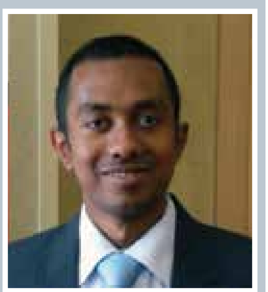
Locate but not Reveal

Byungjun Choi



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Choi, Randeni, Fan, and Forrest investigate the capability of a model-aided inertial navigation system with limited activation of a Doppler velocity log acoustic sensor to localize AUVs.

Who should read this paper?

This paper is of interest to those working with the localization, navigation, and control of autonomous underwater vehicles (AUVs), especially surveillance AUVs.

Why is it important?

Localization and navigation systems with a lower acoustic signature are a requisite for AUVs carrying out surveillance operations. This study employs a Kalman filter (KF) data fusion algorithm in which the acceleration measurements from the inertial navigation system and the vehicle velocities predicted by a motion response mathematical model were combined with intermittent Doppler velocity log (DVL) measurements. The optimized solution was defined as 10% of DVL activation with additional 2.5% at the beginning and the end of the field trials.

About the authors

Byungjun Choi received a B.E.(Hons.) in Naval Architecture from the Australian Maritime College, University of Tasmania, in 2017. He was a mechanical engineer assistant with Dooan Infracore from 2008 to 2010. He is preparing for a PhD in the field of AUVs. His research interest is improving the localization systems of AUVs. Dr. Supun Randeni received a B.Eng. (Hons.) in Naval Architecture in 2013 and a PhD in Maritime Engineering in 2017 from the Australian Maritime College, University of Tasmania. Currently, he is a Postdoctoral Research Associate at the Laboratory for Autonomous Marine Sensing Systems at Massachusetts Institute of Technology. His research interests include developing model aided localization and navigation systems for AUVs. Dr. Shuangshuang Fan received a B.E. in Mechanical Engineering from Shandong University, Jinan, China, in 2008, and a PhD in Mechatronic Engineering from Zhejiang University, Hangzhou, China, in 2013. From 2013 to 2014, she was a Research Engineer with the Institute of Shanghai Aerospace Control Technology. She was with the Acoustic Signal Processing Lab, Zhejiang University, as a Postdoctoral Researcher from 2014 to 2017. Currently, she is a Lecturer at Australian Maritime College, University of Tasmania, Launceston, Australia. Her research interests include the navigation, control and path planning of underwater vehicles in dynamic environments. Dr. Alexander Forrest received a B.E. in Chemical Engineering and Society from McMaster University, Canada, in 2002, and both an M.A.Sc. and PhD degree in Civil Engineering from University of British Columbia, Canada, in 2004 and 2011, respectively. From 2013 to 2016, he was a Senior Lecturer and Ocean Engineering Course Coordinator at Australian Maritime College, University of Tasmania, Australia. Currently, he works as an Assistant Professor at the Department of Civil and Environmental Engineering, University of California Davis. His general area of research focuses on understanding the influences between localized bathymetry and the surrounding water column. Since 2006, he has worked with AUVs as data collection platforms to further his research.

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A MODEL AIDED INERTIAL NAVIGATION SYSTEM WITH A LOW ACOUSTIC SIGNATURE FOR LOCALIZATION OF SURVEILLANCE AUVS

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ABSTRACT

Localization and navigation systems with a lower acoustic signature is a requisite for autonomous underwater vehicles (AUVs) carrying out surveillance operations, which is a challenging task due to limited availability of sensors. Utilizing inertial navigation systems (INSs) is one of the options, although it still presents a certain degree of position drift, even with a high-grade INS. This study investigates the capability of a model-aided inertial navigation system (MA-INS) with limited activation of Doppler velocity log (DVL) acoustic sensor to localize AUVs. Employing a Kalman filter (KF) data fusion algorithm, the acceleration measurements from the INS and the vehicle velocities predicted by a motion response predicting mathematical model were combined with intermittent DVL measurements. The acoustic signature was reduced while maintaining a reliable localization accuracy. These findings show that localization of surveillance AUVs can be conducted by the MA-INS algorithm with a minimized DVL usage. As the DVL operating time could be controlled by the DVL application schemes, the algorithm could be optimized depending on the planned routes of AUV during the field trial. However, considerable investigation may be needed to obtain highly accurate localization solution using non-acoustic sensors. For future work, it is recommended to impeccably restrain the use of DVL for the localization, in order to secure the concealment of AUV from detection.

