Results of the First Sea-test of Tsukuyomi

a Prototype of Underwater Gliders for Virtual Mooring

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***Abstract*— This paper presents the results of the first sea-test of Tsukuyomi – a prototype of underwater gliders for virtual mooring. Its will be able to stay in a designated water for more than one year, reciprocating between the sea-surface and the seafloor up to 3,000 meters in depth. It will sleep on the seafloor to elongate the operation time. We have successfully conducted tank-test in December 2011 and the first sea-test in March 2012. Although for the sake of safety, a thin string was connected to Tsukuyomi in the first sea-test, the dynamic stability, the maneuverability and the basic function of Tsukuyomi were confirmed.**

Index Terms—*Underwater Glider; Underwater Robot; Tsukuyomi; Virtual Mooring; Long-term Monitoring*

I. INTRODUCTION

The ocean has played an important role in the global climate stabilization. Its heat capacity is thousand times larger than that of the atmosphere. However, a rise in temperature even in deeper ocean than 2,000 m was reported. Because of its larger heat capacity, even a small rise in the temperature of deep ocean would have much effect on the global warming.

Ocean environment has been monitored with many methods including profiling floats, mooring systems, ships and satellites. However, due to its immenseness and vastness, it is hard to gather enough data even if using all of these methods. It is also hard to monitor the environment variation in deeper water than 2,000m with a moderate cost over long-time.

In the ocean observation system of next generation, in order to gather data of ocean environment efficiently with limited budget, key area where environmental variation would appear apparently in the early stage should be selected, and observation should be focused on to these waters. The observation should be extended to deeper water than 2,000 m.

On the other hand, underwater gliders [1] such as Seaglider [2], Splay [3], and Slocum [4] have drawn attention recently and have been used widely. Osse et al. [5] reported the development of Deepglider, the objective of the maximum depth was 6,000 m. They can travel autonomously over long distances gathering ocean data with a reasonable cost. However, their operating duration is limited. They cannot provide long-term data as Argo floats can.

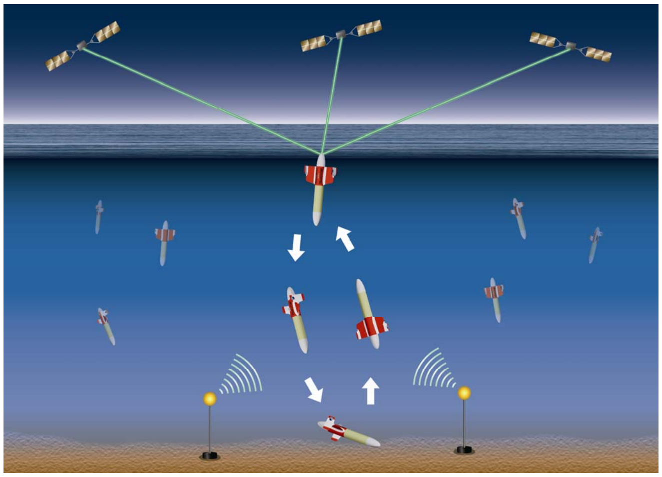
Fig.1 Operation mage of Tsukuyomi

We are now developing a prototype of underwater gliders for virtual mooring. It is named “Tsukuyomi.” It will be able to conduct a long-term monitoring in designated waters. We have already reported its basic design concept and the results of hydrodynamic tests using a small-sized model [6], [7].

Fig. 1 illustrates the image of its operation. Tsukuyomi will stay in a designated water for more than one year to monitor the ocean environment. It will sleep for a fixed time on the seafloor in order to elongate the observation period. It will wake-up periodically to ascend and descend between the seafloor and the sea-surface while monitoring the sea environment. It will locate its position at the sea-surface using GPS, and will send data via Iridium. If it will drift away, it will glide toward the designated area.

