Experimental Validation of the Moving Long Base-Line Navigation Concept

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Abstract - **This paper presents the Moving Long Base-Line (MLBL) navigation concept as well as simulation and experimental results. This multiple vehicle navigation technique consists of using vehicles fitted with accurate navigation systems as moving reference transponders to which other vehicles, fitted with less capable navigation systems, can acoustically range to update their position. Reliable acoustic communications are mandatory for the real time implementation of this navigation scheme. However, while enabling MLBL, acoustic communications reduce the range update rate and introduce delays that need to be dealt with in the navigation algorithm. Simulation results show that relative navigation accuracy between vehicles can be maintained although the absolute navigation accuracy of each vehicle decreases over time. This is a key enabling factor for AOFNC missions where contacts are called by vehicles and re-acquired by other vehicles in real-time.**

I. INTRODUCTION

The Cooperative Autonomy for Distributed Reconnaissance and Exploration (CADRE) system has been proposed by a consortium lead by Bluefin Robotics Corporation to address the Undersea Search and Survey and Communications / Navigation Aid (C/NA) portions of the Office of Naval Research's Autonomous Operations Future Naval Capability initiative (AOFNC). The CADRE system relies on a heterogeneous and scalable collection of Unmanned Underwater Vehicles (UUV), and aims at providing vehicle-level and system-level autonomy for coordinated real-time mission adaptation and sensor-adaptive maneuvers.

Navigation in the CADRE framework is based on our concept of Moving Long Base Line (MLBL) acoustic navigation, where C/NAs carrying high-accuracy INS-based navigation systems act as moving reference points to which vehicles fitted with less accurate compass-based navigation systems (Search Classify Map and Re-acquire Identify vehicles – SCM/RI) can range in order to update their position. By relying on time synchronization between vehicles, the system is made scalable since an unlimited number of SCM/RI vehicles can determine their range to the C/NAs by listening to the C/NA pings. Each SCM/RI runs its own local navigation filter to predict its position based on dead reckoning data and corrects this prediction by using ranges to the C/NAs whenever they are available. Additional inter-SCM/RI ranges measured in real time can be used in post-processing to improve the real time navigation accuracy by further constraining the relative positions of all vehicles in the CADRE system.

This paper describes the navigation algorithm used by the SCM/RI vehicles and discusses the constraints introduced by the use of acoustic communications. Simulation results are presented showing how relative navigation accuracy between SCM/RI vehicles can be maintained as the absolute accuracy degrades due to the growing error affecting the C/NA position estimates. Finally, experimental results obtained with MIT's Bluefin21-class AUV "Unicorn" and two boats acting as C/NAs are also presented. These results are the first step towards a fully autonomous demonstration of the MLBL navigation principle for the AOFNC program.

II. CADRE

The CADRE system consists of a network of UUVs that cooperate to autonomously and concurrently conduct wide-area undersea MCM surveys, while maintaining high-accuracy navigation and contact localization.

The realization of the mission relies on the cooperative execution of three distinct mission roles by three different types of UUV platforms:

- SCM vehicles which carry sensors to detect and classify objects on the seabed,
- RI vehicles which carry sensors to identify objects on the seabed, and
- C/NA vehicles which provide the navigation and communications infrastructure necessary to complete the mission.

The SCMs carry a suite of side-looking Synthetic Aperture Sonars and Forward-Looking Sonars with which they detect mine-like targets on the seabed. When a target is detected, the SCMs inform the C/NAs via an acoustic communications channel. The C/NAs then task RIs to reacquire and identify the targets in real-time. In this manner, the whole chain of detection, classifications, and identifications of mine-like targets is executed in an "in-stride" fashion by the UUV cadre.

By removing reliance of pre-installed navigation aids, the CADRE system is well suited to large area surveys while simultaneously reducing the operational and logistical requirements of the system.

