Preprint from *Robotics Research - The Eighth International Symposium.*
Springer-Verlag, London, 1998. Y. Shirai and S. Hirose, Editors.

Towards Precision Robotic Maneuvering, Survey, and Manipulation in Unstructured Undersea Environments

Louis Whitcomb,[*] Dana Yoerger,[†] Hanumant Singh, David Mindell[‡] [§]

Abstract

This paper reports recent advances in the precision control of underwater robotic vehicles for survey and manipulation missions. A new underwater vehicle navigation and control system employing a new commercially available 1,200 kHz doppler sonar is reported. Comparative experimental trials compare the performance of the new system to conventional 12 kHz and 300 kHz long baseline (LBL) acoustic navigation systems. The results demonstrate a hybrid system incorporating both doppler and LBL to provide superior tracking in comparison to doppler or LBL alone.

1 Introduction

Our goal is to develop new sensing and control systems for underwater vehicles with superior precision, reliability, and practical utility. While the analytical and experimental development of undersea robotic vehicle tracking controllers is rapidly developing, e.g. [14, 7, 5, 4, 12, 6], few experimental implementations have been reported other than for heading, altitude, depth, or attitude control. Conspicuously rare are experimental results for X-Y control of vehicles in the horizontal plane. This lacuna is a result of the comparative ease with which depth, altitude, heading, and attitude are instrumented in comparison to X-Y horizontal position. Precision vehicle position sensing is an often overlooked and essential element of precision control of underwater robotic vehicles. It is impossible, for example, to precisely control a vehicle to within 0.1 meter tracking error when its position sensor is precise only to 1.0 meter. This paper reports the design, implementation, and field-evaluation of a new navigation system for underwater vehicles. The new system utilized a bottom-lock doppler sonar system to provide order-of-magnitude improvements in the precision and update rates of vehicle position sensing and, in consequence, superior closed-loop vehicle positioning performance.

1.1 *Position Sensing for Underwater Vehicles*

At present, few techniques exist for reliable three-dimensional navigation of underwater vehicles. Table 1 summarizes the sensors most commonly used to measure a vehicle's six degree-of-freedom position. While depth, altitude, heading, and attitude are instrumented with high bandwidth internal sensors, X-Y position sensing is usually achieved by acoustically interrogating fixed seafloor-mounted transponder beacons [9]. Ultra-short baseline acoustic navigation systems are preferred for the task of docking a vehicle to a transponder-equipped docking station but are of limited usefulness for general long-range navigation [10]. Inertial navigation systems offer excellent strap-down navigation capabilities, exhibiting position errors that accumulate as a function of both time and distance travled. Their high cost has, however, generally precluded their widespread use in oceanographic instruments and vehicles. The U.S. sponsored Global Positioning System (GPS) provides superior three-dimensional navigation capability for both surface

---

[*] Whitcomb is with the Department of Mechanical Engineering, Johns Hopkins University, 123 Latrobe Hall, 3400 North Charles Street, Baltimore, Maryland, 21218 USA, email: llw@jhu.edu.

[†] Yoerger and Singh are with the Deep Submergence Laboratory, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA, 02543, USA, email: dyoerger@whoi.edu, hsingh@whoi.edu.

[‡] Mindell is with the MIT Program in Science, Technology, and Society, E51-194A, 77 Massachusetts Avenue, Cambridge, MA 02139 email: mindell@mit.edu.

[§] We gratefully acknowledge the support of the Office of Naval Research for the 1997 JASON field experiments under Grant #N00014-95-J-1237 and the National Science Foundation for operational support of the Deep Submergence Operations Group (DSOG) under Grant #OCE-9627160. This paper is Woods Hole Oceanographic Institution Contibution #9614.

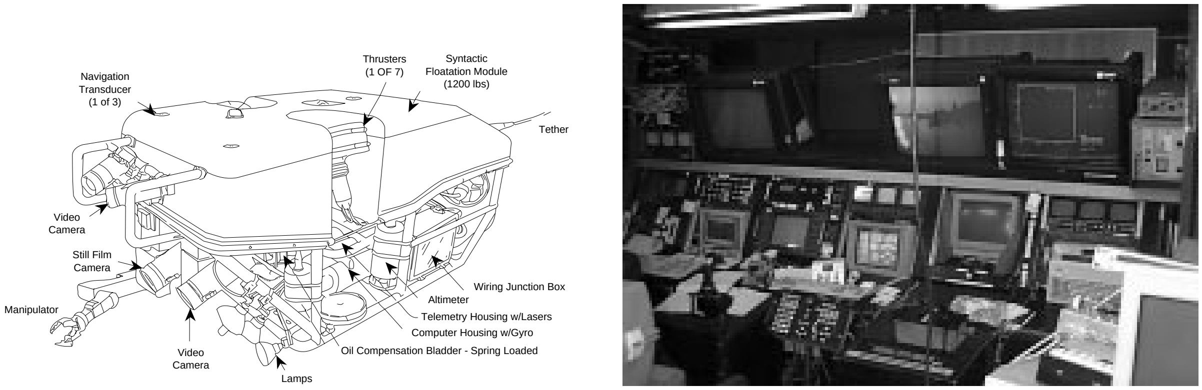


Figure 1: JASON, a 1200 Kg 6000 meter remotely operated underwater robot vehicle used in these experiments. Jason (left) is remotely operated from a control room (right) aboard the mother ship.

