Improving Slocum Glider Dead Reckoning Using a Doppler Velocity Log

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Abstract— **The Slocum Electric Glider is a buoyancy driven Autonomous Underwater Vehicle (AUV) capable of long term deployments typically lasting four to six weeks. During missions execution, the vehicle makes use of the Global Positioning System (GPS) to navigate to its commanded waypoints. GPS, however, can only be used while the vehicle is at the surface. While underwater, the glider uses a simple dead reckoning (DR) algorithm to estimate its location and does not find its true position again until its next periodic surfacing.**

The Slocum Glider's dead reckoning algorithm estimates its position based on speed and heading calculations; they are derived from measurements from onboard sensors. Specifically, speed is determined by the depth rate change and pitch angle over a period of time. Since there is limited sensory input to the algorithm, the vehicle's estimated global position can differ significantly from its true position. Precise location information is important when collecting spatiotemporal sensitive sensor data and for vehicle navigation. In this paper, we will explore the benefits that can be gained if the dead reckoning algorithm makes use of a Doppler Velocity Log (DVL) to improve a vehicle's location estimates. Initial results based on a deployment equipped with the DVL on a Slocum Glider show promising results.

I. INTRODUCTION

The Slocum Electric Glider is a buoyancy driven Autonomous Underwater Vehicle (AUV) used to study the world's oceans [7], [10]. Instead of using a propeller to achieve forward motion, it makes use of a buoyancy engine that changes the vehicle's displacement of water by moving a piston at the front of the AUV. With the use of its wings, and the buoyancy engine, the glider flies a saw-toothed profile as it navigates to its instructed waypoints.

Unlike propeller driven vehicles such as Remus [4] and Iver [5], which require more constant use of their motors, a glider requires the use of its engine only at inflection points [2], [7], [8], [10]. This enables the vehicle to perform prolonged missions that last several weeks or months. However, the disadvantage is that the buoyancy engine propels the Slocum Glider quite slowly, with an average speed of approximately 35 cm/sec. This leaves the AUV extremely susceptible to ocean currents which can have a detrimental effect on its navigation while underwater. This is more problematic in gliders than propeller driven vehicles which can more actively combat currents. Hybrid systems such as MBARI's LRAUV [1] combine a buoyancy engine with a propeller for more operational flexibility.

An AUV's ability to predict its location is important for a number of crucial tasks. Path planning algorithms, for example, need to be able to track the vehicle's location so that it can surface as close to the target waypoint as possible. Additionally, some sensors may need to be tagged with high spatial accuracy. Most AUVs currently use a dead reckoning (DR) algorithm to predict their location. In the case of the Slocum Glider, it is computed from measurements of pitch, heading, and depth change. Though easy to implement, this form of dead reckoning can produce inaccurate estimates, especially for long dive segments. The lack of water current measurements, imprecise sensor readings, and other effects can influence an AUV's flight path and inaccurately cause the glider to drift away from its true location during missions.

More accurate DR localization strategies for the glider could take into account Acoustic Doppler Current Profiler (ADCP) or Doppler Velocity Log (DVL) sensor data. A DVL, for example, is able track the bottom of the ocean floor, allowing it to calculate the relative motion of the vehicle to the floor. The sensor's reported speeds could then be replaced by the traditionally calculated speeds during the DR process. In this paper we will explore such a strategy for the Slocum Glider and demonstrate how it can dramatically improve the vehicle's localization estimates. We evaluate this approach by comparing a glider's estimated flight segments from a 12 day deployment off the coast of New Jersey both with and without DVL assisted dead reckoning (DVLDR).

II. BACKGROUND

A standard Slocum Glider is equipped with two Persistor CF1 processors at 16MHz [6]; one designated as the flight controller, the other the science processor. The flight controller is responsible for the vehicle's flight and interacts directly with critical sensors to ensure the safety of the vehicle. Meanwhile, non-critical scientific sensors are connected to the science computer for processing and logging.

Drivers, also known as proglets, written for science sensors like the DVL, can require knowledge of other sensor values to perform their measurements. This information may be ascertained from other sensors connected to the science processor or from the flight controller. A serial connection (RS-232) between the two processors provides the necessary hardware infrastructure for data transmission. A software protocol known as the "superscience" protocol controls how the processors interact with one another to perform the actual sensor data exchange. For example, the computers can request from one another a sensor value to be sent only once, when changed, or when touched (timestamp update on the sensor value).