KEYWORDS

Autonomous underwater vehicle; Localization algorithm; Mathematical model aided inertial navigation system; Surveillance AUV

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INTRODUCTION

Autonomous underwater vehicle (AUV) technology has provided the opportunity for a massive evolution in the field of underwater research. With the development of AUVs, the risk and cost associated with offshore underwater activities have been reduced significantly [Murad et al., 2016]. Generally, AUVs are involved in oceanographic research activities such as conducting physical, biological, chemical and archaeological investigations [Johnson et al., 2007]. Furthermore, the applications of AUVs are considered in offshore surveys, mine countermeasure, and unexploded ordnance removal missions for military purposes [Zeng et al., 2015]. Although the inception of AUV engineering occurred around fifty years ago, some systems are still being developed for better AUV explorations, and vehicle localization is one of them [Petillot et al., 2010].

Localization of AUVs has been a persistent issue since the early stages due to rapid wavelength attenuation of electromagnetic waves (such as Global Positioning System (GPS) and radio signals) in water. Furthermore, the selection of localization sensors for military surveillance operations is much more restricted as it is essential to have a minimum acoustic signature to avoid detection during the lurking mode and exploration. According to Paull et al. [2014], it is possible to detect, localize and track small vessels and divers by using passive and active sonars when they release acoustic signals. Thus, the application of acoustic sensors should be minimized to avoid the detection of the AUVs by the enemy.

Inertial navigation systems (INSs) aided with bottom-tracking Doppler velocity logs (DVLs) is one of the most common localization schemes for AUVs. Application of INS also can be one of the solutions for non-acoustic localization. However, the uncertainty of the localization solution grows with time (i.e., unless the INS is externally aided) due to the double integration of uncertainties within INS acceleration measurements when deriving the distance [Hegrenæs et al., 2007]. This position uncertainty growth is unavoidable even with high-grade INS sensors.

An alternative approach is using a vehicle model together with a state estimator such as a Kalman filter (KF) to aid the INS localization solution. Such mathematical models represent the hydrodynamic, hydrostatic and mass properties of the vehicle and they predict the linear and angular velocity components of the vehicle [Anderson, 1999]. However, a majority of these models are unable to predict the environmental forces due to currents; i.e., parameters within the model represent the characteristics of the AUV in a calm operational environment. Therefore, model-aided INS (MA-INS) is still prone to position drifts, especially for long range operations conducted in highly variable environments [Hegrenæs and Hallingstad, 2011].

This study investigates the possibility of having a hybrid solution MA-INS with the intermittent DVL aiding to achieve a high-quality localization solution while maintaining a lower acoustic signature. This evaluation was conducted using the field data from a *Gavia* class AUV. The developed localization algorithm that utilizes MA-INS with

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intermittent DVL bottom-track reduces the localization percent difference from 40% of the distance travelled to 0.36% with the experimental data. The designed schemes with the algorithm could manipulate DVL operational time depending on environmental conditions of the field site. The manipulated DVL operational time with the conducted field trial using the schemes showed 0.53% of locational differences.

METHODOLOGY

MA-INS, which is a combination of model and INS measurements, is the key component of this work. A DVL aided INS (DVL-INS) solution is also developed to support the pure MA-INS solution at selected time periods, in order to reduce the localization uncertainty from the pure MA-INS. The KF contributes to the data fusion and uncertainty minimization of the algorithm. MA-INS is only model, and INS and DVL-INS are 100% DVL and INS only.

Inertial Navigation System

The inertial measurement unit (IMU) sensors within the INS consist of gyroscopes and accelerometers that measure the linear and angular accelerations of the AUV in six-degrees-of-freedom (6-DOF). The recorded measurements are converted into velocity, attitude, horizontal position, and depth using navigation equations [Hegrenæs and Hallingstad, 2011].