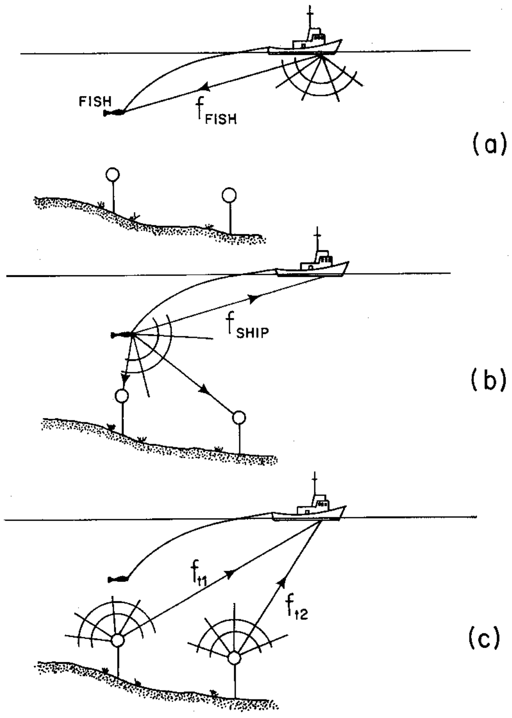
INSTRUMENT	**VARIABLE**	**INTERNAL?**	**UPDATE RATE**	**RESOLUTION**	**RANGE**
Acoustic Altimeter	Z - Altitude	yes	varies: 0.1-10Hz	0.01-1.0 m	varies
Pressure Sensor	Z - Depth	yes	medium: 1Hz	0.01-1.0 Meter	full-ocean
12 kHz LBL	XYZ - Position	NO	varies: 0.1-1.0 Hz	0.01-10 m	5-10 Km
300 kHz LBL	XYZ - Position	NO	varies: 1.0-5.0 Hz	+/-0.002 m typ	100 m
Mag Compass	Heading	yes	medium: 1-2Hz	$1 - 10°$	360°
Gyro Compass	Heading	yes	fast: 1-10Hz	0.1°	360°
Inclinometer	Roll and Pitch	yes	fast: 1-10Hz	0.1° - 1°	$+/-45°$

Table 1: Commonly Used Underwater Vehicle Navigation Sensors

and air vehicles, and is employed by all U.S. oceanographic research surface vessels. The GPS system's radio-frequency signals are blocked by seawater, however, thus GPS signals cannot be directly received by deeply submerged ocean vehicles.

Two problems with existing sensors severely limit the performance of fine maneuvering: *precision* and *update rate*. On-board depth, heading, and attitude sensors generally offer excellent precision and update rates. XY position, however, is generally instrumented acoustically and, over longer ranges, offers poor precision and low update rates. The standard method for full ocean depth XYZ acoustic navigation is 12 kHz long baseline (12 kHz LBL) acoustic navigation. 12 kHz LBL typically operates at up to 10 Km ranges with a range-dependent precision of +/-0.1 to 10 Meters and update rates periods as long as 10 seconds (0.1 Hz) [9]. Although recent work suggests that the next generation of acoustic communication networks might provide position estimation [3, 10], no systems providing this capability are commercially available at present. At present, the best method for obtaining sub-centimeter precision acoustic XY subsea position sensing is to employ a high-frequency (300 kHz or greater) LBL system. Unfortunately, due to the rapid attenuation of higher frequency sound in water, high frequency LBL systems typically have a very limited maximum range. In addition to the standard long-range 12 kHz LBL system, in these experiments we employed a short-range 300 kHz LBL system called "Exact" (developed by the two of the authors) with a maximum range of about 100m. All absolute acoustic navigation methods, however, require careful placement of fixed transponders (i.e. fixed on the sea-floor, on the hull of a surface ship [9], or on sea-ice [2]) and are fundamentally limited by the speed of sound in water — about 1500 Meters/Second.

Our goal is to improve vehicle dynamic navigation precision and update rate by at least one order of magnitude over LBL and, in consequence, improve vehicle control. In the context of 1000Kg underwater robot vehicles, which typically exhibit limit cycles on the order of 0.1-1.0 meters, the goal is to provide position control with a precision of



From WHOI-74-6, Pg. 14, [8].

