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Development and Performance Verification of Real-time Hybrid Navigation System for Autonomous Underwater Vehicles

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ABSTRACT

Military Autonomous Underwater Vehicle (AUV) is utilized to search a mine under the sea. This paper presents design and performance verification of real-time hybrid navigation system for AUV. The navigation system uses Doppler Velocity Log (DVL) integration method to correct INS error in underwater. When the AUV is floated on the water, the accumulated error of navigation algorithm is corrected using position/velocity of GPS. The navigation algorithm is verified using 6 Degree Of Freedom (DOF) simulation, Program In the Loop Simulation (PILS). Finally, the experiments are performed in real sea environment to prove the reliability of real-time hybrid navigation algorithm.

Keywords: AUV, IMU-DVL, GPS/INS, under-water navigation, PILS, HILS

1. INTRODUCTION

An autonomous system has been introduced to play a role in performing dangerous missions which cannot be done by humans. Furthermore, it has used as not only automation systems that replace human works in a restricted area but also moving platforms such as autonomous cars, unmanned aircrafts, and autonomous underwater vehicles, which perform highly autonomous missions in various spaces. In recent years, the research has been actively to moving platforms in various areas such as industry, transportation, and military fields. Especially, Network Centric Warfare based autonomous systems in military are expected to play a core role in future battle fields. The role of the military autonomous system can be divided into sensor role for information collection and assessment as well as verification, communication broker role between platform, sensors, and tools within a network, and tool role for attacking. Now, it is impossible to implement the future military system without autonomous systems. In particular, autonomous underwater vehicles are unmanned systems that will play a significant role in marine and underwater battlefields in the future such as Intelligence, Surveillance and Reconnaissance, Mine Counter Measure, Anti-Submarine Warfare, communication and navigation assistance, military attack. Thus, various autonomous underwater vehicles have been developed. Since a military autonomous underwater vehicle called Near-term Mine Reconnaissance System was developed in 1996 for the first time in the USA, the USA have developed the mobile Remote Environmental Monitoring Unit System -100, light-weight Bluefin-12, mid-weight Long-term Mine Reconnaissance System, and heavy-weight Large Displacement Unmanned Underwater Vehicle and Manta. Also the UK, France, Germany, Norway, Sweden, Japan, and China have accelerated the development of autonomous underwater vehicles.

The core devices used in the autonomous underwater vehicle are high efficient energy source for long-term mission, sensor and task equipment, autonomous mission management and precise navigation, communication and network, docking and recovery equipment and navigation system for autonomous sailing and positioning. Among

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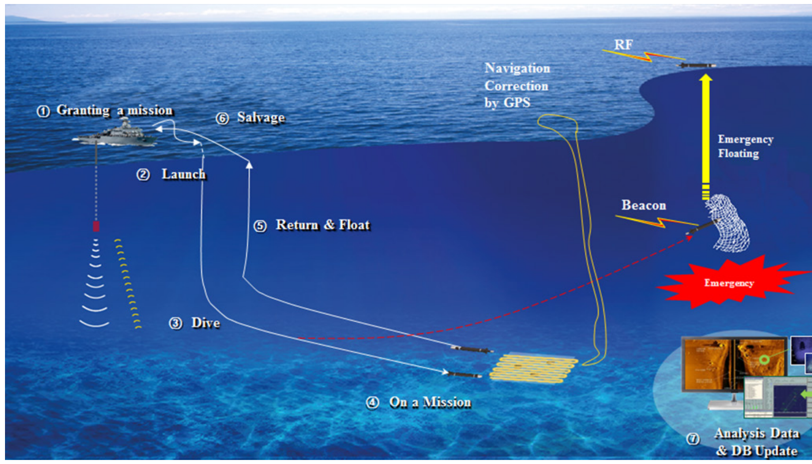

Fig. 1. Operation scenario of the autonomous underwater vehicle.

them, a navigation system is an essential device to reach a target location autonomously. Since the navigation system in unmanned systems shall have not only accuracy but also high reliability, various navigation sensors are utilized and used. Generally, inertial sensors, satellite navigation system, radar, LiDAR, and images are used for autonomous car. In case unmanned aircraft, a similar navigation system is configured including a speedometer, geomagnetic sensor, and barometer. A satellite navigation system plays an important role in the navigation system of the unmanned system. However a satellite navigation signal cannot be used as a main navigation sensor of AUV due to the satellite radio signal cannot propagate in underwater. By the reason, the navigation system should be required to considering for underwater feature.

Recently, in consideration of these water propagation characteristics, underwater navigation sensor using sound waves are used such as long baseline (LBL), short baseline (SBL), and ultra-short baseline (USBL) (Webster et al. 2009). This ultrasound positioning system includes an error due to refraction of ultrasonic wave in underwater environments, multi-path characteristics, scattering and measurement delay (Lee & Jun 2007). In addition, the LBL system has a weakness that sensors shall be installed and corrected at the seabed. It is highly dangerous tasks to install and calibrate the LBL approaching the ship in estimated mine area. In addition, although SBL and USBL can be useful in tracking and monitoring autonomous underwater vehicles, they are not suitable to be used as assistant navigation due to the limitation of underwater communication as a measuring distance becomes longer.

In this paper, the design and test results of hybrid navigation system for autonomous underwater vehicles are described. In order to correct errors in inertial navigation in the underwater, aiding navigation sensors are used such as DVL, depth-meter, and magnetic compass. When the GPS information is available, accumulated error is corrected using GPS/INS integration filter. The described the hybrid navigation has an advantage that navigation can be done by embedded sensors without installation of surface and underwater infrastructures. The designed hybrid navigation algorithm was verified using Program In the Loop Simulation (PILS), van test and real sea test.

