DVL Integration With Autonomous Underwater Gliders for Navigation in Arctic Marginal Ice Zones

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I. Introduction

Scientists are increasingly reliant on autonomous systems capable of under-ice navigation for polar ocean exploration, due to the expense and limited access for ship based expeditions. However, technological innovations are still needed to realize the full potential of these systems for investigation of these extreme regions [1].

A diverse range of technologies have been deployed for sub-ice ocean exploration, each offering unique capabilities while presenting inherent operational constraints: moorings, ice-tethered platforms, and profiling floats are cheap and expendable but remain fixed in place or have uncontrolled trajectories, and they require manual deployment and recovery [1, 2]; Hybrid Remotely Operated Vehicles provide extensive capacity for sensing payloads and sampling capabilities, but require an attendant ship for tethered operations and have limited range under ice [3]; Long-Range Autonomous Underwater Vehicles can achieve missions exceeding 1000 km with versatile sensor configurations but are often large and heavy, due to battery capacity requirements, and costly to build [1, 4]; Autonomous Underwater Gliders (AUGs) provide unmatched endurance and ease of deployment from small vessels but are constrained by limited power budgets, modest payload capacities, and navigation challenges in the absence of frequent GPS surface fixes [4].

We have recently reported on the methodology and results of a field trial in the Arctic Marginal Ice Zone (MIZ), conducted in early August 2023, which demonstrated the utility of a modified Slocum G3 AUG for under-ice survey [5, 6]. This glider leverages hybrid thruster propulsion with buoyancy control to achieve stable flight within sub-ten meter depth bands, making it uniquely suited to long-range under ice survey missions with low-power, active sensing payloads. A challenge for long-range AUG missions is the effect of water column currents on the vehicle navigation accuracy. Currents are complex to characterize in mission, as they can be highly stratified through the water column, be dynamically driven by tides and winds, and in some regions, may be comparable to or exceed the velocity of the AUG through water. For open ocean profiling, AUGs generally do not require highly accurate online navigation, and GPS fixes at regular surfacing intervals are used to constrain the navigation error while on mission and estimate an average current term for the full water column. These fixes can also be used in post-process to improve the estimate of the AUGs flight path. However, sub-ice operations limit the opportunities for the AUG to surface and obtain GPS fixes, and future long-range surveys under ice target the traversal of hundreds of kilometers or more without a surface fix. For AUGs to be a viable platform for long-range under-ice survey without reliance on some means of external absolute positioning, such as acoustic beacons [7], improved navigation methods are needed. In our Arctic field trials, the AUG was equipped with a Teledyne RDI Pathfinder Doppler Velocity Logger (DVL) operating in a low power configuration, that was fused with measurements from a Sparton M2 altitude and heading reference system (AHRS) into a backseat navigation process. A backseat mission controller steered the front-seat flight computer, based on the backseat navigation estimates. While the navigation methodology was detailed in a prior publication [8], this paper focuses on an analysis of the DVL's performance during these trials. We evaluate the accuracy of the DVL-fused navigation process, highlight its practical strengths and limitations for sub-ice operations, and propose future directions for improving the robustness and reliability of this navigation approach.

(a) Trial Site (b) Deployed Glider

Fig. 1. Trials with the AUG were conducted in the Arctic MIZ from Aug. 2-4, 2023.

II. DVL Fused Navigation

We provide a condensed description of the DVL-fused navigation process here, and we refer to our prior publication for the detailed formulation of the method [8]. The navigation

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process is implemented as a ROS node on the backseat computer that integrates sensor data from a DVL, AHRS, CTD, and telemetry from the front-seat flight computer to estimate the vehicle's velocity over ground with respect to a global East-North-Up (ENU) reference frame. The navigation process dynamically accumulates DVL water lock measurements to estimate the water column velocities, which are integrated with the measured vehicle velocity with respect to water to resolve the vehicle's velocity over ground when the AUG is out of bottom lock range. Lacking an absolute velocity reference frame, the vehicle accumulates velocity estimate errors when using water relative velocity estimates. A pose correction term is constructed when the vehicle gains bottom lock to mitigate some of the accumulated error.