Figure 2: Long Baseline Navigation. This figure depicts typical LBL navigation cycle for determining an underwater vehicle's position.

0.01 meters. To achieve this requires vehicle navigation sensors precise to at least 0.005 meter, and an update rate of several Hz.

1.2 *Review of Long Baseline Navigation*

Since its development over 30 years ago long baseline navigation (LBL) has become the *de-facto* standard technique for 3-dimensional acoustic navigation for full-ocean depth oceanographic instruments and vehicles [8].

LBL operates on the principle that the straight-line distance between two points in the ocean can be measured by the time-of-flight of an acoustic signal propagating between the two points. All LBL systems require an unobstructed line-of-sight between transmitting and receiving transducers and, as mentioned above, have an effective range that varies with frequency.

Figure 2 depicts a typical oceanographic deployment of a 8-12 kHz LBL system for navigating an underwater vehicle[1]. A typical LBL system is deployed and operated from the surface vessel as follows:

1. *Transponder Deployment:* Two or more acoustic transponders are dropped over the side of the surface ship at locations selected to optimize the acoustic range and geometry of planned subsea operations. Each transponder is a complete sub-surface mooring comprised of an anchor, a tether, and a buoyant battery-powered acoustic transponder. The tether's length determines the transponder's altitude above the sea-floor. Depending on range, local terrain, depth, and other factors, tether length might be chosen between 5 and 500 meters. The simplest transponders are designed to listen for acoustic interrogation "pings" on a specified frequency (e.g. 9 kHz), and to respond to each interrogation with a reply ping on a specified frequency (e.g. 10 kHz). It is common (but not universal) to set an entire network of transponders to listen on a single frequency, and to set each transponder to respond on a unique frequency.
2. *Sound-Velocity Profile:* An instrument is lowered from the surface ship to measure and tabulate the velocity of sound at various depths the water column. Sound velocity typically varies significantly with depth, and all subsequent computations use this sound velocity profile to compensate for the effects of variation in sound velocity.
3. *Transponder Survey:* The XYZ position of the sea-floor transponders is determined by maneuvering surface ship around each transponder location while simultaneously (*i*) acoustically interrogating the transponder and recording the round-trip acoustic travel time between the ship's transducer and the sea-floor transponder and (*ii*) recording the ship's GPS position, compass heading, and velocity. This data is processed to compute least-square estimate of the world-referenced XYZ position of

---

[1] A variety of LBL systems are commercially available. Vendors include Benthos Inc., 49 Edgerton Drive, North Falmouth, MA 02556 USA, phone: 508-563-1000, fax: 508-563-6444, http://www.benthos.com.

each fixed sea-floor transponder. When using a full-precision P-Code GPS, the transponder's position can typically be estimated with a precision of just a few meters.

4. *Acoustic Navigation of Surface Ship Position:* First, the ship's acoustic signal processing computer transmits an interrogation ping via the ship's LBL transducer on a common interrogation frequency, say 9.0 kHz. Second, each of the fixed sea-floor transponders replies with a ping on a unique frequency that is received by the ship's LBL transducer. The ship's computer measures the round-trip travel acoustic travel time between the ship's transducer and to two (or more) sea-floor transponders. Finally, the ship's computer computes the absolute ship position using (*i*) two or more measured round-trip travel times, (*ii*) the known depth of the ship's transducer, (*iii*) the surveyed XYZ position of the sea-floor transponders, and (*iv*) the measured sound-velocity profile.

5. *Acoustic Navigation of Underwater Vehicle Position:* Two general approaches are commonly employed for acoustic navigation of underwater vehicle position.

   The first general approach, often called "inhull navigation", is used by an underwater vehicle to determine its own position without reference to a surface ship. The sequence is nearly identical to the surface ship navigation sequence described above, with the vehicle's actual time-varying depth (using a precision pressure-depth sensor) in place of the ship's constant transducer depth.

   A second general approach is used to determine the position of an underwater vehicle (or instrument) from the surface ship. This approach is depicted in Figure 2. First, the ship's acoustic signal processing computer transmits an interrogation ping via the ship's LBL transducer on special interrogation frequency, say 8.5 kHz (Figure 2.a). Second, the underwater vehicle's transponder responds to the ship's interrogation by generating a ping on a secondary interrogation frequency, say 9.0 kHz (Figure 2.b). Third, each of the fixed sea-floor transponders replies to the secondary interrogation by generating a ping on a unique frequency that is received by the ship's LBL transducer (Figure 2.c). The ship's computer measures (*a*) the direct round-trip travel acoustic travel time between the ship's transducer and the vehicle and (*b*) the indirect round-trip travel time from ship to vehicle to transponder to ship for two (or more) sea-floor transponders. Finally, the ship's computer computes the absolute ship position using (*i*) the measured round-trip travel times, (*ii*) the known depth of the ship's transducer, (*iii*) the surveyed XYZ position of the sea-floor transponders, and (*iv*) the measured sound-velocity profile. In the case of tethered underwater robot vehicles, the known depth of the vehicle is often used in the position computation.