2. DESIGN OF THE HYBRID NAVIGATION SYSTEM FOR AUTONOMOUS UNDERWATER VEHICLES

2.1 Operation Concepts of Autonomous Underwater Vehicles

An Autonomous Underwater Vehicle (AUV) has been developed for military purpose such as mine search and sea bottom topography search. The operation scenario of the AUV is shown in Fig. 1. Search regions, search methods, and initial navigation information are entered from console controller for AUV mounted in a depot ship before launching. The launched AUV is submerged and moved to a search region and collected data for monitoring and reconnaissance. It can also collaborative search by more than two AUVs for a wide range of area. The AUV is floated on the surface of the water periodically to correct accumulated position error during underwater mission. In addition, it notices emergent situations to the depot ship using a beacon if it cannot be moved, for example, due to being caught in the net. If the AUV completes a search mission, it is floated on the water and transmits

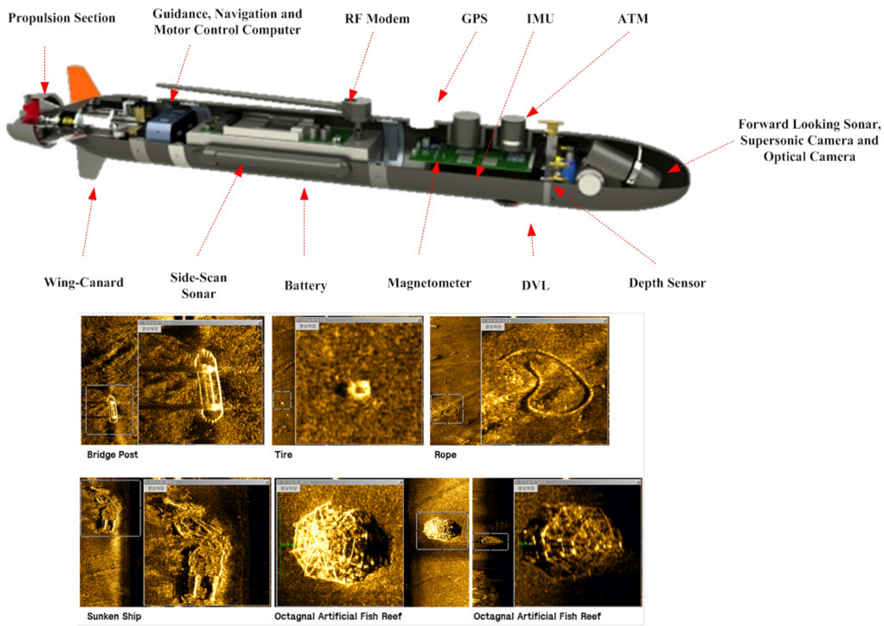

Fig. 2. Schematic diagram of hardware of autonomous underwater vehicle and acquired sample image.

Table 1. AUV specifications.

	Performance
Max. depth	200 meters
Navigation	Less 10 meters CEP (Horizontal position error)@ GPS available Less 0.5% position error @ Distance of travel (3 kts @ 1 hr)
Function	
- Research a mine and overcome tidal current (5 knots) - Mission sensor : Forward looking sonar, Supersonic camera, Optical camera - Transmit an information of seabed exploration to AUV console by RF modem - Capability of multi-AUV operation SW - Real-time OS : QNX 6.1 (Micro kernel)	

data using RF communication or takes another mission and performs a search again. The AUV has capability of overcoming tidal waves based on precision navigation, recognition and avoidance of obstacles. The main hardware configuration diagram in the AUV is shown in Fig. 2 and its main specification is listed in Table 1. As listed in Table 1, the requirements of the AUV navigation can be divided according to surface environment where GPS is valid or underwater environment where GPS is not valid. For the surface environment, a horizontal location error shall be within 10 m CEP. For underwater environment, location error shall satisfy 0.5% of travel distance.

2.2 Design of the Hardware in the Hybrid Navigation System for AUV

The navigation system for AUVs was designed to have a structure where information about Inertial Measurement Unit (IMU), GPS, DVL, depth-meter, and magnetometer is fused at the hybrid navigation computer. Fig. 3 shows a structure of the hybrid navigation computer. The hybrid navigation computer was designed based on OMAP-L138, a dual core CPU, in which ARM core and DSP core were embedded. The ARM core is used in communication with navigation sensors and guidance and control computer. The DSP core is used in operation of navigation algorithm. The task of the sensor interface in the hybrid navigation computer is designed to be stored in the buffer of field programmable gate array via synchronization with the IMU, which has the fastest output rate (100 Hz) and navigation sensor data acquired through the ARM core are transferred to the DSP core using the DSP link layer, which is a shared memory. In the DSP core, the navigation solution such as position, velocity, and attitude is calculated in real time based on navigation sensor information. As shown in Fig. 4, the hybrid navigation computer can be mounted stably inside the AUV.

2.3 Hybrid Navigation Algorithm and Real-time Software Design

The hybrid navigation algorithm estimates optimum position, velocity and attitude by selecting an effective aiding sensor according to operating environments as shown in Fig. 5. The initial alignment was configured to set the initial location, velocity, and attitude of the navigation using a high precision reference navigation system (TALIN5000 by Honeywell). The division of the surface and underwater navigation algorithms can be done by checking

