and payload.

Navigation sensors are an INS, a DVL, a depth sensor, a GPS, an AHRS and a FOG. An AHRS and a FOG are redundant navigation sensors for developing new navigation method without using the INS, but only use relatively cheap sensors by multi-sensor fusion referencing the INS data. This is for multiple vehicles development. The INS is the IXSEA's PHINS, the DVL is Teledyne RD Instruments' Workhorse Navigator 1200kHz, the depth sensor is the Paroscientific, Inc.'s Series 8CB and the GPS receiver is the NovAtel's OEMV-2. The AHRS is the Crossbow's AHRS440CA and the FOG is the Japan Aviation Electronics Industry, Ltd.'s JG-35FD.

Collision avoidance and localization sensors are a range sensor (SGK's ALT4) and a pencil beam profiler (Imagenex's 881L Profiling). These sensors are also used for local path planning.

Self-status monitoring sensors are water leakage sensors of pressure vessels and voltage and current sensors of each battery stacks.

Payload sensors are an acoustic camera, a side scan sonar, high definition video cameras and a high resolution digital still camera. The acoustic camera is the Sound Metrics Corp.'s DIDSON 1000m and it is used for monitoring fish behaviors and the sea bottom materials. The side scan sonar is the Imagenex's AUV side scan sonar kit and it is used for bottom environmental monitoring. High definition video cameras and the digital still camera are commercially available cameras and they are mounted in each custom-made pressure bottles.

Other payload sensors such as a 3-Dimensinal Sonar, a DO sensor and turbulence measurement system (TurboMAP) can be mounted optionally.

Payload equipments for fish interaction are shown in Fig. 7.

E. Communication Systems

Since multiple vehicle operation is an essential feature of biointeractive AUVs as mentioned in the chapter II, C, they should have underwater communication system with network capabilities. It is also desirable that each vehicle can obtain their relative positions with each other at every communications. We chose Teledyne Benthos's LF (9-14kHz) acoustic modem with Directional Acoustic Transponder (DAT), and we have developed network functionalities which are executed separately on a computer board. Ad hoc network by mobile nodes will be implemented in near future. The DAT can provide range and bearing data at each communications.

The vehicle also has 2.4GHz SS wireless modem for surface communication. Fiber optic cable can be installed to provide ROV operation ability and real time monitoring capability of HD video camera, acoustic camera, side scan sonar images and so on. For example, it is used for basic fish interaction test in an aquaculture pen and aquarium tanks.

