Water Profile Navigation with an Acoustic Doppler Current Profiler

M. Jordan Stanway
Applied Ocean Physics and Engineering
Woods Hole Oceanographic Institution
Woods Hole, MA 02543–1535
Email: m.j.stanway@alum.mit.edu

***Abstract*—A novel navigation method is introduced using water current profiles measured by an Acoustic Doppler Current Profiler (ADCP) mounted on a moving vehicle. These current profiles are combined with measurements of vehicle attitude and depth to simultaneously estimate the local current and the vehicle velocity. This velocity estimate can be integrated directly to give a position estimate, or it can be fused with measurements from other navigation sensors, such as an Inertial Navigation System (INS), Long Baseline (LBL) or Ultra-Short Baseline (USBL) acoustic tracking system. The method allows an underwater vehicle to maintain an estimate of its global position throughout all phases of its mission, including descent and ascent.**

***Index Terms*—underwater vehicle, auv, uuv, navigation, Acoustic Doppler Current Profiler, ADCP**

I. Introduction

Underwater vehicle navigation continues to be a challenging and active research area. The problem is often divided into two parts: localization and control. That is, knowing where you are, and knowing how to get where you want to be. This paper addresses the first part, localization.

The Global Positioning System (GPS) has revolutionized navigation in the air and on the planet's surface, but its signals do not penetrate the depths of the ocean. Underwater vehicles have to rely on acoustic navigation methods instead. Long Baseline (LBL) acoustic tracking systems use two-way travel times from precisely surveyed transponders to determine position [1]. Ship-mounted Ultra-Short Baseline (USBL) tracking systems use travel time and phase to calculate range and bearing to a transponder mounted on the vehicle [2]. This is combined with the ship GPS to provide accurate geolocation of the underwater vehicle. Due to the speed of sound in water ($c_s \simeq 1500\ \mathrm{m/s}$), these positioning methods provide a low-rate position update over long distances. Two-way travel times can be $\mathcal{O}(10\ \mathrm{s})$ during long, deep missions. Higher rate navigation is necessary for precision work

Many vehicles achieve this higher rate by dead-reckoning in the time between position fixes. This also increases robustness to LBL/USBL outages, or shadowing from rough terrain.

Dead-reckoning is an ancient navigation technique that integrates the speed and course of a vehicle over time. For an underwater vehicle moving in six degrees-of-freedom, speed is usually measured by a Doppler Velocity Log (DVL) with bottom-lock, while course is measured by a magnetic compass and tilt sensors, or by a gyrocompass. In the absence of bottom-lock, the vehicle must rely on velocity estimates from a mathematical model.

Low-cost inertial navigation solutions have recently become more available. These measure accelerations and angular rates, then integrate over time to estimate velocities, and integrate again to estimate position. They provide another set of sensor inputs for dead reckoning. However, they are subject to drift over time. Recent advancements in localization algorithms using bathymetry or photos promise to provide additional sparse position updates for vehicles operating near the seafloor [3]–[5]. New model-based estimation techniques levereage accurate knowledge of system dynamics. These have provided position estimates with lower variance [6], [7], and enabled robust, high-rate control in systems with minimal sensing [8]. A review of the current state of art is given by Kinsey, et. al. in [9].

No single approach to underwater navigation works precisely and reliably on its own. In a working system, many of the techniques mentioned above are fused together into one navigation estimate.

This paper introduces a novel technique for navigation through the water column, bridging the gap between surface and seafloor. It is proposed as another tool for underwater navigation, to be fused with existing methods where appropriate.

The goal of this research is to demonstrate the feasibility of water profile navigation using measurements from an Acoustic Doppler Current Profiler (ADCP). The method introduced here does not rely on an inertial navigation system, nor does it explicitly use acoustic positioning to bound error growth. The idea is to get as much as possible using only an ADCP, a heading reference, and a depth reference.These measurements are often available from a single package, but may also come from several discrete sensors.

