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Advanced Underwater Vehicle Navigation

M. Jordan Stanway

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Link Fellowship in Ocean Engineering and Instrumentation Research Report

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I. Introduction

Underwater vehicles–both manned and unmanned–are critical in our efforts to explore and study the depths of the ocean. Most underwater sensors possess a relatively small field of view; this means they must be carried over large distances to achieve high spatial coverage and resolution. The vast amount of data these sensors collect is much more valuable if the location of the vehicle is precisely known at the time the data is collected. This gives rise to the maxim: *The data is only as good as the navigation.*

Navigation remains a challenging problem for underwater vehicles. Fundamental limitations of sensing technology necessitate a multi-sensor approach to achieve robust, high precision navigation. This research addressed three[1] critical problems in automatic realtime navigation for underwater vehicles: i) *in situ* alignment identification of navigation sensors, ii) dead reckoning through the water column, and iii) rigorous treatment of time-delayed position measurements. This research has developed novel approaches to solve each of these problems, and each approach is demonstrated using laboratory or field data from an underwater vehicle. These solutions can be considered separately as practical contributions to the science and art of realtime underwater navigation. Together, they promise to enable increased autonomy for underwater vehicles in the future.

II. Results

A. Rotation identification using Geometric Algebra

As a multi-sensor problem, underwater navigation is naturally concerned with the alignments between different sensors. Estimating an unknown rotation from a set of vector measurements is a basic and long-standing problem. It is by no means unsolved–but the novel solution summarized here and detailed in [3], [6] offers a fresh perspective on the problem. Its advantages include: elegant and efficient treatment of rotations using rotors, exposing the underlying geometric properties of the system, and facilitating simple, extensible solutions that can readily be adapted to different situations and data in this general problem.

The rotor identifier used here has a straightforward interpretation as a first-order output error feedback regulator. We find that the scalar geodesic error provides a natural energy-like measure, and use Lyapunov theory to prove asymptotic stability of the identifier system. The identifier formulation and stability proof only use Geometric Algebra (GA) basics.

Figure 1 shows typical results for a simulation with proportional gain $\kappa_p = 0.25$ and varying levels of noise. With each new input/output (i/o) vector pair, the parameter error decreases monotonically until it reaches either the noise floor of the measurements ($\sigma_\nu > 0$), or the machine precision limit ($\sigma_\nu = 0$). These simulation results are consistent with the expected performance of an asymptotically stable identifier subject to persistent excitation.

The original motivation for developing this identifier for underwater navigation was to estimate the alignment between the fiber-optic gyroscope (FOG) and Doppler velocity log (DVL) used in dead reckoning.

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[1]The original proposal also included the ability to use fully coupled nonlinear models of vehicle dynamics. The sigma point Kalman filter used as the base of the navigation state estimator provides this ability, but due to time constraints, this has not yet been fully explored.

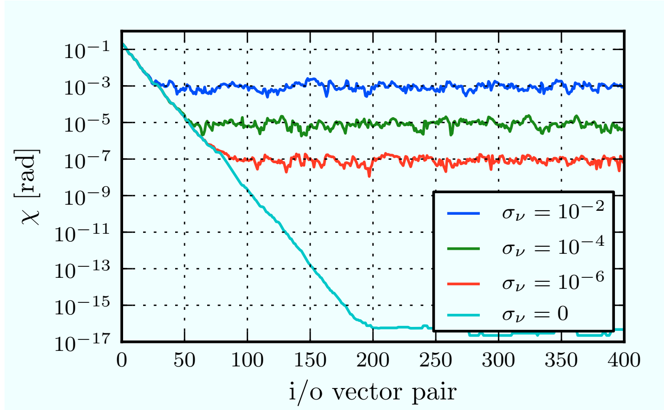

Fig. 1. In simulations, parameter error scalar χ decreases monotonically until it reaches the level of injected noise. This value corresponds to the total error angle, or the geodesic length of the alignment error. ($\kappa_p = 0.25$)

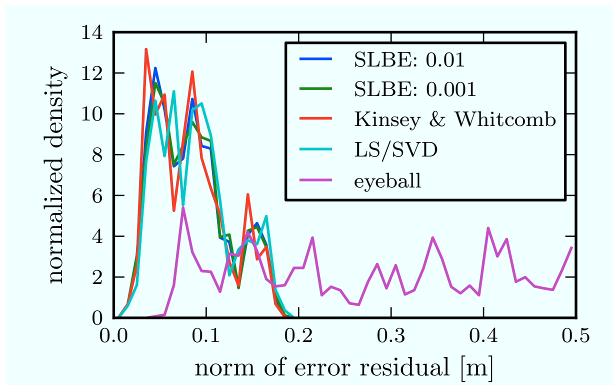

Fig. 2. Norm of position error after renavigating with alignment identified by various methods. (300 kHz LBL used as ground truth.) The lines labeled SLBE are the new rotor identifier, with two different proportional gains. This performs comparably to the $SO(3)$ identifier presented by Kinsey & Whitcomb, and the standard LS/SVD batch method. All alignment estimates improve the position error over the 'eyeball' estimate of 45° heading offset.

