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Hardware in the Loop Simulation on Micro Electro Mechanical System Attitude Heading Reference System for Small Autonomous Underwater Vehicle

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소형 자율 무인잠수정 MEMS 기반 자세측정장치 성능 검증을 위한 HILS

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Abstract

This paper proposes the hardware in the loop simulation (HILS) for the performance evaluation of a small attitude heading reference system (AHRS) based micro electromechanical system (MEMS), suitable for small autonomous underwater vehicles (AUV). AUV have many scientific, military, and commercial applications due to their autonomy. Furthermore, the navigation system is the most important system for AUV because correct position information is essential for autonomous missions. Since GPS signal is not accessible underwater, the inertial navigation system (INS) has conventionally been used as the navigation sys-tem for underwater vehicles. The MEMS AHRS will be a good alternative for the inertial sensor of INS of small AUV. Hardware in loop simulation (HILS) was performed to validate the developed MEMS AHRS with a flight motion simulator, and the results of the HILS showed that the developed MEMS AHRS is capable of providing the attitude information under roll free and no roll free conditions.

Key words : Autonomous underwater vehicle, Hardware in the loop simulation, Attitude heading reference system, Micro machined electro mechanical system

Ⅰ. Introduction

This paper focuses on the application of hardware-in-the-loop simulation (HILS) for the performance evaluation of a small attitude heading reference system (AHRS) based on micro electro mechanical systems (MEMS), suitable for small autonomous underwater vehicles (AUV). Through HILS tests, I seek to validate the real-time three-degree-of-freedom attitude calculation capability of the developed

MEMS AHRS in a simulated underwater environment with dynamic attitude changes. Autonomous underwater vehicles have become the main tool for underwater survey operations in scientific, military, and commercial applications. The usage of these vehicles has also extended to the inspection of ship hulls (Walter, Hover and Leonard, 2008) and underwater manmade structures (Ribas, Ridao, Tardos and Neria, 2008; Kondo,

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Maki and Ura, 2006) because of their ability for autonomous navigation. The usage of AUV by the military has also been increasing and especially some small AUV, with length below 2 m, are used in hazardous missions such as mine countermeasure (MCM) (Christopher, 2003). It is essential that AUV can navigate in unknown environment without *a prior* information for achieving high-level autonomy. Thus, a navigation system that provides the current vehicle's position is the most important factor for a AUV's autonomy.

Since electromagnetic waves cannot propagate in deep water, GPS signal is not accessible underwater. AUV have usually adopted an inertial navigation system (INS), dead reckoning (DR), acoustic navigation, and geophysical navigation techniques as their navigation method. From the various navigation methods, the INS, which calculates the current position from information on inertia changes, have been widely adopted into AUV as the basic navigation method due to the simplicity of implementation even if there is unbounded accumulated error. The tactical grade inertial measure unit (IMU), which has been usually adopted by many underwater vehicles, can provide precise information. However, tactical grade IMU is very expensive and requires additional devices for attitude calculation. Therefore, it is difficult to implement a tactical grade sensor into small AUV in view of the cost and payload (Yim et al., 2002).

One alternative to the tactical grade inertial sensor is the attitude heading reference system (AHRS) based on the micro electro mechanical system (MEMS). The AHRS based MEMS technique utilizes the angular rate, acceleration, magnetometer, and vehicle attitude instead of the position information. Therefore, the device usually requires less payload space and power consumption. Furthermore, it is able to overcome many problems that have inhibited the adoption of an inertial system for small AUV with a tactical grade IMU.

There are some studies to develop the MEMS AHRS for small unmanned vehicle specially unmanned aero vehicle (Li, Dempster, Li, Wang, and Rizos, 2006; Li, Landry and Lavoie, 2008; Johnson, Cabuz, French and Supino, 2010; Jeong, Ko and Choi, 2014). However few research considers MEMS AHRS for small AUV and most of studies focus on system design for obtaining estimation results using virtual signals without actual products under a laboratory condition(Jeong, Ko and Choi, 2014), and research focused on verifying the real-world performance of MEMS AHRS remains limited. This study aims to evaluate the performance of MEMS AHRS in the context of small AUV used for military missions with the target performance set for missions under 30 minutes.

