Water Velocity Field Estimation with an Autonomous Underwater Vehicle

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I. Introduction

Water current velocities are a crucial component of understanding oceanographic processes and underwater robots, such as autonomous underwater vehicles (AUVs), provide a mobile platform for obtaining these observations. Additionally, a real-time estimate of the water-current velocity environment will aid the control and planning of the AUV, and localizing within a predicted water-current vector field is an area of continuing research [1]. Estimating water current velocities requires both measurements of the water velocity, often obtained with an Acoustic Doppler Current Profiler (ADCP), as well as estimates of the vehicle velocity.

In this paper, we focus upon enabling real-time estimation of a water current vector field. This includes further modeling considerations and investigating the performance during data-denial on the DVL to simulate mid-water estimation. The uncertainty estimates as calculated by the estimation process will be compared for the different scenarios.

The result shows potentially real-time water current estimation in-situ and the resultant uncertainty, including bias estimation. This information could be used in real-time during an autonomous mission. One example is for water current informed path planning, so that vehicle control is optimized for energy or time. Another example is real-time adaptive sampling of the water current velocity field. For example, by following the flow upstream or downstream in real-time, along with appropriate chemical sensing, the vehicle could search for a chemical source, or survey the extent of a chemical plume while accounting for the water transport.

The work presented herein extends concepts originally reported in [2]; however this work is distinctly different in that we (a) seek to explicitly estimate and analyze the water velocity vector field result, (b) looking at the best-case estimation performance in a controlled test-tank environment; and (c) we compare the estimation performance with and without the DVL bottom-lock, showing the methods applicability on ocean mid-water missions.

Results from a small-scale test-tank data with the Flatfish AUV while in DVL-bottom lock show small-scale water-current estimation potential in real-time. A mid-water surveying mission at Deepwater Horizon using the Sentry AUV also suggests real-time feasibility, along with mid-water performance when DVL bottom-lock and GPS may be unavailable.

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II. Extended Kalman filter with current estimation

Position, velocity, and attitude states are estimated using an EKF. Additionally, ADCP measurement biases for each measurement cell in each beam are estimated, along with the North, East, Down components of the water current velocity. Water velocity states are modelled as nodes in a trilinear interpolated grid, each with an associated velocity vector. The prediction step in this implementation applies a constant velocity model.

Once the state matrix exceeds a certain size due to initializing newly observed water current velocity states, the oldest of these states are marginalized out of the EKF, which involves removing them from the state vector and covariance matrix. This allows bounded-time updates as the state vector is not allowed to expand indefinitely and is controlled to a maximum size. In this paper, we use a maximum state vector size between 600 and 1000, depending the geometry of the beams, resolution of water current gridding, and processing constraints. Marginalized water current states are stored if required for subsequent analysis, but are no longer estimated, and would need to be re-initialized if re-visited. This is often justified as older water current states may no longer be observed, and if they are re-observed, they can be re-initialized instead. Further detail regarding the formulation of the filter, sensor models and correlation models can be found in [2].

III. Results

We validated this method using data obtained with the *Flatfish* AUV from the German Centre for Artificial Intelligence (DFKI) for subsea inspection [3], as well as *Sentry* AUV, a 6000m rated robot designed and built by the Woods Hole Oceanographic Institution (WHOI) for geophysical, geochemical, and biological surveys [4]. Data from two sets of data are reported here.

DFKI basin — The *Flatfish* vehicle contains a 1200 kHz Rowe Technologies DVL/ADCP with 30m water profiling range, and a KVH 1750 IMU which supplies measurements to a custom attitude estimation algorithm.

This experiment seeks to estimate the water current flow from a submerged hose in an 23m$\times$19m$\times$8m (Length$\times$Width$\times$Depth) saltwater test tank located at the DFKI Robotics Innovation Center in Bremen. The vehicle collects DVL and ADCP measurements over a period of 10 minutes.