The DVL proglet on the science process requires five such sensors from the flight controller to be sent upon every change: current water depth, vehicle depth, pitch, roll, and heading. The most current view that the science computer has of these values is sent to the instrument upon each measurement request to update the DVL's view of the environment. Since the sensor requires these data to perform accurate readings, it is critical that they be as up-to-date as possible. Delays in the transmission of the sensor data could effect the bottom tracking reported by the sensor which propagates to the DVLDR strategy.

The traditional dead reckoning algorithm on the Slocum Glider is quite simple and calculates the vehicle's estimated position at every four second control cycle. The algorithm requires input from two onboard sensors, namely the pressure and attitude sensors. The pressure sensor allows the vehicle to determine its depth (d) in the water, while the attitude sensor measures the vehicle's pitch (θ), roll and heading (h). The following describes the basis of the algorithm as it calculates its new location in the local mission coordinates (LMC) system:

$$ws = \frac{-\Delta d}{\tan \theta} \tag{1}$$

$$\begin{aligned} vx &= (ws * \sin h) * wvx \\ vy &= (ws * \cos h) * wvy \end{aligned} \tag{2}$$

$$\begin{aligned} \Delta x &= vx * \Delta t \\ \Delta y &= vy * \Delta t \end{aligned} \tag{3}$$

$$\begin{aligned} lmcx &= lmcx + \Delta x \\ lmcy &= lmcy + \Delta y \end{aligned} \tag{4}$$

$$dist = \sqrt{\Delta x^2 + \Delta y^2} \tag{5}$$

The LMC system is the internal navigation system used by the Slocum Glider. It describes the distance in meters the vehicle has moved north and east since the start of the current mission. Equation (1) determines the vehicle's speed through the water using the current pitch θ and the change in depth Δd since the last control cycle. Next, in equation (2), the glider's velocities are determined using the current heading (h) and an optional water velocity component for current correction. `Vx` denotes the eastward velocity while `vy` denotes the northward velocity. These components are converted to meters in equation (3) by multiplying them with the time since the last control cycle. The new DR position is then determined in (4) by updating the last calculated location with newly made LMC progress during the current cycle. The final horizontal distance covered is determined in equation (5).

For short dive segments the described technique works quite well. However, for longer dive segments, or segments where the currents are strong, errors in the estimation can accumulate over time. For many applications, a highly accurate DR position may not be required and the existing approach is still valid. Some scenarios like path planning and navigation through shipping lanes require more accurate DR predictions. To improve DR on the glider, we explore how a DVL performing bottom tracking could be integrated into the existing DR algorithm to assist the vehicle in underwater navigation.

III. EVALUATION

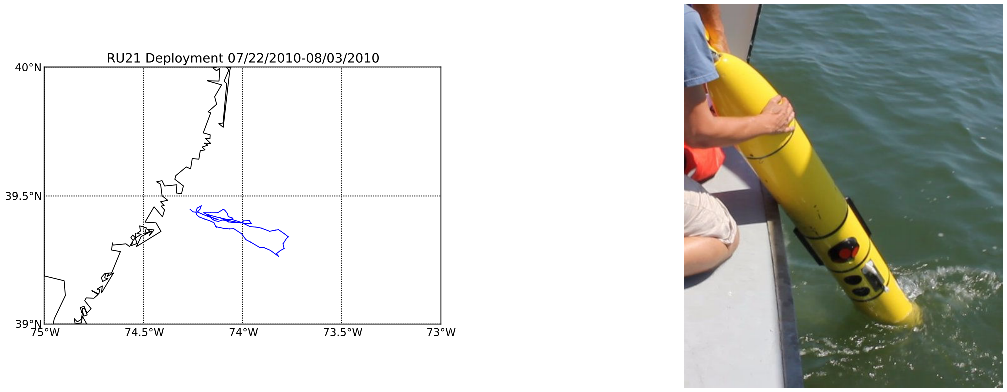
A glider's DR error can be influenced by a variety of effects; a DVL, however, may provide the necessary sensory input to greatly reduce this error. To gain a quantitative perspective as to how much a DVL may assist in the DR of a glider, we evaluate DVLDR with a previously flown deployment equipped with a DVL [9]. The original flight was flown without DVLDR, however we will investigate how much closer a DVLDR implementation could come to the actual surface location of the vehicle for each dive segment.

