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Development of an Autonomous Underwater Vehicle ISiMI6000 for Deep-sea Observation

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The Korea Institute of Ocean Science and Technology (KIOST) has developed AUVs for survey on the swallow sea, and is under developing a deep-sea AUV based on the former experience. Since 2010, the AUV named ISiMI6000 was designed to explore the deep-seabed topography and hydrothermal vent up to 6,000 m depth. ISiMI6000 was designed witha cylindrical shape having Myringform to minimize fluid resistance. It has one main thruster and four control planes, of which the maximum speed is 4 knots and has over 1.5 knots in up/down direction. It equips with an underwater navigation system composed of Ultra Short Baseline (USBL), Doppler Velocity Log (DVL), Attitude and Heading Reference System (AHRS), Inertial Measurement Unit (IMU), Obstacle Avoid System (OAS), and Global Positioning System (GPS). Its communication tools are Acoustic Telemetry Modem (ATM) under the sea and Radio Frequency (RF) modem at surface. Oceanographic sensors were equipped for precise survey on the deep-sea floor, such as Conductivity Temperature Depth (CTD), Side Scan Sonar (SSS), methane sensor, and sub-bottom profiler (SBP) in optional. A HD Camera and LED light was installed for monitoring the sea floor, and an emergency managing device was designed with a weight drop system, a radio beacon and a xenon flash. This paper introduces the system design and configuration of ISiMI6000 and describes the operating software system in brief. This paper also describes a tank tests and field tests to evaluate the operation process and navigation performance at the Southern Sea.

[**Keywords:** Deep-sea observation, Autonomous Underwater Vehicle (AUV), System design and configuration, Operating software, Sea-trial]

Introduction

As needs for development of the deep-sea resources of the ocean have increased gradually, autonomous underwater vehicles fully matured in technology become one of the most popular tools for seabed exploration and wide range observation in precise. Hundreds of AUVs have been developed during last two decades. This paper briefly reviewed the typical AUVs for deep-sea survey or long range observation of the sea floor.

HUGIN 1000 AUV was developed for autonomous submerged operation for long periods of time[1]. It was focused on inertial navigation system (INS) using DVL and IMU sensor. Its effectiveness was verified through sea trials. HUGIN 4500 AUV was designed dynamic models based on experimental data[2]. Vehicle response predicted by the models showed good agreement with real measurements. REMUS 600 AUV was developed by Oceanographic Systems Laboratory (OSL) of the Woods Hole Oceanographic Institution (WHOI)[3]. It used LBL system for reducing an error of INS. "URASHIMA" AUV is 3,500 m class of JAMSTEC[4]. It has a longest cruise distance record in the world using Polymer electrolyte Fuel Cell (PEFC) power system with metal hydrogen storage. Its power system is very useful for long time cruising for AUVs. ØyvindHegrenæ *et al*. showed the development and experimental evaluation of a model-aided inertial navigation system (MA-INS) for underwater vehicles[5]. Conducted experiments at arctic latitudes exceeding 80° for AUV navigation[6].

On the other hand, Korea Institute of Ocean Science & Technology (KIOST) has developed several autonomous underwater vehicles for research and development on underwater exploration; such as VORAM[7] as a test-bed AUV for research on underwater navigation and communication, SAUV[8] as a semi-AUV for dual-purpose in sea bottom survey and intervention, and ISiMI[9] as a test-bed for research on autonomy, which is an acronym of the Integrated Submergible for Intelligent Mission Implementation. For shallow water exploration and survey on the sea floor, KIOST has developed ISiMI100[10-13] in 2009, which is the first practical AUV having improved functions based on ISiMI. The ISiMI100 can survey up to 100 m depth and carried out several times in the shallow ocean exploration. Sea-floor topography mapping and water quality measurements were successfully performed with ISiMI100.

KIOST has focused on developing a deep-sea AUV since 2010 by integrating the core technologies and deep-sea intervention experiences with ROVs.