C/NAs are Bluefin21-class vehicles (21-inch diameter),

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while SCMs and RIs are Bluefin12-class vehicles ($12^{3/4}$-inch diameter). For the purposes of the CADRE demonstration program, an SCM with its lower frequency DIDSON sensor will be used to demonstrate the reacquisition portion of the RI mission.

As this paper focuses on the MLBL navigation, no further details are given regarding the CADRE concept. For more details, the reader is referred to [1].

III. MLBL

A. Principle

The C/NAs will be fitted with an Inertial Navigation System (INS) and a Doppler Velocity Log (DVL). Given the operating depth and the bottom lock range of the DVL, the C/NAs will be able to maintain bottom lock at all times. A Kalman filter running onboard each C/NA will tightly couple INS and DVL data to provide a position estimate that drifts at a rate of about 0.1% of distance traveled (~6.5 m/h at 3.5 knots). Position will be initialized on the surface using DGPS and occasional returns to the surface will be used to reset the position error accumulated underwater. The C/NAs will then be able to bound their position error throughout the mission. The rate at which the C/NAs will surface to update their position will be determined by the absolute navigation accuracy desired for the mission. Considering a 3 m position error following a GPS update and a cruise speed of 3.5 knots, the C/NAs will need to surface approximately every hour to maintain their position error below 10 m or about every 2.5 hours to maintain their position error below 20 m.

The SCMs and RIs will carry a less accurate dead reckoning system based on a DVL and an Attitude and Heading Reference System (AHRS). The attitude and heading data will be calculated by blending of magnetic heading, angular rate, and acceleration data provided by a Ring Laser Gyro (RLG) IMU and a magnetic compass. With this lower cost navigation system (and without using acoustic ranges) the SCM and RI vehicles will be able to dead reckon with accuracy better than 1% of distance traveled. Although the SCMs will be equipped with a less accurate navigation system than the C/NAs and will never surface to update their position, they will still be able to bound their absolute position error by acoustically ranging to the C/NAs and integrating the range information in their navigation solution.

When in the MLBL configuration, the C/NAs are positioned on the sides and at the rear of the cadre of vehicles, forming the two-beacon moving long baseline array that is used by the SCM and RI vehicles. All the vehicles are synchronized to GPS time and maintain accurate synchronization while submerged using a highly stable oscillator. With time synchronization, an unlimited number of SCM and RI vehicles can determine their range to the C/NAs by listening only. The only requirement is that the C/NAs' ping time be known by the SCM and RI vehicles. This is achieved by pre-scheduling ping times and/or informing the cadre of vehicles of the ping sequence through an initialization broadcast. Time synchronization has the additional advantage that all the data logged in different vehicles are referenced to the same time base. Therefore, all the data can be used in post-processing to improve the real time navigation (re-navigation).

Communications for AOFNC will rely on Woods Hole Oceanographic Institution's µModem [2]. In addition to communications, this modem provides the time-synchronized ranging capability needed for MLBL.

A typical MLBL navigation cycle is shown in Fig. 1. C/NA$_1$ pings at a time known by all the vehicles and broadcasts its position at the time of the ping. Upon reception of the ping, the vehicles are able to compute their range to C/NA$_1$. A few seconds later, the vehicles receive the position of C/NA$_1$. The range to C/NA$_1$ can then be used to correct the position of the vehicles along the direction between them and C/NA$_1$. C/NA$_2$ then pings at its predefined time. The vehicles determine their range to the C/NA and receive its position. They can then update their position along the direction between them and C/NA$_2$.

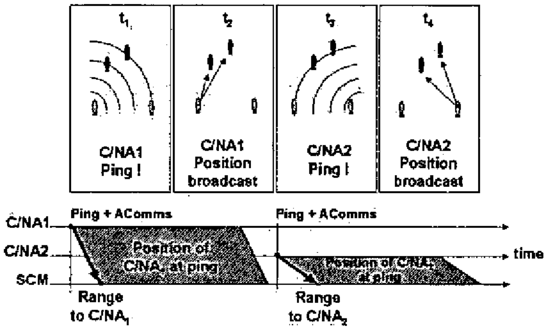

Fig. 1. Typical MLBL navigation cycle.