A. Deployment

The deployment used as the basis for the evaluation of the DVLDR took place off the coast of New Jersey from late July 2010 to early August 2010, lasting 12 days. The overall objective of the mission was to test a new glider equipped with a DVL [9] as well as other new sensors. The flight path taken by the vehicle over the short mission is shown in Fig. 1(a), and a picture of the recovery of the vehicle is shown in Fig. 1(b). The dual science payload bays in the middle of the hull contain the glider's scientific sensors; the DVL was carried in the aft science bay for the deployment.

Since the exact performance of the newly tested sensors under field conditions were not yet known, the vehicle was commanded to remain relatively close to shore to ensure a quick recovery if required. The water depth during all dive segments were within 35 meters, which was well within the maximal (theoretical) 60 meters bottom tracking range of the DVL. Dive segments during the deployment were also kept quite short at an average of two hours with about 20 minutes for data transmission to shore while at the surface. On average, when a glider surfaced and gained a GPS fix, it was approximately 0.5 kilometers off its estimated DR surface location. The minimum and maximum distances from the DR position were 23 meters and 1.4 kilometers respectively. Thus, although not detrimental, the dive segments were rather short so room for improvement to reduce the error of the DR position exists.

As described in Section II, the proglets on the science computer communicate with sensors. Their data can then be logged locally on the science computer, or sent to the glider flight controller to be recorded. Traditionally, before the seventh release of the Slocum Glider software, only logging on the flight Persistor was possible. Although the vehicle for the said mission was running release seven of the codebase,



(a)

(b)

Fig. 1. The flight path of a glider deployment (RU21) from July 22, 2010 to August 3, 2010, off the coast of New Jersey (a). The vehicle was equipped with a DVL [9] that performed bottom tracking throughout the mission. The glider being recovered from the deployment (b). The DVL is part of the aft sensor payload bay in the center of the vehicle. The wings of the glider were removed during recovery to allow the glider to be pulled onto the boat without damaging the sensors.

no science data logging occurred. This was intentional, as the feature was still maturing and the functionality of other components, like the DVL, were the focus of this mission.

The decision to not perform data logging on the science computer also had its faults as it not only impacted the DVL data being logged but also the measurements themselves. The serial connection between the science and glider Persistors is slow, running at 9,600 baud rate on releases before the seven series and 4,800 baud rate since the seven series release. Science data logging reduces the traffic on the serial connection and is likely the reason why the baud rate was lowered. However, sensors like the DVL send a large amount of data which increases the load on the communications system.

In Section II the sensors needed by the DVL to perform its measurements were described. Not only are the five input values regularly sent across the serial link, the results produced by the sensors are also sent. Currently, during bottom tracking, the DVL can produce up to 46 output sensor values. Although not all values must be sent, since they may not have been updated, there is still contention on the serial connection since it is shared by other proglets including the Conductivity, Temperature and Depth (CTD) sensor.

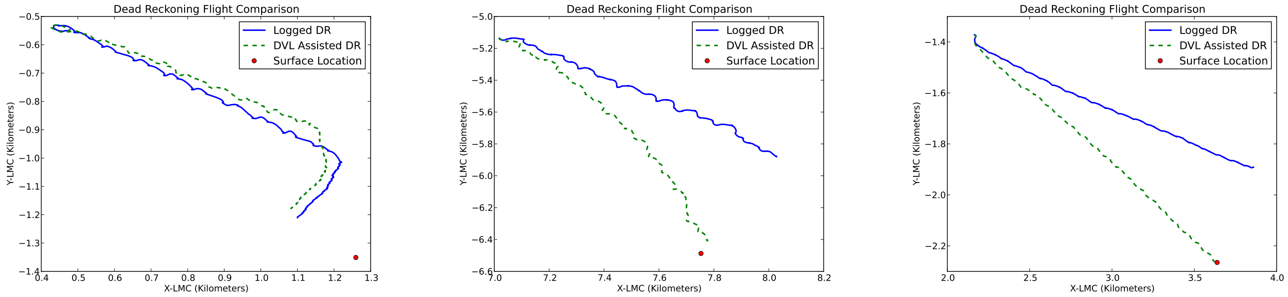
From a science Persistor point of view, the snapshot of the vehicle's physical orientation it receives from the glider may be inconsistent. For example, when updating the DVL's viewpoint of the environment to prepare the sensor for a measurement, a new pitch value may have been received by the proglet. However, an older depth value from a previous glider cycle will be used if it has not been updated in time. In this scenario, the DVL may perform a measurement while diving that lags behind by several meters in depth which could effect the results. The opposite also holds true. The readings logged by the flight controller may be a conglomerate of both new and stale values that are several cycles old. Thus, although the data used in the evaluation is not always the most up-to-date, it can still prove useful in improving DR. Future deployments that enable science data logging should show even more promise since less contention exists on the serial link which enables more updates to be sent to the sensor.