In 2012, KIOST developed ISiMI6000[14-15], as shown in figure 1, which able to survey up to 6,000 m depth to obtain a wide variety of marine science data in deep-sea, such as precise mapping of sea-floor, hydrothermal vent exploration and sub-bottom profiling. This paper presents the system design and configuration of the deep-sea AUV and the operating software. This paper is organized as follow: Basic design concept of ISiMI6000 and demanded design specification are presented in the first section. ISiMI6000's system is introduced in second section with four subsections; mechanic parts, electric-electronic parts, computer and communication system, and control architecture. Basin tests and field tests in the Southern Sea of Korea are discussed in the next section. The last section provides concluding remarks and the future of the research work.

Figure 1—Deep-sea AUV ISiMI6000

Materials and Methods

ISiMI6000 System Configuration

Basic Design Concept

ISiMI6000's hull was designed based on the My ring hull profile equations[16] to minimize the drag force coefficient, and its inside was designed with open frame structure. There are two pressure housings to protect battery and electric systems from sea water. The first one is battery housing and the other is control housing. Battery housing includes power system, and control housing includes computer system, electronic system, linear actuator drivers, side scan sonar, wireless router, and interface board.

The ISiMI6000 equipped several devices as shown in figure 2. Sensors for navigation are equipped with an AHRS, a DVL, an IMU, a depth sensor, and three altimeters. Devices for positioning are an USBL and a GPS. Mission sensors are a CTD instrument, a HD camera, 7 LED lights, a methane sensor, and side scan sonar, and transponder. We defined requirements of the ISiMI6000 system as follows:

- ISiMI6000 system should be operated in high-pressure environment of 6,000 m depth.
- ISiMI6000's size should be less than 4.5 m length and 0.6 m diameter.
- Maximum forward speed should be over than 4 knots
- Maximum diving and rising speed should be over than 1.5 knots.
- Operation time should be more than 10 hours at 3 knots speed.
- Weight drop system should be provided to dive and rise to target depth using buoyancy. When two weights are equipped, the buoyancy is negative. The buoyancy is neutral or a little positive after one of two weights is dropped, and the buoyancy is positive after all the weights are dropped.
- Frame structure analysis should be done both in air and water. Static stability analysis should be performed considering the dynamic load and safety factor should be over than 2.5.

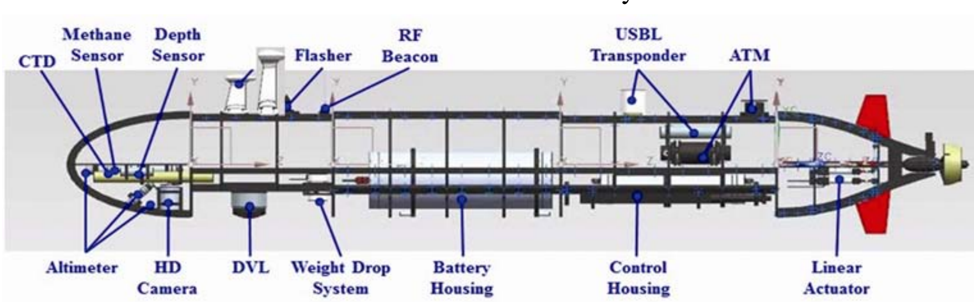

Figure 2—General Arrangement

- Pressure housing structure analysis should be performed on maximum depth pressure structure analysis with 1.25 safety factor.

Mechanical Parts

Specifications of mechanical design are shown in table 1. Equipment list of ISiMI6000 is shown in table 2. Mounted equipment on ISiMI6000 are placed that center of gravity can be located in the center of the body. From this, the amount of weights and buoyancy module is reduced and the motility of the hull can be improved. All sensors, battery housing and control housing made of AL-6061 are equipped on the frame. Sacrificial zinc anode is also equipped to prevent rust is installed. Figure 3 shows an arrangement of a head section. In the head section has three altimeters, a depth-meter, a CTD sensor, a methane sensor. Figure 4 shows arrangement of a middle section. Mounted equipment on the middle section are as follows - ATM for acoustic communication, GPS, DVL and USBL(transponder) for navigation, Xenon flash and Radio beacon for indicate ISiMI6000's position on surface, side scan sonar to obtain information of submarine topography, control housing and battery housing. Weight drop system placed in the middle section. Figure 5 presents the weight drop system for control of ISiMI6000's buoyancy. Dive to the mission depth 6,000 m using a thruster is not

