PAPER

Autonomous Underwater Vehicle Motion Response: A Nonacoustic Tool for Blue Water Navigation

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ABSTRACT

Autonomous underwater vehicles (AUVs) use secondary velocity over ground measurements to aid the Inertial Navigation System (INS) to avoid unbounded drift in the point-to-point navigation solution. When operating in deep open ocean (i.e., in blue water—beyond the frequency-specific instrument range), the velocity measurements are either based on water column velocities or completely unavailable. In such scenarios, the velocity-relative-to-water measurements from an acoustic Doppler current profiler (ADCP) are often used for INS aiding. ADCPs have a blanking distance (typically ranging between 0.5 and 5 m) in proximity to the device in which the flow velocity data are undetectable. Hence, water velocities used to aid the INS solution can be significantly different to that near the vehicle and are subjected to significant noise. Previously, the authors introduced a nonacoustic method to calculate the water velocity components of a turbulent water column within the ADCP dead zone using the AUV motion response (referred to as the WVAM method). The current study analyzes the feasibility of incorporating the WVAM method within the INS by investigating the accuracy of it at different turbulence levels of the water column. Findings of this work demonstrate that the threshold limits of the method can be improved in the nonlinear ranges (i.e., at low and high levels of energy); however, by estimating a more accurate representation of vehicle hydrodynamic coefficients, this method has proven robust in a range of tidally induced flow conditions. The WVAM method, in its current state, offers significant potential to make a key contribution to blue water navigation when integrated within the vehicle's INS.

Keywords: water column velocity, INS, autonomous underwater vehicles (AUVs), acoustic Doppler current profilers (ADCPs), WVAM

Introduction

Autonomous underwater vehicles (AUVs) are submarine robots that are able to carry out ocean sampling campaigns (Curtin et al., 1993), bathymetric data collections (Grasmueck et al., 2006), and military and security exercises in unstructured environments (Paull et al., 2014). Accurate point-to-point guidance of an AUV (i.e., navigation) as well as precise knowledge of its position within a 3-D domain (i.e., localization) are mandatory (Paull et al., 2014). Despite the AUVs are being developed since the 1970s, the current navigation and localization techniques need improvement, particularly for blue water operations (Hegrenæs & Berglund, 2009).

Inertial navigation is one of the key navigation techniques used by AUVs where the rotational and translation accelerations of the AUV are determined using the Inertial Navigation System (INS) sensors. Inertial navigation is most effective when the acceleration solution from the INS is aided with the velocity over ground measurements from a bottom-tracking Doppler Velocity Logger (DVL) or a GPS. An INS determines the position, velocity, and orientation of the vehicle using the data from inertial measurement units (IMUs) relative to inertial space. Due to inherent errors, the INS navigation solution will have an unbounded drift unless counteracted with the speed over ground velocity estimates (Hegrenæs & Hallingstad, 2011). The DVL bottom track, where the velocity relative to the ground is determined from the Doppler frequency shift of soundwaves reflected off the seabed, is commonly used for this purpose. This technology is limited by frequency-specific penetration of tens to hundreds of meters through the water column (Hegrenaes et al., 2008).

In blue water, specifically during deep descents/ascents, operating in the mid-water zone and over rough bathymetry, DVL bottom track data may be intermittently or completely unavailable (Hegrenaes et al., 2008). In such cases, as illustrated in Figures 1a and 1b, an alternative approach is to use the DVL water-tracking mode, that is, acoustic Doppler current profiler (ADCP) mode, in conjunction with a real-time current estimation methods to aid the INS navigation solution (Hegrenæs & Berglund, 2009). This method has proven to produce better navigation solutions and less free inertial drift compared to systems utilizing INS alone; however, they are inherently susceptible to instrument noise (Hegrenæs & Berglund, 2009).

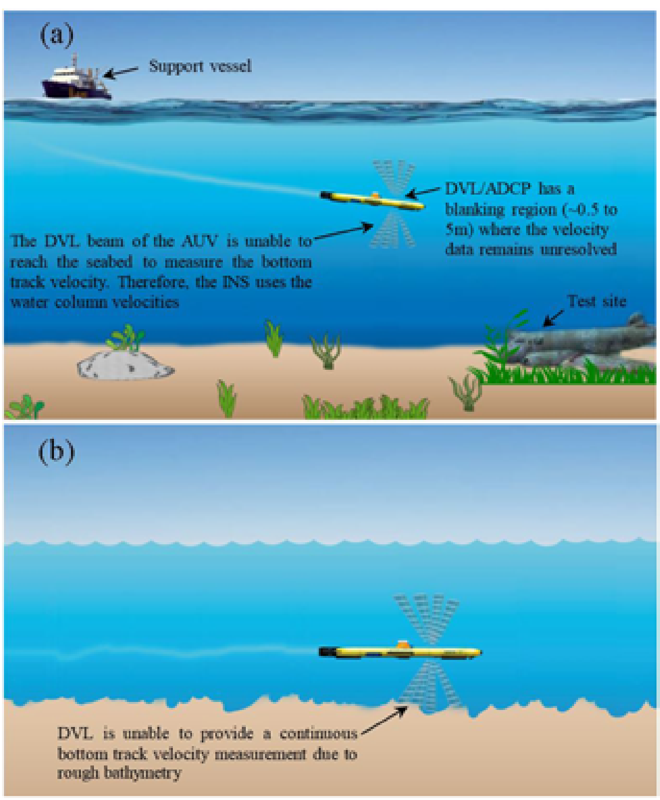
In addition to instrument noise, ADCPs or water-tracking DVLs have a blanking distance (i.e., a dead zone) in proximity to the device in which the flow velocity data remain unresolved (Simpson, 2001). The blanking distance can typically span from 0.5 to 5 m from the vehicle depending on the sampling frequency and selected bin size of the instrument (see Figure 1a). Therefore, the water velocity used to aid the INS navigation is at least 0.5 m and sometimes even up to 5 m from the vehicle resulting in an uncertainty of the water velocity near the vehicle. This can induce error and cause adverse effects on the navigation and localization solutions.