A. *Water Column Representation*

Water column velocities are represented as a 3D tensor, discretized into depth bins. Each bin maintains a circular buffer of water column velocity measurements from the DVL. Measurements are stored as 4-element vectors (easterly, northerly, upward velocities, and timestamp) in a global ENU reference frame. Measurements are corrected for sound speed using CTD data and transformed to ENU coordinates based on synchronized AHRS readings.

B. *Initialization and Processing of DVL Measurements Without Bottom Lock*

1) Surface Drift Initialization: Before a dive, DVL measurements from the upper water column are accumulated. When the vehicle dives, the median of the measurements is taken and corrected for vehicle drift velocity to initialize the water column velocity estimates for the upper bins.

2) Water Column Updates: During subsurface operation, water column velocities are estimated based on DVL shear measurements. These are adjusted using the vehicle velocity relative to the water, estimated from the DVL's observations of the nearest bins. Measurements are stored and updated dynamically, with invalid or stale values excluded based on predefined time thresholds. The velocity of a queried water column bin is estimated by taking a median filter of the accumulated measurements.

3) Odometry Without Bottom Lock: In the absence of bottom lock, the vehicle's velocity over ground is estimated as the sum of its water-relative velocity and the water column velocity at the corresponding depth bin. The odometry update step incorporates a time-smoothed velocity estimate to enhance accuracy in the presence of acoustic noise and active vehicle pitching.

C. *Bottom Lock and Pose Corrections*

When bottom lock is available, the DVL provides absolute velocity over ground. Accumulated water column velocity errors are calculated by comparing these absolute velocity over ground measurements with the velocity over ground estimated relative to the water column velocities. Corrections to the water column velocities are applied as a delayed state filter, once sufficient error measurements are accumulated, and a pose correction is formulated, assuming a regular accumulation of velocity errors since the last absolute velocity measurement.

TABLE I
NAVIGATION ACCURACY AS REPORTED IN [5] FROM OUR 9 TRIALS IN THE ARCTIC MIZ. THE SAME LEG LABELING IS USED HERE AS IN [5] FOR CONSISTENCY.

Leg	Dist (m)	Error (m. %)
D1	986	131 (13%)
D2	1274	249 (20%)
D3	1375	257 (19%)
D4	2089	141 (7%)
E1	2144	343 (16%)
E2	3135	249 (8%)
F1	1617	129 (8%)
F2	409	22 (5%)
F3	989	37 (4%)

III. EVALUATION IN THE ARCTIC MIZ

In this section, we describe the operational conditions for our field trials in the Arctic MIZ, and we analyze the performance and sources of error for the DVL based odometry from the data collected during these trials, providing insights into the fundamental limits of our navigation method, best-practices, and pathways for future improvement.

A. *Operational Conditions*

The location of our field trials was dictated each day by the extent of the marginal ice flow, which drifted on the order of 10 km per day in a southeasterly direction [5]. The bathymetry across our operational area was relatively shallow for AUG deployments, averaging just over 30 m depth. At these shallow depths, we were not able to operate directly under the ice sheet transition zone, due to large chunks of grounded ice along the shelf front (Fig. 2). For the purpose of these field trials and to limit risk of losing the vehicle, we chose operational sites, as depicted in Figure 1, where we expected the floating ice keel depth beneath the surface would not exceed 10 m. During the three days of main trials, the wind ranged from 8-14 kn, and the estimated surface current from 0.2-0.4 m/s.

For all missions, the glider was programmed to follow a bathtub profile mission, leveraging the thruster for propulsion and using the buoyancy pump to maintain the target depth within a band of +/-5 m with a target pitch angle of 0^o. We initially configured the bin width for water column profiling to 2 m. However, we found water column lock highly unreliable, so we increased the bin width to 4 m and observed reliable water lock measurements across all following trials.