II. Previous Work

A Doppler Velocity Log (DVL) provides accurate measurements of three-component vehicle velocity over ground within bottom lock range. This range varies with DVL frequency; it is about 250 meters for a 300 kHz DVL [10]. The velocity is calculated from the frequency shift in an acoustic signal sent from the DVL to the seafloor, and reflected back to the

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DVL. This process can be treated as the case of a moving transmitter (the DVL) signaling a stationary reciever (the seafloor), immediately followed by a stationary transmitter (the seafloor) signaling a moving receiver (the DVL) [11]. The resulting frequency shift is:

$$\Delta f = f_r - f_t \simeq \pm \frac{2uf_t}{c}, \qquad (1)$$

where f_t is the transmit frequency, f_r is the receive frequency, u is the DVL velocity, and c is the speed of sound in the medium. The sign on the right-hand side depends on whether the vehicle is moving toward or away from the bottom along the direction of the beam. A DVL has multiple transducers so that it can measure the frequency shift along different acoustic beams, then combine the measurements to provide the three-component velocity measurement.

In dead reckoning, two types of uncertainty are most important. One is in the velocity measurement, and the other is in heading. The velocity measurement error is driven by the acoustic environment and the alignment of the transducers within the DVL. The heading error is driven by the heading sensor itself and by the alignment between it and the DVL.

For precision navigation, the alignment of the DVL beams within the instrument is critical. Brokloff describes a matrix algorithm for Doppler navigation in [11]. This algorithm is an improvement on the standard Janus equations which were previously used in marine vehicle navigation. It provides a rigorous mathematical treatment of the different reference frames used in Doppler navigation, and also allows for corrections in transducer-instrument alignment. This algorithm reduced the mean position error in a navigated mission from 0.51 to 0.33 percent distance traveled, and reduced the standard deviation from 0.26 to 0.23. These errors may seem small, but they are important in precision underwater navigation, as error accumulates over the course of a several kilometer mission.

Heading error from a magnetic fluxgate compass is $\mathcal{O}(1^\circ)$. Optical gyrocompasses with precision $\mathcal{O}(0.1^\circ - 0.01^\circ)$ are becoming more readily available, which leaves DVL/compass alignment as the prime source of navigation error. Kinsey and Whitcomb address this issue in [12] by developing a least-squares method to identify the transformation matrix describing this alignment. They show that a solution constrained to the special orthogonal group of rotation matrices provides the best navigation performance on multiple missions. In three separate field experiments, these alignment methods reduced position error This work is extended in [13] to include an adaptive identifier with proven stability.

All of this work has made dead-reckoning with DVL bottom-lock and a compass both precise and robust. This approach has become the workhorse of high-rate navigation for underwater vehicles near the seafloor.

However, these vehicles are essentially ‘flying blind’ when they are out of bottom-lock range. When operating in deep water, this happens at least twice during every mission, during descent and ascent.

III. NAVIGATING RELATIVE TO WATER CURRENTS

An ADCP works on the same principles as a DVL. It is physically the same instrument, but it tracks the velocity of the water relative to the vehicle instead of the velocity of the vehicle relative to the ground. It does this by measuring the frequency shift of an acoustic signal reflected by particles (plankton, sediment, marine snow) suspended in and moving with the ambient flow. Since these particles have a much lower target strength than a hard bottom, a broadband ADCP uses a slightly different type of ping for water profiling, and has a shorter range for measuring water velocities than for bottom-track.

The water velocities measured by an ADCP can provide important navigation feedback while the vehicle is out of range for bottom-lock.

On some instruments, a ‘water reference layer’ is tracked once bottom track is lost, and vehicle velocity is measured relative to that reference layer [10]. This makes the implicit assumption that the reference layer is stationary, so performance suffers when that assumption is violated.

Two methods of current extrapolation have been suggested in the past. An accurate measurement of through-the-water vehicle velocity can be made by averaging ADCP measurements over several depth cells. When an ADCP makes concurrent water-profile and bottom-track measurements, the effect of local currents can be estimated. Then, when bottom lock is lost, high-quality velocity estimates can be maintained for a short term [14].

This paper proposes a new method of dead reckoning through the water column using water profiles measured by an ADCP. This method provides an estimate of vehicle velocity in the global frame, using three basic assumptions: (i) the vehicle starts with a global position and velocity estimate, (ii) the vehicle can measure overlapping water current profiles, and (iii) the globally-referenced water current may vary with depth, but it does not change in time over the timescale of the descent. If these assumptions are met, the vehicle can maintain an estimate of its global velocity while at the same time building an estimate of the local current profile as shown in figure 1.