The authors previously introduced a nonacoustic method to calculate the water velocity components of a turbulent water column using the AUV motion response without the aid of an ADCP referred to as the WVAM method (Randeni et al., 2015b). In this method, the water velocities are determined by comparing the motion response of the vehicle when operating within turbulent and calm water environments. A key advantage of the WVAM method is that it is able to estimate the flow velocities at the vehicle's center of buoyancy; however, the authors indicated that the accuracy of the WVAM method might vary with the intensity of the measuring velocity components (Randeni et al., 2015b). That is, the precision of the water velocity measurements from a highly turbulent environment with relatively large velocities may be different than those of low turbulence conditions with lower velocities. The remaining unanswered question was whether the WVAM method is able to measure low and high flow velocities that are likely to be encountered in blue water conditions.

In this context, the current work was conducted as a feasibility study to find the threshold limits by investigating the variation of the WVAM method's accuracy in varying turbulence levels in the water column through field deployments in a river estuary that exhibits strong tidal currents up to 2 m s^{-1}. The uncertainty of the method was calculated based on a direct comparison with velocity measurements obtained from the AUV's ADCP at different

FIGURE 1

(a) An AUV descending to a test site in blue water where the bottom track velocities of the vehicle are unavailable to the INS since the DVL beam span is unable to reach the seabed. (b) DVL is incapable of providing continuous bottom-track velocity measurements when traveling over rough bathymetry.



stages within the tidal cycle. Additional steps to improve the applicability of the WVAM method for blue water navigation are also discussed.

Methodology

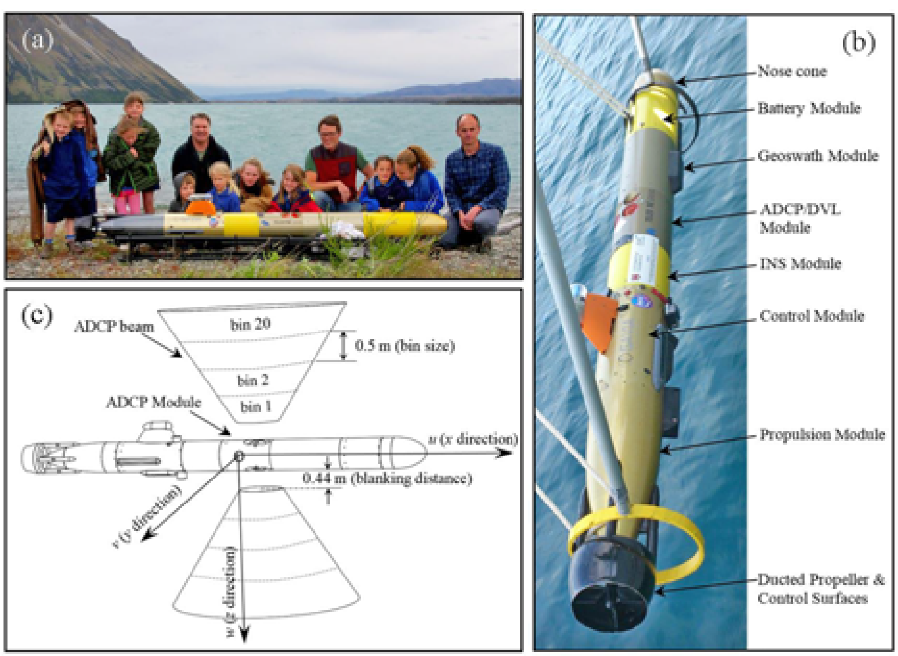
Instruments

A *Gavia*-class modular AUV was used to test the WVAM method (Randeni et al., 2015a), with the vehicle configured to an overall length of 2.7 m, diameter of 0.2 m, and a dry weight in air of approximately 70 kg (see Figure 2a). The modularized vehicle in the tested configuration consisted of a nose cone, battery, GeoSwath interferometric sonar, 1,200-kHz Teledyne RDI ADCP/DVL, Kearfott T24 INS, and control and propulsion modules, as shown in Figure 2b. The ADCP module of the AUV included two 4-beam ADCPs arranged in a vertical plane to make both upward- and downward-oriented velocity measurements (see Figure 2c). The ADCPs were set to profile the 9.94 m of water column in 0.5-m range bins so that the three directional water velocity components in the vehicle's body-fixed coordinate system are measured in each bin. Adjacent to the transducers (both above and below), there was a blanking distance of 0.44 m, as shown in Figure 2c. The maximum uncertainty margin of the DVL in measuring the speeds over ground is ±0.03 m s^{-1} (Hildebrandt & Hilljegerdes, 2010).