The end result measure of identifier performance is to renavigate the dataset using the identified alignment. Figure 2 shows a normalized histogram of the magnitude of the position error vector after renavigation with several different alignment estimates. This example uses data from a previous study [8] with a laboratory remotely operated vehicle (ROV), and the ground truth is a trajectory of independently measured 300 kHz LBL positions. Analysis is underway using field data from autonomous underwater vehicle (AUV) *Sentry* dives.

The new rotor identifier performs comparably to the $SO(3)$ identifier from [8] and the constrained least squares/singular value decomposition batch method from [9]. All estimated alignments provide improved position estimates over the uncalibrated 'eyeball' alignment ($45°$ in yaw).

B. Dead reckoning through the water column

Although existing navigation methods work well at the surface and near the seafloor, vehicles must rely on external acoustic tracking systems for localization in the water column. This research developed a new method to localize an underwater vehicle through all phases of its mission, including descent and ascent, without using external acoustic tracking systems. This can enhance the autonomy of underwater vehicles since it relaxes the dependence on ultra-short baseline (USBL) or LBL acoustic positioning, both of which cost valuable ship time.

Dead reckoning through the water column, as depicted in Figure 3, uses overlapping current profiles measured by an acoustic Doppler current profiler (ADCP) to simultaneously estimate the velocities of the

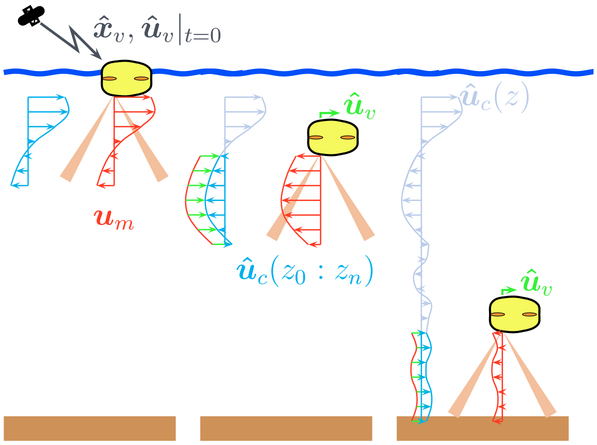

Fig. 3. Surface-to-seafloor navigation using an ADCP to measure the current profile. 1) The vehicle starts with GPS position information and a partial current profile. 2) The vehicle descends below the surface, losing GPS but extending its current profile measurement deeper. 3) The vehicle reaches operational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

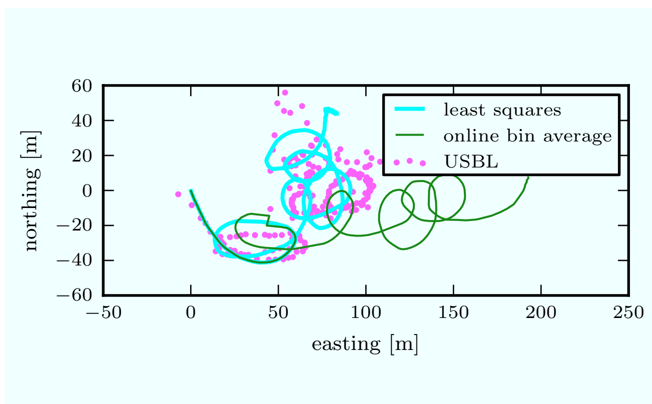

Fig. 4. Estimated vehicle trajectory during ascent from 1000 meters at the end of Sentry dive 085. The least squares method for DR through the water column is consistent with the independednt USBL fixes, but the estimate from the online bin average method exhibits its weakness in this dataset. It is thrown off by a few bad velocitied early in the ascent, and the coupled nature of the estimates for vehicle and water velocity throws the entire dead reckoned trajectory off.

vehicle and the surrounding water. This provides necessary navigation data in addition to a current profile that may be useful to oceanographers. The main assumption is that the local ocean current varies slowly compared to the descent/ascent time. The vehicle only needs an ADCP, a heading reference, and a depth gauge. The method has been developed this way so that it is applicable to a wide variety of vehicle types. However, it could also be used to provide velocity aiding for an inertial navigation system (INS), or it could be aided by intermittent acoustic positioning signals.