Since many costly sea trials are required to validate the newly developed MEMS AHRS, modeling and simulation can provide a cost effective method for carrying out the developed MEMS AHRS verification. As part of efforts to address cost and time issues associated with offshore testing, a system verification method based on Hardware in the Loop Simulation (HILS) has been introduced. The HILS system simulates the motion characteristics of underwater vehicles in underwater environments, verifying the real world performance of both hardware and software simultaneously (Hwang and Yoon, 2015; Hwang et. al, Yoo, 2020). In this research, HILS was chosen as modeling and simulation methods for performance evaluation under 2 conditions. The first condition assumes a general operating scenario where the roll of the AUV is maintained at 0. The second condition represents a military operating scenario where the roll transitions from a non-zero value to 0. The HILS results are presented. HILS results showed the developed AHRS was capable to calculating the pose of AUV under various conditions and was suitable for small AUV.

The structure of this paper is as follows: The developed MEMS AHRS for small AUV is introduced in the next section. The following section describes the HILS configuration of the developed MEMS AHRS and the HILS results. The last section concludes this paper

Ⅱ. Research method

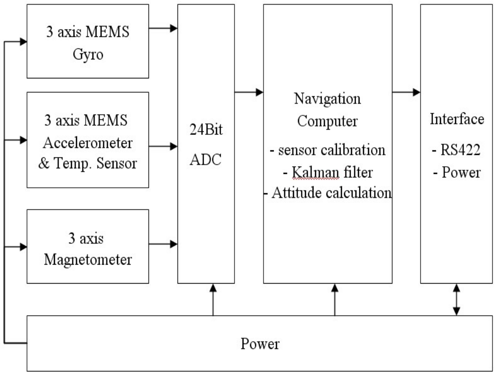
1. System Configuration

I have developed small AUV for military missions, such as submarine training. Moreover, the AHRS based MEMS has been developed for small military AUV. The AHRS is equipped with a three-axis MEMS gyro, accelerometer, and magnetometer. [Fig. 1] presents the overview of the AHRS and its specifications are summarized in <Table 1>. The navigation computer in AHRS calculates the acceleration with three degrees of freedom motion, roll, pitch, and yaw with sensor's output with a calculation algorithm based on the Kalman filter.

[Fig. 1] AHRS based MEMS for small high speed AUV

<Table 1> Specification of AHRS based MEMS

Specifications	Value
Size	80 mm x 49 mm x 70 mm
Weight	200 g (including case)
Power	<2.2 W(nominal)



[Fig. 2] Architecture of AHRS based MEMS.

The configuration of AHRS is presented at [Fig 2].

2. Attitude determination

Strap down Inertial Navigation Systems (INS) can provide attitude and heading estimates after initialization and alignment by integrating the attitude rates that are related to the attitude angles and the angle rate measurements of the gyroscopes. However, the strap down INS implementation suffers from error growth due to the integration of the inertial gyro measurements that contain various errors. Therefore, the MEMS AHRS cannot implement the integration method due to its high error growth rate.

An alternative for the AHRS based MEMS sensor is the method using a transformation matrix from linear acceleration to specific force based on the Euler's theorem, called the direction cosine matrix (DCM) method. According to Euler's theorem, I can specify the orientation of the body frame relative to the navigation frame using three angles, known as Euler angles, which can be obtained using three successive rotations about different axes, known as the Euler angle sequence (Reddy and Murray, 1991; Titterton and Weston, 1997).

The roll and pitch angles are calculated with the DCM method under the assumption that the AUV does not move and the gravity is g. Each specific force is described by Eq. (1):

$$f^b = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix},\ f^n = \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \cdots\cdots\cdots\cdots (1)$$

where f^b is the is the measured rate force at body fixed coordinates and f^n is the measured rate force navigation coordinates.