Mathematical Model

The mathematical model presented in Randeni et al. [2017] was utilized for this study. The model provides the linear vehicle velocities of the *Gavia* AUV in response to the time series of the propeller revolutions per minute commands, and pitch angle (θ), pitch rate (q), pitch acceleration ($\dot{q}$), yaw rate (r) and yaw acceleration ($\dot{r}$) values recorded during the physical runs, assuming that the vehicle is operating in a calm water environment.

The mathematical model was programmed with MATLAB Simulink software. The notation of the Society of Naval Architects and Marine Engineers (SNAME) was used for the mathematical model. 6-DOF motions of the AUV in the vector form are presented in Equation 1.

$$M\vec{v}+C(\vec{v})\vec{v}+D(\vec{v})\vec{v}+g(\vec{\eta})=\tau_{control} \quad (1)$$

where, M is the system internal matrix, $C(\vec{v})$ is the Coriolis-centripetal matrix, $D(\vec{v})$ is the damping matrix, $C(\vec{v})$ is the vector of the gravitational/buoyancy force and moments, $\tau_{control}$ is the vector of propulsion, control surface forces, and moment, $\vec{v}$ is the velocity vector (i.e., [u, v, w, p, q, r] where $p, q,$ and r are the angular velocities around the $x, y,$ and z axes) and $\vec{\eta}$ is the vector of position/Euler angles (i.e., [x, y, z, Φ, θ, Ψ] where Φ, θ and Ψ are the roll, pitch and yaw angles, respectively). M and $C(\vec{v})$ are further expanded in Equations 2 and 3, where M_{RB} and $C_{RB}(\vec{v})$ are their added mass components [Randeni et al., 2017].

$$M = M_{RB} + M_A \quad (2)$$

$$C(\vec{v}) = C_{RB}C(\vec{v}) + \tau_A(\vec{v}) \quad (3)$$

The velocities of AUV predicted by the mathematical model are relative to the water column, not relative to the ground. Hence, if

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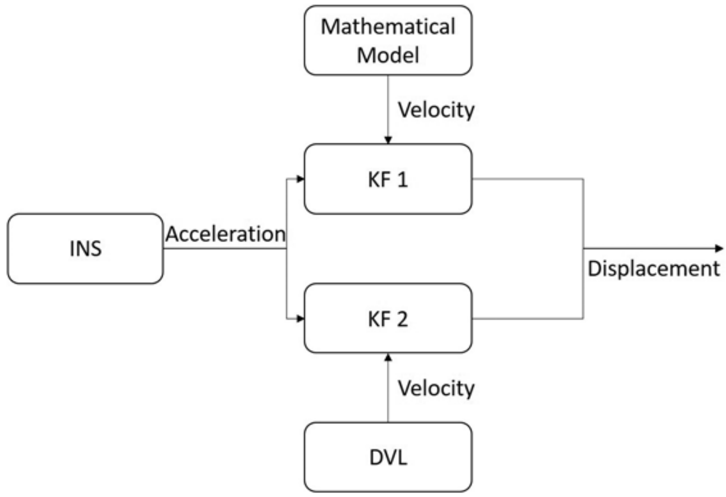

Figure 1: The block diagram of an overall process for model-aided INS localization. Once INS measures acceleration data from AUVs' trials, the data are combined and amended with a mathematical model using KF (MA-INS). INS data are also combined with DVL result by another KF, and the data are applied to MA-INS intermittently.

there is a movement of water column due to the currents, the accuracy of velocity estimation decreases.

Kalman Filter

Figure 1 shows the process block diagram of the proposed localization system. Vehicle velocities from the mathematical model and INS measurements are combined using a KF data fusion algorithm; i.e., referred to as KF 1 in Figure 1. DVL-INS was obtained by fusing the bottom-tracking vehicle velocities from the DVL with INS measurements using a second KF algorithm (i.e., KF 2).