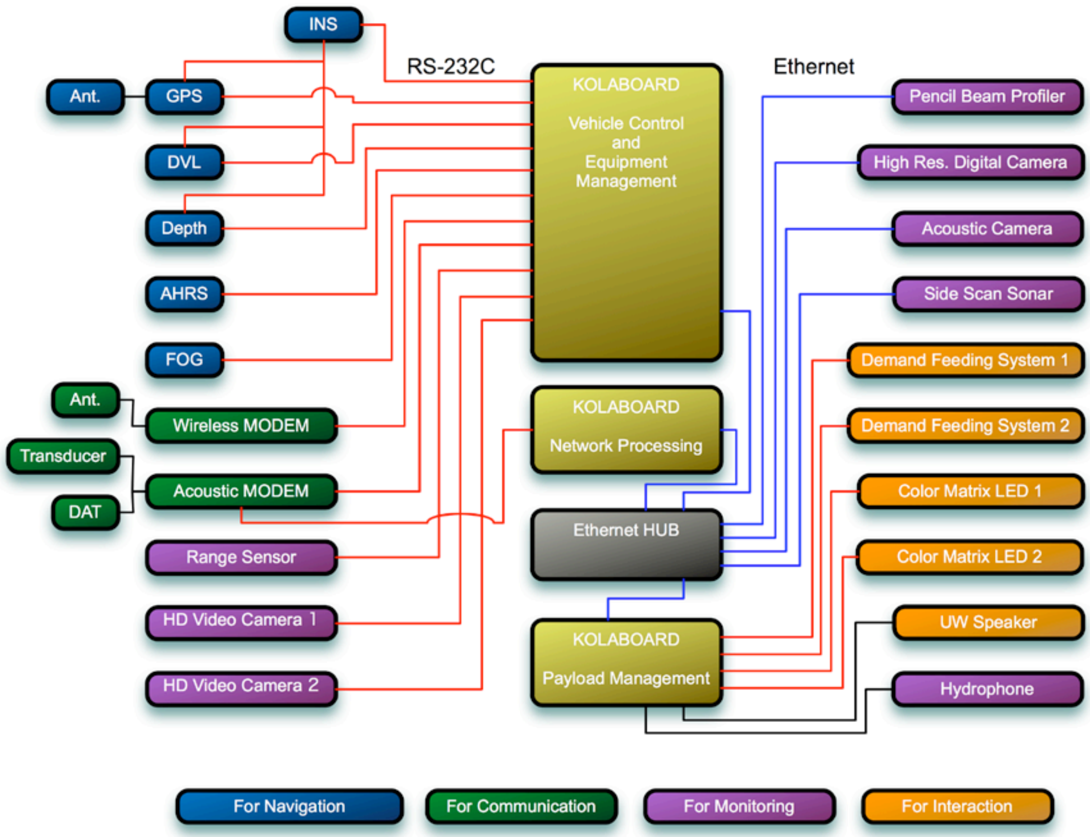

Figure 9. System configuration of the BA-1

TABLE II
SPECIFICATIONS OF THE KOLABOARD

Main, Power and Peripherals	Multi-I/O
CPU Renesas SH7775 600MHz DDR2-SDRAM 256MB NOR FLASH 8MB NAND FLASH 1GB micro SDHC Card interface 1ch VGA (XGA) out 1ch Ethernet 10BASE-T/100BASE-TX 1ch USB 2.0 2ch CAN 1ch RS-232C (console) 1ch DIO 16ch Audio out 1ch, Line in 1ch Video capture (NTSC/PAL) 1ch 2.5"HDD IDE interface Real Time Clock Watch Dog Timer Calendar 3 axis Accelerometer 3 axis Magnetometer Extension BUS POWER DC18~33V	A/D 16bit 8ch (±5V, ±10V) D/A 14bit 4ch (±5V, ±10V) DIO in 8bit out 8bit RS-232C 6ch **FPGA** ALTERA EP2C15AF484C8N in 24bit (single / differential) out 24bit (single / differential) **GPS, Wireless LAN, A-net** GPS u-blox LEA-5T 2.4GHz wireless LAN 1ch ALGO System A-net 1ch

F. *Oceangoing Equipments*

Flasher and ballast releasers will be mounted when the vehicle will be deployed in ocean.

G. *Computer Systems*

To develop multiple vehicles efficiently, a custom computer board with multi-i/o extensions is designed and fabricated. The name is "KOLABOARD" which is named after KOndo LABOratory AUV controller BOARD. It also has a meaning of "Collaboration."

As shown in Fig. 8, the full set of the controller boards consists of 6 boards; main CPU board, power and peripherals board, FPGA I/O board, Multi-I/O board x2, GPS receiver, Wireless LAN and industrial LAN board.

The specification of the KOLABOARD is shown in Table II. Operating system is the T-Kernel, which is a real time operating system. Once the control software of the prototype vehicle is developed, it is easy to apply to multiple vehicles.

H. *Battery*

The BA-1 has four 100V, 10Ah, Ni-MH secondary battery stacks. Two stacks are loaded into each battery vessels. Totally, the BA-1 has 4kWh battery capacity.

I. *System Configuration*

System configuration of the BA-1 is shown in Fig. 9. There are three KOLABOARDs. First one is to control the vehicle and manage the equipments. Second one is to manage payload

Figure 10. Fish interaction test in the aquaculture pen.

Figure 11. Sea breams approaching the lure.

for fish interaction. Third one is to process network communication.

GPS, DVL, Depth sensor are directly connected to the INS. The vehicle basically uses INS data to control its motion. However, every connection is diverged and connected to KOLABOARD's Multi-I/O board. Thus, the users can implement their own algorithms to calculate the vehicle's state.

IV. INTERACTION TEST IN AN AQUACULTURE PEN

Series of interaction test using sea breams has been executed in an aquaculture pen. Fig. 10 shows the configuration of the experiment. The size of the pen is 10m x 10m x 4m. 100 sea breams were released inside the pen and were taken care for 1 month to become used to the environment.

The BA-1 loads the payload system for interaction as shown in Fig. 7 and swim in the pen following waypoints. When the vehicle properly follows the waypoints, the cruising path draws the character "8" to avoid entangling the fiber optic cable.

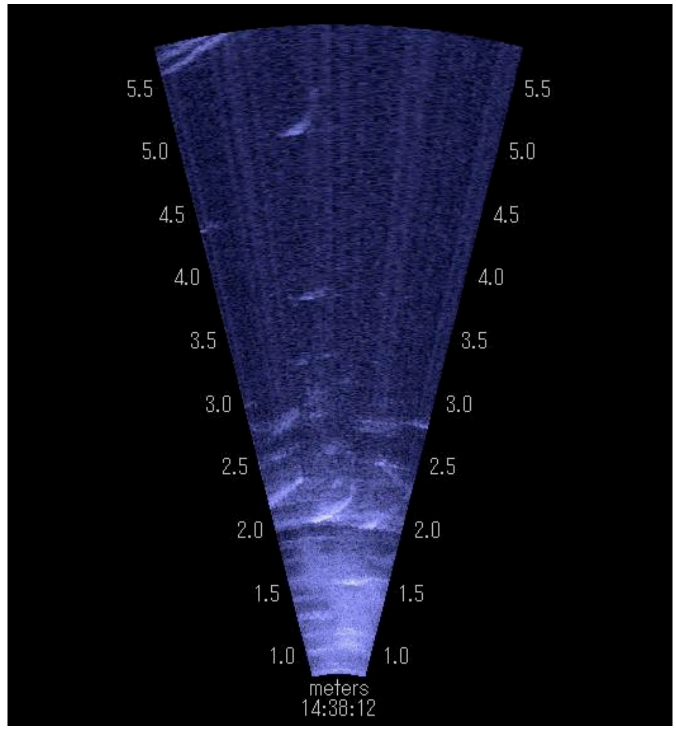

Figure 12. Acoustic camera image of the sea breams approaching the aft of the BA-1.