The transformation matrix from the body coordinates to the navigation coordinates is C_n^b in Eq. (2):

$$C_n^b(:,1) = \begin{bmatrix} \cos(\theta)\cos(\psi) \\ \sin(\phi)\sin(\theta)\cos(\psi) - \cos(\phi)\sin(\psi) \\ \cos(\phi)\sin(\theta)\cos(\psi) + \sin(\phi)\sin(\psi) \end{bmatrix}$$

$$C_n^b(:,2) = \begin{bmatrix} \cos(\theta)\sin(\psi) \\ \sin(\phi)\sin(\theta)\sin(\psi) - \cos(\phi)\cos(\psi) \\ \cos(\phi)\sin(\theta)\sin(\psi) - \sin(\phi)\cos(\psi) \end{bmatrix}$$

$$C_n^b(:,3) = \begin{bmatrix} -\sin(\theta) \\ \sin(\phi)\cos(\theta) \\ \cos(\phi)\sin(\theta) \end{bmatrix} \cdots\cdots\cdots\cdots (2)$$

where $C_n^b(:,n)$ is n^{th} column matrix of $C_n^b(3\times 3)$.

The relationship between f^b and f^n is described as follows:

$$f^b = C_n^b f^n = \begin{bmatrix} -g\sin(\theta) \\ -g\sin(\phi)\cos(\theta) \\ -gcos(\phi)\cos(\theta) \end{bmatrix} = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} \cdots\cdots (3)$$

From Eq. (3), the pitch and roll are calculated as follows:

$$\theta = \tan^{-1}\left(\frac{f_x}{\sqrt{(f_y^2 + f_z^2)}}\right)$$

$$\phi = \tan^{-1}\left(\frac{f_y}{f_x}\right) \cdots\cdots\cdots\cdots (4)$$

If the alignment time is T, pitch and roll in Eq. (4) are calculated through integration as shown in Eq. (5).

$$\theta = \tan^{-1}\left(\frac{1}{T}\int_0^T \frac{f_x}{\sqrt{(f_y^2 + f_z^2)}}\right)$$

$$\phi = \tan^{-1}\left(\frac{1}{T}\int_0^T \frac{f_y}{f_x}\right) \cdots\cdots\cdots\cdots (5)$$

As shown in Eq. (2), the yaw angle cannot be calculated from the transformation matrix using a linear accelerometer. Therefore, a measurement other than linear acceleration is required. In this study, the angular acceleration is used to solve this problem because the developed AHRS contains a three axis gyro and yaw can set the heading value of the geomagnetic sensor as the initial value. And after stabilizing the attitude through initial behavior control, secondary alignment is performed, and the roll, pitch, and yaw attitudes are estimated.

The relationship between the rate of Euler's angles and the output from the gyro is described as follows:

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix} + \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{pmatrix} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix}$$

$$+\begin{pmatrix}1 & 0 & 0\\ 0 & \cos(\phi) & \sin(\phi)\\ 0 & \sin(\phi) & \cos(\phi)\end{pmatrix}\begin{pmatrix}\cos(\theta) & 0 & -\sin(\theta)\\ 0 & 1 & 0\\ \cos(\theta) & 0 & \cos(\theta)\end{pmatrix}\begin{bmatrix}0\\0\\ \dot{\psi}\end{bmatrix} \cdots\cdot (6)$$

From Eq. (6), the derivative equation can be derived as follows:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix}=\begin{pmatrix}1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta)\\ 0 & \cos(\phi) & -\sin(\phi)\\ 0 & \sin(\phi)\sec(\theta) & \cos(\phi)\sec(\theta)\end{pmatrix}\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix} \cdots\cdots (7)$$

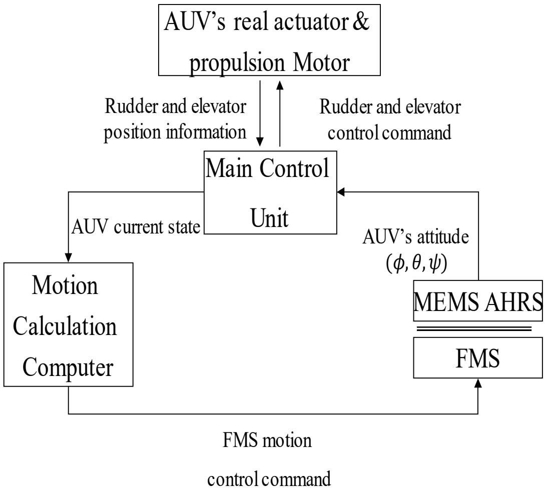
The yaw angle can be calculated from Eq. (7) with the calculated roll and pitch angles calculated from Eq. (5). Since Eq.s (5) and (7) require the solution of the integration and determination, the estimation method is essential to solve the attitude determination problem. Therefore, the extended Kalman filter (EKF) is used in this study. The system state and measurement vectors for the EKF is summarized as follows.