As reported in [5], we conducted 9 dives over three days. For the readers convenience, we reproduce the key navigation accuracy results in Table I, which reports navigation error as the percentage of the horizontal distance traveled. We also retain the original trial leg labels for consistency. The mean navigation error across all dives, weighted by dive distance, was 11% distance traveled. We break down the analysis of the navigation performance into what we consider the primary

Fig. 2. Large chunks of ice were grounded along the ice-sheet transition in the relatively shallow (<40 m depth) operational area.

potential sources for uncertainty. For these evaluations, we focus on the four trials that we consider most interesting. Three of these trials, F1-F3 (Fig. 3), were conducted at the same location, during the same deployment, and include missions with multiple way-points that guided the AUG in subsurface turns. The fourth trial, D4 (Fig. 4), demonstrates the best observed performance of a bathtub profile mission, where the glider maintained nearly perfect 0^o pitch and very stable depth control over a distance of 1.5 km.

B. Sources of Uncertainty

The first potential source of systematic error we consider is uncalibrated orientation bias between the AHRS and the DVL. In these trials, they were assumed to be perfectly aligned. We first evaluate for a pitch and roll bias and then for a heading bias, as they can be separately observed.

The dive plotted in Figure 4 provides an ideal trajectory for calibrating a pitch and roll bias, where the glider held steady nearly 0^o pitch over relatively flat bottom for an extended distance. Making the assumption that on average, the bottom is flat over this dive, every set of DVL bottom range measurements should project onto a horizontal plane. A pitch or roll bias in the DVL will result in measurements consistently projecting onto a tilted plane relative to the horizontal. We observe that the center point of each measurement set will also lie on the tilted plane. As illustrated in Figure 5a, we normalize all sets of DVL measurements by subtract their centroid and then project them into 3D space. We fit a plane to the clusters of projected points by taking the SVD and finding the plane normal as the direction of lowest variance. From the slant of this plane normal from the vertical axis, we estimate the pitch and roll Euler angle biases. While the roll bias was estimated to be negligible at 0.2^o, a pitch bias was estimated to be 1.4^o or 0.024 rad. The projection of the velocity error due to a pitch bias in the horizontal plane is given by the cosine of the bias angle. For small angles, the cosine is

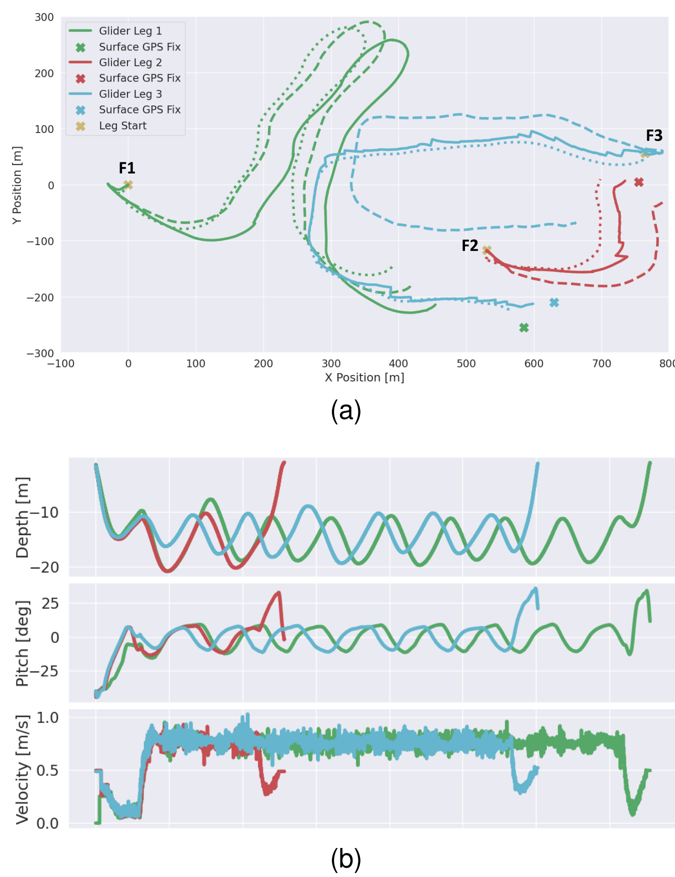
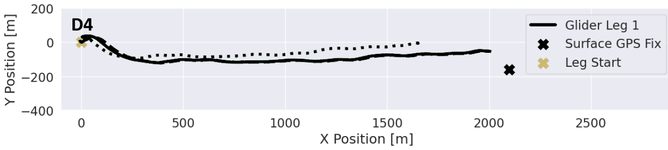