The water current estimates were calculated in MATLAB, with the result shown in Figure 1, with a processing time of 527 seconds, thus showing potential real-time application. The estimated water current resolution was 1m$\times$1m$\times$1m. The filter maintains 1000 water-current states simultaneously

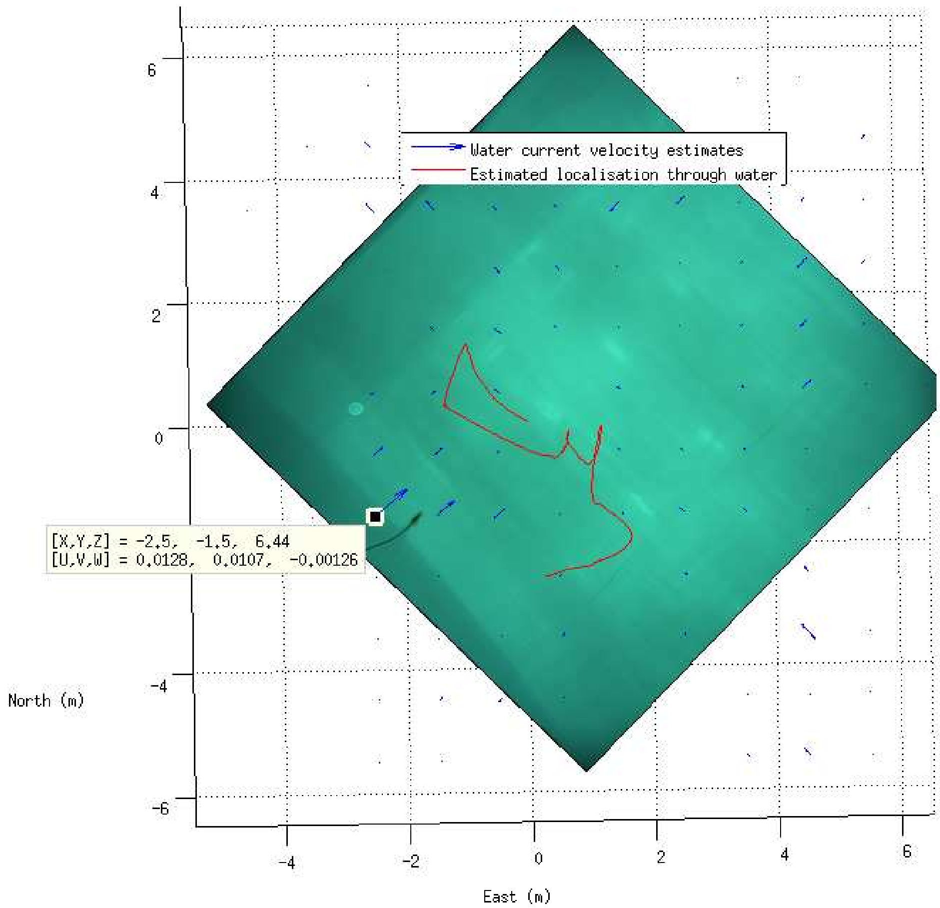


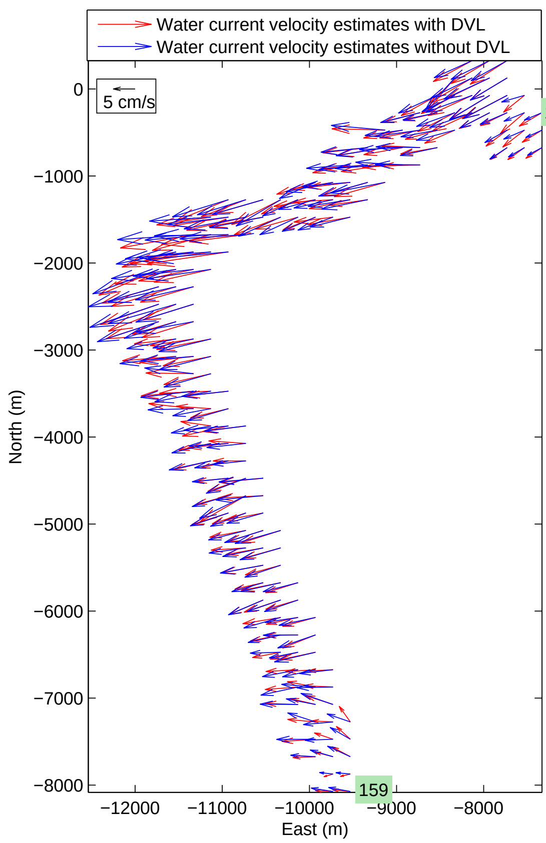
Fig. 1. DFKI basin - The hose is seen in the bottom left of the figure. The water current signal appears from that region, with an estimated magnitude of about 1.5 cm/s.

in the filter to track the water currents below the vehicle. This is artificially limited, and any movement by the vehicle outside this region would result in marginalization of the oldest observed states. The reported accuracies by the filter were about 6 mm/s (2σ) for the water currents where the water current signal of approximately 1.5 cm/s is show in Figure 1.