As the KF is a recursive data processing algorithm, it can be used for stochastic estimation from noisy sensor measurements. KF conducts the error estimation using a form of feedback control; the filter estimates the process state at some time and then contains feedback in the form of noise measurement [Welch and Bishop, 2006]. Generally, KF is divided into two stages: the time update and measurement update equations. The time update equation predicts the next time step based on the current state while the measurement update equation corrects the predicted next time step by incorporating the actual field measurement at that particular time step.

DVL Application Schemes

DVL-INS generally provides an accurate localization solution with an uncertainty of around 0.1% of the distance travelled [Kearfott Corporation, 2017]. However, the activation of DVL should be restricted as frequent use of the acoustic sensors significantly increases the possibility of compromising the vehicle location to the enemy. Three schemes (a primary scheme and two secondary schemes) are utilized to minimize the DVL usage while maintaining the accuracy of the localization solution to the algorithm. Basically, the primary scheme manipulates the use of DVL-INS with overall operation of the field trial, while secondary schemes control it with beginning and final stage of the trial.

Primary Scheme – Scheme 1

During the field trials, the DVL is activated for N seconds in regular time intervals and the DVL-INS solution is generated for that N seconds, then the DVL-INS solution is

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compared with the MA-INS, which combines DVL and mathematical model solution. The DVL operational time is defined by user with the environmental consideration. For instance, if DVL operational time is defined for 2 s in regular 20 s intervals, DVL will be activated between, 0 s to 2 s, 20 s to 22 s, 40 s to 42 s, etc. Whenever the DVL-INS solution is compared with the MA-INS solution, the velocity difference between two solutions are recognized as the percent difference due to unaccounted environmental forces; hence, the percentage difference of the velocity between MA-INS and DVL-INS is calculated and applied to the rest of the MA-INS localization solution. For example, when DVL is activated by user defined time from 0 to 1 second in total 10 seconds, the velocity difference is applied to 2 to 10 seconds. If DVL is activated again by user from 5 to 6 seconds, the difference is calculated and applied to 6 to 10 seconds.

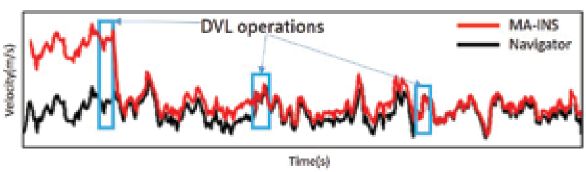

Figure 2: An expected MA-INS result with the application of Scheme 1. The considerable percent difference is expected at the initial stage and reduced with initial DVL-INS data application. Then, DVL is regularly activated to maintain the reduced percent difference.

DVL should be operated in regular intervals according to this process, in order to maintain a minimum percent difference. Figure 2 shows the example of expected plot result of percent difference reduction from Scheme 1. A high level of percent difference is expected before combining the DVL-INS data with pure MA-INS solution. Application of DVL-INS solution in regular intervals helps maintain an optimized percent difference in the MA-INS solution, since it observes and updates the MA-INS solution against the INS drift caused from unexpected variables such as underwater currents.

Secondary Schemes

Two secondary schemes (i.e., Schemes 2 and 3) are presented to combine DVL-INS solutions with MA-INS to contribute to the minimization of the AUV's localization percent difference. Scheme 2 obtains DVL measurements at the initial and last periods of the AUV's field trial, as a large amount of percent difference occurs during these stages due to the rapid vertical horizontal movements. Figure 3 describes application of Schemes 2 and 3.

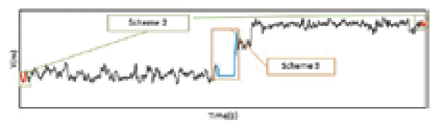

Figure 3: The applications of Schemes 1 and 2 for the localization data defined usages period by a user. Scheme 2 adjusts the initial and last stage for a certain time. When there are considerable changes in heading values, Scheme 3 is operated.

In addition, a considerable amount of INS drifting occurs when the heading angle of the AUV changes significantly. Hence, a user defined number of previous heading values are averaged and compared to the current heading value and DVL aiding would be applied if the averaged heading change values are large which is defined by a user. Table 1 summarizes the three different schemes.