Fig. 3. Three of the trials demonstrated multiple waypoint following, where the AUG was guided through a series of waypoints with subsurface turns. In (a), solid lines are the odometry trajectory, dashed lines are the bottom lock trajectory, and dotted lines are the integrated water lock trajectory.



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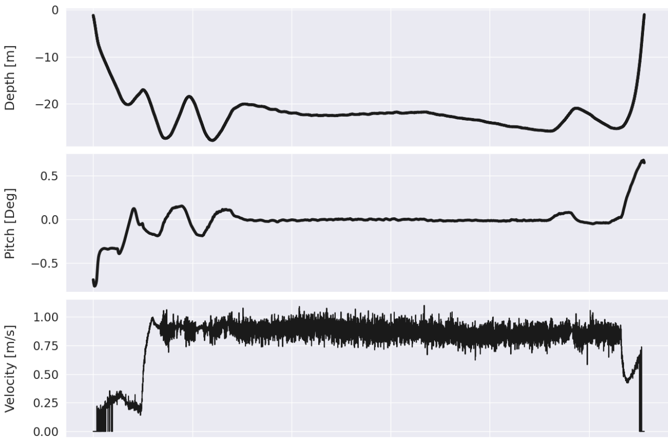
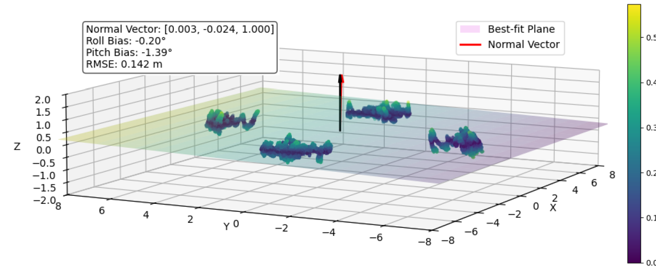


(b)

Fig. 4. The trial visualized here achieved the best bathtub profile performance, where the AUG achieved steady pitch and depth control over a 1.5 km distance.



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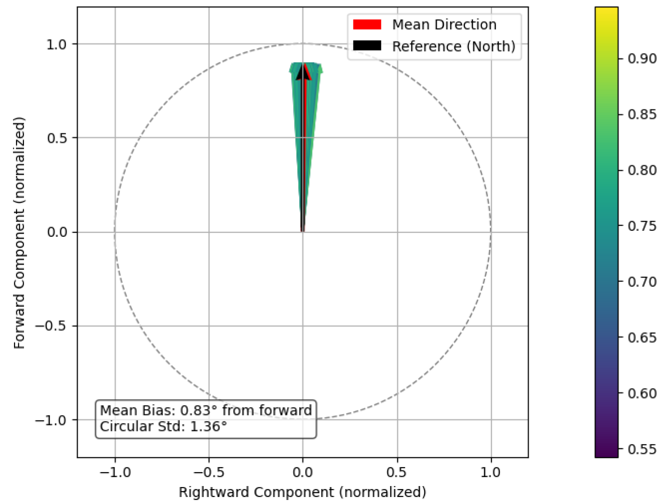

(b)

Fig. 5. Analysis of DVL pitch, roll, and heading bias relative to the AHRS from analysis of the trial datasets.

approximately equal to one, so a small pitch bias angle also becomes negligible relative to the observed magnitude of the navigation error. This is because the navigation method uses absolute depth measurements to resolve the z-axis, so all velocity measurements are projected and integrated in the horizontal East-North plane.