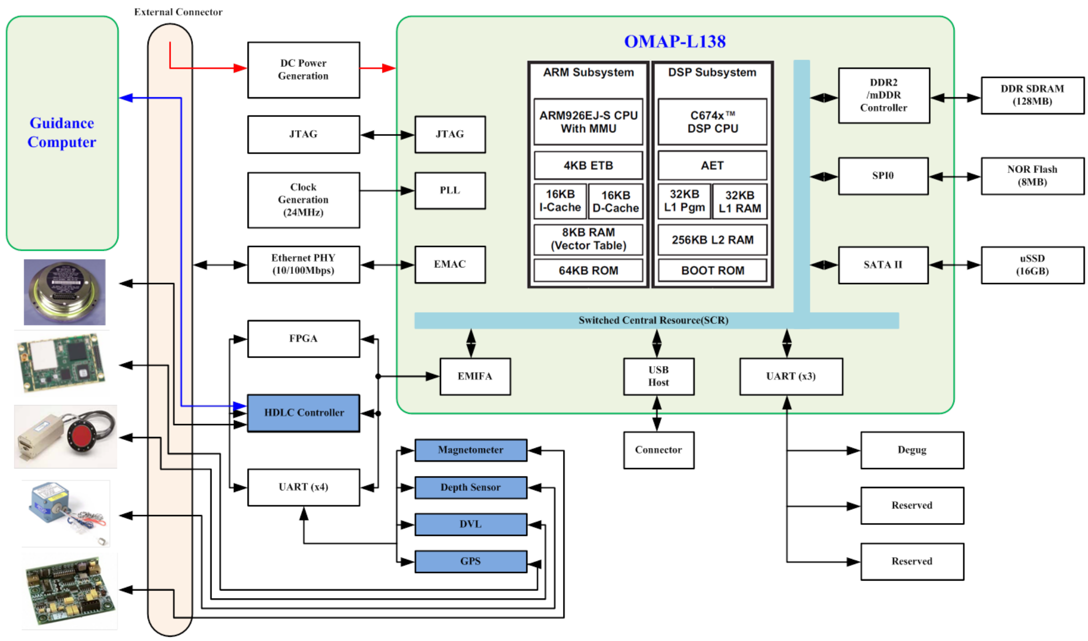

Fig. 3. Block diagram of the hybrid navigation computer.

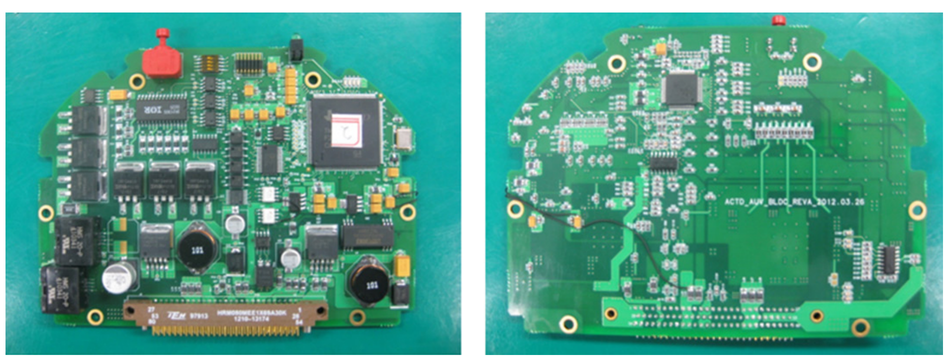

Fig. 4. Hybrid navigation computer of the autonomous underwater vehicle (left: top, right: bottom).

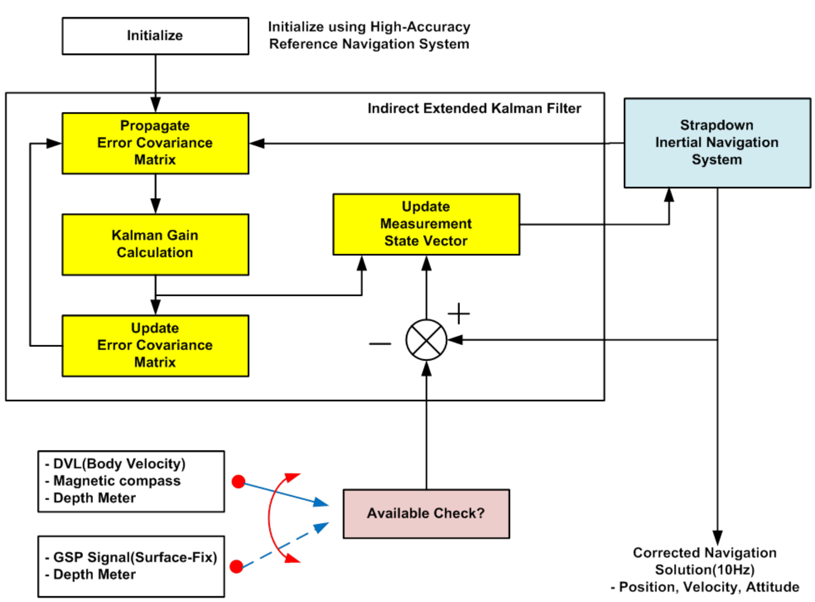

Fig. 5. Structure of the hybrid navigation algorithm.

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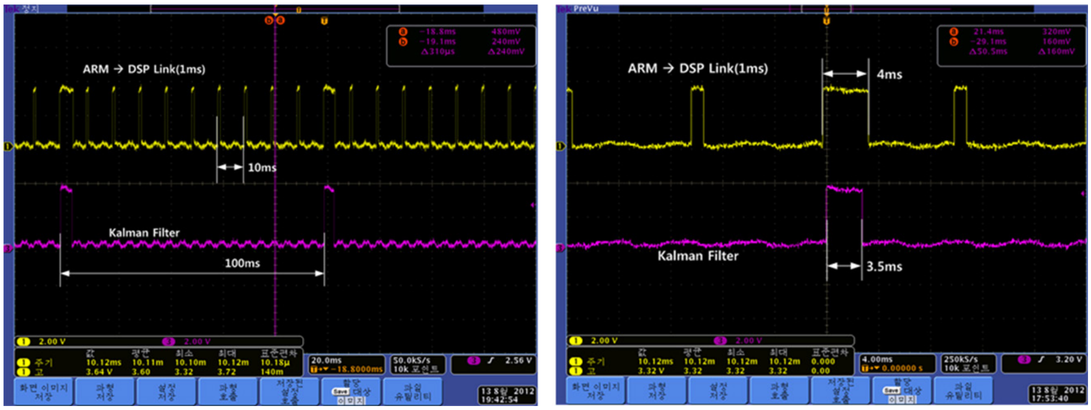

Fig. 6. Verification of computation capability of real time navigation in the hybrid navigation computer.