$$x=[\phi\,\theta\,\psi]^T$$
$$z=\left[\omega_x\,\omega_y\,\omega_z\right]^T \cdots\cdots (8)$$

The state error vector has six components consisting of a 3-vector accelerometer error and 3-vector gyro bias error because the attitude error due to the accelerometer sensor error does not increase and has a precision proportional to the bias, so relatively accurate attitude values can be calculated over time. Additionally, the bias which is known as primary error of the gyro varies with each power cycle and leads to a rapid accumulation of errors over time as integration algorithm is applied. Therefore, it is essential to estimate a stable value using an EKF. The specific procedures and parameter values are classified and therefore not disclosed.

3. Simulation Configuration

In many cases, experiments under practical conditions are essential to verify the function of the developed device. However, since sea trial tests for underwater vehicles usually require considerable support equipment such as a surface vessel, sea trail tests usually require a significant amount of time and expenses. One of alternatives for sea trial tests is HILS. HILS is a modeling and simulation method, which uses real developed devices and software under virtual environment conditions in real time. In this study, HILS is performed to verify the measure function of AHRS in various cases with flight motion simulator (FMS), the main control unit of small AUV for military missions and motion calculation computer for virtual underwater environment for simulation. [Fig. 3] shows the concept of HILS procedure and used devices.



[Fig. 3] HILS system hardware configuration and control command flowchart.

The main control unit is the custom-made processor board designed and manufactured for a small AUV and is operated based on the VxWorks, which is a real time operation system. The role of the main control unit is the calculation of the control commands for the rudder and elevator using the transferred roll, pitch, and yaw data from the MEMS AHRS and the simulated depth signal. Subsequently, it transmits the calculated commands to the motion calculation computer through Ethernet communication based on TCP/IP. One role of the motion calculation computer which is a personal computer is the calculation of the AUV's motion using the received commands for the rudder and elevator. Another role is to generate the control commands for the FMS based on the rate of roll, pitch, and yaw. The communication functions supported by the motion calculation computer are the GPIB for the control of the FMS based on the generated FMS control commands, the Ethernet, and analog outputs, which provide the calculated depth to the main control unit. All HILS were controlled by an autopilot program at the main control board without human operator intervention.

Ⅲ. Research results

1. Simulation results

The conditions for the HILS simulation were configured based on publicly available torpedo decoy deployment scenarios(Shin et. al, 2016) and were organized into two cases. Two simulation cases were decided for HILS. One of them is when the roll of the AUV is zero, in the other words, there is roll free motion. The other is when the roll is non-zero and changes to zero. Since AUV have been usually operated in roll free motion, the first case when the roll is zero aims to verify the function of the developed MEMS AHRS in normal AUV operation conditions. The second case represents the conditions when the AUV is launched from a submarine for military missions, and the roll is not zero but goes to zero for stable motion.

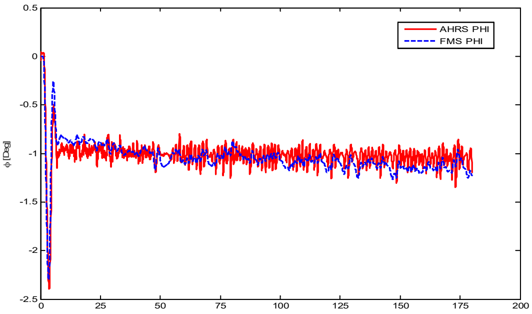
<Table 2> Conditions for first case of HILS.