In order to estimate a heading bias from the collected data, we evaluate the vehicle velocity over ground measured from bottom lock with respect to the vehicle frame. An ideal trajectory would have the AUG fly in a square, so that velocity heading biases induced by currents would cancel out over the mean of the trajectory. The closest trajectory we have to a square is mission F3 illustrated in Figure 3. Figure 5b shows the plot of the normalized horizontal velocity vectors with respect to the vehicle frame. The mean heading bias is estimated to be 0.8^o with a standard deviation of 1.36^o. If we consider a conservatively estimated heading bias of 2^o, with small angle approximations, the error due to this bias as a percentage of distance traveled is equal to the bias angle in radians or 3.5%.

An additional source of systematic error we consider is the active pitching of the glider while in bathtub profiling flight. The pitch is by far the highest actuated axis of rotation in glider flight, and despite controlling for 0^o pitch, the AUG controller generally achieves a consistent cyclical pitch profile of approximately +/-10^o. We begin with a consideration of the order of magnitude error that might be induced by this active pitching. We evaluated a portion of the pitch data from dive F1 in Figure 3b and found that the maximum rate of pitch change during bathtub flight did not exceed 0.5 ^{o}/s. The main error induced from active pitching at this rate would be a velocity bias on the DVL fore and aft beams. If the DVL is considered at a very conservative 1 m offset from the center of pitch rotation, this angular rate of change would induce a maximum linear velocity error of approximately 9 mm/s or 1.3% of the typical velocity through water during bathtub missions observed to be close to 0.7 m/s for dives F1-F3. In actuality, the error projected onto the horizontal velocity component would also be smaller.

For long term performance, the DVL user manual specifies a long term error bias of +/-0.3% of speed plus an offset of 0.2 cm/s. At bathtub flight speeds, the offset represents an error bias of approximately 0.3% for a total error bias of 0.6% of the vehicle velocity. The DVL manual specifies that short-term error in each beam is independent of other beams, and the error in each ping (except near zero velocity) is independent of other pings. Short term error is specified to have zero mean that, over long time intervals, will not affect the navigation accuracy.

We note there is also some uncertainty in how we evaluate the navigation accuracy, which is based on the discrepancy between the estimated position when the glider surfaces and the first GPS fix. The navigation process does not operate while the AUG is surfaced, and there is a delay before the first GPS fix is obtained. For example, dive D4 (Fig 4) had a delay of 45 seconds between the glider surfacing and the first valid GPS fix. The surface drift for this trial was estimated to be 0.4 m/s to the SSE based on GPS surface fixes [5], which accounts for a discrepancy of 18.4 m or approximately 1% of horizontal distance traveled. The error offset is also observed to align with the direction of drift.

Bias in the AHRS calibration may also represent a significant source of error. While the AHRS was calibrated before the Arctic trials, it was not re-calibrated on site. Also, the AHRS is mounted in close proximity to batteries and the power wires to the thruster. During bathtub missions, the continuous operation of the thruster may induce a consistent bias in the heading estimates. Such a bias is difficult to quantify and beyond the scope of this report, but we expect this bias could induce an error in excess of 1% distance traveled.

An interesting observation emerges when we examine the performance of DVL bottom lock versus water lock velocity estimates. In Figures 3a and 4a, we plot the navigation estimate of the full odometry process as a solid line, the direct integration of only bottom lock velocity as a dashed line, and the integration of only water lock velocity as a dotted line. The latter two make no corrections for water column currents. In general, we expect bottom lock to achieve the best performance and match our estimated odometry path closely, while water column estimated velocities are expected to be less accurate and influenced by water column currents. This expected result is reflected in dive D4 (Fig. 4), where the bottom lock is aligned closely with the odometry track and the water lock track offset is consistent with the estimated water column current direction. However, dives F1-F3 (Fig. 3) yield an unexpected result. Across all of these dives, the navigation track achieves a good level of accuracy, but the bottom lock track performs significantly worse. Dive F3 is the most surprising, where the bottom lock track has an offset error of over 100 m from the surfacing fix, while the navigation track is under 40 m. In this dive, the water track also aligns closer with the odometry track than the bottom lock track. A closer inspection of the data reveals that in these dives, the bottom lock lost good tracking consistently throughout the dive (as evidenced by a reported high velocity correlation error or a null error term) for extended periods in excess of a minute at a time. During the operational day for dives F1-F3, a sea state was building through the day with gale force winds and breaking waves. We noticed an increase in acoustic noise levels for data collected from the AUG with a sector scanning imaging sonar, and we hypothesize a similar effect on the bottom tracking measurements of the DVL, due to the shallow water environment and acoustic effects induced by the breaking waves. Interestingly, it appears water lock may be less influenced by these effects. When bottom lock measurements do not report a good confidence, our odometry process reverts to water lock velocity measurements until good bottom lock is achieved. This adaptive fusion of bottom lock and water lock enables our navigation process to achieve better performance than bottom lock or water lock alone, in varying environmental conditions. These results motivate a closer consideration of the fusion of water lock versus bottom lock in the navigation process, where a naive assumption that bottom lock is always best appears inconsistent. We leave this investigation to future work.