Table 2. Underwater navigation sensor error model.

Sensor	Bias	Random noise	Sample rate (Hz)
Gyro	1.0 deg/hr	0.15 deg/rt-hr	100
Accelerometer	1.0 mg	0.15 ft/sec/rt-hr	100
DVL	0.01 m/s	0.1 m/s	5
Magnetic compass	0.5 deg	1.0 deg	10
Depth-meter	0.5 m	0.5 m	10

Dilution of Precision and PRN information, which is state information of the GPS receiver. That is, if GPS signal is available, the surface navigation is performed. But if the GPS signal is not valid, the mode is changed to the underwater navigation. The hybrid navigation filter consisted of extended Kalman filter that uses the measurement of three-axis body velocity in the DVL, an azimuth of the magnetic compass and a depth of the depth-meter (Lee et al. 2005). If the AUV is surfaced over the water in order to compensate an accumulated error for a long time, position and velocity are corrected through loosely coupled GPS/INS algorithm (Titterton & Weston 2004).

The software algorithm was designed based on QNX, which is a real-time operating system in the hybrid navigation computer. The real-time task consists of sensor signal processing unit, initial alignment unit, inertial navigation unit, and integrated filter unit. All the sensor data are processed based on interrupts. In the interrupt service routine, the data are connected to arithmetic operation using semaphore-based synchronization after they are stored in the buffer in order to process sensor data in real time. The data for navigation operation is transferred using structure-based global variables. In order to verify the performance of the hybrid navigation computer and software in real time, execution times of the main functions were measured using the external General Purpose Input/Output ports. Fig. 6 shows that the navigation sensor data are transferred periodically at a rate of 100 Hz (10 ms) and the Kalman filter is operated normally at every 10 Hz (100 ms). Both the execution times of the DSP link and Kalman filter shall be operated within 10 ms, which were satisfied the time requirement.

3. PERFORMANCE VERIFICATION OF THE HYBRID NAVIGATION SYSTEM

3.1 Computer Simulation and PILS

In order to verify the designed underwater navigation algorithm, 6 DOF model designed based on MATLAB Simulink was used as shown in Fig. 7. The input of the AUV 6 DOF Simulink model is AUV velocity and way-point information. And the output is the position, velocity and attitude of AUV. The generated three-axis angular velocity and acceleration, and DVL measurement have error characteristics in Table 2. The hardware configuration for PILS is shown in Fig. 8. The hybrid navigation computer calculates a navigation solution using received data from the interface in real time. Fig. 9 shows the real-time navigation software results verified using PILS. The result of navigation was satisfied the required accuracy using DVL measurement, depth-meter and a magnetic compass.

3.2 Van-test

The performance of the surface navigation algorithm was verified using a van test on the ground prior to verifying the surface and underwater hybrid navigation in AUVs in real sea environment. In the van test, TALIN5000 was used for the initial alignment. The purpose of this test was to verify the initial alignment algorithm and surface navigation algorithm using only GPS/INS. The test was performed four times totally in which a vehicle was run over the road for 30 min in each test to evaluate the position accuracy.

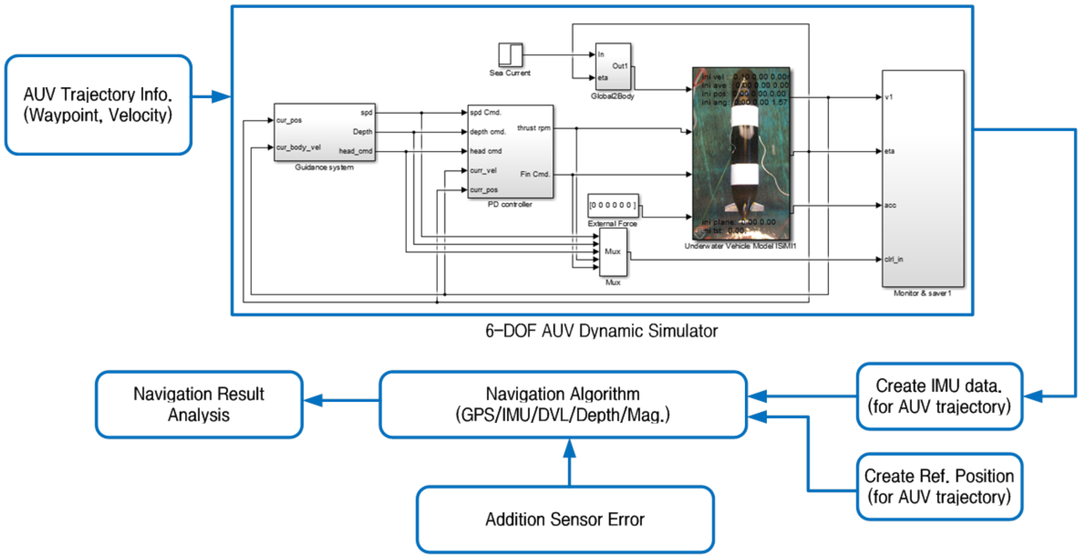

Fig. 7. Schematic diagram for verification of the 6-DOF simulator-based underwater navigation.