B. *Methodology*

To evaluate how a DVL can assist in dead reckoning, a metric to compare the two DR methods must be established. Ideally, an underwater localization algorithm should be without error and be capable of calculating the true position of the vehicle at any time. However, the glider's DR algorithm, for example, has sensory input and computation limitations which can cause errors to accumulate over time. This becomes apparent when the vehicle surfaces after a dive segment, as the DR location usually differs from newly acquired GPS position. The distance between the the DR and the GPS locations is used as the metric for our evaluation. The closer that the DR comes to the GPS fixed surface location, the better the algorithm was able to estimate the vehicle's position.

During the deployment, the glider only performed the standard DR algorithm as described in Section II, so DVLDR must be simulated. To ensure that the results produced by a simulated DVLDR can be trusted, and the retrofitted glider software would produce similar results, DVLDR should be based on a similar algorithm to the one in the glider. We have ported the glider's DR algorithm to run independently from the vehicle and adapted it to make use of data recorded during previous deployments. When running the ported DR algorithm with the dive segments of the sample mission, the difference between the ported and vehicle's logged DR position were negligible, usually within one meter. This is due to the difference in the glider's state information used for the DR calculation. While the true vehicle's state is evolving during a control cycle, the ported algorithm instead uses a state snapshot that is recorded for each cycle.

To simulate DVLDR, the ported algorithm is altered to take into account the DVL. When valid data is produced from the sensor, the northward and eastward velocities are used in place of the calculated velocities of equation (3) in Section II.



(a) (b) (c)

Fig. 2. Comparison of flight paths of logged dead reckoning flights against DVL assisted dead reckoning (DVLDR) flights. In general, DVLDR significantly improves estimated vehicle position as in (b) and (c), while at times the traditional DR estimates are more accurate (a).

When the sensor is not able to perform bottom tracking, or its data is determined stale, the DVLDR will fall back to the traditional DR strategy. The sensor may not be able to perform bottom tracking, for example, if the water depth is too deep or the DVL cannot reliably detect the ocean floor. Using a combination of both strategies produces significantly better results compared to the standard approach.

C. Results

By replaying the mission with recorded data from the deployment, and using the velocities gathered from the DVL, DVLDR is able to significantly reduce the DR error compared to the traditional approach in most cases. Three sample segments from over 130 segments of the deployment are shown in Fig. 2. The figure compares algorithm performance from the worst case scenario to the best.

Fig. 2(a) presents the worst case of the ten segments where DVLDR did not outperform the standard DR algorithm. The logged DR position placed the vehicle 212 meters from the GPS fixed position, while DVLDR estimated 246 meters, an additional error of 34 meters. The standard deviation of the ten segments was less than 13 meters, which in the overall scheme of the deployment including the successful segments is not significant.

The flights paths of Fig. 2(b) and Fig. 2(c) showcase an average and one of the best segments that was improved. The errors, such as in Fig. 2(b), are likely caused by the vehicle losing bottom tracking and the algorithm falling back to the traditional DR method, or possibly by errors in the measurements themselves. As stated in Section III-A this may have been caused by the delay in sensory input either to the DVL or from the DVL to the flight controller.

For all segments of the mission, DVLDR reduced the average surface location DR error from over half a kilometer to under a quarter of a kilometer. The minimum and maximum error were 6.5 meters and 1 kilometer respectively, compared to the 23 meters and 1.4 kilometers by the traditional approach. Overall, usage of a DVL during DR has a great impact on reducing the error of the glider's localization strategy. Using this new algorithm during deployments could improve overall vehicle navigation. Having a better sense of the vehicle's location translates into being able to calculate more accurate heading corrections towards the target waypoints. Sensors that require more accurate tagging would also be benefited from this method.

