BLUEFIN LOW-COST UUV NAVIGATION SYSTEM AND PERFORMANCE

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Abstract: Bluefin Robotics is a leading developer and supplier of Unmanned Underwater Vehicles (UUVs) and associated technologies for use in underwater systems. We offer two different grades of UUV navigation solutions. To meet the highest navigation accuracy requirements, Inertial Navigation Systems (INS) have been integrated in Bluefin UUVs. This paper presents our low-cost, non-acoustic, dead-reckoning navigation system, which combines low cost sensors with advanced software algorithms to yield the best dead-reckoned navigation accuracy of any compass-based UUV platform. We discuss our navigation approach and present navigation performance results from navigation trials with our Bluefin-9, Bluefin-12, and Bluefin-21 platforms.

Keywords: Navigation, Autonomous Vehicles.

1. INTRODUCTION

Bluefin's lower-cost navigation system is so-called because the individual sensors are each lower cost in comparison to the high-end Inertial Navigation Systems used on most UUVs. Our lower-cost navigation system consists of a magnetic compass, an Inertial Measurement Unit (IMU), a Doppler Velocity Log (DVL), a depth sensor, and a commercial- or military-grade GPS receiver. The IMU is a tactical-grade tri-axial Ring Laser Gyro (RLG) and accelerometer package for high accuracy and reliability (e.g. 1 deg/hr drift).

UUV dead reckoning navigation performance is typically expressed by the position error accrued as a percentage of Distance Traveled since the last external position update. This % of DT value is usually associated with a confidence level that expresses the percentage of the time the performance will be achieved. For instance, if a vehicle is said to dead reckon better than 1% of DT (2σ), it means that if the vehicle executed 100 tracklines of length 1 km, the position error at the end of 95 of the tracklines would be less than 10 m. Only five of the tracklines would result in larger position errors.

The UUVs fitted with our lower-cost navigation solution navigate by underwater dead-reckoning phases interspersed with GPS updates. These GPS fixes bound the position error growth after the dead-reckoning phases. Thus, the overall navigation accuracy, in terms of maximum expected navigation errors, can be tailored for a particular mission by adjusting the distance that the UUV travels between GPS updates.

In order to maximize the survey time and increase the coverage rate, the duration of a GPS update is kept as short as possible by checking the quality of the GPS data: as soon as the vehicle collects GPS positions that meet certain quality criteria, the vehicle dives for the next trackline. Between GPS updates, the UUV dead-reckons by integrating its velocity relative to the bottom rotated in a north-pointing local-level reference frame.

As the UUV conducts its mission, a real-time navigation calibration algorithm estimates systematic navigation errors at the end of each trackline. As the mission progresses, the navigation accuracy continues to improve until we meet the lower-bound that is imposed by unobservable GPS position fix errors and compass resolution. Once the mission is concluded, the mission can be re-navigated to further improve the navigation accuracy, especially on the first few tracklines. With this system, the accuracy achieved is better than 0.25% of DT (1σ) in post-processing and better than 0.5% of DT (2σ) in real-time. This performance measures very favorably against that achieved by the typical INS-based AUV navigation systems, where errors of 0.1 to 0.3% of DT are typical, and eclipses the performance of other UUV dead-reckoning navigation systems, where errors of 1 to 2% of distance traveled are typical. Furthermore, our lower-cost navigation solution does not require the installation of acoustic beacons in the operation area or lengthy INS alignment periods, special ship maneuvers (dog-legs and boxes) during an alignment, or other extensive calibration periods.

2. DEAD RECKONING ERROR SOURCES

The main contributor to position errors during compass-based dead reckoning is the compass heading bias, which causes cross-track position errors. The situation is made more difficult by the fact that the compass bias varies with the direction the compass is pointing. The problem then becomes that of calibrating this heading-dependent heading error. The sources of compass disturbance can be divided in soft-iron effects associated with magnetic materials in the vehicle that deflects the earth magnetic field direction, and hard-iron effects due to electromagnetic field generated by the onboard electronics for instance. Calibrating the compass in a vehicle requires taking care of both error sources.

The second contributor to dead reckoning errors is the DVL velocity scale factor which produces along-track position errors. The scale factor is primarily environmentally driven. Inaccurate knowledge of the sound speed profile between the DVL transducers and the seafloor, the bottom roughness, and the acoustic absorption all contribute to it. Scaling errors can be reduced by using a sound speed sensor or a Conductivity Temperature Depth (CTD) probe in the vehicle, but a residual error will always remain that needs to be calibrated out as best as possible.