EXPERIMENTAL SETUP

Validation of the localization algorithm was conducted using the field data from a *Gavia* modular AUV. Figure 4 shows the configuration and Table 2 illustrates the physical

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Scheme	Description	Used values	Period
1	Find the difference of the values between DVL and INS. Apply the differences to rest of MA-INS result.	Velocity	N seconds in each interval
2	Find the differences of the values between DVL and INS. Apply the differences to rest of MA-INS result.	Distance and velocity	Initial N seconds and Last N second
3	Find the rapid heading changes and compare to the average of previous headings.	Velocity	When heading change is larger than xx

Table 1: Three different schemes for minimizing DVL activation.

Parameter	Value
Dry Weight	About 70 kg
Length	2.7 m
Diameter	0.2 m

Table 2: The geometric parameters of *Gavia* AUV in the experiment.

Parameter	Accuracy
Position	0.1% DT, Circular Error Probability
Heading	1.0 mils RMS
Roll/Pitch	mills RMS

Table 3: Accuracy of SeaNav-24 INS [Kearfott Corporation, 2017].

Parameter	Values
Bottom tracking AUV velocity	±0.001 ms^{-1} (RMS) or 0.2% of the velocity
Maximum bottom tracking range	30 m
Ping rate	2 Hz (Typical)

Table 4: Accuracy of 1200 kHz Teledyne RDI DVL.

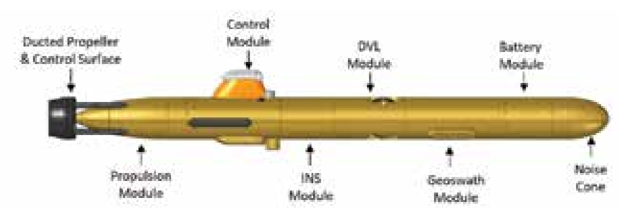

Figure 4: The configuration of the utilized *Gavia* class AUV consisted of a nose cone, battery module, Geoswath module, DVL module, INS module, Control module, Propulsion module, and ducted propeller and control surfaces.

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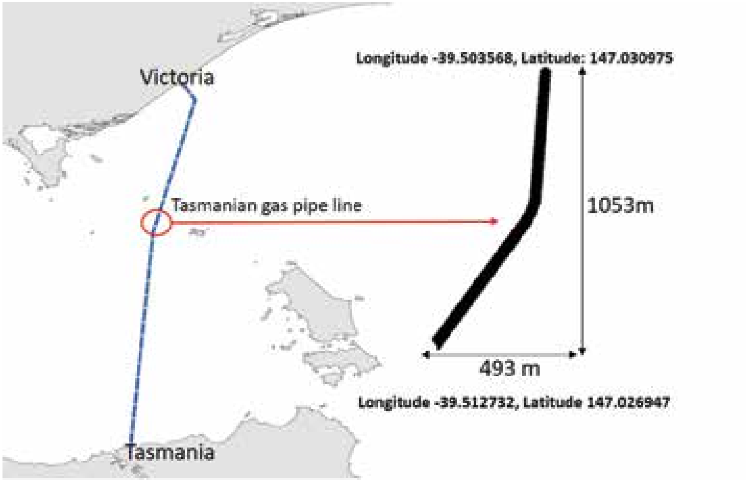

Figure 5: Offshore pipeline map and location of AUV's trial. The trial was conducted near Deal Island for 733 seconds.

parameters of the AUV utilized for this study.

The vehicle was equipped with a SeaNav 24 INS, which was manufactured by Kearfott Corporation [2017]. Table 3 shows the accuracy of INS.

A 1200 kHz Teledyne RDI DVL was equipped in the *Gavia* AUV. The accuracy of 1200 kHz Teledyne RDI is illustrated in Table 4.

Site description – Deal Island

The AUV field deployment was conducted near Deal Island, which is located between Victoria and Tasmania. The field study was conducted to observe the spanning of the Tasmanian gas pipeline. The total distance of the field trial of the AUV was 1,163 m for 733 seconds. Figure 5 shows offshore pipeline map and location of AUV's trial.