IV. CONCLUSION

In this paper we show that a DVL can significantly improve a glider's dead reckoning location estimates. A brief overview of the current DR algorithm on the vehicle was described and a port of the algorithm was created to run independently from the glider. The ported code was retrofitted to incorporate data from previously flown missions. In particular, compared to the logged DR records from the deployment used for the evaluations, the port averaged within less than one meter of error.

With a solid foundation in place, the code was further modified to incorporate the logged velocity measurements produced by the DVL while bottom tracking. Although the DVL data during the mission was imperfect, it was more than adequate to showcase the impact the sensor can have. Over 92% of the segments for the sample deployment would have projected the surfacing location more closely if the vehicle made use of DVLDR. The estimate for each segment was also on average 42% closer to the actual surfacing position. Out of the few segments where DVLDR did not improve, for the worst segment, it calculated a position only 34 meters further from the surface location than the traditional approach (that itself was off by over 212 meters). Overall, DVLDR is worthwhile if missions or applications require more accurate underwater localization and can cope with the additional energy required by the DVL sensor.

There are different payload sets that can be deployed in the gliders, including DVL, FIRe, and bio-puck sensors. The power dissipation of some sensors, communication modems, and motors is shown in Table I. It is important to note that the duration of sensor operation and other operational parameters (e.g.: sampling frequency, depth at which buoyancy pump is activated) will determine the overall energy consumption and battery life. For example, even though the power requirements of the CTD sensor is rather low, its overall energy consumption may be significant since the sensor is typically active during an

TABLE I
POWER DISSIPATION OF SELECTED SENSORS AND MOTORS

Sensor/Motor	Description	Power (Watts)
DVL [9]	Doppler velocity log	1.5
FIRe	Fluorescence induction and relaxation	5
Bio-pucks	Fluorometer	0.75
CTD	Conductivity, temperature, depth	0.1
Buoyancy Engine	Changes buoyancy	3 - 26 (depth dependent)
Fin motor	Navigation	0.5
Pitch motor	Changes center of gravity	2
WHOI's Micro-Modem [3]	Acoustic underwater communication	10
Iridium	Satellite communication	4.5

entire mission. This is not the case for motors (e.g.: buoyancy pump is only active at inflection points) and communication modems. All the listed sensors are available for deployment in our glider lab. Based on these measurements, running the DVL continuously is feasible, but its energy consumption can become an issue for longer missions. As a result, a DVLDR location algorithm is desirable that uses the DVL on-demand (e.g.: only in conjunction with a spatiotemporal sensitive sensor) or only intermittently.

V. FUTURE WORK

We are in the process of creating a new generic sensor platform for the Slocum Glider which will extend the vehicle's current sensor integration capabilities. The initial goals for this platform are to create an accurate power measurement infrastructure that will be used to determine energy profiles of individual glider components, including the DVL. This is to expand our previous efforts to improve the energy models of the glider for our simulation infrastructure [11].

In terms of the glider, the DVL is a relatively energy expensive sensor. Algorithms should schedule and manage its usage to get the most utility out of the sensor. For example, an algorithm may determine that after a dive segment without the DVL powered that a significant drift is detected, the DVL should be used for some time during the next profile. The opposite could also be true; if the currents do not appear to affect the vehicle as much, an algorithm may choose not to use the DVL. Shore based data from weather prediction models could also play a part in the decision making and would relay new instructions to the glider while it is at the surface. The power measurement infrastructure will quantify the energy usage and provide feedback to the algorithms so that they may make any necessary adjustments.

We plan to deploy one of our Slocum gliders with a DVL in the near future. Unfortunately, RU21, the DVL equipped glider which performed the discussed initial DVL measurements, was lost at sea during a mission in Antarctica shortly after the test deployment. Since then, support for raw data logging mode has become available on the science bay processor. Although we still plan to use the bottom tracking mode for DR, the raw data may also become useful in the near future and could be processed in real time by our onboard Linux Single Board Computer (SBC).

Finally, we also hope to develop an additional sensor for our sensor platform that will measure the vehicle's pitch, roll and heading. Although these sensors will then become redundant in the vehicle, they could greatly improve the accuracy of the DVL. A driver developed for the science computer will collect the measurements from the sensor platform and feed them directly to the DVL driver. This will reduce the latency of the data required by the DVL because the data is local and must no longer be transmitted by the glider processor through the slow serial connection. The sample quality collected by the DVL directly effects the performance of the DVL assisted DR. Thus, more accurate readings translate into more accurate vehicle position estimates.

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