Each SCM/RI vehicle runs its own local navigation filter to predict its position based on dead reckoning data and corrects this prediction by using ranges to the C/NAs (and C/NA positions) whenever they are available. The navigation algorithm running in the SCM and RI vehicles is capable of:

- Accounting for delays between the range measurement and the reception of the C/NA's position,
- Estimating navigation error sources (compass, DVL),
- Rejecting outliers in the range measurements,
- Re-initializing the filter using two-transponder fixes if necessary.

This approach, where every vehicle runs a navigation algorithm that is independent of the other vehicles, is considered to be the "simplest" because:

- It is very similar to classical LBL except that the positions of the "transponders" change over time and acoustic communication delays have to taken into account,

- It only requires the ranges to the C/NAs (using SCM/RI ranges would require to maintain cross-correlations between position estimates and therefore a large amount of data to be exchanged over the acoustic link [3]),
- It makes minimal use of acoustic communications for the purpose of navigating,
- It can still be used without time synchronization using round trip travel times (would not scale as well as when using time synchronization though).

Although the navigation system in the C/NAs is very accurate, the positions broadcast by the C/NAs are affected by errors that grow over time. This position error will be transferred to the SCM and RI vehicles when they integrate acoustic ranges. To illustrate this, consider that C/NA$_1$ is located at position (-500,0) but its navigation reports a position that is 5 m further to the West (Fig.2). Similarly, C/NA$_2$ is located at position (500,0) but its navigation reports a position that is 10 m to the East of its true position. Fig. 2 shows the resulting absolute position error as a function of the location of the SCM/RI vehicle with respect to the baseline.

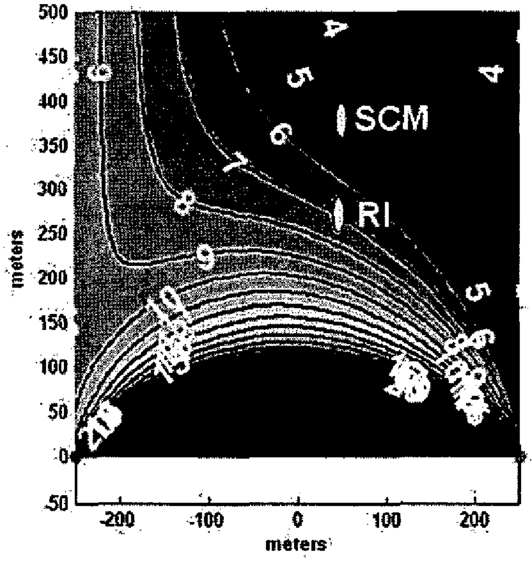

Fig. 2. Relative navigation accuracy.

An interesting fact is that although the SCM and RI vehicles shown in Fig. 2 are in error by 5 and 7 meters respectively, the relative position error is only 2 meters, even though the C/NA vehicles have a cumulative position error of 15 meters. This is a significant advantage of the CADRE multi-vehicle navigation system as it is the relative position error that matters the most in real-time where contacts are called by an SCM vehicle and rapidly reacquired by an RI vehicle. The absolute location of identified targets can be further refined in post-processing by correcting the positions of the C/NAs based on the navigation errors at the GPS position updates, and by using inter SCM/RI ranges and full cross-correlations.

B. Absolute vs. relative navigation accuracy

Several parameters affect the accuracy with which each SCM or RI is able to position itself. The main contributor to absolute position errors is the position drift of the C/NAs which lead to a distortion of the estimated baseline with respect to the true baseline defined by the vehicles. The magnitude of the position error depends on the position of the SCM/RI with respect to the baseline.