6. *Transponder Recovery:* Most sea-floor acoustic transponders are equipped with an acoustically triggered device which releases the mooring tether in response to a coded acoustic release signal, thus allowing the transponder to float freely to the surface for recovery. In most oceanographic deployments the transponders are triggered, released, and recovered at the conclusion of operations.

The above description is typical for 8-12 kHz LBL systems in deep water where ranges may vary from about 1 to 10 Km. The details of deployments may vary when in shallow water, when operating over very short ranges, and when using high frequency LBL systems (100 kHz-1,000 kHz), but the essential steps of transponder placement, calibration, and operation remain invariant. As discussed previously, the precision and update rate of position fixes can vary over several orders of magnitude depending on the acoustic frequency, range, and acoustic path geometry. LBL navigation accuracy and precision can be improved to some extent by careful application of Kalman filtering techniques [1]. Figure 3 shows raw vehicle position fixes obtained simultaneously using a long-range 12 kHz LBL navigation system and a short-range 300 kHz LBL system.

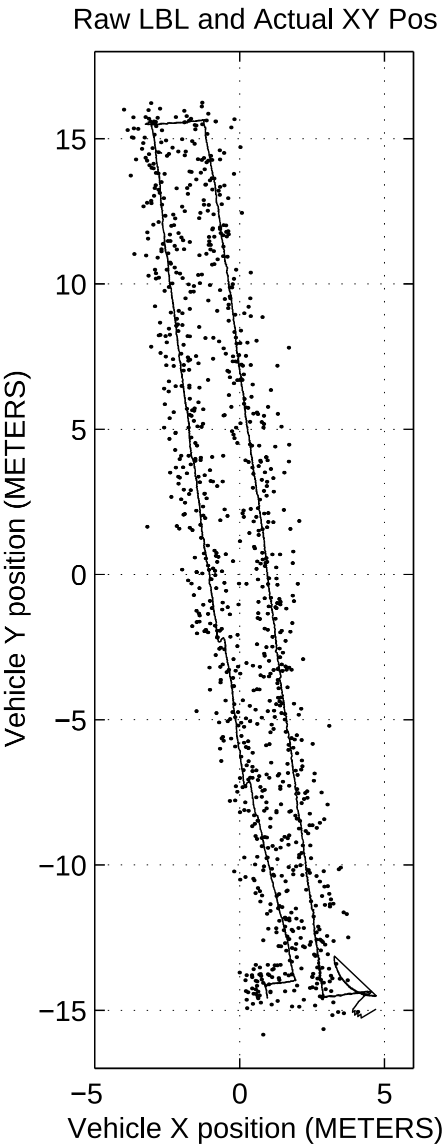


Figure 3: X-Y Plot of 12 kHz LBL Jason position fixes (dot cloud) fixes and 300 kHz LBL X-Y fixes (solid line). Data collected during a closed-loop sea-floor survey at approximately 850 meters depth, Jason dive 222, 24 June 1997.

2 Doppler-Based Navigation and Control

This section reports the design and experimental evaluation of a control system employing a new 6000 meter depth rated 1200 kHz bottom-lock doppler sonar[2]. to augment the standard vehicle navigation suite. The new doppler sonar precisely measures the UUV's velocity with respect to the fixed sea-floor. This promises to dramatically improve the vehicle navigation capabilities in two ways: First, use of the doppler velocity sensing in the vehicle control system will overcome the "weak link" of conventional velocity estimation techniques, and result in improved precision maneuvering. Second, by numerically integrating the vehicle velocity, the vehicle will for the first time be able to "dead reckon" in absence of external navigation transponders. This will enable missions in unstructured environments that were previously considered infeasible such as precision station-keeping and tracking; high-precision survey; improved terrain following; and combined vehicle-manipulator tasks such as sample gathering while precisely "hovering" at a site of interest.

2.1 System Design: A multi-mode vehicle navigation and control system

The new navigation system is configured by the pilot to operate in one of five modes detailed in Table 2. All of the control modes employ the same closed-loop control algorithms for vehicle heading and depth. The five control modes differ only in the type of control and sensing employed for the vehicle X-Y position.

Mode 1 employs manual X-Y positioning while Modes 2-5 employ closed-loop X-Y positioning. In all cases the vehicle heading position is instrumented by a heading gyroscope, and the vehicle depth is instrumented by a pressure depth sensor. The the X-Y control for the five modes are as follows:

---

[2] The Workhorse 1,200 kHz doppler sonar was developed and is manufactured by RD Instruments Inc, 9855 Businesspark Ave., San Diego, CA 92131-1101 phone: 619-693-1178, web: http://www.rdinstruments.com.