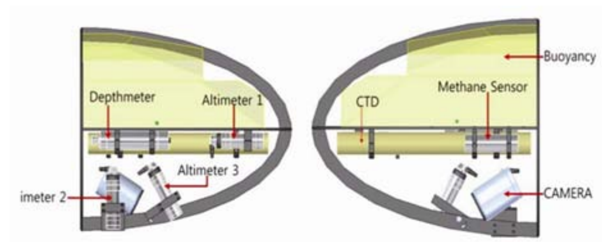

Figure 3—Arrangement of a Head Section

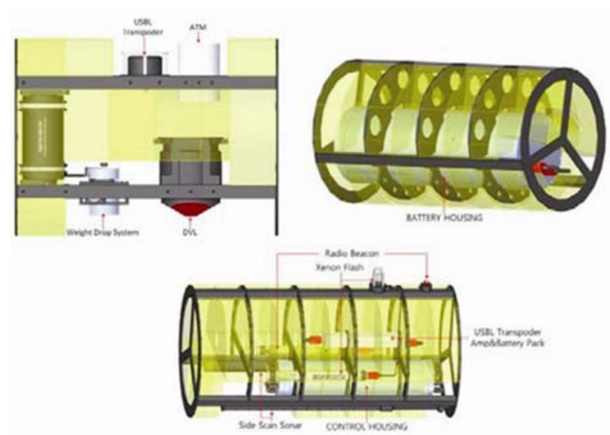

Figure 4—Arrangement of a Middle Section

Table 1—Specification of ISiMI6000

Items	Specification
Hull Diameter/Length	0.6 m / 4.5 m
Weightin air / in water	809 kg / neutral buoyancy
Payload	20 kg
Propulsion-control method	One thrusterwith four control planes
Hull configuration form	Open frame with titaniumpressure vessels and hull fairing
Battery	Li-Po, 110 VDC, 4.38 kWh
Operating time	6 hours at 3 knots, 10 hours max.
Max. speed	Forward 4 knots,dive/float 1.5 knots
Safety factor	1.3

Table 2—Embedded Equipment of ISiMI6000

Equipment	Company & Model name	Size(mm)	Weight Air/Water	Power Consumption
IMU	Honeywell HG1700	Φ127×73.2	1kg	1.05 W
DVL	RDI Workhorse Navigator 300kHz	Φ186×190	11.82kg/ 9.27kg	3 W
ATM	Benthos ATM-967-LF1	Φ140×126	2.2kg/ 1.4kg	20 W @ level 8
Altimeter	Tritech PA200	Φ47.15×149.5	1.325kg/ 1.065kg	80 mA @ 24 V
Depth Sensor	ParoscientificDigiquartz	Φ55×268	1.33kg/ 0.4kg	16.5 mA @ 6 V
GPS	Ascen FGPMMOPA6B	16×16×6	6 g	0.1584 W
RF Modem	RFTechWin iRF4520P-455	45×30×11	50 g	2 W
Side scan sonar	Marine SonicsDual Frequency	Φ96×600	15kg	1 kW
CTD	SeabirdSBE49 FastCAT	Φ83×620	2.7kg/ 1.4kg	3.42 W
Methane sensor	ControsHydroC	Φ90×380	5.6kg/ 3.2kg	6 W
Flasher	Novatech XENON	Φ44×500	2.2kg/ 1.7kg	0.6 W
VHF Beacon	Novatech RF-700AR	Φ44×495	1.6kg/ 0.95kg	0.1 W
Sub-Bottom Profiler	EdgeTech	200×220	14.4/ 6.6kg	22-40 VDC, 34 W
HD Camera	Finevu CR-300HD	39×64×50	88g	2 W
LED Light	KIOST	323×440	12/ 5kg	16-24 VDC,1.5 A (Max)