Assuming perfect range measurements between the SCM or RI and the C/NAs, and using erroneous C/NA positions, 'pseudo-true' positions can be calculated. These positions are the best the navigation filter running on the SCM/RI vehicle would be able to estimate since there is no way for these vehicles to know the error on the baseline. However, several parameters affect the accuracy with which the SCM/RI filter is able to estimate the pseudo-true position. GPS, heading, and DVL scale factor errors as well as noise on dead reckoning measurements and on sound speed measurements will prevent the navigation algorithm from perfectly estimating the pseudo-true position. The total absolute position error is then the sum of the position error induced by inaccurate baseline knowledge and the position error in estimating the pseudo-true position due to systematic errors and noise.

Vehicles located near each other with respect to the baseline will be affected by similar errors between true and pseudo-true positions, because the baseline-induced position errors vary slowly as a function of the horizontal distance, if the vehicles are not too close to the baseline (Fig.2). Each SCM/RI will add its own error when using its navigation filter, but the relative position error will be maintained to a small value compared to the absolute position error. This is what matters the most in terms of re-acquisition by a RI vehicle of a contact called by an SCM. In an operational scenario, the RI should then follow the SCM close enough for its absolute position error to be of the same magnitude and direction as that affecting the SCM's position.

The absolute position of the re-acquired contact can be further refined in post-processing by using inter SCM/RI ranges and applying linear corrections to the C/NAs' position estimates based on the position error observed with respect to GPS when the C/NAs surface. The absolute position error can, however, not be allowed to grow too large as this would require planning too much overlap between the SCM sonar swath to ensure 100% bottom coverage.

IV. SIMULATION

A. Conditions of the simulation

In the simulation, the ground truth is that the four vehicles (2 C/NAs, 1 SCM, and 1 RI) move in a perfect straight line at the same constant velocity and heading. This means that the true initial relative positions are conserved throughout the simulation. The true ranges between each SCM/RI and the C/NAs are therefore also constant.

A simulation consists of repeating the same run N times with error sources randomly chosen according to predefined statistics at the start of each of the N runs making a simulation (Fig. 3).

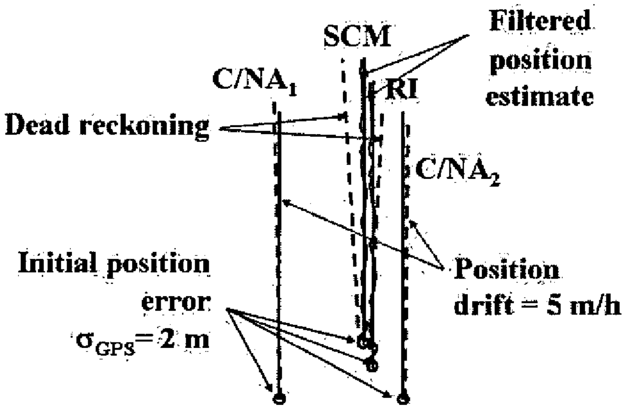

Fig. 3. A run consists of the execution of parallel tracklines. This run is repeated N times to make a simulation.

The parameters that are randomly chosen at the start of each run and kept constant for a given run within the simulation are: the initial position error for each vehicle (drawn from Gaussian distribution with σ=2m), the direction of the 5 m/h position drift for each C/NA (drawn from a uniform distribution between 0 and 2π), the magnitude of the heading bias for each SCM/RI (drawn from a uniform distribution between ±0.5°), the magnitude of the DVL scale factor error for each SCM/RI (drawn from a uniform distribution between ±1%). Simulated sensor measurements are affected by additive Gaussian noise with predefined variance (velocity, attitude, acoustic ranges, and sound speed).

To simulate a real MLBL scenario, where acoustic communications will not always be available for navigation purposes, the acoustic ranges updates happen as follows: range updates are allowed very 15 minutes for a period of 2 minutes. During this two-minute period, C/NA$_1$ pings at t=0, 20, 40… 120 seconds. The SCM and the RI can then determine their range to C/NA$_1$ at those times. C/NA$_2$ pings at 10, 30, 50… 110 seconds. The SCM and the RI can then determine their range to C/NA$_2$ at those times. In any case, the C/NA position corresponding to a range measurement is made available for processing 5 seconds after the range is measured to simulate delays associated with acoustic communications.