Conditions	1	2
Target Depth	50 m	50 m
Target Yaw	30 °	-30 °
Velocity	16 knots	16 knots

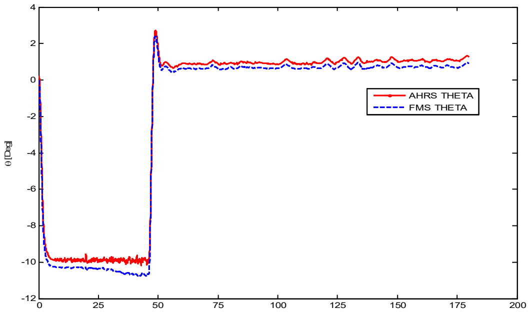
<Table 3> Parameters for the first case of HILS

Items	Value
Operation interval	50 ms
Initial position	Sea surface
Operation time	180 sec

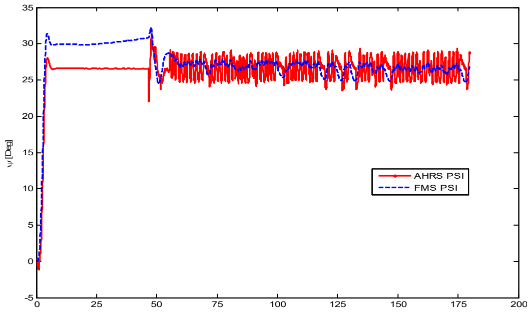
Both cases consider that the yaw varies from zero to a positive or negative value in order to change the orientation of the AUV. The conditions when the roll is zero are summarized in <Table 2>. These conditions consider the operation concept of small AUV, into which the developed MEMS AHRS will be implemented. Condition 1 assumes that the yaw varied from zero to positive and condition 2 that the yaw varied from zero to negative. A common assumption for both conditions is that the velocity is fixed as soon as the launch takes place. Thus, there is no initial acceleration. The parameters utilized in the HILS test are summarized in <Table 3>. As outlined in the table, the operation interval was set to 50 ms to enable real-time testing, with the initial condition established at the water surface,



a) Roll



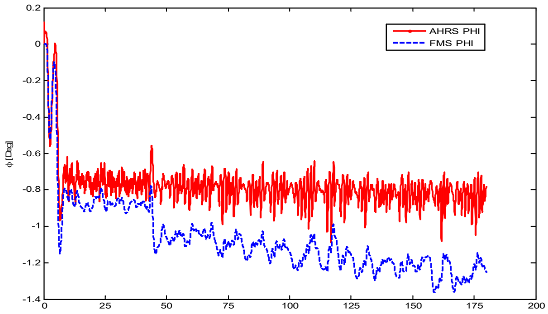
b) Pitch



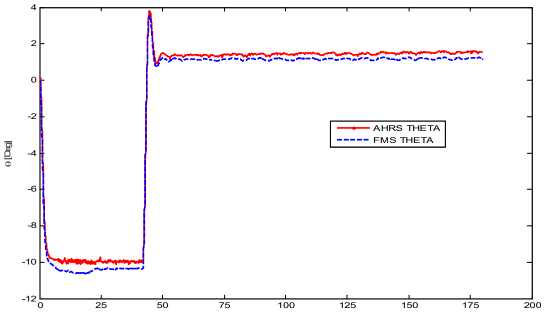
c) Yaw

[Fig. 4] HILS results under condition 1 in <Table 2>

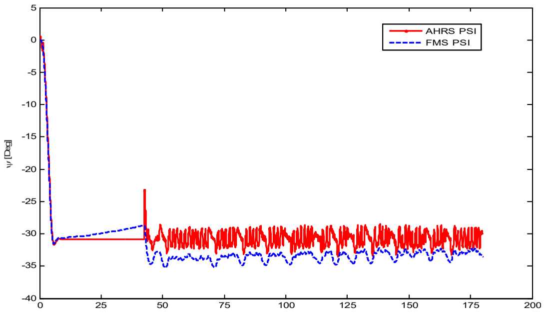
reflecting standard AUV operating conditions. The total operation time was set to 180 seconds to evaluate the device's performance for potential military AUV applications. [Figs. 4 and 5] show the representative HILS results, the measured value of roll, pitch, and yaw from the developed MEMS AHRS and the reference data from the FMS inertial sensor under conditions 1 and 2 outlined in <Table 2>. [Figs. 6 and 7] show the HILS error, which describes the difference between the MEMS AHRS and FMS measurements in both conditions in <Table 2>. [Figs. 4 and 5] demonstrate that the MEMS AHRS can provide precise roll and pitch information. Furthermore, the yaw information from the MEMS AHRS have a small error to FMS data.