RESULTS AND DISCUSSION

The localization solutions from DVL-INS and pure MA-INS were compared to investigate the localization percent difference of the latter. The percent difference of the proposed schemes was then evaluated for different DVL operational times and DVL activation intervals, and the optimum values were obtained.

Theoretical Prediction

Initially, theoretical result has been predicted. When DVL was fully activated, an average 0.16% of localization differences was calculated. The main reasons of the errors that make the localization difference of DVL-INS are determined by the estimated Earth-fixed velocity and heading [Jalving et al., 2004]. Therefore, the predicted result was between 0.16% and 40% (pure MA-INS) of the localization difference.

Pure MA-INS Results

Figure 6 compares the DVL-INS localization data against the pure MA-INS solution. It could be seen that there is a significant positioning difference between the two results. The location difference of pure MA-INS at the end of the field trial is around 40% of the distance travelled compared to DVL-INS. This is most likely due to unaccounted environmental forces such as underwater currents. The overall performance of DVL-INS in the field trial shows that the AUV had a diagonal movement from the origin. Then, the heading of the AUV was changed to north slightly and had another diagonal travel while the result of MA-INS shows the expanded resulted of DVL-INS.

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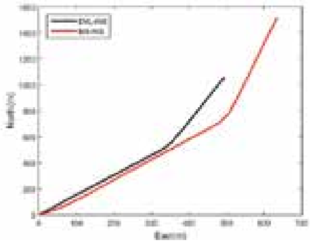

Figure 6: MA-INS in comparison to DVL-INS. 40% of distance differences are shown. MA-INS localization solution shows expanded localization data of DVL-INS.

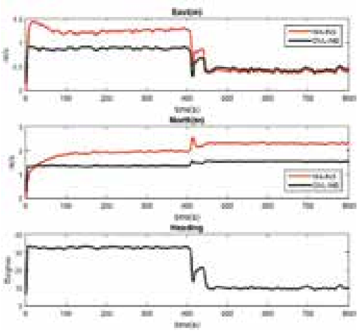

Figure 7: Velocities and headings from MA-INS and DVL-INS. (A) and (B) show the velocity differences in x-axis and y-axis, respectively, while the third plot shows the heading changes.

The differences between DVL-INS and MA-INS vehicle velocities with heading changes are shown in Figure 7. The major percent difference was at the beginning and when the heading was rapidly changed (i.e., when the AUV turned). Normally, MA-INS and DVL-INS maintained a fixed steady-state difference, but it changes when there is a sudden variation in heading angle. Moreover, based on Figure 7, it could be clearly seen that the velocities in x and y directions experienced sudden speed changes at the same time.

Based on the root mean square (RMS) velocities, the differences between MA-INS and DVL-INS data are above 20%, and these are presented in Table 5.

Direction	Data	RMS velocity	Differences
X	MA-INS	0.96 m/s	26.04 %
	DVL-INS	0.71 m/s	
Y	MA-INS	2.07 m/s	30.08 %
	DVI-INS	1.44 m/s	

Table 5: The differences between MA-INS and DVL-INS with root mean square velocities.

Percent Difference Analysis of the Proposed Scheme

As the MA-INS alone has a significant localization difference as shown in Table 5, the application of the proposed scheme was necessary. Initially, the operational time of the DVL and the regular time interval were analyzed and optimized using application of different time values for Scheme 1. For Scheme 2, ten seconds of DVL-INS data were applied to MA-INS solution at the beginning and the end of the AUV trials, while 10 degrees were defined as considerable heading change for Scheme 3. The proposed schemes are meant to be applied to the same time.

The localization percent difference of Scheme 1 for several DVL operating time periods (i.e., N) in 20 second intervals was analyzed as shown in Figure 8. It can be seen that the localization percent difference rapidly reduced the application of Scheme 1. With the proposed scheme, the localization percent difference could be decreased by having a DVL usage of only 5% (37 seconds of DVL activation time in 733 seconds of travelling time). However, the percent difference reduction rate is not significant between 5% and 40% of DVL usages. The 40% of DVL-INS usage shows only 0.17 more accuracy compared to 5% usage of DVL operation.