2.1.1 Mode 1: Manual X-Y

X-Y is controlled manually, as the precision and update rate of 12 kHz LBL are insufficient to support closed-loop control. The pilot observes full real-time navigation data (including graphical bottom-track) and live video, and controls the vehicle X-Y thruster forces directly via joystick control. Mode 1 is the standard control mode employed in virtually all commercial remotely operated underwater vehicle (ROV) systems in which vehicle heading and depth are closed-loop controlled, while X-Y position is manually controlled.

2.1.2 Mode 2: Closed Loop X-Y with 300 kHz LBL

X-Y position is under PD control using a 300 kHz LBL transponder navigation system for X-Y state feedback. This acoustic navigation system provides sub-centimeter precision vehicle positions over 100 meter ranges with update rates of 1 to 5 Hz [13].

2.1.3 Mode 3: Closed Loop X-Y with 1200 kHz Doppler

X-Y position is under PD control using a 1200 kHz bottom-lock doppler sonar for X-Y state feedback. The vehicle referenced velocities are transformed to world coordinates using an on-board flux-gate heading compass and on-board attitude sensors, and then is integrated to obtain world-referenced vehicle position.

2.1.4 Mode 4: Closed Loop X-Y with 1200 kHz Doppler and 12 kHz LBL

X-Y position is under PD control using a combination of the 1200 kHz bottom-lock doppler sonar and 9 kHz LBL transponder navigation system for X-Y state feedback. To take advantage of the incremental precision of the doppler with the absolute (but noisy) precision of the LBL, we implemented a system utilizing complementary linear filters to combine low-passed LBL position fixes with high-passed doppler position fixes. The cutoff frequencies for both filters were set to 0.005 Hz. The Mode 4 system requires no additional fixed sea-floor transponders, in contrast to previously reported LBL+doppler systems which utilize fixed sea-floor mounted continuous-tone beacons [11].

2.1.5 Mode 5: Mode 4: Closed Loop X-Y with 1200 kHz Doppler and 300 kHz LBL

X-Y position is under PD control using a combination of the 1200 kHz bottom-lock doppler sonar and 300 kHz LBL transponder navigation system for X-Y state feedback. Here again, we utilized a system of complementary linear filters to combine low-passed LBL position fixes with high-passed doppler position fixes. The cutoff frequencies for both filters were set to 0.1 Hz.

2.2 Feedback Gains and Magic Parameters

In all of these experiments, the velocities used for feedback control are obtained by direct numerical differentiation of the corresponding position signal. All axes are controlled by standard Proportional-Derivative (PD) feedback laws. The feedback gains were tuned by normal pole-placement methods, based on estimated vehicle hydrodynamic parameters, to obtain approximately critically damped response. Identical feedback gains were used in all closed-loop control modes.

2.3 Experiments

This section reports experiments comparing the absolute precision of doppler-based, LBL, and hybrid navigation and control systems. Section 2.3.1 examines the absolute precision of the Mode 4 LBL+doppler navigation system in comparison to Mode 1 LBL-only navigation. Section 2.3.2 examines actual experimental closed loop tracking performance of the five control modes.

2.3.1 Navigation Performance

What is the absolute precision of Mode 1 (raw 12 kHz LBL) navigation? This is the de-facto standard technique for long-range 3-D underwater navigation of underwater vehicles. Mode 1 typically provides position fixes at 2-10 second intervals (too slow for closed-loop X-Y control) with precision that varies with network size, water depth, ambient noise, and a variety of other factors. This section reports an experimental evaluation of the absolute precision of both Mode 1 (LBL alone),