3. CALIBRATION

We take particular care of the compass measurements by performing calibrations at different levels. After a vehicle is manufactured, it is taken out to sea by Bluefin's operations personnel to run a compass calibration mission. This mission is specifically designed to exercise compass errors. After execution of the compass calibration mission, the navigation data are post-processed by a post mission analysis tool integrated in our operator software suite. The result is a set of correction parameters that once applied to the compass measurements improve the overall navigation accuracy. Typically, with the calibrated parameters, the vehicle will navigate with accuracy better than 1% of DT (2σ) if it is operated close to where the compass calibration mission took place (Willcox, *et al.*, 2001; Rish, *et al.*, 2001). This provides the vehicle with its basic navigation capability. The compass calibration mission does not need to be redone unless the magnetic environment of the compass is changed in the vehicle, by adding electronics close to it or modifying the soft-iron effects.

If the vehicle is moved to another location, however, this navigation accuracy can no longer be guaranteed due to unknown variations in certain external parameters affecting the dead reckoning navigation accuracy. Therefore, a real-time calibration capability has been added to allow correction of the error sources that are no longer correctly compensated for by the calibration parameters. The real-time calibration component of the navigation algorithm will determine residual heading and velocity errors and correct them during the execution of the mission.

4. RENAVIGATION

When the vehicle is brought back on deck, vehicle data are automatically downloaded and post-processed. Part of the post-processing consists of re-navigating the missions to further improve navigation accuracy. Given the excellent performance of the real-time navigation, re-navigation is only beneficial for the first few tracklines for which no prior real-time corrections are available.

5. BLUEFIN-12 UUV NAVIGATION ACCURACY DURING GOMEX 2006

Figure 1 shows a typical mission with a Bluefin UUV employing our lower-cost navigation solution. The navigation data presented is taken from a recent U.S. Navy exercise in the Gulf of Mexico (GOMEX 2006) with a Bluefin-12 vehicle. The mission consisted of 14 tracklines of 3300m length, each. The mission was completed in 7 hours 30 minutes.

The navigation performance for the mission is shown in Figure 2, where the black line indicates the real-time position error as a percentage of distance traveled, and the red-line indicates the post-processed navigation error as a percentage of DT. Because we rely upon GPS fixes at the beginning and end of trackline to estimate the parameters in the error model, short tracklines like the initial transit waypoint provide poor measurement of heading error biases. The navigation accuracy on this waypoint is therefore not shown. With successive observations along survey tracklines, the real-time error decreases until a lower bound due to GPS position fix uncertainty and compass resolution is met.

Figure 3 and figure 4 show the same plots for a 48 trackline survey, with 2200 m tracklines, lasting 18 hours and 27 minutes. Trackline #26 is a transit leg between two different survey areas. Since this trackline on a different heading, it does not benefit (or perturb) the real-time navigation calibration along the survey tracklines.

Figure 5 shows the probability distribution function for real-time navigation accuracy and accuracy after renavigation. All 78 tracklines executed by the Bluefin-12 during GOMEX 2006, other than calibration and transit tracklines, have been used. It can be seen that the vehicle navigated in real-time with an accuracy better than 0.5% of distance traveled (2σ), or better than 0.35% of DT (1σ). Renavigation accuracy was better than 0.4% of DT (2σ) or better than 0.25% of DT (1σ). Figure 6 clearly shows the advantage of using longer tracklines that provide better resolution for the calibration of the heading errors. The figure also shows that going from 3.3 km long tracklines to 4.7 km tracklines does not provide additional accuracy benefits.

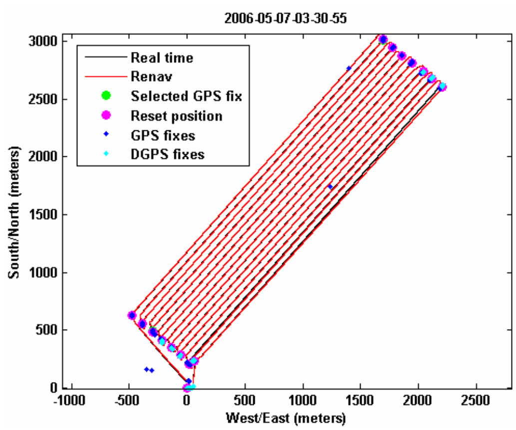

Fig. 1. Bluefin-12 survey consisting of 14 tracklines of 3300m length – GOMEX 2006.