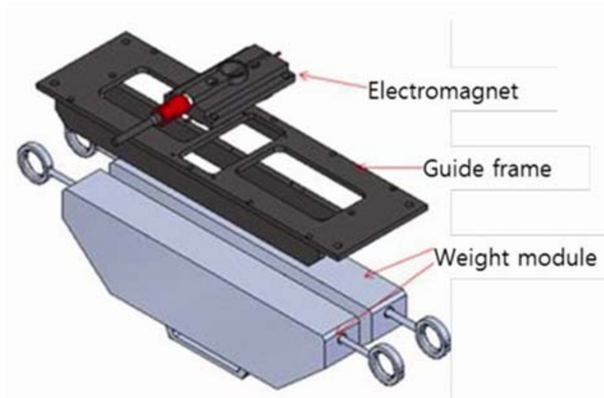

Figure 5—Weight Drop System

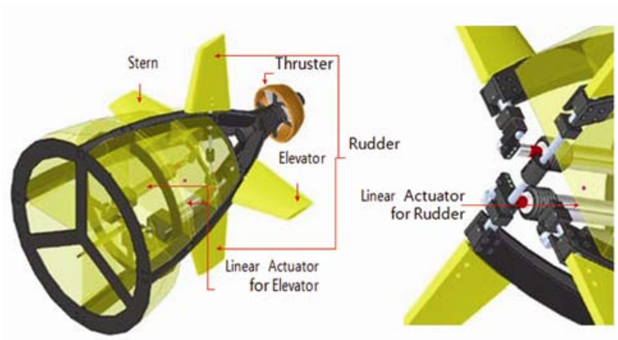

Figure 6—Arrangement of a Tail Section

suitable to the limited battery capacity. For this reason, weight drop system is developed to control ISiMI6000's own buoyancy by dropping weight module using electromagnet. In the weight drop system, two weight modules are equipped and each module is 10 kg. At launch, both weight modules are equipped so ISiMI6000 has negative buoyancy and it moves to the mission area without operating the thruster. When arrive at mission altitude, dropping one of the two weight module so ISiMI6000 can perform the mission with neutral buoyancy. After finish the mission, ISiMI6000 is floating with positive buoyancy by dropping the weight module of the remaining one. Figure 6 shows a tail section. On the tail section, thruster for propulsion, control pin for steering, linear actuator for control the pin and depth sensor. Control pin has ±20° of operating angle and it is operated by three linear actuator. Elevator pins are actuated by one linear actuator and each stern pin is actuated by one actuator, independently.

Electric-electronic Parts

Main design of ISiMI6000's electric and electronic part consist of power system, status monitoring system, emergency system, control and navigation computers and their I/O interface system. According

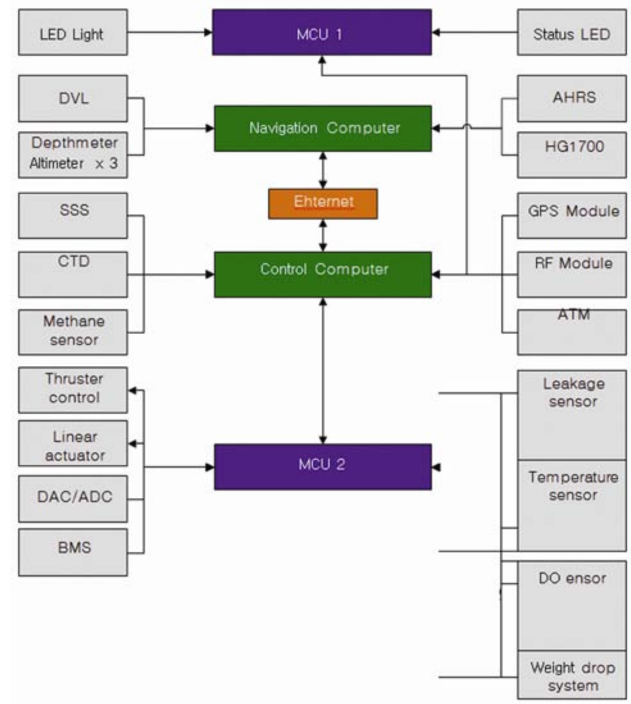

Figure 7—System Block Diagram

to estimated power consumption, battery was designed so that ISiMI6000 can explore 6 hour at 3 knots. Interface system consists of 12 boards, totally. Figure 7 shows block diagram of interface system and computers. MCU (Micro Controller Unit) control BMS (Battery Management System), linear actuators, video camera operation, thruster operation, and monitoring leakage and temperature. And in emergency situation, MCU drops all weight modules and makes the AUV positive buoyancy. And the MCU sends GPS data to surface unit on the mother ship using RF modem.