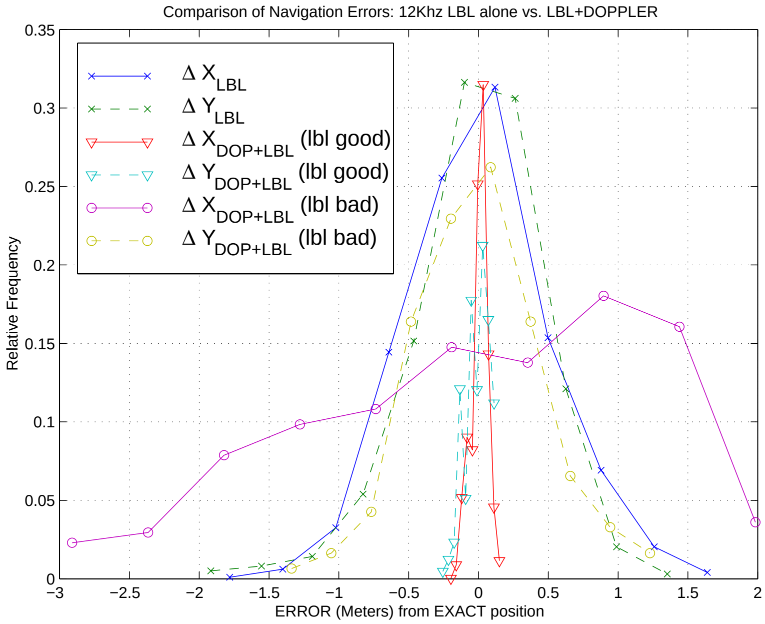


Figure 4: Histogram Plot showing X and Y position sensing errors of 12 kHz LBL showing (a) LBL alone (Jason dive 222), (b) LBL+Doppler with LBL working well (Jason dive 222), and (c) LBL+Doppler with LBL working poorly (Jason dive 219). The 12 kHz navigation errors were computed with respect to the 300 kHz LBL vehicle position.

and and Mode 4 (12 kHz LBL+Doppler) navigation systems. The experiments were conducted in June 1997 during a JASON field deployment at sea in approximately 850 meters depth. Mode 4 was first implemented and tested in these experiments. Our goal was to develop a new navigation system to provide update rate and precision suitable for closed-loop X-Y control, yet requiring no additional navigation sensors external to the vehicle itself. Mode 4 requires only a vehicle-mounted doppler sonar unit to augment the usual 12 kHz LBL navigation transponder system normally employed for Mode 1 deep-ocean navigation.

Figure 3 shows X-Y plot of 983 Jason XY position fixes obtained by Mode 1 12 kHz LBL navigation (dot cloud), and 8,845 highly precise actual Jason X-Y positions obtained by the 300 kHz LBL system (solid line). The geometry of the 12 kHz LBL transponders was nearly optimal in this deployment, yet LBL position errors of up to a meter were typical.

Figure 4 shows histogram plots of the X and Y navigation errors observed during these actual vehicle deployments using Mode 1 and Mode 4 navigation. The X and Y navigation errors under Mode 1 (LBL only) have a standard deviation of 0.50 meters and 0.46 meters, respectively. In contrast, the X and Y navigation errors under Mode 4 (LBL+doppler) have a standard deviation of 0.06 meters and 0.08 meters, respectively, when the LBL system is receiving good fixes. Thus the Mode 4 (LBL+doppler) system is an order of magnitude more precise than Mode 1 (LBL only). Moreover, the Mode 4 system provides vehicle position fixes every 0.4 seconds, while the the Mode 1 system provides vehicle position fixes every 3.0 seconds — about an order of magnitude improvement.

It is common for a 12 kHz LBL navigation system to suffer from a variety of systematic errors that cause it to give imprecise readings. Typical LBL problems include acoustic multi-path, loss of direct acoustic path, and poor signal-to-noise due to machinery and electro-magnetic noise. As a result, it is typical for LBL systems to occasionally generate "bad fixes" for periods of time ranging from seconds to hours. These bad fixes are characterized by high, non-gaussian errors. The most difficult aspect of the errors is that they are not

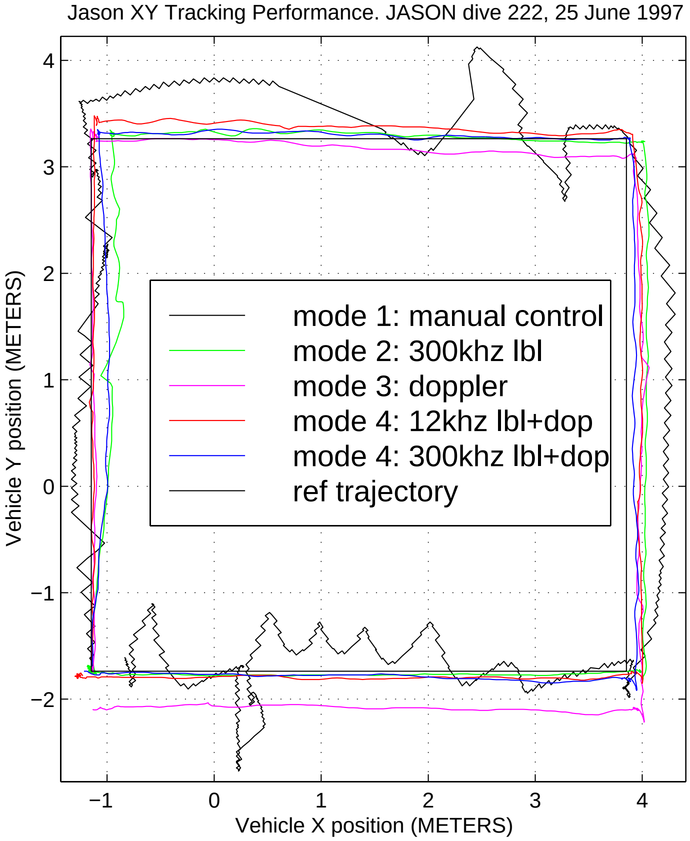


Figure 5: Jason X-Y Tracking Performance: Actual X-Y vehicle trajectories under Mode 1 (manual control) and Modes 2-5 (closed-loop control).

zero-mean. How do these "bad fixes" effect Mode 4 navigation precision? Figure 4 shows the Mode 4 X and Y navigation errors to be several meters when subject to bad LBL fixes.