The positions of the SCM and RI are calculated in two different ways: based on the simulated GPS, DVL, compass measurements (pure dead reckoning from the initial GPS position) and based on the MLBL filter that integrates the acoustic ranges to the C/NAs with the dead reckoning data (one filter per vehicle). Ground truth being available, absolute accuracy and relative accuracy can easily be calculated. To get a statistic representation of the navigation algorithm's accuracy, a large number of runs are executed to exercise as many error combinations as possible.

B. Results

The fixed geometry used in the simulation is shown in Fig. 4 (the number in parentheses are the position in meters relative to C/NA$_1$ taken as the origin).

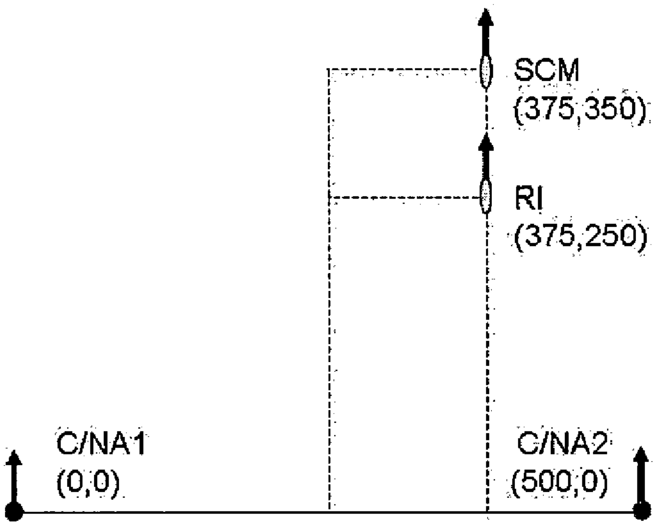

Fig. 4. Simulation geometry.

The results for N=100 runs of a 2 hour long trackline are shown in Fig. 5 to 9.

Fig. 5 shows the absolute position error for C/NA$_1$ which does not surface at all after the initial position update with GPS (it would look similar for C/NA$_2$). This error is a combination of the initial position error and the direction of the 5 m/h position drift.

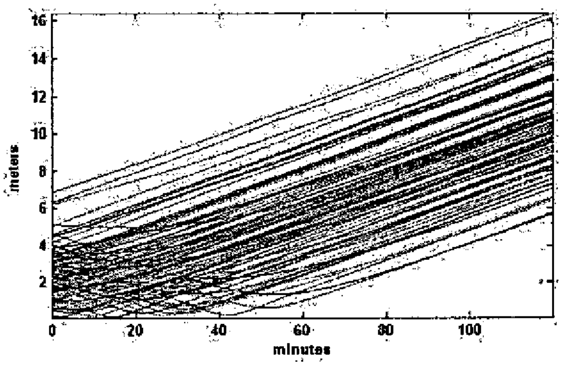

Fig. 5. C/NA1 absolute position error.

Fig. 6 shows the absolute position error for the SCM if it had dead reckoned the whole time without using the ranges to the C/NAs (similar results would be obtained for the RI). The position error is a combination of initial position error and drift over time due to the heading bias and the DVL scale factor (constant during each run, but randomly modified from one run to the next).

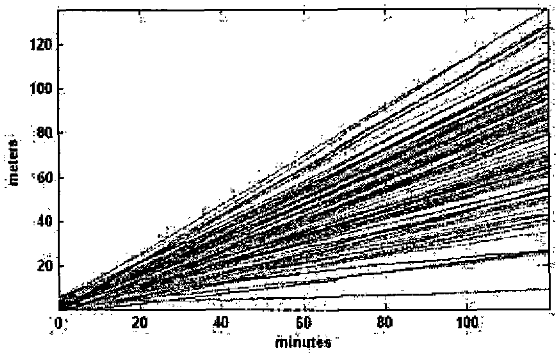

Fig. 6. SCM absolute position error when dead reckoning.