A. *Bin-average approach*

Water-profile navigation is based on multiple, overlapping measurements of the local current. These measurements are provided by the ADCP as three-component velocities in discrete bins at different distances away from the instrument. The basic assumption is that the local current varies with depth, but not in time. So the velocity measured in each bin is first rotated into the global reference frame (using the attitude reference provided by the compass), then offset to its corresponding depth (using the depth reference and the distance of the bin away from the ADCP). In the simplest implementation, all measurements and all bins are given equal weight, so new measurements can be directly averaged into the global current estimate.

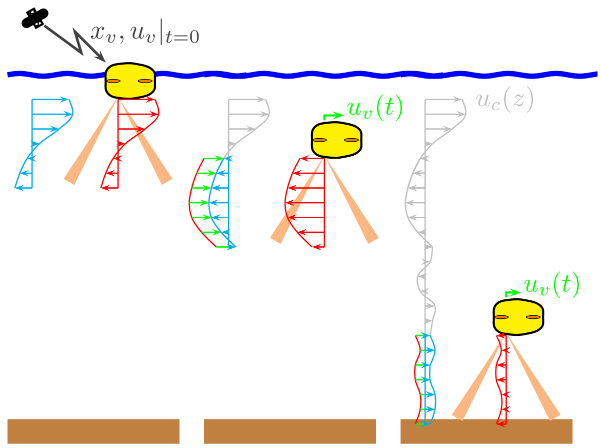

Fig. 1. Surface-to-seafloor navigation using an ADCP to measure the current profile. 1) The vehicle starts with GPS position information and a partial current profile. 2) The vehicle descends below the surface, losing GPS but extending its current profile measurement deeper. 3) The vehicle reaches operational depth and gains bottom-lock with the ADCP.

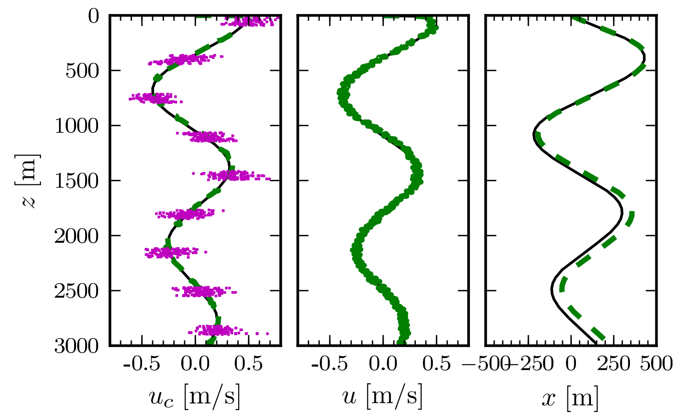

Fig. 2. Current profile and vehicle state estimated by bin-average algorithm in simulation. The solid black line is the truth, and the dashed green line is the estimate. The magenta dotted segments on the current profile represent noisy single water profile measurements.

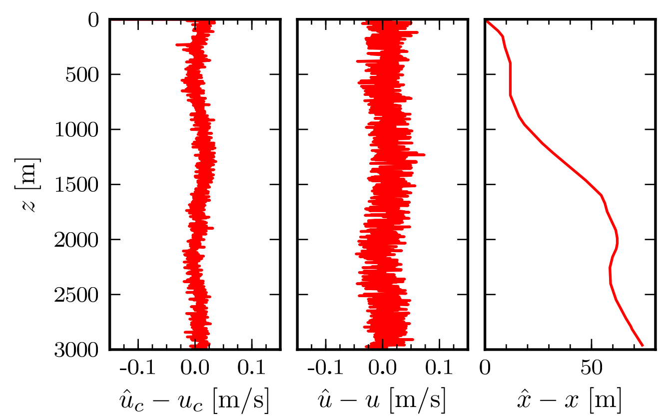

Fig. 3. Error residuals in simulation results.