We conclude Mode 4, a hybrid of doppler and 12 kHz LBL, provides order-of-magnitude improvement in vehicle navigation precision and update rate over Mode 1, yet requires the deployment of no additional transponders. Good 12 kHz LBL fixes are essential to Mode 4 precision; when LBL precision degrades, Mode 4 precision is proportionally diminished. Moreover, Mode 4 provides both the precision and update rate necessary for precision closed-loop X-Y vehicle control that is not possible with Mode 1.

2.3.2 The Effect of Navigation Precision on Closed-Loop Positioning

How do the various navigation modes effect underwater vehicle tracking performance? To answer this question we ran five experimental trials — one for each of the five modes described Section 2.1. In each trial, we commanded Jason to follow an X-Y trajectory in the shape of a 5 meter by 5 meter square at approximately 850 meters depth. In the Mode 1 trial the vehicle was under the manual X-Y pilot control. In the Mode 2, 3, 4, and 5 trials, the vehicle was under closed-loop X-Y control. The closed-loop trials all employed identical PD feedback control algorithms for X-Y motion; they differ only in their position sensing technique. In each case we recorded the *actual* vehicle position with the sub-centimeter precision 300 kHz LBL transponder navigation system.

Figure 5 shows the reference trajectory, a 5-meter

MODE	X-Y POSITION SENSING	CLOSED-LOOP XY?	TRACKING ERRORS	COMMENTS
Mode 1	12 kHz LBL	No	Worst	Industry standard. Only standard long-range 12 kHz sea-floor transponders required.
Mode 2	300 kHz LBL	Yes	Best	Requires deployment of additional short-range 300 kHz sea-floor transponders.
Mode 3	Doppler	Yes	Good	Tracking error increases as function of time and distance traveled due to integration errors. No additional sea-floor transponders required.
Mode 4	Doppler + 12 kHz LBL	Yes	Very Good	No additional sea-floor transponders required.
Mode 5	Doppler + 300 kHz LBL	Yes	Best	Requires deployment of additional short-range 300 kHz sea-floor transponders.

Table 2: Performance Summary: Five modes of underwater robot navigation and control.

square, and the *actual* Jason X-Y trajectories for each of the five trials. In manual X-Y control, Mode 1, the pilot could typically keep the vehicle within about 1 meter of the desired trackline. This manual tracking performance is typical of the Mode 1 tracking performance we have observed in hundreds of hours of Mode 1 deep-sea robot deployments. In closed-loop Mode 2, the vehicle remains within 0.1-0.2m of the desired trajectory. Here again, this closed-loop tracking performance is typical of the Mode 2 tracking performance we have observed in hundreds of hours of Mode 2 deployments.

Modes 3, 4, and 5 were implemented and tested for the first time on this deployment. Mode 3 (1200 kHz doppler alone) exhibits a tracking error roughly proportional to distance traveled — in this case we see errors up to 0.5 m, or about 2.5% of distance traveled. We observed two principal sources of error for pure-doppler navigation: First, the inherent 1% accuracy of the doppler velocity measurement is integrated directly into accumulated distance errors. To minimize this error it is essential to carefully calibrate the local sound velocity value used in the doppler velocity computation. Second, for longer tracklines (not shown) we observed that small errors in the doppler unit's on-board flux-gate magnetic compass will dramatically increase the accumulated XY position errors. To minimize this error, it is essential to have an absolutely stable earth-referenced heading sensor.

Mode 4 (12 kHz LBL and 1200 kHz doppler) and Mode 5 (300 kHz LBL and 1200 kHz doppler) provide the best tracking performance, with tracking errors within 0.1-0.2 m — commensurate to the performance of Mode 2. As indicated in the previous section, good 12 kHz LBL fixes are essential to Mode 4 precision; when LBL precision degrades and the error distribution becomes skewed, Mode 4 performance is diminished.