Fig. 7 shows the absolute position error of the filtered estimate for the SCM (similar for the RI). Although largely improved compared to dead reckoning, the absolute position error still grows as the position error on the C/NA increases.

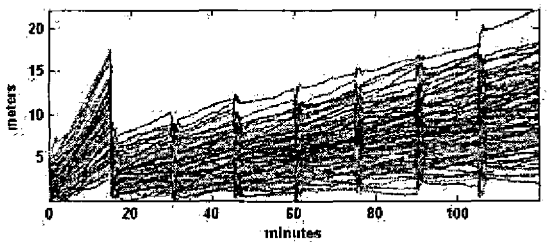

Fig. 7. Absolute error of the filtered SCM position.

Fig. 8 shows the position error relative to the pseudo-true position for the SCM (similar for the RI). This is basically the MLBL filter error at estimating the pseudo-true position.

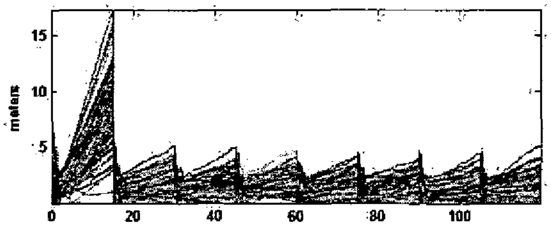

Fig. 8. SCM position error relative to pseudo-true.

Fig. 9 shows the relative position error defined as the norm of the difference between the vector from the estimated RI position to the estimated SCM position and the vector from the true SCM position to the true RI position. In spite of a growing absolute position error, the relative position error between the SCM and the RI remains smaller and facilitates contact reacquisition.

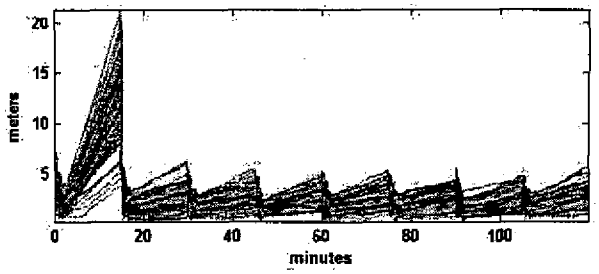

Fig. 9. Relative position error between the SCM and the RI

V. EXPERIMENTAL RESULTS

A. Setup

MIT's Bluefin21-class AUV "Unicorn" was used during one day of sea trials in October 2003 off of Quincy, Massachusetts. The objective was to collect real MLBL data that could be used to test MLBL navigation algorithms.

In this first MLBL experiment, two boats (the R/V "Bluefin" and MIT sailing Pavilion's "Rivah Chuck") acted as C/NAs (Fig.10).

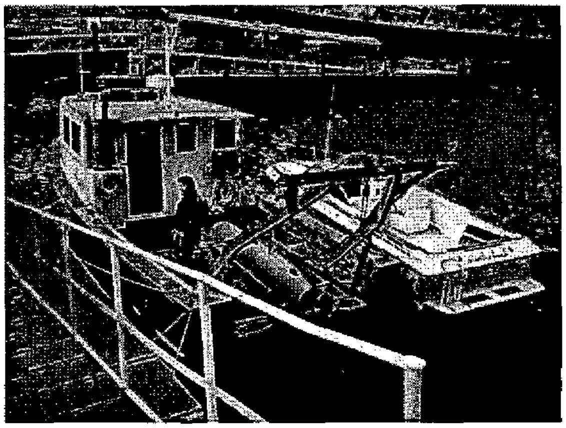

Fig. 10. MIT's "Unicorn" on the Bluefin boat next to the MIT boat.

Sonardyne's Avtrak systems were used to collect ranges between the AUV and the two boats. MIT furnished, put together, and tested the hardware used on each boat. The hardware consisted of an Avtrak, a GPS receiver, a pulse capture board and a laptop. MIT also developed the data logging software running on the laptop.