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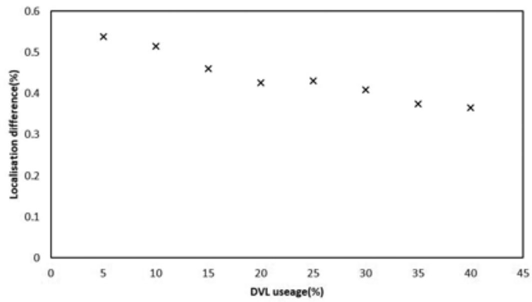

Figure 8: The localization percent difference comparison of MA-INS localization solution with various DVL uses in 20 second regular intervals. The percent difference is decreased when DVL usages is longer, but only 0.37% of percent difference was decreased between 1 second and 8 seconds.

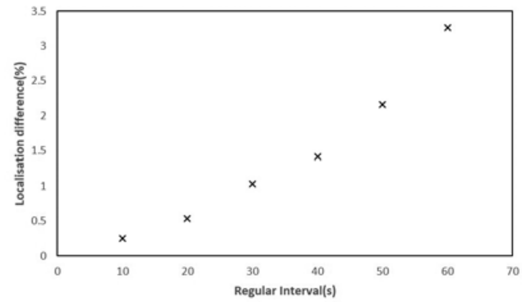

Figure 9: The localization percent differences of MA-INS localization solution with various DVL uses in a 20 seconds regular interval. As the interval of DVL operation is increased to 60 seconds, the percent difference increases to 3.5%.

Teledyne RDI 1200KHz DVL typically provides 2 Hz of ping rate. That is, the number of pings was 2 when the DVL operating time was 1 second per regular interval, while the ping number was 16 when DVL operating time was 8 seconds per interval. The averaged altitude of the travel was 15.03 m.

Subsequently, the regular time interval was varied. When the regular time interval is longer, the number of DVL operations in the trial could be reduced. Figure 9 illustrates the localization percent differences of MA-INS localization solution with various DVL uses in a 20 second regular interval. It could be seen that the percent difference has experienced an exponential increase with DVL operation interval. When the regular time interval of DVL operation is extended, it affects the percent difference changes significantly when compared to the change in DVL operating time. However, the increase in localization percent difference is still not significant.

When DVL-INS data are used 20% in a regular interval (2 seconds of DVL operation in the 10 seconds interval), the expected percent difference of localization solution was 0.37%, while 3.33% of DVL usage (2 seconds of DVL operation in the 60 seconds interval) in the regular interval shows a 3.26% localization percent difference. Although 3.26% of percent difference could be considered insignificant compared to pure MA-INS, if the AUV involves long distance travelling, the localization solution could be highly inaccurate due to the accumulation of percent difference over time.

Localization Result after Application of the Schemes

With the obtained result, the optimized operation time of DVL-INS solution with the schemes was defined as shown in Table 6. Application of 10% DVL-INS data (2 seconds in 20-second regular interval) with additional 2.5 % (10 seconds at first and last stages in duration) to pure MA-INS result was considered as a reliable time setting for the localization solution. Teledyne Marine [2017] states that typical endurance of the *Gavia* AUV is around 5-6 hours at 3 knots with a single battery module. Therefore, a maximum error of 140 metres is expected between the actual location and the MA-INS solution for an AUV mission of 6 hours in duration (or approximately 33.3 km of travelled distance). Although it is possible to

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Scheme	Description	Time(s)
Scheme 1	Interval	20
	DVL activation	2
Scheme 2	Initial	10
	Final	10
Scheme 3	5 averaged previous heading + 10 degrees	5

Table 6: Optimized values for the proposed schemes.

Localization solutions	Uncertainties from DVL-INS solution
Pure MA-INS	39.97%
MA-INS with DVL (proposed scheme)	0.54%
Total reduce rate	39.43%

Table 7: Localization solution percent difference comparison between pure MA-INS and MA-INS with DVL operation schemes.