The Kearfott T24 INS together with the ADCP/DVL module measured the orientation, velocities in 6 degrees of freedom (6 DOFs), and the position of the AUV. The depth of the vehicle was obtained from the pressure sensor on-board the AUV. These sensor measurements were recorded in the vehicle log at a frequency of 0.87 Hz. The percentage uncertainty of the pressure sensor is 0.1% giving a depth rate uncertainty margin of $\pm 1.0 \times 10^{-4}$ m s^{-1} (Hildebrandt & Hilljegerdes, 2010). The respective uncertainties of the INS in providing the pitch and yaw rates of the AUV are $\pm 7.96 \times 10^{-5}$ rad s^{-1} and $\pm 1.60 \times 10^{-4}$ rad s^{-1}.

FIGURE 2

(a) Omarama Primary School (Lake Ohau, New Zealand) students inspecting the *Gavia*, the modular AUV that was utilized to test the WVAM method; (b) the tested configuration of the vehicle; and (c) the body-fixed coordinate system (origin at the center of buoyancy—marked by the circle) showing the ADCP beam geometry.



Site Description

The objective of this study was to determine the accuracy of the WVAM method in different flow conditions in order to assess the feasibility of using the method for blue water AUV navigation. To achieve this, the WVAM method was tested in the Tamar estuary near the Batman Bridge (see Figures 3a and 3b), located in Tasmania, Australia. Due to the proximity to the open sea and the flow constriction of the river bed, the Tamar estuary exhibits strong tidal currents with maximum flow velocities of up to 2.5 m s^{-1} (see Figure 3c).

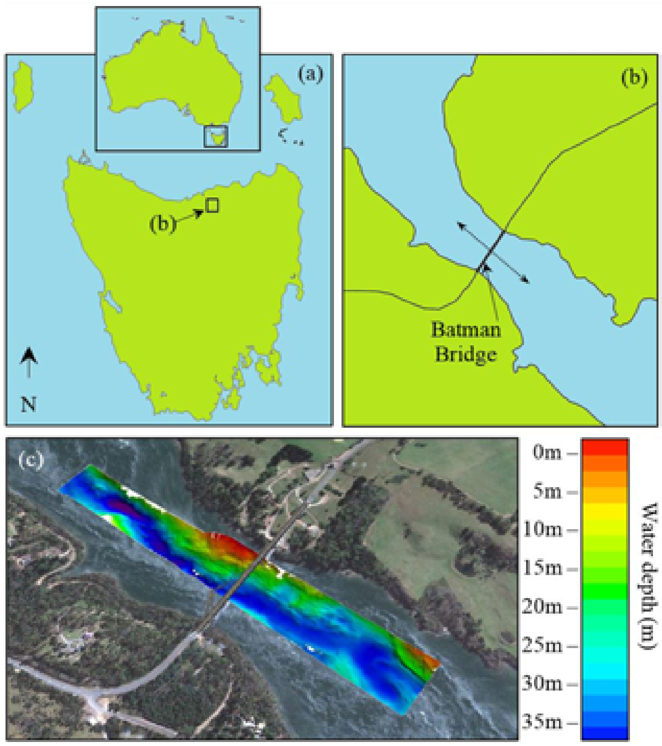
Nine AUV runs were conducted along the track line shown in Figure 3b. The first five were conducted on April 14, 2015, and the last four were conducted on April 15, 2015. Runs 1–3 and 6–9 were conducted during slack water as shown in the tidal curve given in Figure 4. The velocity of the tidal currents during the first runs on each day (i.e., Runs 1 and 6) was approximately 0.25 m s^{-1}. Due to the development of the strong flood tide, the flow speeds increased rapidly during the subsequent runs on each day. Runs 4 and 5 were carried out at partially and fully developed flood tide conditions with strong tidal currents (around 2 m s^{-1}).

WVAM Method

For the WVAM method (Randeni et al., 2015a, 2015b), the AUV needs to undergo a straight line, constant

FIGURE 3

(a) The experimental field site in Tasmania, Australia (inset). (b) The Tamar estuary with a bidirectional arrow representing the AUV track. (c) Due to the proximity to the open sea and the flow constriction of the river bed, the site exhibited strong tidal currents.



depth trajectory through the region where the water column velocities are to be measured. Typically, when an AUV is operating in an environment with fluctuating water velocities, the forces and moments induced by these velocities can interrupt the control stability and change the vehicle speed, depth, pitch, and yaw angles from the desired values. In order to compensate for such changes in performance, the vehicle's control system adjusts the revolution speed of the propeller and the angles of the four control surfaces. In response to these adjustments, the motion of the AUV will change in order to return the AUV to the prescribed mission track unless the propeller and the control surfaces are unable to compensate for the external forces (Kim & Ura, 2003).