Computer and Communication System

The computer system consists of two single board computers (SBC) and two microcontrollers. One computer is for AUV control and the other computer is for navigation. Each computer is a PC/104+ type with Intel Atom N450 1.66 GHz CPU and its operating system is Microsoft Windows 7. Two microcontrollers were installed to control the digital-to-analog interface, analog-to-digital interface, weight drop system, the linear stepper motors, and thruster.

Communication system includes an Ethernet hub, a wireless LAN (WLAN) adapter, a Radio Frequency (RF) modem, and an Acoustic Telemetry Modem (ATM). Wireless devices and RF modem are used for

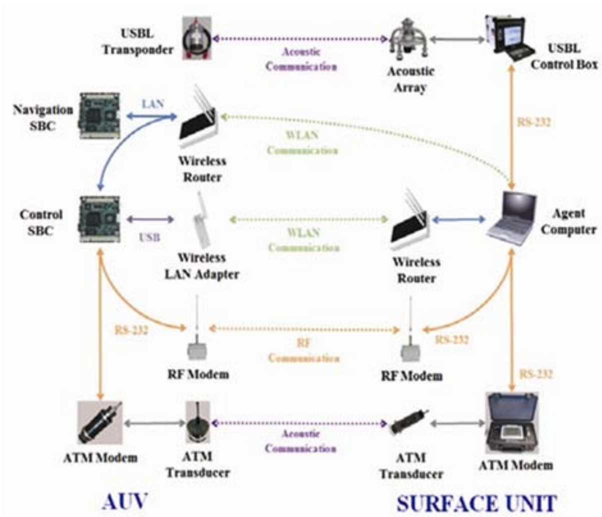

Figure 8—Computer and Communication System

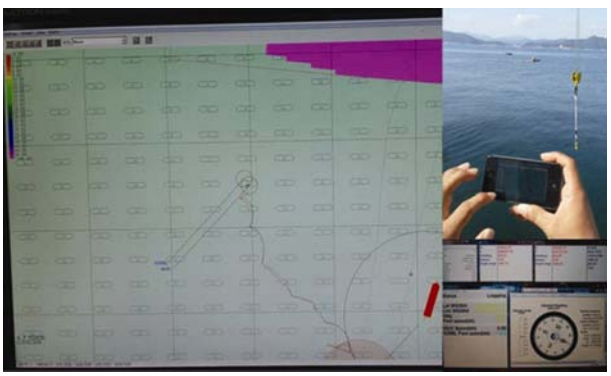

Figure 9—Monitoring ISiMI6000 and Mother Ship Position

surface communication in air between ISiMI6000 and surface unit. The WLAN communication is used for high speed data transfer while the RF communication is used for long distance communication. ATM is used for underwater communication between ISiMI6000 and surface unit.

The surface unit consists of a wireless router, a RF modem, an ATM modem, an Agent computer, and a Hypack computer. Agent computer interfaces ISiMI6000 with the surface unit. All communication devices are connected to the Agent computer. Operator can monitor and control ISiMI6000 using the Agent computer. Figure 8 shows the relationship of computer and communication system for ISiMI6000.

Agent computer periodically sends position of AUV and mother ship to Hypack software running on Hypack computer. The Hypack software provides graphic position information to operator as shown in figure 9. The position display service is also provided by Web through WLAN, so other operators around the mother ship can see same screen using wireless device such as smart phone, tablet PC, notebook, and so on.

Control Architecture

The control architecture of ISiMI6000 is a hybrid architectures organized into four layers as shown in figure 10:

- Mission layer: is in charge of the high level control of the AUV during the mission. It is responsible for the mission planning, execution and supervision. Tiny Mission Language (TML)[17] has developed for this layer.
- Behavior layer: coordinates active behaviors. AUV action starts from this layer.
- Logical sensor layer: does not include the hardware interface to sensors and actuators, but manages their data through virtual communication buffer. Data can be physical or logical.
- Library layer: contains many useful libraries for fundamental functions of the AUV such as hardware interface, communication and real-time management.

Mission layer was implemented by the TML virtual machine, which decodes and executes the executable image of a TML mission file. While the mission file is text file, the executable image consists of predefined binary codes. TML compiler compiles the mission file into the executable image at an Agent computer. Executable image is downloaded into the program memory in the virtual machine, which decodes and executes instructions in the program memory sequentially. Some behaviors can be inserted or deleted in the behavior pool by the result of execution.