We have conducted gliding tests in December 2011 in Ocean and Engineering Tank of Research Institute for Applied Mechanics, Kyushu University. After that we have conducted the first sea-test in March 2012. Although for the sake of safety,

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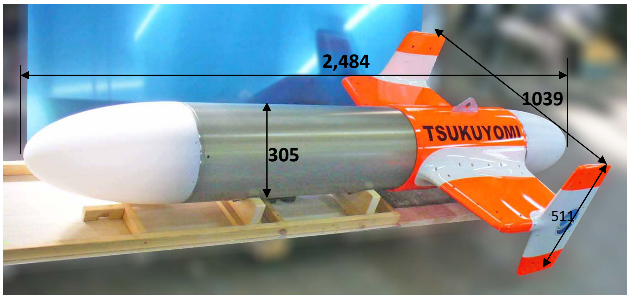

Fig. 2 Photo of Tsukuyomi unit in mm

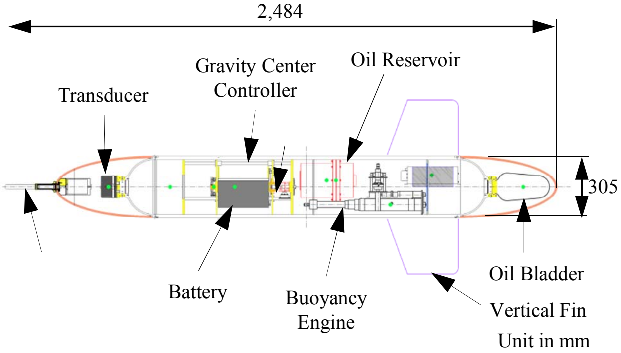

Fig. 3 General arrangement of Tsukuyomi

a thin string was connected to Tsukuyomi the dynamic stability, the maneuverability and the basic function of Tsukuyomi were confirmed.

In this paper, we present the results of this tank-test and sea-test.

II. OUTLINE OF TSUKUYOMI

Fig. 2 and Fig. 3 respectively show the photo and the general arrangement of Tsukuyomi. The maximum water depth, the weight in air and the length are 3,000 m, 150 kg and 2,484 mm respectively.

The shape of the wings were selected considering the results of tank-test using a half-sized model. The detail of this tank-test was reported in the reference [7].

The buoyancy engine (BE) is a key device that governs the performance of Tsukuyomi. We adopted the buoyancy engine [8] that was developed for profiling floats Deep-NINJA [9] applicable to deep waters. It consists of a hydraulic piston pump and valves. A two-way valve was added to the original configuration to enhance the speed of the oil-suction from the bladder into the reservoir when Tsukuyomi is starting to descend. The piston's cylinder volume is 50 cm^3. The cycle time is about five to seven minutes. The energy efficiency is better than 40% at pressure higher than 30 MPa [8]. A rolling diaphragm is used for the reservoir. The volume of the oil reservoir volume is monitored with a linear potentiometer. The pressure-tight housing is depressurized so that the oil in the bladder is drawn into the reservoir when the two-say valve is open at the se-surface.

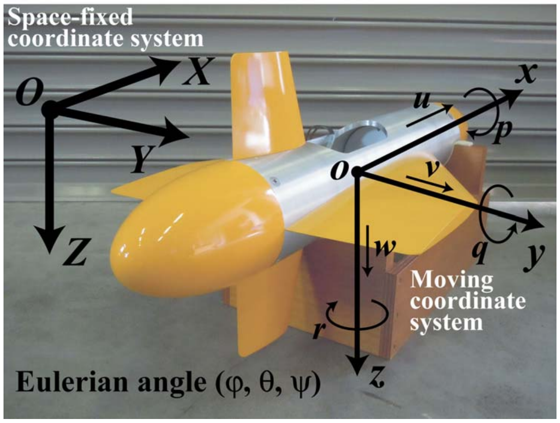

Fig. 4 Coordinate system for measuring the position of gravity-center

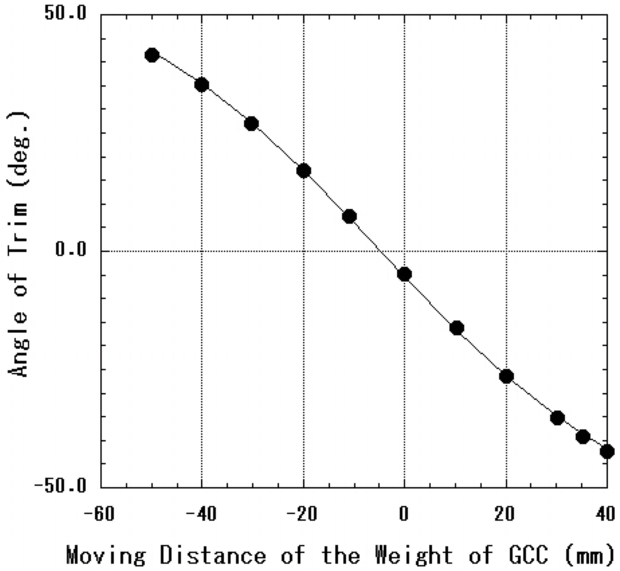

Fig. 5 Relation between the angle of trim and the moving distance of the weight of GCC in x-direction