a) Roll

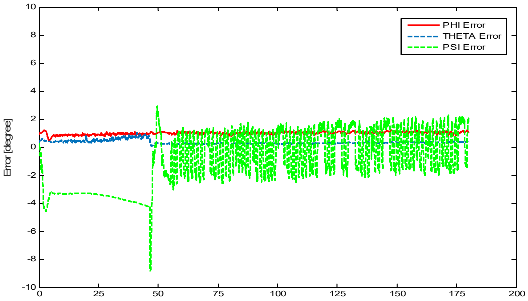


b) Pitch

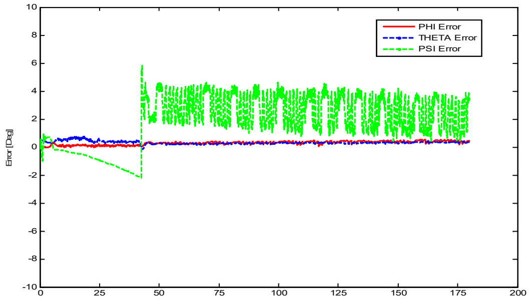


c) Yaw

[Fig. 5] HILS results under condition 2 in <Table 2>



[Fig. 6] Error under condition 1 in <Table 2>.



[Fig. 7] Error under condition 2 in a <Table 2>.

[Fig. 6 and 7] show that the errors of roll and pitch are very small and the error of yaw, which oscillates with some bound, does not increase in both cases. The error oscillation in yaw is assumed to be caused from the FMS motion to fix the desired orientation of the AUV by the autopilot program under condition that the electromagnetic field is continuously generated from the FMS drive motor. It is expected that the error of yaw will be reduced by the modification of the autopilot program control coefficients and to obtain a precise initial value that is robust against sensor errors through transmission alignment. The HILS results show that the developed MEMS AHRS can provide the attitude information, with less than two degrees yaw error, and can be used to keep the desired direction of the AUV by the autopilot program. <Table 4> presents the mean and variance of error in [Figs. 6 and 7] and proves the error about roll and pitch from the MEMS AHRS is small and error about yaw is below than 10 % of desired change.

From the above-mentioned HILS results, the developed MEMS AHRS was proven to be able to provide attitude information with little yaw error under the condition that the roll changes only slightly, and the yaw and pitch varied to the desired value and remained unchanged. In other words, the motion is very simple. Although the MEMS AHRS was validated under simple motion conditions, the function of MEMS AHRS needs to be validated under a more complex AUV motion.

<Table 4> Error of the first case of HILS.

Conditions	DOF	Mean(degree)	Variance(degree)
1	Roll	0.0277	0.0107
	Pitch	0.3517	0.0195
	Yaw	-1.0168	3.9144
2	Roll	0.2908	0.0170
	Pitch	0.3209	0.0112
	Yaw	1.8898	3.2868

<Table 5> Conditions for second case of HILS.

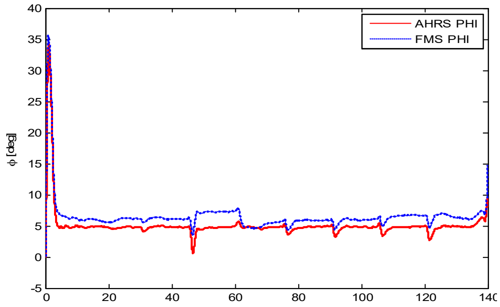
Conditions	1	2
Count of yaw change	4 times	8 times
Operation time	140 sec	250 sec

Thus, the second case for HILS consider the condition in which the roll will vary from a large value to zero and the yaw will vary at multiples from zero to positive or negative 180 degrees. The conditions for the second case were decided to be closer to the real AUV motion in real operational under underwater environment and are summarized in <Table 5>.