Finally, the challenge of navigation using a magnetic heading reference in close proximity to the Earth's magnetic pole has been considered since at least the late 17th century [9]. Modern approaches using true north-seeking heading references overcome this challenge, but with a tradeoff of increased power demand and size. Examination of the Earth's magnetic field properties at our Arctic study site reveal a magnetic inclination of approximately 81° and a field intensity of 8.9μT. As a benchmark for comparison, the field operations described in [5], which were conducted off the south coast of Puerto Rico, are characterized by a 42° magnetic inclination, which is roughly half that of the Arctic deployment area, and with a magnetic intensity roughly triple that of the Arctic deployment (27μT). While magnetic declination, inclination, and field strength should be relatively constant throughout the duration of the dives, prior investigation of an AUV's magnetic heading reference performance in the Arctic [10] revealed that heading varied by as much as 3° depending on pitch angle, due to the local magnetic inclination of 83.5°. This translates to a navigation error as high as 5% horizontal distance traveled. AUG size and power limitations do not permit the direct measurement of heading error, using an embedded INS as simultaneous ground truth [10]. However, the similarly extreme inclination and relatively weak field intensity of the Arctic operation site are likely to have degraded the AUG's heading accuracy, and contributed to at least a minor fraction of the navigation bias.

IV. Conclusion

In total, we have identified what we believe are the major sources of error bias in our DVL based navigation process. Our estimation puts the total contributed error from these biases at upwards of 5-10% distance traveled, which aligns with the typical observed performance in our Arctic MIZ trials. This represents a near lower bound error in the current AUG configuration, where the AUV maintains consistent bottom lock over the majority of its dive. Careful calibration could potentially reduce these bias errors by a few percent.

Extended, surface-denied navigation poses a critical challenge for AUG missions under-ice, due to the absence of absolute position references. This leads to unconstrained error growth over time. In the absence of absolute position references, odometry methods typically rely on absolute velocity references, where error in the velocity term is constrained and the integration of positional error is well characterized. When the AUG is within bottom lock range, the DVL provides absolute velocity measurements with respect to ground that are independent of water column currents. However, outside of bottom lock range, velocity over ground estimates become poorly constrained, as they are estimated relative to estimated water column currents, leading to compounding velocity errors that propagate into unbounded position errors. While our trials in the Arctic MIZ were all conducted within bottom lock range, in general, practical mission planning must aim to minimize time spent outside of absolute velocity-referenced regimes, such as bottom lock with a downward facing DVL or ice lock with an upward facing DVL. When operating without these references, careful strategies are required to constrain water column velocity errors, which could otherwise grow unbounded. One direction of future research is to leverage physical current modeling to bound the water column shear estimates and the maximum current velocity predictions.

An unexpected observation from our Arctic MIZ field trials is that, in certain environmental conditions, water lock velocities seem more reliable than bottom lock velocities. Our navigation method dynamically fuses both into its estimates, but careful investigation of the relationship between water lock and bottom lock velocities and environmental conditions could reveal interesting insight towards improving the performance and robustness of the navigation method across diverse operational settings.

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