III. TANK-TEST

The relative position and the distance between the center of gravity and the center of buoyancy is the important factor which has large effect on the maneuverability. Before conducting gliding tests, we have measured the distance between the center of buoyancy and the center of gravity (BG). In the measurement, we hanged the vehicle with a thin nylon string, and measured the trim angle while moving the weight of the gravity-center-controller (GCC) in x-direction. Fig. 4 and Fig. 5 show the coordinate system and the result of the

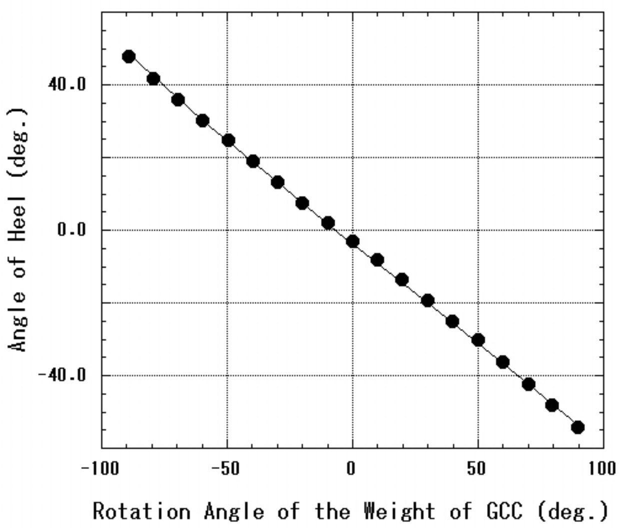

Fig. 6 Relation between the static heal angle and the rotation angle of the GCC around x-direction

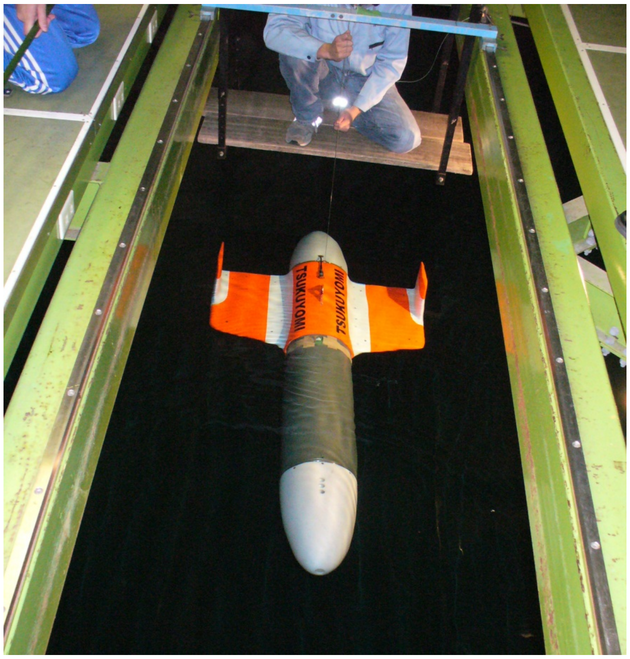

Fig. 7 Photo of the gliding tests in Ocean and Engineering tank.

measurement. By moving the weight, the angle of trim can be changed between +/- 40 degrees statistically. Because the weight of the moving part of the GCC is about 15.9 kg, we estimated BG to be 4.2mm by least squares method.

We can also rotate the weight of GCC around x-axis. Fig. 6 shows the relation between the static heal angle and the rotation angle of the GCC around x-direction. By rotation the weight of the GCC, we can change the heel angle between about +/- 45 degrees.