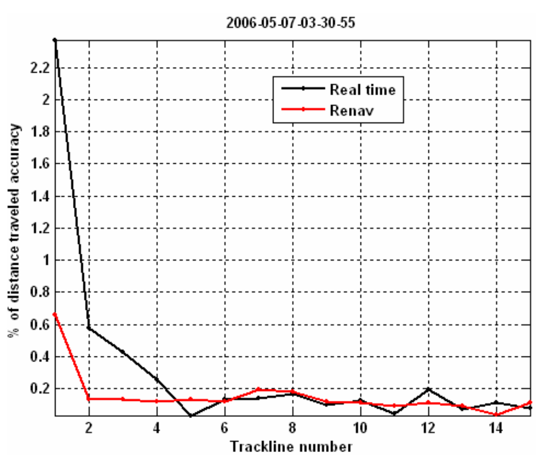

Fig. 2. Navigation accuracy for the Bluefin-12 survey shown in Figure 1.

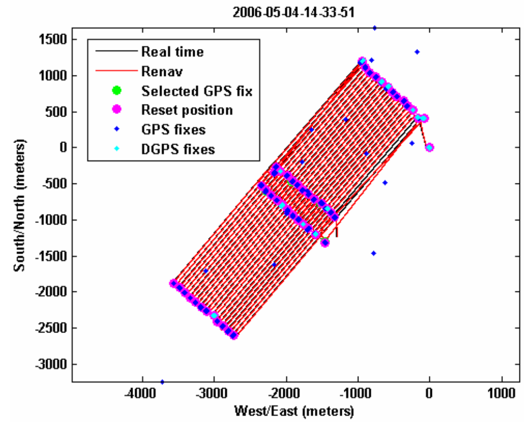

Fig.3. Bluefin-12 survey consisting of 49 tracklines of 2200m length – GOMEX 2006.

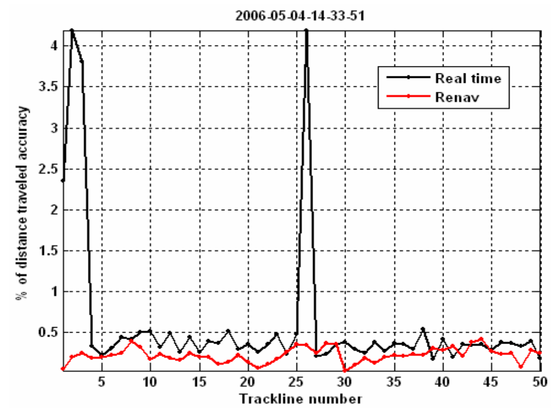

Fig. 4. Navigation accuracy for the Bluefin-12 survey shown in Figure 3.

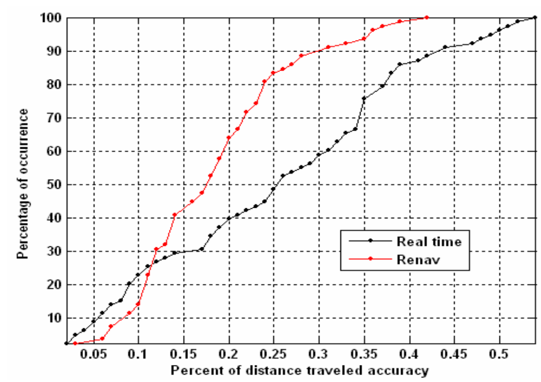

Fig. 5. Bluefin-12 navigation accuracy statistics during GOMEX 2006.

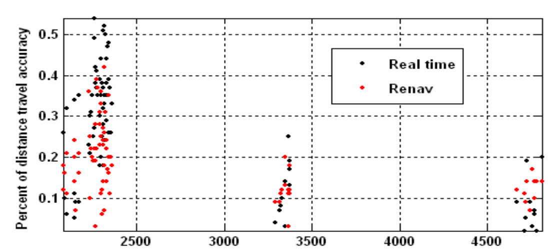

Fig. 6. Navigation accuracy as a function of trackline length for 4 different GOMEX 2006 missions.