An online bin-averaging algorithm was developed in [1], [4] to demonstrate dead reckoning (DR) through the water column. It is computationally simple, but also sensitive to measurement noise–a few bad velocities can throw off the entire DR solution. Ordinary and recursive least squares implementations are discussed in [5]. These implementations are less suceptible to measurement quality issues, and perform more consistently on field data. Figure 4 shows the DR trajectory during the ascent from *Sentry* dive 085. The least squares estimate agrees fairly well with independent USBL fixes, while the estimate from the online bin average diverges.

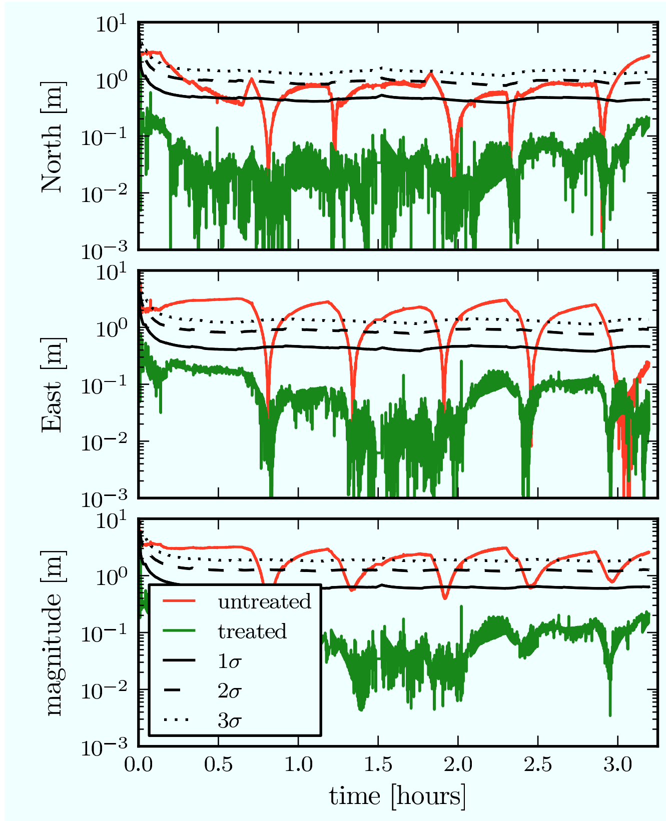

Fig. 5. Estimated position residuals for the fist survey block of *Sentry* dive 059. The estimates from realtime online filters with and without delay treatment are compared to the estimates from an offline postprocessing filter with the measurement delay removed.

C. Delayed measurement fusion

All position measurements available to submerged vehicles are inherently delayed in time. For acoustic positioning systems (e.g., USBL or LBL) the delay is primarily due to the finite speed of sound in water. In visually-aided or terrain-relative navigation schemes, the delay may be due to processing or data association. Current realtime navigation systems often ignore this delay. This research developed a flexible, model-driven approach to fuse delayed measurements using a realtime Kalman filter, and presented it in [2].

Consider a submerged vehicle navigating by dead reckoning (DR) with position aiding from a surface tender using a ultra-short baseline (USBL) acoustic tracking system and an acoustic modem. This is a real-world example[2] of a delayed state problem, and is becoming more commonplace in both oceanographic and commercial sectors.

Since this is *Sentry* field data, there is no 'ground truth' to benchmark filter performance. Instead, we use a third filter–it operates offline in postprocessing, where the measurement latency can be removed entirely. Figure 5 shows that the delay-compensated filter performs much better than a standard uncompensated filter. In fact, it performs comparably to the reference filter with the delays removed.

The residuals from the untreated filter fall outside the confidence bounds reported by the filter. This is particularly true in the East-West (i.e., alongtrack) direction, which is consistent with a time delay.

III. Significance and Impact

Underwater navigation is a difficult and intellectually stimulating area of research. The rotor identifier highlights the importance of clarity and geometric intuition in understanding problems with rotations–it

[2]Asynchronous LBL positioning is another compelling example, and will be covered in [7].

also serves as a concrete example of how Geometric Algebra can be applied to solve real problems in robotics. Dead reckoning through the water column is possible if the data is high enough quality. This has big implications for shallow AUV surveys where a vehicle may surface several times during a mission–the vehicle can now navigate between the surface and the seafloor without losing track of its position and without any external aids. The model-driven approach to delayed measurement fusion can be applied to any problem with delayed measurements–underwater navigation is only the first example. The actual implementation also encourages the user to understand how a Kalman filter really works, instead of just using it as a magic black box. This research has developed novel solutions to three problems in underwater navigation, and the deliverable result is improved realtime performance with the potential for increased autonomy.

IV. Where might this lead?

Each problem and solution presented here leads to even more questions. Posing the rotation identification problem in GA simplifies the solution–can we extend that solution to also include the translation parts of the sensor alignment? Will we find similar simplifications by applying GA to other problems in ocean engineering? How far are we from dead reckoning between the surface and seafloor during day-to-day operations? How much can we improve LBL navigation using model-driven delayed measurement fusion, and what other systems exhibit significant measurement delays? These are all important questions. Some of them are topics of ongoing research, and I hope that others are curious enough to join the investigation.