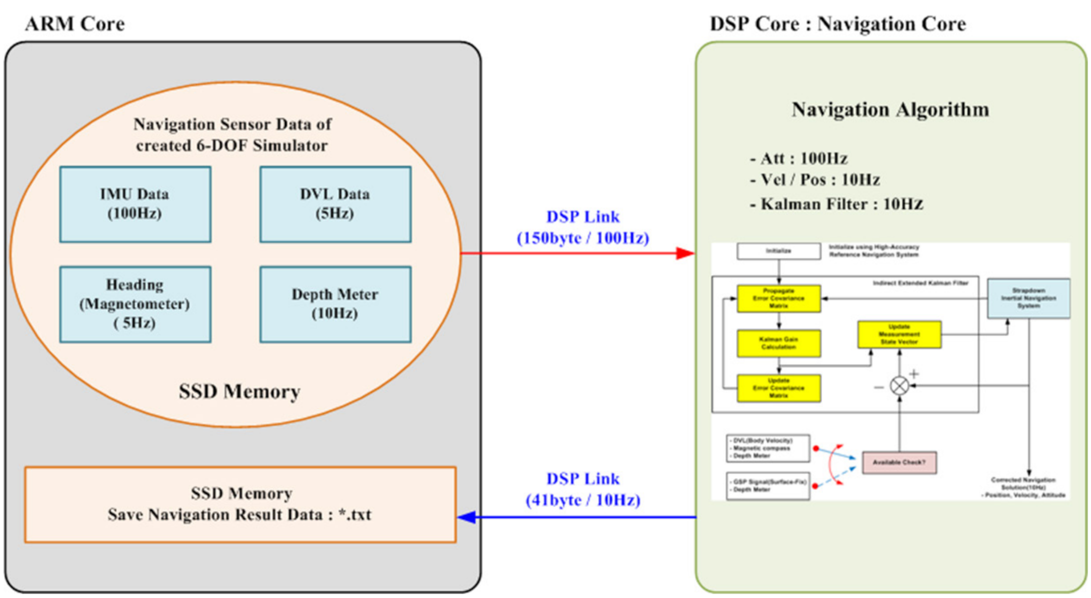

Fig. 8. PILS structure for verification of the underwater navigation algorithm.

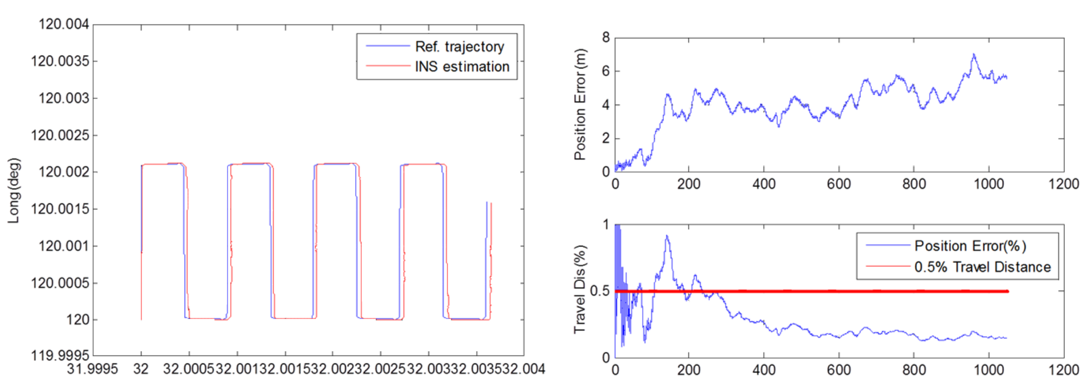

Fig. 9. Underwater navigation results verified by the PILS.

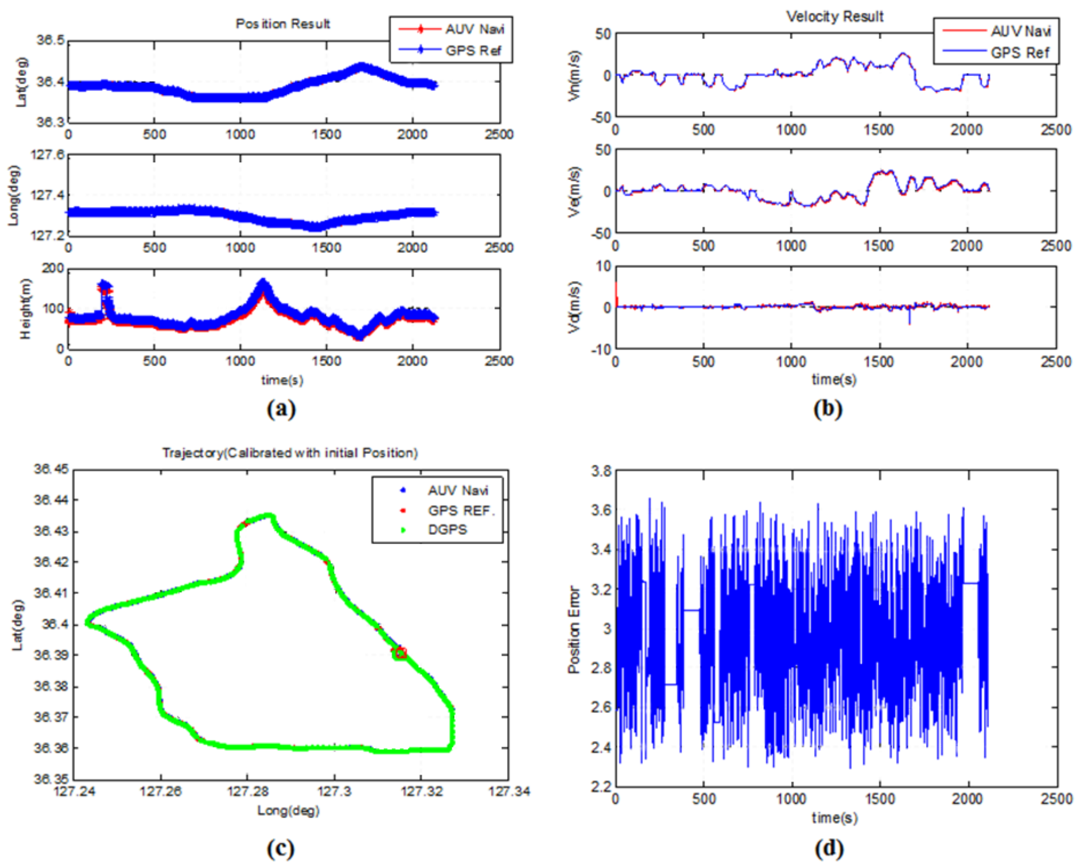

Fig. 10. Result of experiments on real-time hybrid navigation vehicle.