Figure 7 shows the probability distribution function of all GPS update durations during GOMEX 2006. The duration of a GPS update is calculated as the time elapsed between the time the first GPS fix is obtained and the time the vehicle starts diving for the next tracklines. Therefore, this duration does not include the time needed to re-acquire satellite data for the first fix (specified at about 15s for a warm re-acquisition with the GPS receiver we use). Figure 7 then shows how long it took the GPS receiver to obtain fixes meeting the quality criteria that we have defined, thus allowing early termination of the GPS update behavior (180 seconds timeout). A wide variety of durations can be observed, ranging from less than a minute to more than 2 minutes. During the exercise, the results can be summarized as follows: 95% of the GPS updates took less than 2 minutes. 50% of them took less than 1 minute.

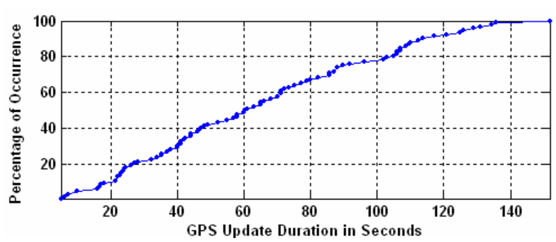

Fig. 7. Probability distribution function for all GPS update durations during GOMEX 2006.

6. REAL-TIME CALIBRATION CAPABILITY

6.1. Bluefin-21

Figures 8 and 9 show how the real time calibration is able to take care of errors that appeared due to the transport of the vehicle to another location than that where the compass calibration took place. The Bluefin-21 UUV ran the compass calibration mission in Massachusetts and used the calibration parameters for a survey executed in Florida (Figure 8). The accuracy on the first (westbound) trackline is obviously not as good as it should be (1.5 % of DT), whereas the accuracy on the first eastbound trackline is still good. Without real-time calibration of the error in the westbound direction, the navigation accuracy plot (Figure 9) would have shown a saw tooth pattern with spikes near 1.5 % of DT every other trackline. With real-time calibration, the accuracy in both directions is improved and leads to a navigation accuracy better than 0.5 % of DT.

6.2. Bluefin-9

The Bluefin-9 mission shown in Figure 10 and Figure 11 clearly outlines the effect of real-time dead reckoning errors calibration. For this mission, the compass onboard the vehicle had not been calibrated prior to running the sonar survey. Therefore the navigation accuracy at the end of the first two trackline is substantially off (2.6 and 4.3% of DT). Without real time calibration the navigation accuracy would have been similar for all the following tracklines. Thanks to the real-time calibration capability, embedded in the navigation algorithm, heading and velocity errors are calibrated out and removed for the following tracklines. As soon as the third trackline starts, the real-time navigation accuracy drops below 0.6% of DT for the remainder of the mission.

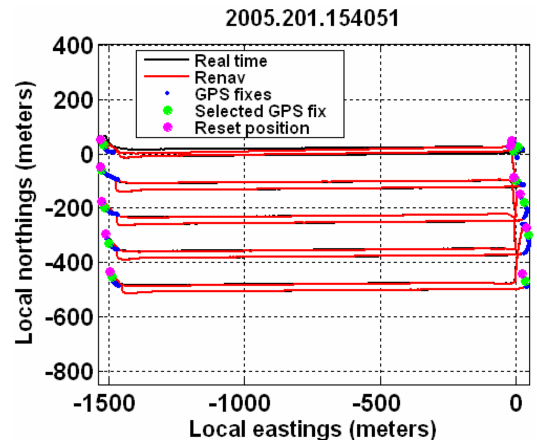

Fig. **8**. Bluefin-21 survey. Compass calibrated in Massachusetts, mission run in Florida.

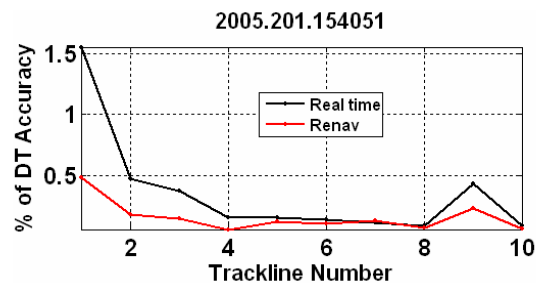

Fig. 9. Navigation accuracy for the Bluefin-21 survey shown in Figure 8.