The WVAM method uses the compensation commands given by the vehicle's control system to the propulsion motor and control surfaces as recorded in the vehicle log and executes these commands within a simulation model representing a calm water environment. Since there are no disturbing forces due to flow variations in calm water conditions, the simulated vehicle motion will be different than the actual motion. The difference between the two motion responses provides an estimation of the absolute water column velocities in the body-fixed coordinate system.

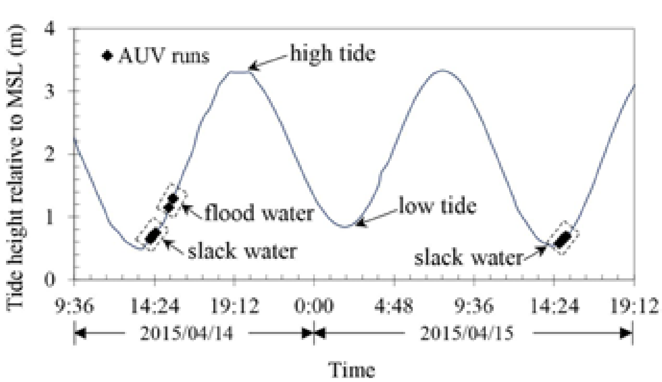
Equation 1 gives a generalized form of the water velocity calculation used within the WVAM method:

$$\vec{v}_{\mathrm{water}(t)} = \vec{v}_{\mathrm{AUV(turbulent)}(t)} - \vec{v}_{\mathrm{AUV(calm)}(t)} \qquad (1)$$

where $\vec{v}_{\mathrm{water}}$ is the velocity component of the surrounding water column relative to the earth in the body-fixed coordinate system (see Figure 2c), $\vec{v}_{\mathrm{AUV(turbulent)}}$ is the velocity component of the AUV observed in the turbulent environment, and $\vec{v}_{\mathrm{AUV(calm)}}$ is the velocity component obtained from the calm water simulation when the control commands recorded during the field tests were simulated. Subscript t indicates the time step. To estimate the water velocity component along the x, y, and z axes, $\vec{v}$ is replaced with the surge, sway, and heave velocity components (i.e., u, v, and w) of the vehicle in the body-fixed frame of reference, respectively.

FIGURE 4

The water level relative to the mean sea level (MSL) observed on April 14 and 15, 2015, with the periods that the AUV runs were conducted indicated by filled diamond markers.



Simulation Model and Hydrodynamic Coefficients

The simulation model of the *Gavia* AUV was developed to reproduce the vehicle's trajectory within a calm water environment in response to the time series of the control commands. It requires an accurate approximation of the associated hydrodynamic coefficients (i.e., a representation of the forces and moments acting on the vehicle at different orientations, velocities) to adequately predict the motion of the AUV. Generally, the forces and moments acting on submerged bodies in 6 DOFs are highly nonlinear (Lewis, 1988). For example, the vertical hydrodynamic force acting on an AUV varies linearly with its pitch angle up to a value of around ±8°, beyond which it becomes nonlinear (Randeni et al., 2015a). Similar threshold values exist for other hydrodynamic forces and moments transiting between their respective linear and nonlinear rangers. Therefore, the hydrodynamic coefficients estimated for the linear ranges are only valid up to a certain threshold value (Lewis, 1988).

During the initial development of the WVAM method, a basic curve fitting method was utilized to determine the hydrodynamic coefficients due to its relative simplicity (Randeni et al., 2015a). The coefficients obtained from this method were limited to small angles of incidence (i.e., generally below 8°) restricting them to the linear range. When an AUV operates in turbulent environments, its pitch and yaw angles typically fluctuate around the baseline values. The magnitude of these fluctuations increases with increasing levels of turbulence due to the inability of the AUV's control system to compensate for the severe disturbance forces (Kim & Ura, 2003). Therefore, in extremely turbulent water columns, these fluctuation angles will be greater than ±8°. Thus, a simulation model that is limited to linear hydrodynamics data is unable to adequately replicate the motion of the vehicle in extreme environments.