However, the ADCP is mounted on a moving vehicle, so it is actually measuring the water velocity relative to the vehicle. The contribution of vehicle motion can be accounted for using the global current estimate and the new water profile. The difference, $\Delta u(z)$, between the measured profile, $u_m(z)$, and the global current estimate, $u_c(z)$, is:

$$\Delta u(z) = u_m(z) - u_c(z), \quad \forall\, z \in [z_0(t), z_n(t)]\,, \tag{2}$$

where the interval $[z_0(t), z_n(t)]$ is the depth range overlapped by the global current estimate and the new measured water profile. The average of this difference over depth provides an estimate of the vehicle velocity:

$$u_v(t) = \frac{1}{n}\sum_{i=0}^{n} \Delta u\left(z_i\left(t\right)\right). \tag{3}$$

This velocity should then be removed from the new measured profile before it is averaged into the global current estimate. Then the vehicle velocity estimate can be used for dead reckoning, and the process can be repeated as long as water profile measurements overlap.

More sophisticated algorithms are of course possible–an approach weighting each bin measurement by echo intensity, for example, might provide better performance in the long run. This and other investigations are the topic of ongoing research.

IV. Simulation

The bin-average approach presented in the previous section was implemented in simulation using a simple vehicle descent model. The current was restricted to the x-direction, and modeled as a randomly generated decreasing sinusoid. The vehicle descended at a rate of 0.27 m/s, and was forced in the x-direction by the current. The simulation generated ADCP water profile measurements with 1-meter bin size and zero-mean, $\sigma = 0.13$ m/s, random noise. This simulated noise level was chosen based on figures given by the PlanADCP software package, provided by Teledyne RD Instruments.

Figure 2a shows that the current profile is identified well, while Figure 2b shows the estimated vehicle velocity follows the actual velocity closely. The actual and estimated vehicle position are shown in Figure 2c. The errors residuals for the estimated current profile, vehicle velocity, and dead-reckoned position are shown in Figure 3, and error statistics are given in Table I.

It should be emphasized that this simulation restricted the current profile and vehicle velocity to the x-direction. It did not consider any effects of noise in the attitude sensor. The primary purpose of this simulation is to show that the ADCP water profile measurements and a simple bin-average algorithm can provide adequate velocity estimates for dead reckoning.

V. Field Experiments

The previous sections have shown how to navigate using water profiles in theory and simulation. This section describes experiments in the field using the deep submergence Autonomous Underwater Vehicle (AUV) Autonomous Benthic Explorer (ABE). Results presented here are postprocessed, but

TABLE I
BIN-AVERAGE WATER PROFILE NAVIGATION ERROR METRICS.

error in	μ	σ	
u_v	0.00675	0.0163	m/s
u_c	0.00574	0.0136	m/s
x_v	39.8	23.1	m

the approach should be fully capable of real-time operation if properly implemented in the vehicle code.

A. Description of the Autonomous Benthic Explorer

One of the oldest deep submergence AUVs, ABE was designed and built in the early 1990s and completed its initial sea trials in 1994. During its 222 dives, ABE made numerous contributions to deep submergence science, including many high-resolution maps of the mid-ocean ridge [15] and aiding in the discovery of several hydrothermal vent sites [16].

ABE dead-reckons in real-time using a fluxgate magnetic compass (TCM2) and a 300 kHz DVL (Teledyne RD Instruments). This paper uses data from the compass included in the DVL unit, since it is calibrated with the ADCP beams and sampled concurrently with the water profile measurements. A Paroscientific digiquartz measures pressure, and Sea-Bird SBE3 and SBE4 units both measure conductivity and temperature. These three quantities are combined using standard equations [17] to calculate depth.

B. Mission Description

The data presented in this paper is from the descent phase of ABE221. The dive was a chemical and multibeam mapping mission at the Chile Triple Junction. It began with a descent to 2957 meters, at an average rate of 0.27 m/sec, ending at approximately 06:50. ABE spins at a fairly constant rate ($\dot{\psi} \simeq \pm 0.035\ \mathrm{rad/s}$) during the descent (Figure 4a). A large separation between the center of buoyancy and center of gravity gives ABE good passive stability, so roll and pitch angles are small and nearly constant throughout the descent (Figure 4b). Since roll and pitch are small, their effects will be neglected for the remainder of the paper to simplify the explanation.