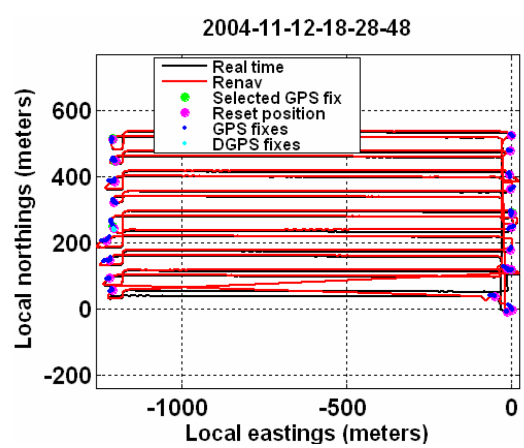

Fig. 10. Bluefin-9 survey executed with an un-calibrated compass near San Diego, CA.

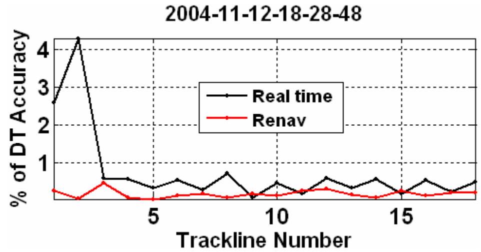

Fig. 11. Navigation accuracy for the Bluefin-9 survey shown in Figure 10.

7. NAVIGATION ACCURACY GROUND TRUTHING

For Mine Countermeasure (MCM) missions, real-time navigation accuracy is crucial to eliminate unintentional gaps or "holidays" in the sidescan sonar record. Post-processed navigation accuracy is important because it determines the accuracy with which any mine-like objects can be localized. Often, the precise location (so-called "ground-truth") of an exercise mine shape it not well known and, as such, is not a good metric against which to measure localization accuracy. However, when a UUV executes multiple passes over a contact, the consistency or "spread" of the contact gives an excellent, though indirect, method of confirming navigation accuracy.

The narrow spread of mine contacts in Figure 12 provides independent confirmation of the accuracy of Bluefin's lower-cost navigation system. The data was taken with a Bluefin-9 UUV operating in La Spezia, Italy. Blue dots represent contact locations. Red dots represent the geometric centroid of all contacts taken together. All contacts fall within a 3 m radius centroid. Circles of 1, 2, 3, and 4 meter radius are shown for reference.

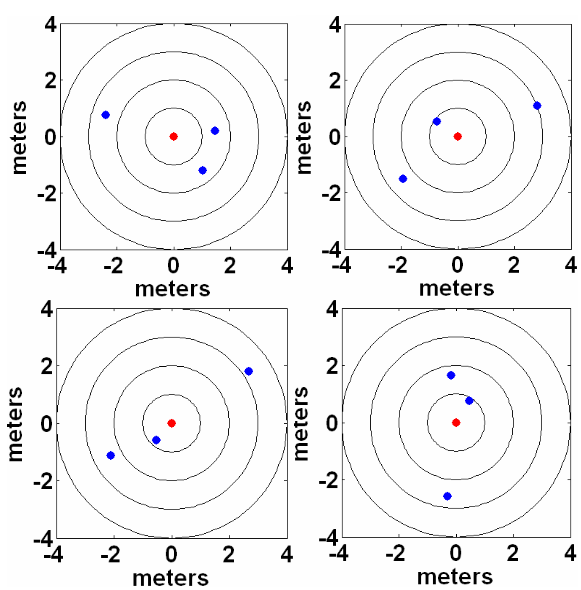

Fig. 12. Bluefin-9 contact localization consistency from multiple looks on various contacts.

8. ALGORITHM LIMITATIONS

The algorithm described in this paper was specifically designed for sonar survey missions, which typically consist of lawn-mower patterns on reciprocal headings. The real-time calibration component of the algorithm relies on this specificity. Missions consisting of tracklines executed in continuously varying directions would not be executed with the same accuracy. Q-routes can also benefit from the real-time calibration capability provided that the legs are long enough (several kilometers). Each leg can then be broken down in shorter segments, the first segment being used to get an initial estimate of the heading error along the leg.

DVL bottom lock has to be maintained at all times to prevent the position from drifting due to unknown underwater currents. This limits operations to areas shallow enough with respect to the DVL maximum tracking range.

9. CONCLUSION

This paper described Bluefin's lower-cost navigation system and presented navigation trial results obtained with Bluefin-9, Bluefin-12, and Bluefin-21 UUVs. Although this system uses a magnetic compass, excellent navigation accuracy is achieved through prior calibration of the compass, followed by real-time calibration of the residual errors affecting the dead reckoning sensors. This system is particularly well-suited to large area MCM missions and constitutes an easy-to-use and cost-effective alternative to more expensive Inertial Navigation Systems.

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