Table 3. Result of vehicle test.

No	Travel distance (m)	Operation time (s)	Position error of end point (m)
1	25,785	1,880	5.2
2	25,778	1,961	2.1
3	26,829	2,125	3.27
4	25,777	1,905	10.6

Differential GPS (DGPS, ProPak, Novatel) was installed as reference position information to compare that used in the hybrid navigation for AUVs. Fig. 10 shows the real-time navigation result and Fig. 10d verifies that a level of horizontal position error was within 4 m. As shown in Table 3, a position error was CEP 6.2 m, which satisfied the requirement of surface navigation (10 m CEP).

3.3 Hybrid Navigation in Real Sea

Generally, the test of AUVs in real sea should consider various factors such as sea environment, completeness of guidance and control algorithm. A dedicated jig for verification was manufactured in order to verify the hybrid navigation algorithm in real sea. The test method was similar to Hardware In the Loop Simulator.

Fig. 11 shows the real sea environment test picture (left) and test configuration (right). The jig for verification of the underwater navigation is divided into a fixture that is fixed to the ship, navigation sensors mounted to the AUV, and built-in hybrid navigation computer. If the AUV behavior was moved using the ship, the data of navigation sensor were stored in the hybrid navigation computer in real time according to the trajectory of the ship. And the underwater navigation result of calculated in real time has been stored at the same time. This configuration has an advantage of the verification of the navigation algorithm using the post-processing analysis. The real sea environment test was conducted at the offing in Geoje Jangmok in Korea. Fig. 12 shows the location and trajectory of the real sea test. In the figure, GPS trajectory (blue color) and underwater navigation trajectory of the AUV (green color) are marked. In order to satisfy the requirements of underwater navigation, which were mentioned in Table 1, a scenario was made to have iterative run along the trajectory for one hour or longer and the sailing velocity of the ship was set to maintain the underwater navigation requirement (3 kts (= 1.54 m/s) or faster). As shown in the real sea test results in Table 4 and Fig. 13, all data satisfied a position error within 0.5% of travel distance.

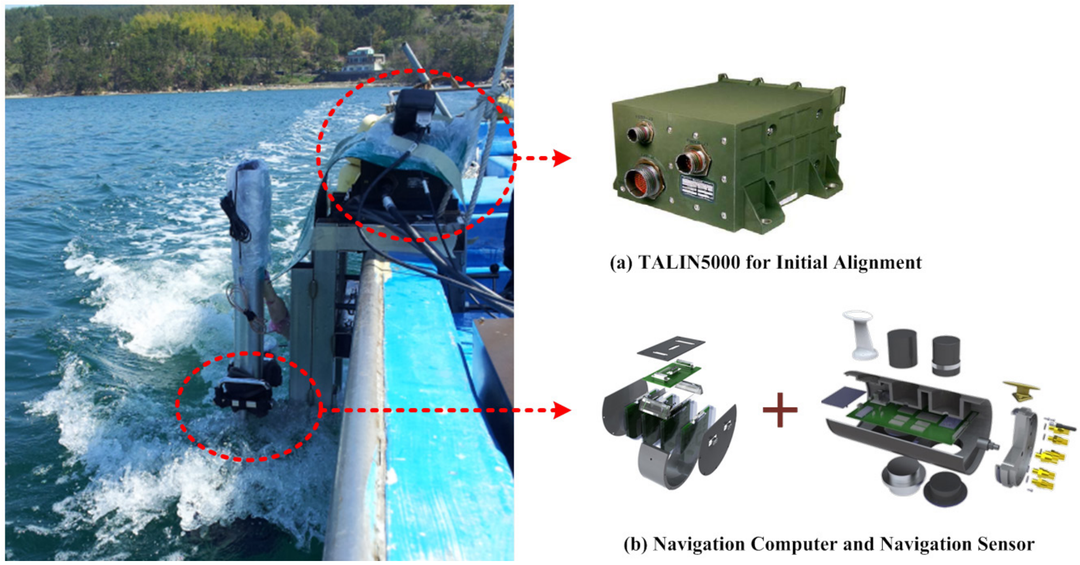

Fig. 11. Configuration of real sea environment test using specialized equipment for verification of underwater navigation.

Fig. 12. Test location of real sea environment for verification of underwater navigation and trajectory.

Table 4. Test results of real sea environment of autonomous underwater vehicle.

No	Travel distance (m)	Operation time (s)	Position error (m) of end point	Position error (%) compared travel distance
1	6,681	3,230	12.03	0.17
2	7,775	4,217	11.8	0.14
3	7,745	3,373	10.4	0.13

The performance of the hybrid navigation system using jig was verified and tests were considered a mission of the AUV. The test area for long-term mission was the offing in Mokpo. The surface and underwater navigation was carried out for 17 hours continuously. Fig. 14 shows the experimental area of the AUV and mission trajectory. The AUV started from Point (1) and went to other three point sequentially in schedule. A length of the shorter side of way-point was set to 150 m and a length of the longer side was set to 350 m. Thus, a total length of one rotation was 1 km and a trajectory was a shape of square. One test set in the experiment consisted of three rotations. In each test set, the surface navigation is operated at the first (1) – (3) way-points and the underwater navigation is operated in the rest of 2.5 km. Fig. 15 shows the trajectory of the scenario for the last one hour of 17-hour test results. The analysis on the experimental result showed that a horizontal position