C. Comparison of velocity estimates

The ADCP acquired bottom-lock at the end of the descent phase of the mission. Figure 5 compares the vehicle velocity estimated from the water profiles, u_{wp}, to the velocity measured by bottom-track, u_{bt}. Overall, the water profile estimate agrees well with the bottom track measurements, with a mean difference of $\mu = 6.67$ mm/s.

However, some outliers are clearly visible, especially where bottom lock is lost again from 06:35 - 06:36. The ADCP may have received bad acoustic signals or wraparounds as it was trying to maintain bottom tracking on the approach. These outliers are very large in magnitude, with a range of 1.56 m/s. driving the standard deviation of the residuals to $\sigma = 76.1$ mm/s. These errors will add up to increase position

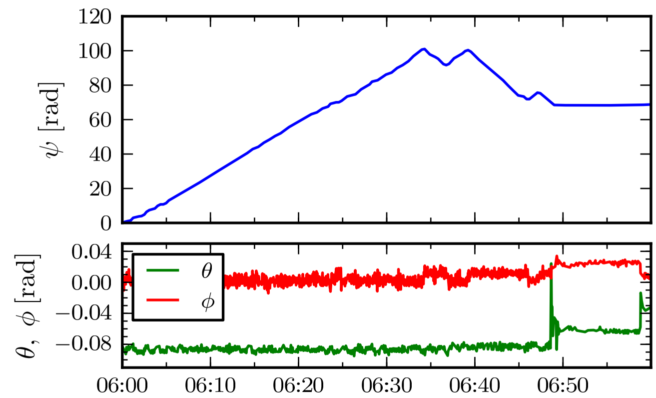

Fig. 4. Vehicle heading (a) and attitude (b) through descent. All angles are in radians, heading has been unwrapped over 2π.

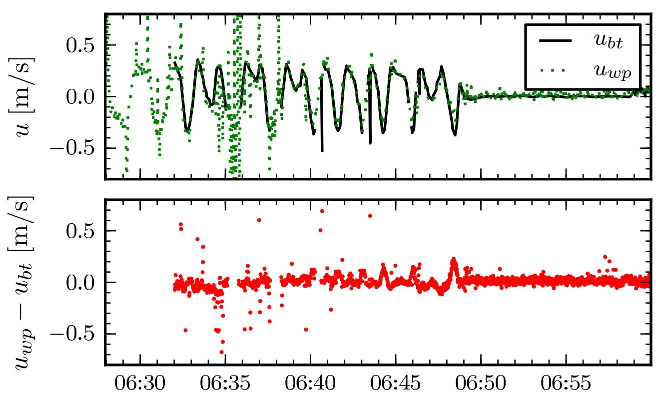

Fig. 5. Estimated vehicle velocity during final phase of descent, in range of DVL bottom lock. Residuals are shown in the second subplot.

error considerably upon integration. The transverse velocities v_{wp} and v_{bt} exhibit similar behavior. For realtime dead reckoning, the raw velocity estimates from the water profiles will need filtering. As always, external position measurements are necessary to limit long-term error growth and provide an absolute georeferenced position.

VI. DISCUSSION AND CONCLUSIONS

This paper has introduced a novel method for underwater vehicle navigation during descent and ascent. The method relies on only three sensor inputs: (i) a depth reference, (ii) an attitude reference, and (iii) an Acoustic Doppler Current Profiler. A simple bin-average algorithm was presented which simultaneously estimates the vehicle velocity and local current profile. This algorithm was demonstrated in simulation and using data collected in the field by ABE. Vehicle velocity estimates produced using the water profiles compare favorably with true values in simulation, and with bottom-lock DVL measurements, when available, in the field. The results indicate promise in the proposed navigation method, with the usual caveat of unbounded position error growth for dead reckoning in absence of absolute position measurements.

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Acronyms

AUV Autonomous Underwater Vehicle
ABE Autonomous Benthic Explorer
LBL Long Baseline (Acoustic Positioning System)
USBL Ultra-Short Baseline (Acoustic Positioning System)
GPS Global Positioning System
ADCP Acoustic Doppler Current Profiler
DVL Doppler Velocity Log
INS Inertial Navigation System