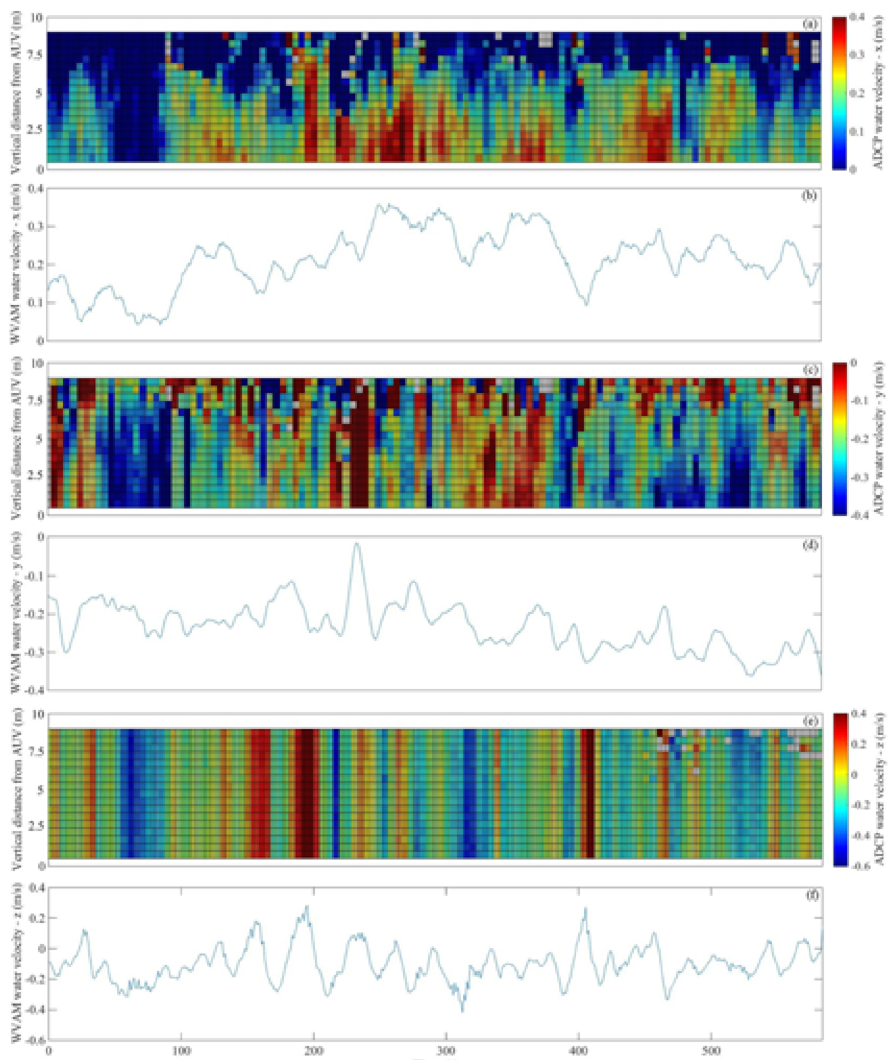
Results and Discussion

Validation of the WVAM Method

Figures 5a, 5c, and 5e illustrate the variations of the ADCP-measured water velocity components (i.e., velocities in x, y, and z directions, respectively) with the vertical distance from the AUV. Figures 5b, 5d, and 5f present the respective flow velocity components estimated with the WVAM method. The velocity data shown in Figure 5 were recorded during Run 1 (i.e., when the AUV was moving with the predominant tidal currents). As seen, the WVAM velocity estimates

FIGURE 5

Panels a, c, and e illustrate the ADCP-measured variations of the water column velocity components in *x*, *y*, and *z* directions (respectively) with the vertical distance from the AUV. The respective flow velocity components estimated by the WVAM method are presented in Panels b, d, and f. The illustrated velocity data were obtained from Run 1 when the AUV was moving with the predominant tidal currents.



well correlate with the ADCP measurements, especially around the bins closer to the vehicle.

The uncertainty of the water velocity measurements from the WVAM method compared to the ADCP results was quantified using Equation 2 that approximates the standard error (SE) with a percentage confidence of 99.7% (Devore, 2011).

$$SE = \frac{3}{\sqrt{n}} \sqrt{\frac{\sum_{t=1}^{n} \left(\overline{v}_{\mathrm{water(ADCP)}} - \overline{v}_{\mathrm{water(WVAM)}}\right)^2}{n}} \tag{2}$$

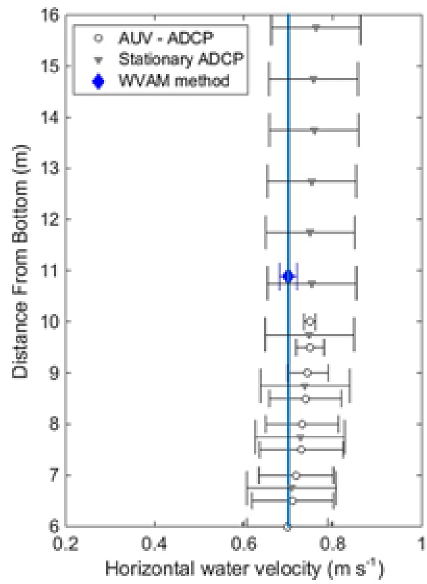
where $\overline{v}_{\mathrm{water(ADCP)}}$ is the water velocity measured using the ADCP, $\overline{v}_{\mathrm{water(WVAM)}}$ is the water velocity calculated using the WVAM method, and n is the number of time steps. The SEs for the velocity components in the x, y, and z directions for the first run were ±0.068, ±0.017, and ±0.045 m s^{-1}, respectively. These numbers represent the difference between WVAM and ADCP velocity predictions in each of the three directions, with the greatest error seen in the x direction.