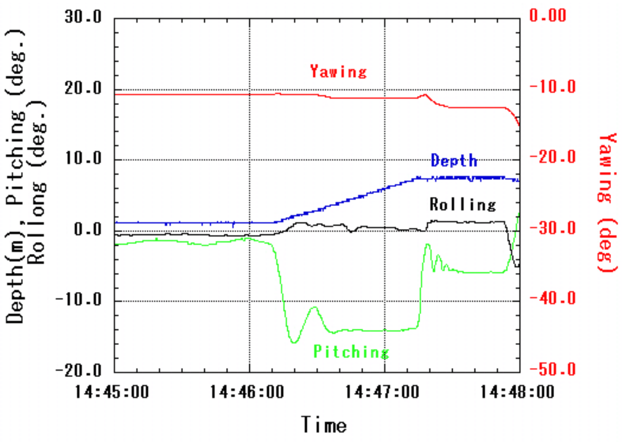

Fig. 8 An example of straight gliding tests
The weight in water was 0.09 kg

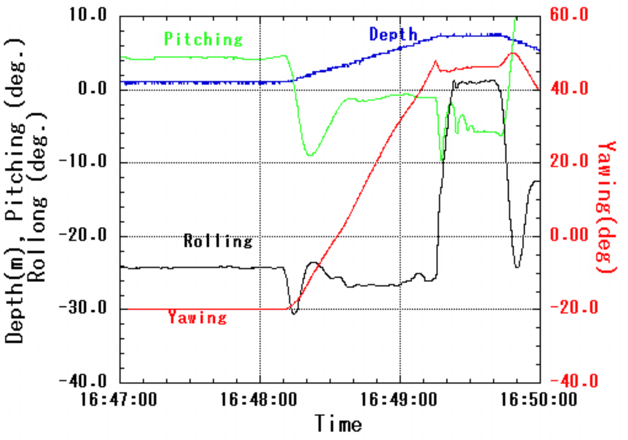

Fig. 9 An example of turning tests
The weight in water was 0.09 kg

In order to examine the gliding performance, we have conducted gliding tests in Ocean and Engineering tank. The dimension of the tank is 65 m (length) x 5 m (width) x 7.5 m (depth). Before starting to glide, the vehicle was hanged with a thin nylon string and stood still. Then the string was released, and Tsukuyomi started to glide. Fig. 7 displays a photo of the gliding test just before releasing the string.

Fig. 8 depict an example of the results of straight gliding. At 14:46:20, we released the nylon string and the vehicle started gliding. The pitching became downward and once overshot, but it became almost stable about 30 seconds after the release. This result indicates the dynamic stability of Tsukuyomi. At about 14:47:16 it touched the bottom.

The pitching angle while gliding was about -14 degrees, which was larger than that when being hanged (about -2 degrees). Pitching, rolling and yawing were measured with an attitude measurement unit (AMU Light by Sumitomo Precision Products Co., Ltd.) which was mounted in Tsukuyomi. The data were recorded using a built-in electric system, the outline of which was described in the reference [6].

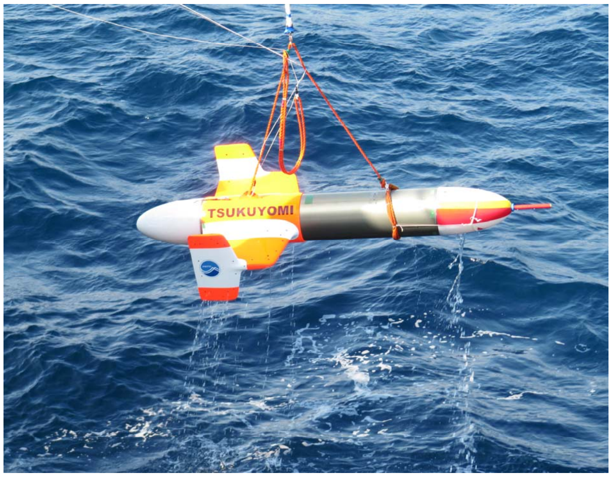

Fig. 10 A photograph of Tsukuyomi when recovered from the sea-surface

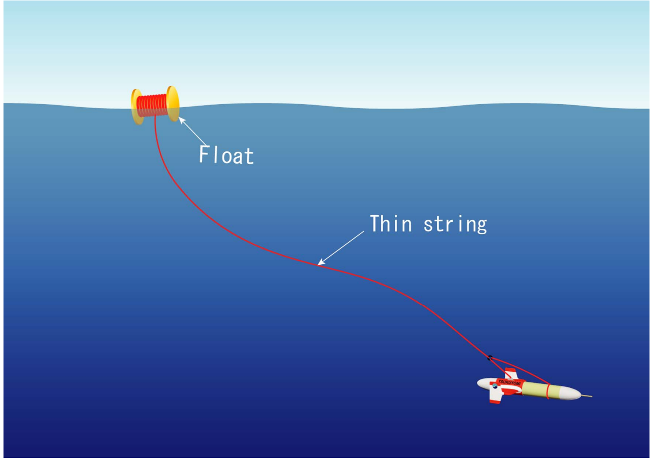

Fig. 11 The image of the sea-tests
A thin string was connected to the vehicle for the sake of safety