Figure 13. Sea breams approaching to the vehicle taken by the BA-1's HD video camera.

The first day of the experiment, sea breams never come close to the vehicle. But, from the second day, the fish started to become familiar with the vehicle (Fig. 11). The demand feeding system is activated while the vehicle follows the waypoints. It is necessary for the fish to learn that when they peck the lure, bait will come out and they can eat. Therefore, operator sometimes activates the pump by sending the command to feed the fish so as to help fish to learn. The acoustic camera and the high definition video camera are directed to the aft of the vehicle to take image of the fish. Both camera images are shown in Fig. 12 and Fig. 13 respectively. When the bait is coming out from the syringe sea breams rush to catch the bait. Acoustic camera movie and HD video camera movie provide very unique data to study fish behaviors.

After the sea breams became used to the vehicle, they do not afraid to come close to the feeding system to receive bait. As a result, the sea breams follow the vehicle. However, it is also realized that once they become familiar with the bait, it seems that any color lighting and any sound do not give clear effect to them.

V. CONCLUSION

In this paper very unique "Biointeractive" AUV's concept and design are described. The first model of the biointeractive AUV "BA-1" has been constructed and has started to execute fish interaction test in the aquaculture pen. The vehicle has the special payload equipments for fish interaction. It has been observed that the sea breams are following the vehicle in the pen. Therefore, we can conclude that the biointeractive concept can be realized in the near future. The vehicle can provide very unique viewpoint to observe living fish in the sea.

ACKNOWLEDGMENT

This study is supported by the Special Coordination Funds for Promoting Science and Technology by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

The authors would like to express our thanks to Dr. Junshi Takashina (President), Mr. Naoya Matsubara (General Manager) and staffs of the Akishima Laboratories (Mitsui Zosen) Inc. for their support in the tank tests. The authors also would like to thank to those who are giving their concern.

REFERENCES

[1] Boris Worm, Edward B. Barbier, Nicola Beaumont, J. Emmett Duffy, Carl Folke, Benjamin S. Halpern, Jeremy B. C. Jackson, Heike K. Lotze, Fiorenza Micheli, Stephen R. Palumbi, Enric Sala, Kimberley A. Selkoe, John J. Stachowicz, Reg Watson, "Impacts of Biodiversity Loss on Ocean Ecosystem Services," *Science* vol.314, 2006, pp.787-790.

[2] Hayato Kondo, Tamaki Ura, Yoshiaki Nose, "Development of an Autonomous Underwater Vehicle "Tri-Dog" toward Practical Use in Shallow Water", Journal of Robotics and Mechatronics, JSME, Vol.13, No.2, 2001, pp.205-211.

[3] Hayato Kondo, Toshihiro Maki, Tamaki Ura, Yoshiaki Nose, Takashi Sakamaki, Masaaki Inaishi, "Relative Navigation of an AUV Using Image-and-Acoustic Based Profiling Systems", Proc. of MTS/IEEE Oceans '04 Conference and Exhibition, 2004, pp.1330-1335.

[4] Toshihiro Maki, Hayato Kondo, Tamaki Ura, Takashi Sakamaki, "Positioning method for an AUV using a profiling sonar and passive acoustic landmarks for close-range observation of seafloors", Proc. of IEEE OCEANS '07 Aberdeen, Scotland, 2007, CD-ROM.

[5] Singh, H., Armstrong, R., Gilbes, F., Eustice, R., Roman, C., Pizarro, O., Torres, J., "Imaging Coral I: Imaging Coral Habitats with The SeaBED AUV", The Journal for Subsurface Sensing Technologies and Applications, vol 5, no 1, 2004, pp.25-42.

[6] F. Hover, J. Vaganay, M. Elkins, S. Willcox, V. Polidoro, J. Morash, R. Damus, and S. Desset, "A vehicle system for autonomous relative survey of in-water ships," Marine Technology Society Journal, vol. 41, no. 2, 2007, pp.44-55.

[7] Yuh, J., Choi, S.K., Ikehara, C., Kim, G.H., McMurty, G., Ghasemi-Nejhad, M., Sarkar, N., Sugihara, K., "Design of a semi-autonomous underwater vehicle for intervention missions (SAUVIM)", Proceedings of the 1998 International Symposium on Underwater Technology, 1998, pp.63-68.