It is evident from these plots that the WVAM method provides a good replication of the flow velocities measured using the onboard ADCP. Since the vehicle was moving with the predominant tidal flow direction, a positive water velocity along the x direction is seen in Figures 6a and 6b. The negative water velocity component in the y direction (Figures 6c and 6d) indicates that the transverse flow direction is from northeast side to southwest. Although the transverse water velocity does not follow the ADCP velocity trend for some periods, the averaged velocities are in favorable agreement. However, further studies will be conducted to investigate the reasons for this. The best replica between the WVAM and ADCP velocities is seen in the vertical velocity component. The largest mismatches in the vertical velocities are seen at the peaks. The hydrodynamic coefficients of the simulation model estimated using the basic system identification method were only valid for small angles of incidence of the vehicle, where the coefficients are in their linear ranges. Therefore, as the yaw and pitch angle fluctuations become larger, the accuracy of the simulation model decreases, adversely affecting the WVAM velocity prediction (Randeni et al., 2015a). The disparity at peaks of the vertical velocity component is due to the hydrodynamic coefficients exceeding their linear ranges causing a reduction in the accuracy of the simulation model.

A recent study (Green, 2015) compared the water velocity measurements obtained from the *Gavia* AUV's onboard ADCP with a stationary ADCP moored to the seabed. This investigation was carried out in the same test location (i.e., Tamar estuary) with the same *Gavia*-class AUV as used in this study. Green (2015) found very good agreements between the AUV-mounted and stationary ADCP measurements. In addition, the stationary ADCP data set was used to validate estimates with the WVAM for a period when the AUV was in close proximity to the moored ADCP. Similar to the findings from the AUV-ADCP and stationary ADCP comparison, the velocities between WVAM and stationary ADCP showed a good agreement with differences of 0.05, 0.08, and 0.01 m s^{-1} for the respective velocity components in the x, y, and z directions (see Figure 6).

FIGURE 6

Comparison of the horizontal water velocities obtained from the WVAM method, stationary ADCP, and the AUV-fixed ADCP; modified from Green (2015).



Accuracy of the WVAM Method With the Level of Turbulence

Runs 1–3 and 6–9 were conducted in lower turbulent environments, with a vertical water velocity range of around −1 to 1 m s^{-1} compared to the Runs 4 and 5, which were at vertical water velocity range of −2 to 0.5 m s^{-1}. Due to the developing flood tide, the level of turbulence increased gradually with each run. The averaged fluctuations of the vehicle's yaw angle, pitch angle, and surge speed from the target values are given in Table 1. If the AUV's control system is capable of guiding the vehicle accurately along the prescribed path in turbulent environments, these values would be close to zero. As seen from Table 1, the fluctuations have raised with the increasing level of turbulence.

The SEs of the WVAM water velocity predictions compared to the ADCP measurements for each run are presented in Table 1 and Figure 7.

TABLE 1

SEs of the water velocity components determined from the WVAM method compared to the onboard ADCP measurements and the associated averaged deviations for the prescribed parameters.

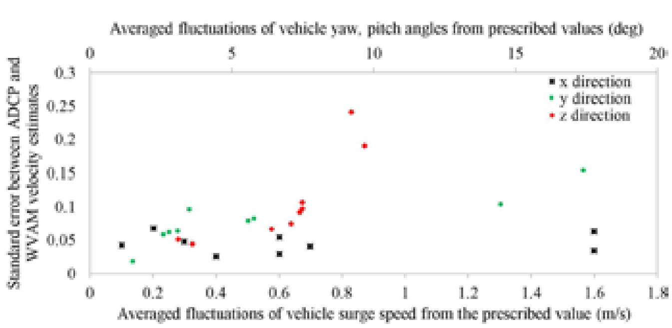
Run Number	SE			Averaged Deviation From the Prescribed Value		
	u	*v*	*w*	Yaw Angle (Degrees)	Pitch Angle (Degrees)	Surge Speed (ms^{-1})
1	0.068	0.017	0.045	±1.5	±3.6	±0.2
2	0.029	0.153	0.075	±17.4	±7.1	±0.6
3	0.041	0.095	0.108	±3.5	±7.5	±0.7
4	0.063	0.061	0.241	±2.8	±9.2	±1.6
5	0.035	0.079	0.191	±5.6	±9.7	±1.6
6	0.042	0.063	0.052	±3.1	±3.1	±0.1
7	0.048	0.058	0.067	±2.6	±6.4	±0.3
8	0.025	0.104	0.092	±14.5	±7.4	±0.4
9	0.054	0.082	0.097	±5.8	±7.5	±0.6

The uncertainties of the vertical and transverse water velocity estimates increase with the averaged fluctuations of the pitch and yaw angles, respectively. For example, in Run 2, the averaged deviation of the yaw angle is around ±17°, and the SE of the transverse velocity prediction is much larger than for Run 1 (i.e., 0.153 m s^{-1}). Run 1 has a smaller deviation of the yaw angle of around ±1.5°, which results in a much smaller uncertainty in the vicinity of 0.017 m s^{-1}. A similar outcome is seen in the vertical water velocity component. In Run 9, the averaged deviation of the pitch angle is ±7.5° giving an SE in the vertical water velocity prediction of around 0.1 m s^{-1}. However, in Run 6, the deviation of the pitch angle is comparatively lower at ±3.1° resulting in a smaller SE for the velocity of around 0.05 m s^{-1}. Although the tides were not fully developed during the Runs 2 and 8, the yaw angle deviations are relatively higher. This could be as a result of a strong crosscurrent acting on the vehicle at the particular water height.