This experiment did not use time synchronization. Round trip travel times between the AUV and the boats were used. Upon reception of the AUV's LBL interrogation, the Avtrak on a given boat generated a pulse that was detected by a capture board and time stamped by the laptop software. The laptop also logged system time, boat's GPS position and GPS time. The data logged in each boat basically allowed to determine the boat's position at the time the Avtrak replied to the AUV interrogations.

The Avtrak on the AUV was configured to ping the boats every 3 seconds. This relatively high LBL ping rate was chosen to get the maximum amount of data that we would then be able to decimate at will in post-processing to get more realistic operational conditions.

Two missions were executed during the day: a 15-minute setpoint due East (about 1.5 km in length), followed by a 45-minute setpoint due West (about 4.5 km).

We had decided to have Bluefin's boat follow the AUV and MIT's boat stay about 300 m to the side. Controlling the baseline defined by the two boats based on poor USBL tracking turned out to more complicated than we thought it would. The AUV and boats' tracks show that we were only partially successful in maintaining the desired geometry especially during the long setpoint (Fig.11).

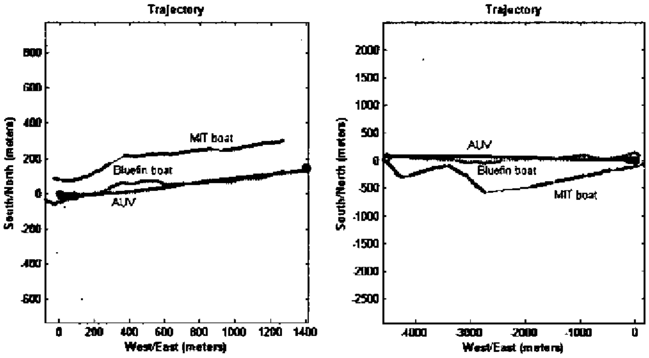

Fig. 11. AUV (red) and boat trajectories (blue and green) during the East (left) and West (right) setpoints.

All the ranges, collected at 3 seconds interval, are shown in Fig. 12. As in the case of simulation, however, the ranging data collected in real time have been under-sampled and alternated between boats to simulate the AOFNC concept of operation (Fig.1).

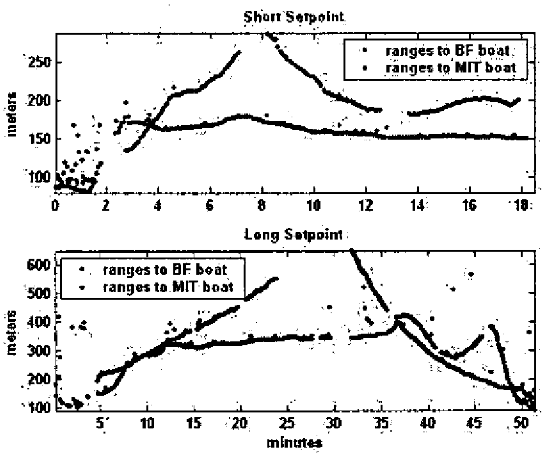

Fig. 12. Ranges to the boats during the two missions.

In the results shown below, the vehicle is provided with the ranges to one of the boat at t=0, 20, 40 seconds… and ranges to the other boat at t=10, 30, 50… (If such ranges were available). Ranges and boat positions are made available for processing only 5 seconds after they are measured to simulated acoustic communication delays. Given the short duration of the setpoints, periods without LBL updates were not simulated on purpose. In the long setpoint, however, replacement of the GPS receiver battery in the MIT boat caused a long dropout in the ranges to that boat (Fig.12 blue line in the bottom plot). During that period, the vehicle only got ranges to the Bluefin boat.

After running the missions, we found out that the compasses had not been calibrated so that the heading was off by about 1.8° on the east setpoint and about 1.4° on the west setpoint.

B. Results

Fig. 13 shows the real time navigation (dead reckoning) affected by the un-calibrated heading bias, the position calculated in post-processing using the MLBL filter and the MLBL fixes calculated using pairs of ranges to the two boats.