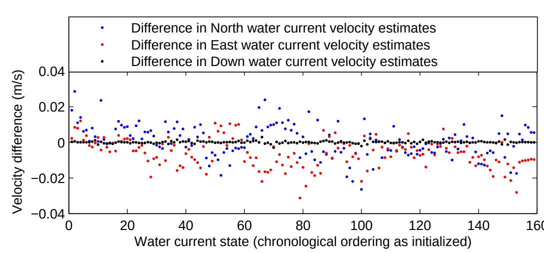
Thus, these potentially real-time small-scale water current estimates could be incorporated into precision planning and control such as in [5], and is an avenue of future work.

Sentry65 — This mission completes a horizontal surveying mission undertaken by *Sentry* while tracking a hydrocarbon plume at $\sim$1100m depth. It often loses DVL bottom-lock as it is tracking the hydrocarbon plume at constant depth, but varying altitude.

The *Sentry* AUV contains a 300 KHz RDI Navigator with 120m maximum range for water profiling and 200m for bottom-lock. On the Sentry vehicle, Attitude information is supplied by a PHINS inertial navigation system (IXSEA SAS, Marly-le-Roi, France) used as a gyrocompass, depth is



(a)



(b)

Fig. 2. Sentry65 - (a) Water current velocity estimates with and without DVL. The axis origins are aligned with the same mission in [2] Figure 4(a). The numbers 1 and 159 correspond to the water current state numbers in the analysis for the water current velocity states directly to the left of them, which bound the lower axis in Figure (b). (b) The difference in the estimates between the two filters.

provided by a nano-resolution pressure depth sensor (Paroscientific Inc., Redmond, WA), and USBL measurements are supplied by a Ranger USBL system (Sonardyne International Ltd., Aberdeen, UK).

The water current grid resolution is set at 200m in the horizontal and 4m in the vertical, as the mission was undertaken in open water with large expected scales in the water current field, with the maximum state vector size set at 600.

During a 10000 second section of the mission with full DVL bottom-lock, a higher altitude mid-water is simulated by data-denying the DVL. This result simulates a capability which has not been possible previously in oceanography, namely accurate water current estimation in the mid-water without DVL bottom-lock or GPS velocities available, and only relying on ADCP and USBL. This is compared to the water velocity field result with DVL. For the DVL data-denial case, 600 seconds of DVL is used for initialization of the water current field. After this initialization, the DVL is not fused into the filter and the remaining sensors are used for estimation. The processing time for the 10000 second mission in MATLAB on an Intel i7-4770K CPU at 3.50GHz was 3672 and 3016 seconds with and without DVL respectively, indicating real-time is feasible.

To aid the analysis, the localization error resulting from USBL dropout case is ignored. In reality, the water current submap will be shifted due to dead-reckoning error over the time period of creation in the case of no USBL. Appropriate usage of submaps and accounting for the warping from dead-reckoning error will help tackle the matching problem for re-localization, which has potential for future research.

For analysis of the water current velocities, a 2D slice at 1140m depth is taken, which is approximately 40m below the vehicle trajectory. The water current estimates for the North and East directions are shown in Figure 2(a), showing that removing DVL bottom-lock results in minimal impact on the estimation in this case, with both results showing a west-south-west current trend of similar magnitude.

The water current velocity uncertainty in the DVL-denied case is as low as 9 cm/s (2σ) and is less than the vehicle velocity uncertainty of approximately 13 cm/s (2σ).

The differences for the North and East velocity estimates are primarily within 2 cm/s between the two filter runs according to Figure 2(b). Thus, this result shows potential as an aid in matching with predicted ocean currents in the mid-water, when DVL would be unavailable, and will be a topic of future work. Additionally, these real-time estimates can be used for existing controllers and planners accounting for where the vehicle must traverse through the water currents, and is left as further research.

Further validation is possible with the use of bottom-mounted ADCPs and Acoustic Doppler Velocimeters. This would allow ground truth without the possibility of motion-induced biases as noted in [6] to compare with the ADCP-aided method, and to further identify the nature of the ADCP biases.

References

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