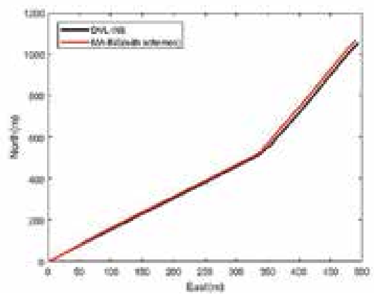

Figure 10: MA-INS localization outcome with the application of the proposed schemes. The navigation and experiment data are nearly identical, and the percent difference is only 0.54%.

reduce the operation time of DVL or increase the regular time intervals, the location algorithm should be able to handle unexpected variables such as water flow. Scheme 2 was implemented with 10 seconds on the initial and final time because it was assumed that the deployment and collection of the AUV could not be in the enemy's territory. Finally, if the current heading is more than 10 degrees with five averaged previous heading, DVL would be used.

Figure 10 illustrates the localization solution from the optimized values given in Table 6. It could be seen that the proposed MA-INS solution with the proposed DVL operation schemes closely replicates the pure DVL-INS solution and has almost the same trend.

Based on the localization method, the percent difference reduction of 39.43% was achieved as shown in Table 7.

DISCUSSION

There are several issues which should be pointed out to improve the localization solution. The localization percent difference with the optimized scheme was 0.54% and it is within an acceptable error range in the offshore industry. However, when the AUV has to operate for a longer duration, the small percent difference would accumulate over time to become significant. Kongsberg [2014] mentioned HUGINS 4500 could travel 60 hours at 4 knots. Then, 2 km of localization difference would occur at the end of the AUV's duration with a defined MA-INS algorithm with the DVL application schemes. As one solution for that problem, the operation of DVL could be extended with the schemes. It was revealed longer uses of DVL with Scheme 1 could minimize the localization percent difference.

Scheme 1 manipulates DVL operating time of the AUV in specified seconds with the regular

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interval. However, there is a possibility that obtained sample DVL measurement contains high percent difference and it affects the entire MA-INS solution. For instance, if there is a sudden rapid flow change in a short period of time while DVL is operated, the collected data would be reflected in the future result. Therefore, a scheme should be developed to detect sudden changes in velocity of the AUV and account for its effect during that particular time step.

The application of passive sonar into the surveillance AUVs could improve the surveillance and localization scheme, as passive sonar of the AUV detects the sonar signals from enemies' vessels. As such, when the AUV is conducting a mission, the operating time of DVL on the AUV could be rapidly reduced to avoid detection by the enemies' sensors. For example, if the AUV detects sonar signal from the other vessels such as submarines, the AUV increases the time of interval or reduces DVL usage of Scheme 1.

Although this study was verified with experimental data, the purpose of the experiment was different, and it could be simple to verify the proposed algorithm as the purpose of the study is focused on the surveillance AUVs. Moreover, the travelling of the AUV may be not enough for surveillance AUVs. Therefore, additional experimental data will be required with future study. The effects of the altitude of the AUV and ping rate during operating time should be also researched.

CONCLUSIONS

This study investigates the possibility to develop a localization and navigation system with a reduced acoustic signature for AUVs carrying out surveillance operations. As there are significant limitations in sensor selection for AUVs, MA-INS was considered as a key component with minimized activation of DVL bottom-track sonar. MA-INS is developed by combining the data from the mathematical model and INS measurement using a KF. Subsequently, the DVL-INS, which is a combination of DVL and INS, was intermittently applied to the pure MA-INS solution with three schemes. The main schemes compare the velocity differences between DVL and MA-INS in a certain period with regular intervals, then the differences are applied to the MA-INS localization solution.

The novel schemes proved that the localization percent difference could be decreased by having a DVL usage of only 5% (i.e., 1 second of DVL operation in the 20-second regular interval). However, the percent difference reduction rate is not significant between 5% and 50% (i.e., 2 seconds in the 10-second regular intervals) of DVL usage. The 40% of DVL-INS usage showed only 0.17 more accuracy compared to 5% usage of DVL.

The optimized solution was defined as 10% of DVL activation (i.e., 2 seconds of DVL activation in 20-second regular time intervals) with additional 2.5%; i.e., 10 seconds at the beginning and the end of the field trials. As the DVL operating time could be controlled by the DVL application schemes, the algorithm could be optimized depending on the environmental condition of the field trial.

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