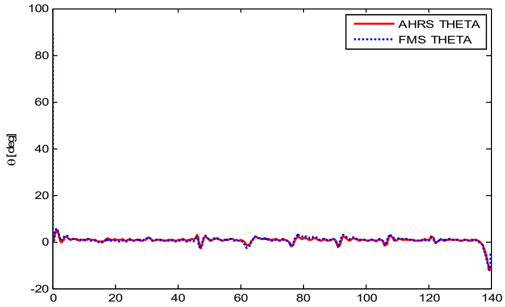
<Table 6> Parameters for the second case of HILS

Items	Value
Operation interval	None
Initial roll	35 °
Operation depth	50 m

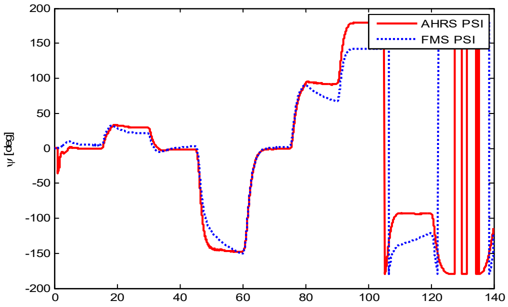
Both conditions in <Table 5> are based on the predetermined AUV trajectory for real missions. The parameters and the operation interval used in the second case of the HILS are presented in <Table 6>. Operation interval in Table 3 also used in second case and operating velocity of AUV is same in first case, 16 knots. However, in order to reflect the conditions for operating a torpedo decoy, the second condition was set to depart from a depth of 50 meters, which is different from the first condition. The first condition in <Table 5> is the condition for short acceleration duration and the other is for long acceleration duration. The results under the first condition are depicted at [Fig. 8] and [Fig 9] shows the error in the HILS results of the first condition in <Table 5>. Furthermore, the roll and pitch information from the AHRS are very close to the real roll and pitch values from the FMS. However, the calculated yaw from the AHRS has more errors compared to the FMS values as operation time increases. The significant yaw error after 100 s in [Fig. 8] is assumed to be caused from the change of sign from a positive to a negative angle. The yaw error is considered to be caused from the autopilot control of the AUV, and not the AHRS, because the error decreases as time increases after changing the yaw angle. The effect of longer operation times and yaw changes on the attitude caution function of the delved MEMS AHRS are presented in [Figs. 10 and 11].



a) Roll

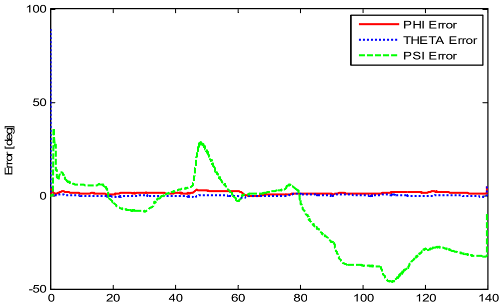


b) Pitch

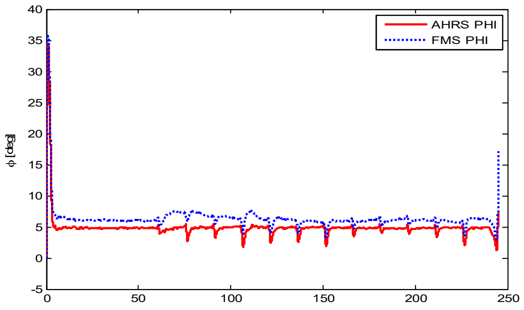


c) Yaw

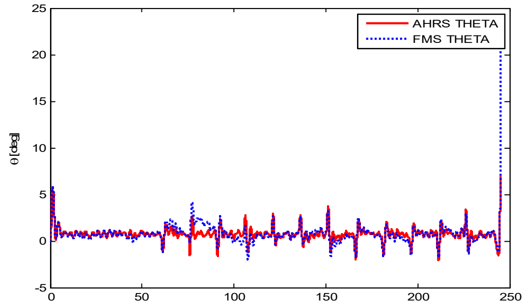
[Fig. 8] HILS results under condition 1 in <Table 4>.