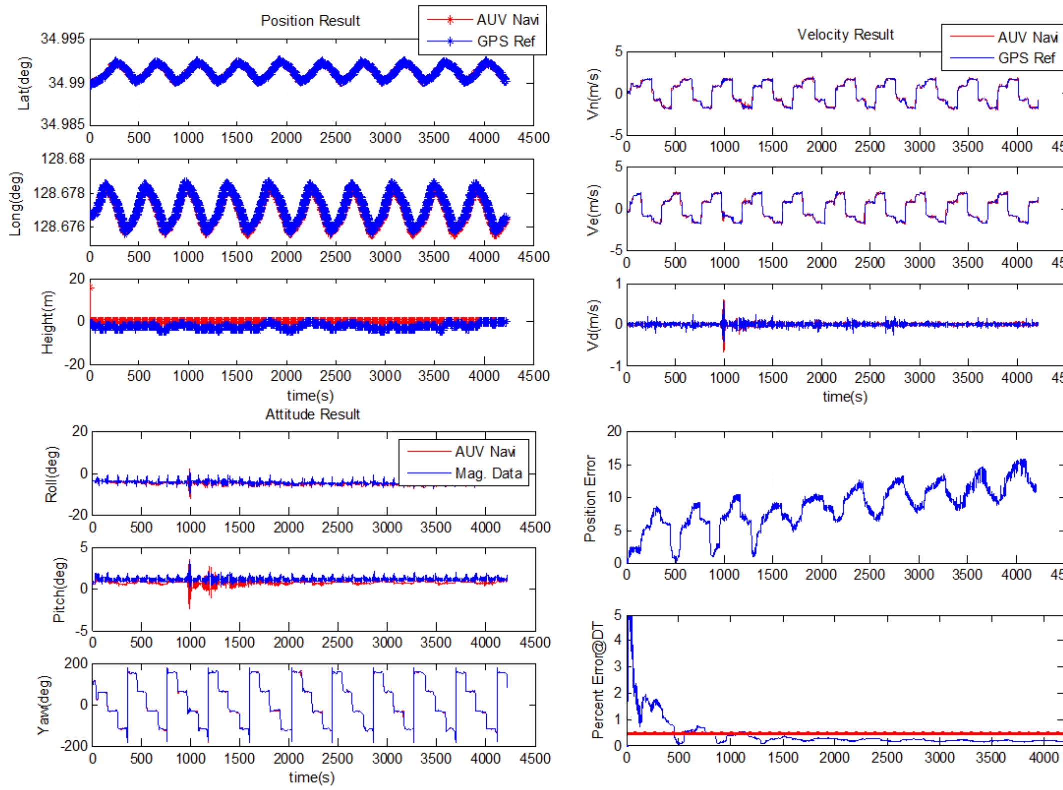

Fig. 13. Test results of real sea environment underwater navigation.

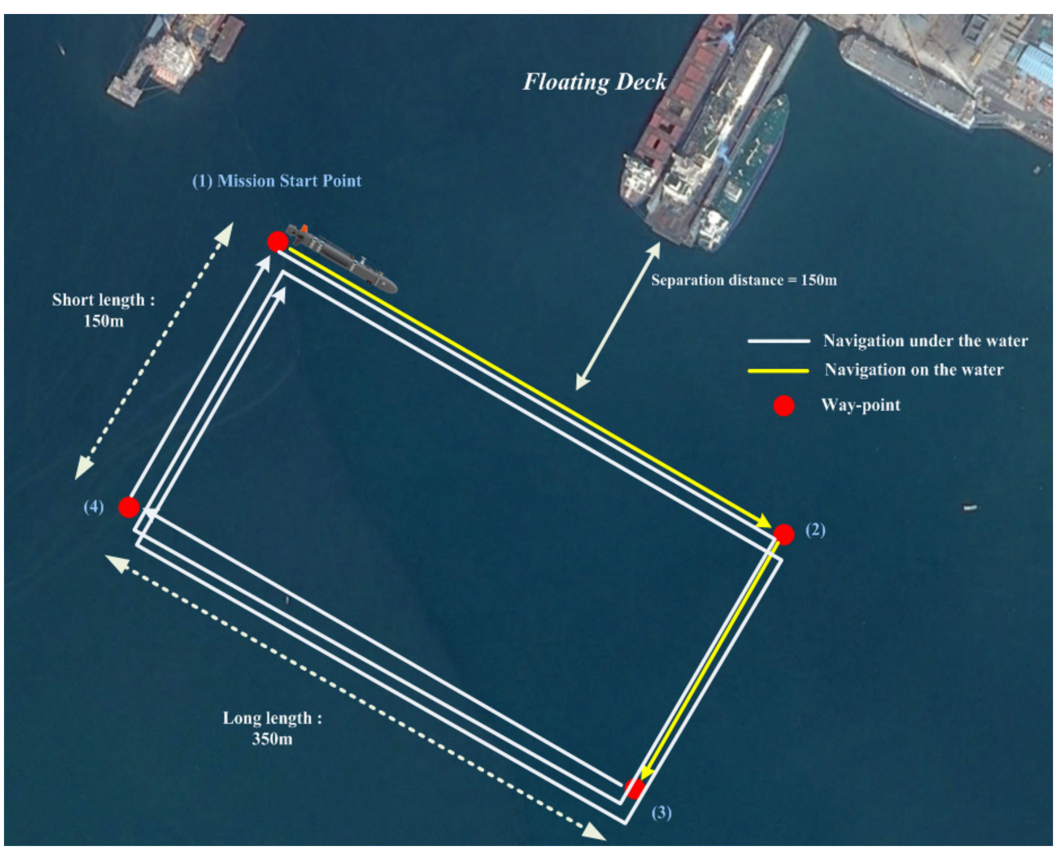

Fig. 14. AUV long-term (17 hr) mission performing trajectory.