Generally, an SE between the ADCP and WVAM that results up to 0.1 m s^{-1} is acceptable as the uncertainty of the measurements from an AUV-mounted ADCP is of similar magnitude (Fong & Jones, 2006). The threshold averaged deviation of the pitch and yaw angles that provide the water column velocities with an SE below 0.1 m s^{-1} is around 7°–8°. Above this threshold angle, the hydrodynamic coefficients usually become nonlinear. The hydrodynamic coefficients estimated for the simulation model using the curve fitting method are only valid for small angles of incidence of the vehicle, that is, when the coefficients are in the linear range (Randeni et al., 2015b). Therefore, when the pitch and yaw angles are above the linear range, the accuracy of the simulation model decreases, and the uncertainty of the vertical and transverse water velocity components obtained from the WVAM method increases. Hence, the WVAM method, in its current state, is less accurate in determining transverse and vertical water velocities in high turbulent environments.

FIGURE 7

The variations of the WVAM method's SEs with the averaged fluctuations of the vehicle surge speed and yaw and pitch angles from the prescribed values. The water velocity components in *x*, *y*, and *z* directions correspond with the surge speed, yaw angle, and pitch angle, respectively.



The accuracy of the water velocity component in the x direction remains generally the same for all the runs regardless of the averaged fluctuations of the surge speed (see Figure 7). During the development of the simulation model, the hydrodynamic coefficients dominating the motion in the x direction were estimated for a propeller speed range of 525–825 RPM (i.e., an approximate vehicle speed range of 1.43 to 2.46 m s^{-1} in a calm water environment). During this study, the AUV field runs were conducted at 700 RPM providing a mean forward speed of around 2.04 m s^{-1} in calm water conditions with a standard deviation of 0.01 m s^{-1}. The observed speed during the runs varied as much as ±1.6 m s^{-1} from the calm water speed of 2.04 m s^{-1}, especially during Runs 5 and 6 due to the strong drag on the vehicle imparted by the strong tidal currents. Although the actual vehicle speed deviated from the simulated speed, the prescribed propeller speed of 700 RPM provides a calm water simulated speed of around 2.04 m s^{-1}, which is within the identified forward speed range of 1.43–2.46 m s^{-1}. Therefore, the simulation model provided an accurate representation of the forward speed of the AUV in calm water. It can thus be concluded that the SE results between the WVAM and ADCP in the x direction generally remained unrelated to the turbulence level of the water column.

Applicability of the WVAM Method for Blue Water Navigation

The outcome of the above analysis shows that the WVAM method captures the water velocity up to around 1–1.5 m s^{-1} with an acceptable accuracy. Therefore, it can be used to aid the INS navigation solution for the situations discussed in Figure 1 without further improvements. However, the threshold of the WVAM method in measuring velocity components in the y and z directions can be improved for higher turbulent environments by a more accurate estimation of the vehicle hydrodynamic coefficients within their linear as well as nonlinear ranges. Captive model experiments and computational fluid dynamic (CFD) simulations are capable of determining the nonlinear hydrodynamic coefficients of AUVs with a greater accuracy; albeit the associated experimental costs and the computational times are higher (Randeni et al., 2015c). The coefficients obtained from such methods are only valid for the vehicle configuration that was tested during the experiments. However, the arrangements of modular AUVs change with the mission and addition/removal of payloads occurs frequently. As it is not feasible to conduct cost-intensive experiments and simulations for each alteration, estimating the nonlinear hydrodynamic coefficients using a system identification method such as least squres optimization is more suitable (Ljung, 1998).

Ascend and Descend Parallel to Sea Currents

Gavia-class AUVs are underactuated vehicles (i.e., they have a lower number of actuators than the vehicle's DOF). Its actuator control is limited to the surge speed, roll angle, pitch angle, and yaw angle of the vehicle. Depth and transverse displacement is obtained by changing the pitch and yaw angles, respectively. Generally, underactuated underwater vehicles are difficult to control when external forces such as currents are acting parallel to the underactuated directions (Aguiar & Pascoal, 2007). For example, the control system of the *Gavia* AUV struggles to maintain the trajectory when crosscurrents are acting perpendicular to the AUV's motion.