Main process in the control computer repeats four steps. The first is the input data update process, the second is the TML virtual machine process, the third is the behavior process, and the last is the waiting process for synchronization. Interval of a period is 10 ms and the system is sleep in the waiting process until next turn time. The basic interval of a period is 100 ms for navigation computation.

Though the ISiMI6000 does not use any RTOS, tasks of control architecture can be synchronized using a user-defined software timer. Timer does not miss desired timing occurrence since the timer was implemented by background thread and system time of SBC. To verify the real-time process using software timer, we performed experiments on

Windows 7. The results show that the average error of timing occurrence was almost 0 when the desired control frequency is from 10 Hz to 100 Hz, so our approach using the software timer instead of RTOS is enough to control ISiMI6000 by desired frequency. Actually, the software timer method is not hard real-time but soft real-time. This approach has no problem because most AUV applications do not need hard real-time characteristics.

The control architecture have been implemented to one execute file using C language, but it runs as agent mode, control mode, and navigation mode. Agent mode runs on agent computer, control mode runs on control SBC, and navigation mode runs on navigation SBC. Unified software can be maintained easily because of low complexity and dependency.

Result

To verify basic functions of equipment, we conducted basin tests such as thruster test, rudder/elevator test, sensor data input test, sensor calibration, weight drop system test, LED light test, HD camera test, and software debugging. Next we performed sea-trials for ballasting, heading keeping, depth keeping, gain tuning, and navigation test in Southern Sea of Korea as shown in figure 11. We also exercised launch and recovery of ISiMI6000 for these tests.

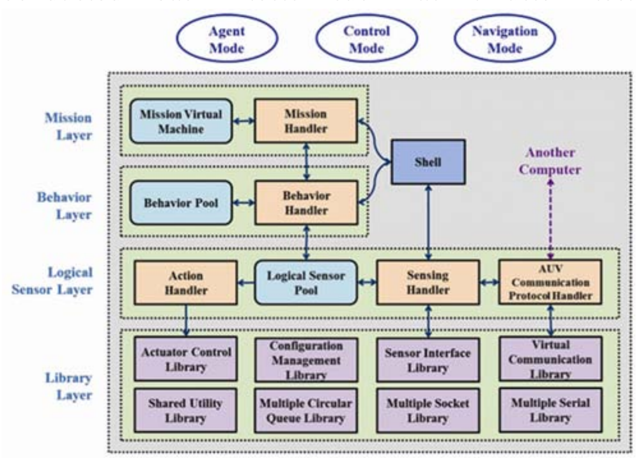

Figure 10—Control Architecture of ISiMI6000

Figure 11—Surface Test of ISiMI6000

The navigation system was based on the IMU-DVL navigation system[17], which is composed of the inertial measurement sensor HG1700 assisted with the DVL RDI Navigator-300. USBL acoustic positioning system is adopted to monitor the AUV's position. USBL measurements also transmitted to ISiMI600 through the Benthos ATM. The AUV initialized the position of the AUV with the USBL measurements when the AUV arrived at the sea floor[18]. Vehicle periodically reset the position with the USBL information when the error of the IMU-DVL navigation system is larger than a certain value.

Figure 12 shows a mission file for navigation test. The time interval of the data transmission-reception through the ATM was 20 seconds with 300 bps for 1,500 meter depth operation, and several seconds with 1200/600 bps in shallow water survey. This mission is

```
$ datum 3459.5315 12840.6110          # Datum(Lat, Lon)
        BHA    BhKeepRpm, 2000        # Thruster RPM
        LDI    R1, 1                  # Num of loop
L10:    WPA    0, -100, -1            # Waypoint
        WPA    0, 200, -1
        WPA    0, 230, -1
        WPA    -50, 280, -1
        WPA    0, 330, -1
        WPA    50, 280, -1
        WPA    0, 230, -1
        WPA    0, 200, -1
        WPA    0, 0, -1
        WPA    0, -30, -1
        WPA    50, -80, -1
        WPA    0, -130, -1
        WPA    -50, -80, -1
        SBI    R1, 1
        BRNE   L10
        IN     R1, TIME
        BHA    BhWpTrace
L20:    SUS
        IN     R2, TIME
        SUB    R2, R1
        CPI    R2, 3600               # Timeout
        BRLE   L20
        BHA    BhEmergency
        SUS
        HALT
```

Figure 12—Mission File for Navigation Experiment

round-trip cruise of 200 m straight line on surface using way point tracking. The AUV rotates with 100 m radius at the end of straight line. Propulsion of thruster was fixed at 2,000 rpm, and IMU-DVL inertial navigation method[11] was applied. If ISiMI6000 is reached within 20 m radius of a target point, the waypoint is recognized as arrival.