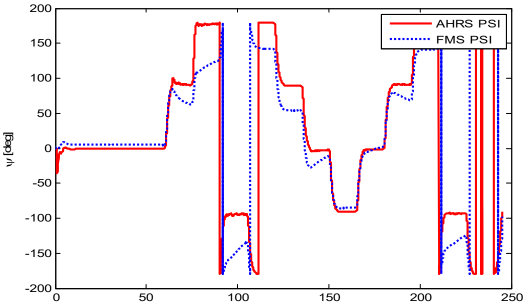
[Fig. 9] Error under condition 1 in <Table 4>.



a) Roll

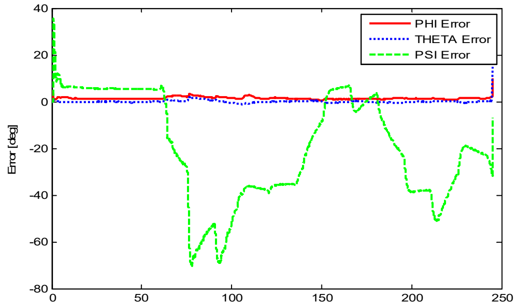


b) Pitch



c) yaw

[Fig. 10] HILS results under condition 2 in <Table 4>.



[Fig. 11] Error under condition 2 in <Table 4>.

Similar to the results concerning condition 1 in <Table 5>, the errors of roll and pitch are small and below 2 and 0.5 degrees, respectively. And under long simulation time conditions, the errors in yaw exhibit a similar trend to those observed under short simulation times. Specifically, while the MEMS AHRS values during yaw changes closely align with the originally set control values, the attitude values calculated by the FMS, which simulates AUV motion, fail to adequately reflect the MEMS AHRS values. This results in comparable error characteristics between the two simulation conditions. However, since the long time simulation condition was configured with a greater number of yaw changes, the discrepancy between the FMS calculated values and the MEMS AHRS calculated values increased, resulting in a larger observed error.

The yaw error exhibits a dependency on the characteristics of the magnetic sensor over time, leading to potential errors in environments where the magnetic field is subject to distortion. In the HILS test, it is believed that the electromagnetic field generated by the FMS drive motor continuously affected the magnetic sensor within the MEMS AHRS due to the positional characteristics of the FMS, resulting in persistent errors. Therefore, to accurately estimate the yaw of an underwater vehicle, it is essential to investigate a method for obtaining a precise initial value that is robust against sensor errors through transmission alignment. In addition, another reason of error is believed to be due to the characteristics of the coordinate transformation matrix, where the calculations influenced by roll have a greater impact on yaw.

Ⅳ. Conclusion

This paper describes the AHRS developed with MEMS gyro and magnetometer, which is suitable for a small AUV that has a limited payload and high speed. The MEMS AHRS uses the DCM and the extended Kalman filter to calculate the current attitude of AUV in real time. The developed AHRS was tested through a closed loop HILS for thre degrees of freedom motion with FMS. The main control unit of a real AUV under various conditions included varying the vehicle a yaw angle, depth and initial roll and operation time. The HILS results showed that the MEMS AHRS could calculate the current attitude of the AUV when the AUV was assumed to navigate with three degrees of freedom. depth control errors within 1% and heading control errors within 3 degrees. Despite the use of a low-cost MEMS AHRS, the developed system is considered suitable for application in small, cost-effective military unmanned underwater vehicles.

In order to overcome the yaw errors observed in the HILS results, future research will focus on developing a technique to appropriately design an INS algorithm for the initial signal instability period following mission commencement. Additionally, I will explore the application of an EKF that utilizes geomagnetic sensor and gyro data once a stable attitude has been achieved.

And I plan to validate the MEMS AHRS through HILS using two conditions. The first one involves using the actual battery pack intended for a small AUV, simulating long-duration operational conditions of up to 30 minutes. The second incorporates a real acoustic sensor to assess the computational capabilities of the main control unit. I also plan to conduct HILS tests that reflect various AUV military operations. In addition, I intend to perform sea trial experiments with real AUV that would utilize the developed AHRS MEMS system to verify its performance by incorporating the effects of ocean currents and tide that were not considered in the HILS test.

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