3 Conclusion

The preliminary results are promising. We conclude Mode 4, a hybrid of doppler and 12 kHz LBL, provides order-of-magnitude improvements in vehicle navigation over Mode 1, yet requires the deployment of no additional transponders. Good 12 kHz LBL fixes are essential to Mode 4 precision; when LBL precision degrades, Mode 4 precision is diminished. Moreover, Mode 4 provides both the precision and update rate necessary for precision closed-loop XY vehicle control that is not possible with Mode 1. The principal error sources for any bottom-referenced doppler position estimation technique are (i) sound velocity calibration precision, (ii) heading reference precision. A companion paper (in preparation) describes high-precision sonar and optical surveys of sea-floor sites performed using closed-loop vehicle control with combined LBL/doppler navigation on the June 1997 Jason deployment.

We are presently pursuing several questions articulated in the present study: First, to what degree will an improved heading reference (e.g. north-seeking ring-laser gyroscope) improve the doppler XY position estimate? Second, how will variations in sea-floor composition and topography effect the X-Y position precision of doppler-based systems? This will be particularly important in the rough terrain typically found in geologically active seafloor sites. Third, bottom-referenced doppler fails at altitudes greater than about 30 meters (for 1200 kHz) to 100 meters (for 300 kHz). We expect that the techniques employed herein could be extended to use water-column referenced doppler for mid-water closed-loop navigation and control.

Acknowledgements

We gratefully acknowledge the invaluable support of WHOI Deep Submergence Operations Group and Dr. Robert D. Ballard; EM11(SS) Robert Stadel, U.S. Navy, who piloted the manual (Mode 1) Jason tracking trials; Captain Steve Laster, and the officers and crew of the S.S.V. Carolyn Chouest; and Officer-in-Charge LTCDR Charles A. Richard, and the officers and crew of the U.S. Navy Submarine NR-1.

References

[1] B. M. Bell, B. M. Howe, J. A. Mercer, and R. C. Spindel. Nonlinear kalman filtering of long-baseline, short-baseline, gps, and depth measurements. In *Conference Record of the Twenty-Fifth Asilomar Conference on Signals, Systems and Computers*, pages 131–136, Pacific Grove, CA, USA, November 1991.

[2] J. G. Bellingham, M. Deffenbaugh, J. Leonard, and J. Catipovic. Arctic under-ice survey operations. *Unmanned Systems*, 12(1):24–9, 1994.

[3] J. A. Catipovic and L. E. Freitag. High data rate acoustic telemetry for moving rovs in a fading multipath shallow water environment. In *Proceedings of the Symposium on Autonomous Underwater Vehicle Technology. AUV '90*, pages 296–303, 1990.

[4] S. K. Choi and J. Yuh. Experimental study on a lerning control system with bound estimation for underwater robots. *Proc. IEEE Int. Conf. Robt. Aut.*, pages 2160–2165, April 1996.

[5] R. Cristi, F. A. Papoulis, and A. J. Healey. Adaptive sliding mode control of autonomous underwater vehicles in the dive plane. *IEEE Journal of Oceanic Engineering*, 15(3):152–160, June 1990.

[6] T. I. Fossen. *Guidance and Control of Ocean Vehicles.* John Wiley and Sons, New York, 1994.

[7] K. R. Goheen and E. R. Jeffereys. Multivariable self-tuning autopilots for autonomously and remotly operate underwater vehicles. *IEEE Journal of Oceanic Engineering*, 15(3):144–151, June 1990.

[8] M. M. Hunt, W. M. Marquet, D. A. Moller, K. R. Peal, W. K. Smith, and R. C. Spindell. An acoustic navigation system. Technical Report WHOI-74-6, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543 USA, December 1974.

[9] P. H. Milne. *Underwater Acoustic Positioning Systems.* Spon Ltd., New York, 1983.

[10] H. Singh, J. Catipovic, R. Eastwood, L. Freitag, H. Henricksen, F. Hover, D. Yoerger, J. Bellingham, and B. Moran. An integrated approach to multiple auv communications, navigation and docking. In *Proceedings of the OCEANS 96 MTS/IEEE Conference*, pages 59–64, Fort Lauderdale, FL, USA, September 1996.

[11] R. C. Spindel, R. P. Porer, W. M. Marquet, and J. L. Durham. A high-resolution pulse-doppler underwater acoustic navigation system. *IEEE Journal of Oceanic Engineering*, 1(1):6–13, September 1976.

[12] L. L. Whitcomb and D. R. Yoerger. Preliminary experiments in the model-based dynamic control of marine thrusters. In *Proc. IEEE Int. Conf. on Robotics and Automation*, 1996. (Invited paper).

[13] D. R. Yoerger and D. A. Mindell. Precise navigation and control of an rov at 2200 meters depth. In *Proceedings of Intervention/ROV 92*, San Diego, June 1992. MTS.

[14] D. R. Yoerger and J. E. Slotine. Adaptive sliding control of an experimental underwater vehicle. In *Proc. IEEE Int. Conf. Robt. Aut.*, Sacremento, CA, USA, April 1991.