Fig. 12 A photograph of Tsukuyomi floating on the sea-surface

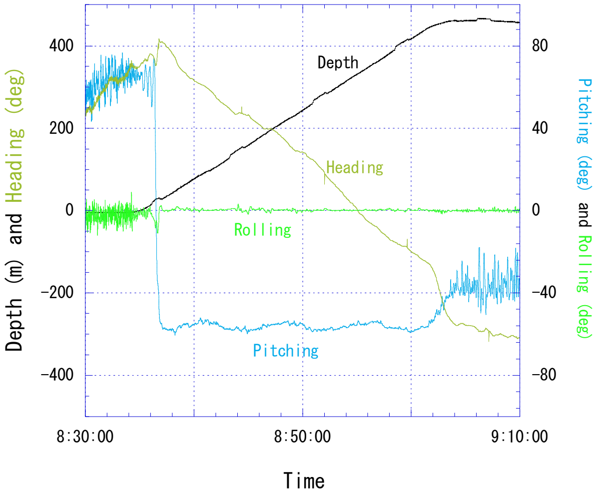

Fig. 13 An example of measured data when Tsukuyomi was descending straight.

The ocean and engineering tank was equipped with an electrically driven towing device of 7.0 m in length and 6.0 m in width. By manually controlling the velocity of the towing device so that its velocity is almost same as that of Tsukuyomi, we estimated the horizontal velocity of Tsukuyomi. The estimated velocity of the vehicle in case of Fig. 8 was 0.25 m/sec. The maximum recorded horizontal velocity in the tests was 0.59 m/sec. It is noted that only gliding tests with a small pithing angle had been conducted because of the limited depth of the tank.

Fig. 9 shows an example of turning tests. By rotating the weight of GCC around x-axis, the vehicle rolled around x-axis. The rolling angle when being hanged and gliding were about -28 degrees and -33 degrees respectively. It started gliding at 16:48:10 and touched the bottom at 16:49:15, meanwhile the vehicle gradually turned from -20 degrees to +45 degrees. Pitching and rolling were unstable just after the release, but became stable after about 27 seconds. This result demonstrates the turning ability of Tsukuyomi and its dynamic stability.

IV. SEA-TESTS

The first sea-test was carried out in Sagami Bay from March 1st to March 5th using JAMSTEC's research vessel KAIYO (cruise KY12-04). Fig. 10 show a photo when Tsukuyomi was recovered from the sea-surface. For the sake of security, a thin string was connected to the vehicle as illustrated in Fig. 11. The other end of the string was wounded around a float. The thin string was made of Kevlar fiber coated with nylon. The length, the diameter and the breaking strength are 500 m, 1.9 mm and 252 kgf respectively. The string were wound on the float and were pulled out while the vehicle was descending. Although it was anticipated that the drag force on this string would have considerable effect on the dynamic characteristics of the vehicle, we have decided to use this thin string as it was the first sea-test.

At the result of the sea-test, we could confirm that Tsukuyomi could fairly locate itself with GPS and communicate with operators using Iridium Short Burst Data Service. Fig. 12 shows a photograph of Tsukuyomi when floating on the sea-surface. The antenna was rising and falling on the sea-surface by a wave.

Some sequences of movement of the GCC and the BE were pre-programmed, and one of them was selected by a command sent by Iridium. When receiving this command, Tsukuyomi began to descend.

Fig.13 is an example of the recorded data when Tsukuyomi descend to 470 m in depth and ascend back to the sea-surface. The thin string connected to Tsukuyomi restricted the maximum descending depth. The thin string also could affect the other dynamic characteristics of the vehicle, but it is hard to estimate its amount. The rolling and the pitching were stable, but Tsukuyomi turned gradually more than 600 degrees. The pitching angle was about -60 degrees. The descending velocity in this test was about 27 cm/sec.

We could confirm that Tsukuyomi has good dynamic stability and would be able to control its heading and pitching using automatic controlling program.

V. CONCLUDING REMARKS

In this paper, we presented the results of tests using the engineering tank and sea-test.

By the gliding tests using the tank, we could confirm that Tsukuyomi has good dynamical stability. It was also confirmed that Tsukuyomi could turn stably by rolling itself.