APPENDIX A
DISCRETIONARY FUNDS STATEMENT

The equipment fund was used to purchase two small inertial measurement units (IMUs) that I used to familiarize myself with the technology and set up some very basic demos. I also purchased parts to build a workstation computer to run my postprocessing codes much faster and reduce my debug cycle. This proved very useful, especially when I started renavigating full field datasets from *Sentry* dives. This computer also serves as a redundant repository for all my data and code, providing a safeguard if my personal laptop is lost, stolen, or falls off the side of a ship. Finally, I bought a small digital storage oscilloscope. This helped me when debugging sensor and timing issues, and I am sure that I will find it useful in future projects as well. The funds allocated to help defray publication costs will be applied to a future[3] journal paper on rotation identification using GA [6], which is currently in preparation.

APPENDIX B
THE LINK FELLOWSHIP DIFFERENCE

Receiving the Link Fellowship provided me with continuing freedom to follow my own direction in research. I found it very rewarding to pursue the thread on Geometric Algebra, which I may not have been able to continue without external support. I am now better prepared to define and execute my own research plan, and feel confident that I will be successful in life after Graduate School. The expertise I gained in Geometric Algebra, Kalman filtering, and real-world oceanographc operations, will serve me well. I am sure that having this prestigious award on my *curriculum vitae* will also be beneficial.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Dana Yoerger, and my other committee members, Prof. Alexandra Techet, Prof. Franz Hover, and Dr. James Kinsey for asking the right questions and helping me stay on track. Many thanks to the *Sentry* team for helping me collect meaningful data during field deployments, to Dr. Sinton for allowing me to use data from the GRUVEE2010 cruise aboard R/V *Atlantis*, and to Dr. de Ronde for the navigational data from the NZASMS 2011 cruise aboard R/V *Tangaroa* (funded by GNS Science and OS2020 of New Zealand).

ACRONYMS

AUV autonomous underwater vehicle
ROV remotely operated vehicle
DR dead reckoning
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
IMU inertial measurement unit
FOG fiber-optic gyroscope
GA Geometric Algebra
SVD singular value decomposition
CLS constrained least squares

[3] I have confirmed with Dr. Maul via email that it is acceptable for Woods Hole Oceanographic Institution (WHOI) to hold these funds until the paper is published and I am billed for the publication costs.

Conference papers published

[1] M. J. Stanway, "Water profile navigation with an acoustic Doppler current profiler," in *Proceedings of OCEANS*. Sydney, Australia: IEEE, May 2010.
[2] ——, "Delayed-state sigma point Kalman filters for underwater navigation," in *Proceedings of the Autonomous Underwater Vehicles Conference (AUV)*. Monterey, CA: IEEE, September 2010.
[3] M. J. Stanway and J. C. Kinsey, "Sensor alignment using rotors in geometric algebra," in *Proceedings of the International Conference on Robotics and Automation (ICRA)*. Shanghai, China: IEEE, May 2011, peer-reviewed.
[4] M. J. Stanway, "Contributions to automated realtime underwater navigation," in *Proceedings of the 17th International Unmanned Untethered Submersible Technology Conference (UUST)*. Portsmouth, New Hampshire: AUSI, August 2011, (student paper award winner).

Conference papers accepted

[5] M. J. Stanway, "Dead reckoning through the water column with an acoustic Doppler current profiler: Field experiences," in *Proceedings of OCEANS*. Kona, Hawai'i: MTS/IEEE, September 2011, (student paper accepted).

Journal articles in preparation

[6] M. J. Stanway and J. C. Kinsey, "Rotation identification using geometric algebra," *IEEE Transactions on Robotics*, 2011.
[7] M. J. Stanway and D. R. Yoerger, "A model-driven approach to delayed measurement fusion and its application in realtime underwater navigation," *Journal of Navigation*, 2011, (could be IEEE JOE instead).

External references

[8] J. C. Kinsey and L. L. Whitcomb, "Adaptive identification on the group of rigid-body rotations and its application to underwater vehicle navigation," *IEEE Transactions on Robotics*, vol. 23, no. 1, pp. 124–136, Feb. 2007. [Online]. Available: http://dx.doi.org/10.1109/TRO.2006.886829
[9] ——, "In situ alignment calibration of attitude and Doppler sensors for precision underwater vehicle navigation: Theory and experiment," *IEEE Journal of Oceanic Engineering*, vol. 32, no. 2, pp. 286–299, April 2007. [Online]. Available: http://dx.doi.org/10.1109/JOE.2007.893686