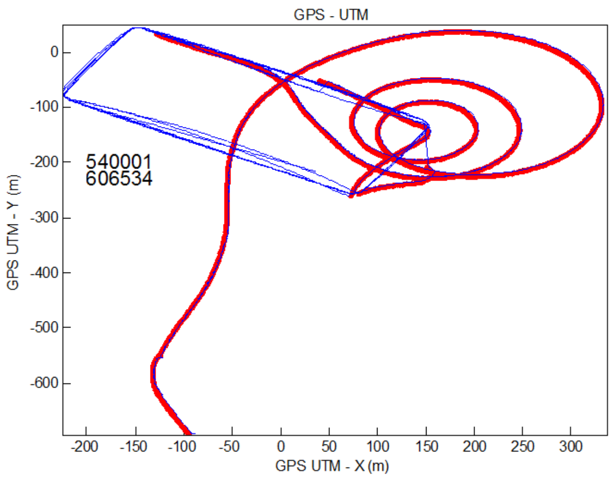

Fig. 15. Performing result of hybrid navigation in the autonomous underwater vehicle.

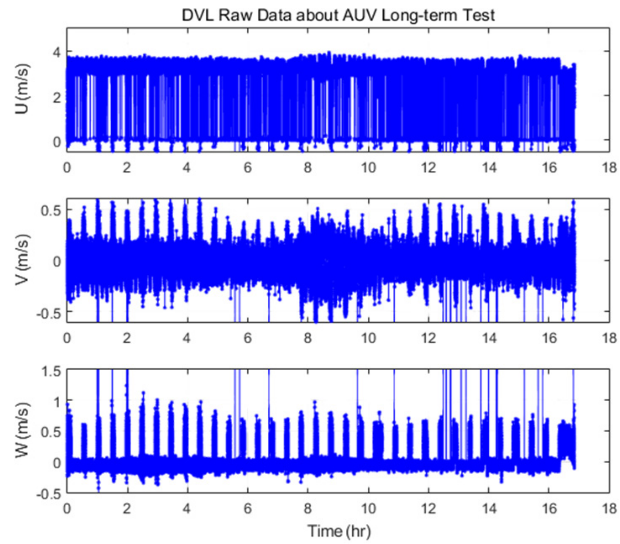

Fig. 16. DVL raw data during the long-term operation test.

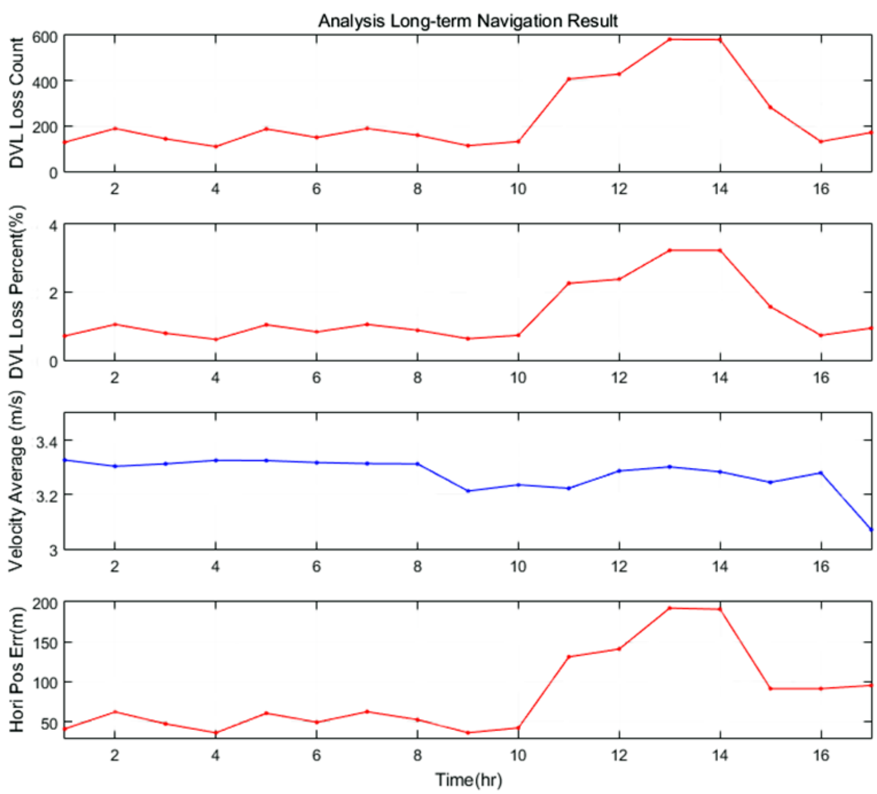

Fig. 17. Underwater navigation results according to DVL loss during the long-term operation test.

error during underwater navigation was increased gradually over time. The trajectory result showed that even if the AUV was rotated to pass through (3) way-point after surfacing, it did not approach the next way-point due to a large radius of rotation. The reason for this was due to a large amount of DVL sensor data loss during the long-term operation test as shown in Fig. 16. The loss of DVL data was due to unstable factor of hardware and underwater condition. Accordingly, the performance of underwater navigation was degraded. Fig. 17 shows the position error of the underwater navigation compared to DVL loss. The analysis result verified that the main reason for the navigation error was due to the DVL data loss as well as the initial alignment error. Although an error of underwater navigation was increased due to the DVL measurement loss, we verified that the hybrid navigation system was operated reliably for a long time.

4. CONCLUSION

In this paper, structure, design, verification method, and implementation results of the real-time hybrid navigation system for AUVs were described. The real-time hybrid navigation system consisted of multiple navigation sensors such as IMU, GPS, DVL, depth-meter, and magnetic sensor. It was designed with a structure that can select and fuse available sensor information according to environments. The structure can provide navigation solution to perform a mission for a long time in underwater. The real-time navigation performance of the hybrid navigation system for AUVs was verified through computer simulation, PILS, ground van tests and real sea environment tests. And we verified that this navigation algorithm is suitable of mine search mission in military. In the further works, even if DVL data loss is occurred, there are plans to conduct a study the accuracy of underwater navigation algorithm is guaranteed.

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