We estimated BG to be 4.2mm. When being hanged, the trim angle could be controlled between +/- 40 degrees statistically. The maximum pitching angle while gliding is larger than the maximum static trim angle. This is, we think, due to hydrodynamic force acting on the vehicle while gliding. By rotating the weight of the GCC, we can change the heel angle between about +/- 45 degrees. It is enough amount to roll the vehicle and to make the turn.

The maximum horizontal velocity in the tank-test was about 0.59 m/sec. However test conditions were restricted by the shallow depth of the tank.

In the sea-test, although the thin string was connected to the vehicle for the sake of safety, stable movement was confirmed. We could also confirmed that Tsukuyomi would be able to control its heading and pitching using automatic controlling program.

In the sea-test, it descended to 470 meter in depth and ascended back to the sea-surface by itself. The descending depth was restricted by the thin string. Stable localization by GPS and Iridium communication were also confirmed. The wave height was about 1.5 m. The antenna was rising and falling on the sea-surface by a wave.

The research and development of Tsukuyomi was still at early stage. We are now developing automatic control program for heading and pitching, and will test its performance in next January.

We would like to thank the captain Hitoshi Tanaka and the all other crews of the R/V Kaiyo for their invaluable supports during the cruise. We are also grateful to Mr. Nakayama of Onicos Corporation who had developed the software, and Mr. Masaru Inada, Tetsuya Kawatani and Tsuyoshi Ueda of Kyushu University for their collaboration in the tank-test.

REFERENCES

[1] Daniel L. Rudnick, Russ E. Davis, Charles C. Eriksen, David M. Fratantoni, and Mary Jane Perry, “Underwater Gliders for Ocean Research,” Marine Technology Society J., vol. 38, no. 2, pp. 73-84, 2004.

[2] Charles C. Eriksen, T. James Osse, Russell D. Light, Timothy Wen, Thomas W. Lehman, Peter L. Sabin, John W. Ballard, and Andrew M. Chiodi, “Seaglider: A Long-Range Autonomous Underwater Vehicle for Oceanographic Research,” IEEE J. of Ocean. Eng., vol. 26, no. 4, pp. 424-436, 2001.

[3] Jeff Sherman, Russ E. Davis, W. B. Owens, and J. Valdes, “The Autonomous Underwater Glider ‘Spray’,” IEEE J. of Ocean. Eng., vol. 26, no. 4, pp. 437-446, 2001.

[4] Douglas C. Webb, Paul J. Simonetti, and Clayton P. Jones: “SLOCUM: An Underwater Glider Propelled by Environmental Energy,” IEEE J. of Ocean. Eng., vol. 26, no. 4, pp. 447-452, 2001.

[5] T. James Osse and Charles C. Eriksen, “The Deepglider: A Full Ocean Depth Glider for Oceanographic Research,” in Proc. of OCEANS’07 MTS/IEEE Vancouver, 2007.

[6] Kenichi Asakawa, , Masahiko Nakamura, Taiyo Kobayashi, Yoshitaka Watanabe, Tadahiro Hyakudome, Yuzuru Ito and Junichi Kojima, “Design Concept of Tsukuyomi − Underwater Glider Prototype for Virtual Mooring –, in Proc. of OCEANS 2011 IEEE Santander, 2011.

[7] M. Nakamura, K. Asakawa, T. Hyakudome, S. Kishima, H. Matsuoka and T. Minami, “Study on Hydrodynamic Coefficients of Underwater Vehicle for Virtual Mooring,” in Proc. of Int. Symp. on Underwater Technology 2011 & Int. Workshop on Scientific Use of Submarine Cables and Related Technologies 2011, in CD-ROM, 2011.

[8] Taiyo Kobayashi, Kenichi Asakawa, Kazuhiro Watanabe, Tetsuro Ino, Ken-ichi Amaike, Hiroshi Iwamiya, Michihiko Tachikawa, Nobuyuki Shikama and Keisuke Mizuno, “New Buoyancy Engine for Autonomous Vehicles Observing Deeper Oceans,” in Proc. of ISOPE 2010, pp. 401-406, 2010.

[9] Taiyo Kobayashi, Ken-ichi Amaike, Kazuhiro Watanabe, Tetsuro Ino, Kenichi Asakawa, Toshio Suga, Takeshi Kawano, Tadahiro Hyakudome, and Masami Matsuura, “Deep NINJA: A new profiling float for deep ocean observation,” in Proce. of the Twenty-second (2012) International Offshore and Polar Engineering Conference, Rhodes, Greece, June, 2012.