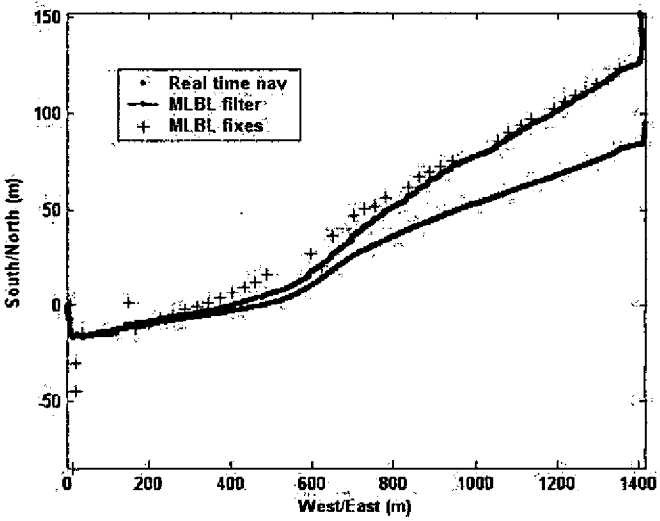

Fig. 13. Real time trajectory (dead reckoning) and post-processed trajectory (MLBL filter) during the short setpoint – (South/North axis stretched).

It can be seen that the filter takes some time to converge (estimation of the heading bias) and finally gets on track. In practice, the compass would be calibrated before running the mission, leaving only small residual errors for the filter to estimate. The MLBL solution would then be more accurate right from the start (this has been tested by removing the heading bias from the measurements prior to running the MLBL filter). However, we believe it is more interesting to show the results for the case where the filter has to compensate for the heading bias even though it takes longer to get an accurate position estimate. The under-sampling of the data is obvious when looking at the number of MLBL fixes (Fig. 13 and 14) compared to the number of range measurements (Fig. 12).

It also takes the MLBL filter some time to estimate and compensate for the large heading bias during the long setpoint (Fig.14). However, after convergence, good agreement can be seen between the MLBL trajectory and the MLBL fixes.

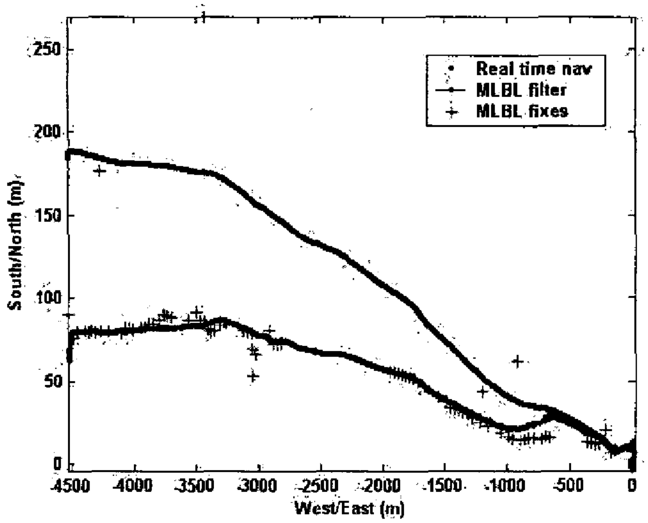

Fig. 14. Real time trajectory (dead reckoning) and post-processed trajectory (MLBL filter) during the long setpoint (South/North axis stretched).

VI. CONCLUSION

This paper described the principle and presented results for our MLBL navigation concept. Through simulation and post-processing of real data, we have shown how this navigation approach applies to the autonomous detection and re-acquisition of the targets between vehicles operating in a coordinated manner (AOFNC USS-C/NA).

VII. FUTURE WORK

The experiment described in this paper is the first step of a series. We plan on running tests with incremental complexity to converge towards the final AOFNC MLBL concept of operations. The next step will be to run the same experiment in real time: a single vehicle ranging off of two boats and using the ranges in real time to update its position. Acoustic communications will be the key addition to the setup.

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