In such situations, the vehicle tends to oscillate, resulting in higher unbound drifts in the INS navigation solution compared to normal operations, unless properly counteracted with the velocity over ground measurements from the DVL bottom track. These drift fluctuations are considerably less when the vehicle is traveling in line with the currents (i.e., currents are acting along the x axis of the AUV). A positive outcome of this study is that water column velocities in x direction obtained from the WVAM method were accurate for all turbulence levels present during the field campaign in the Tamar estuary. The results suggest that deep water ascents and descents should be carried out with the vehicle in line with the currents to improve the accuracy of the WVAM-INS navigation solution (i.e., as seen in Figure 5, the accuracy is higher in the flow measurements along the x direction compared to y direction), although this may be challenging in unknown environments. Occasionally, a reconnaissance mission may be conducted over the test site prior to the deep dive to ensure the safety of the vehicle and to adjust instrument settings, for instance, sonar parameters of the multibeam unit. In such cases, the main flow direction could be simply and accurately determined using the WVAM method during this mission, and an algorithm can be created to autonomously decide the direction of ascent/descent.

Velocity Overground Measurements for the WVAM Method

During the vehicle operations outlined in Figure 1, continuous velocity measurements of the AUV relative to the ground are not obtainable from DVL bottom tracking to assist the INS navigation solution. Therefore, the INS could be aided with velocity estimates from secondary instruments or methods, although this does not represent typical operations. An accurate simulation model is able to predict the vehicle velocities in real time when the control commands of the AUV are provided (Hegrenæs & Hallingstad, 2011). The hydrodynamic coefficients of simulation models generally represent the calm water operational condition of the AUV. Therefore, vehicle drift resulting from currents in the water column will not be included in the velocity predictions, causing inaccuracies in the AUV position estimated by the INS (Augenstein & Rock, 2008; Hegrenæs & Berglund, 2009). The results discussed in the above sections show that the WVAM method could be successfully utilized to determine the water column velocities that can be used in conjunction with model-predicted vehicle velocities to aid the INS navigation solution.

A disadvantage of the WVAM method is that it requires an estimation of the vehicle velocity relative to the ground in order to measure the water column velocities. The position and velocity estimates of the vehicle can be determined using acoustic transponders (i.e., ultra short baseline or long baseline), albeit with an infrequent update rate. The intermittent velocity updates from the transponders will be used for the WVAM to determine the water column velocities, and the estimated flow measurements will then be assumed to remain constant until the next reliable velocity update is received.

As an alternative to the velocity estimates from acoustic transponders, the velocity of the AUV relative to the ground can be computed in a propagative manner starting from the initial measurements taken at the beginning of the process when DVL bottom track or GPS data are available. That is, the initial vehicle velocity measurements will be used to determine the water column velocities using the WVAM method and will be used in conjunction with the velocities predicted from the simulation model to recalculate the vehicle velocities relative to the ground. The initially measured and calculated vehicle velocities will be compared, and, if the correlation is satisfied, the computation will be iteratively updated by obtaining the velocity solution of the current time stamp using the previous time stamp's velocity information. However, further measures should be taken to reduce the error accumulation. The INS navigation solution is more robust and less prone to errors when velocity overground readings from various sensors and estimates are considered, for example, by using a Kalman filter, since the signal outputs from individual sensors can be discontinuous (Hegrenæs & Hallingstad, 2011). Thus, the INS aided with the vehicle velocity estimates determined from the proposed method is expected to provide a better localization performance.

Conclusions

The WVAM method is a non-acoustic technique to determine the water velocity components of a turbulent water column using the motion response of an AUV. The accuracy of the WVAM method was examined at different turbulence levels of the water column. Nine AUV runs were conducted along the same track line at different times in the tidal cycle in the Tamar estuary in Tasmania, Australia. Typically, when an AUV undertakes missions in rough water environments, the pitch and yaw angles of the vehicle fluctuate around the target values due to the inability of the AUV's dynamic controller to adequately compensate for the external disturbing forces. The greater the turbulence level of the water, the larger the fluctuations. The estimated water velocity components in the y and z directions using the WVAM method agreed well with the experimental measurements obtained from the AUV's onboard ADCP for low turbulent conditions (with a vertical water velocity range of around -1 to $+1$ m s^{-1}), where the averaged deviations of the vehicle's pitch and yaw angles are below 7°–8°. The correlation reduced when the averaged deviations were above 7°–8°. The accuracy of the water velocity component in the x direction remained generally the same for all the runs regardless of the turbulence level of the water column.

The hydrodynamic coefficients for the simulation model utilized in the WVAM method were determined using a curve fitting technique. These estimated coefficients were only valid for small angles of incidence of the vehicle, where the coefficients are within their linear range. Therefore, as the pitch and yaw angle fluctuations become larger, the accuracy of the simulation model decreases adversely affecting the prediction of the vertical and transverse water velocity components obtained from the WVAM method. During the AUV missions, the vehicle speed remained within the identified forward speed range of 1.43–2.46 m s^{-1}. Therefore, the simulation model was able to provide an accurate prediction of the forward speed of the vehicle enabling the WVAM method to accurately determine the water velocities in the x direction.

The WVAM method is capable of capturing the velocity up to around 1–1.5 m s^{-1} with an acceptable accuracy. Therefore, it could be incorporated to aid the INS navigation solution without further improvements for situations where the DVL bottom track is intermittently or completely unavailable or ineffective. However, the accuracy of the method will be increased by upgrading the simulation model to replicate the motion response of the vehicle in both the linear and nonlinear ranges.

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