Statement from '#' to the end of the line is comment. Line starting prefix '$' is external shell instruction, and "datum" defines datum position. "BHA" instruction adds a behavior into behavior pool and makes it active. "LDI" instruction loads integer value to a register, "WPA" instruction adds a way point as relative location, "SBI" instruction subtracts given integer value from a register, "SUB" instruction subtracts a target register from a source register, "IN" stores value of logical sensor pool into a register, and "CPI" instruction compare a register with given integer value. "BRNE" instruction branches to given label when the result of recent arithmetic and logical operation is not equal, while "BRLE" instruction branches to given label when recent result is negative. "SUS" instruction suspends TML execution, and starts behavior arbitration.

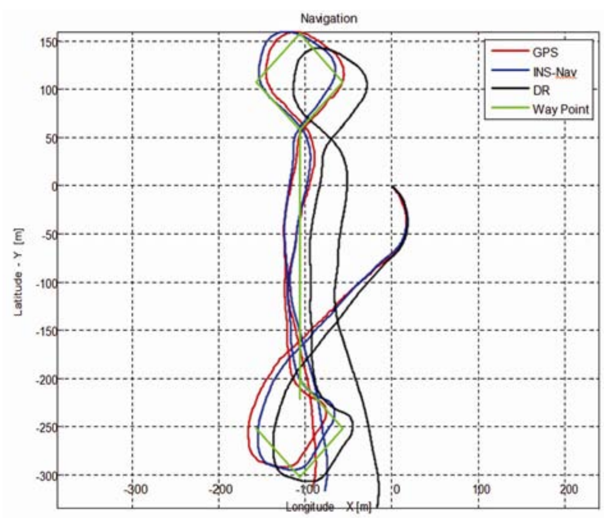

Figure 13—Navigation Trace

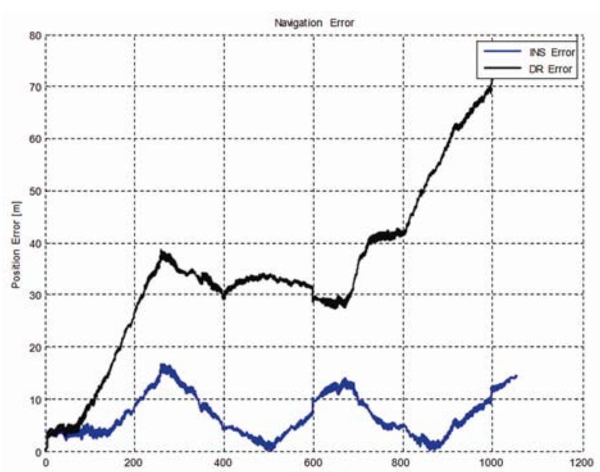

Figure 14—Navigation Error

Figure 13 shows trace results of navigation test. Red line is GPS trace, blue line is inertial navigation trace, and green line is waypoint. ISiMI6000 started in random position, and traced the given waypoints successfully. Navigation errors are shown in figure 14. The error of inertial navigation is less than 18 m. But the error of dead-reckoning navigation is less than 40 m until 700 second, and it diverged after that.

Conclusion

Present study consists the system design of the deep-sea AUV ISiMI6000 which was focused on the mechanic and electric-electronic parts of the vehicle and the surface unit for operation. A basin test was conducted to check the system functions and field tests were conducted at the Southern Sea of Korea to evaluate the system integrity, operating software and operational process, emergency managing devices, and applicability for seabed survey. From these tests we could verify the basic performance of the control system, navigation system, underwater/surface communication and monitoring/surveying equipment of ISiMI6000. We plan to conduct the sea trial in the East Sea of Korea up to 3,000 m depth next year.

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