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

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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

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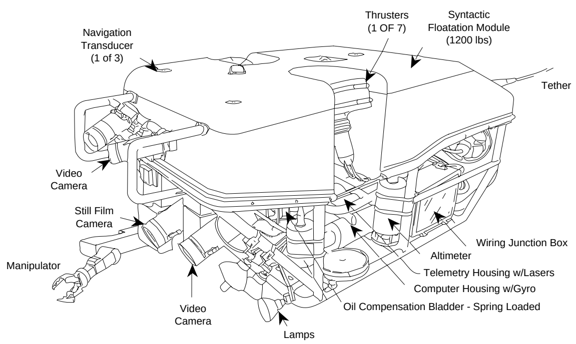


Figure 1: JASON, a 1200 Kg 6000 meter remotely operated underwater robot vehicle used in these experiments. Jason (left) is remotely operated from a control room (right) aboard the mother ship.

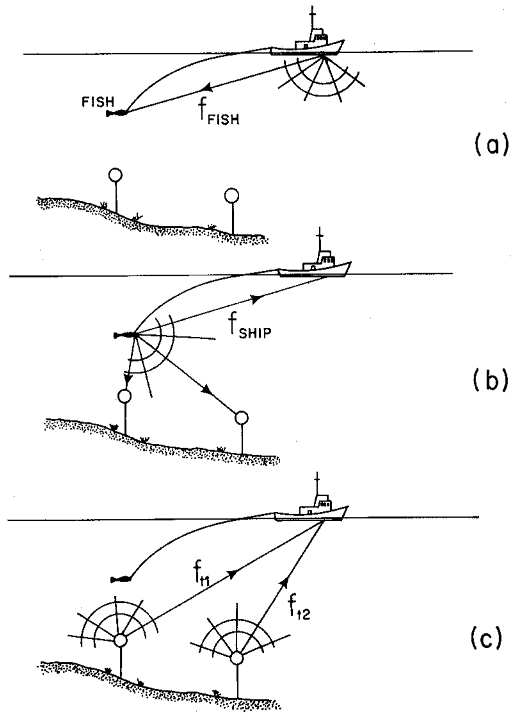
INSTRUMENT	VARIABLE	INTERNAL?	UPDATE RATE	RESOLUTION	RANGE
Acoustic Altimeter	Z - Altitude	yes	varies: 0.1-10Hz	0.01-1.0 m	varies
Pressure Sensor	Z - Depth	yes	medium: 1Hz	0.01-1.0 Meter	full-ocean
12 kHz LBL	XYZ - Position	NO	varies: 0.1-1.0 Hz	0.01-10 m	5-10 Km
300 kHz LBL	XYZ - Position	NO	varies: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

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.

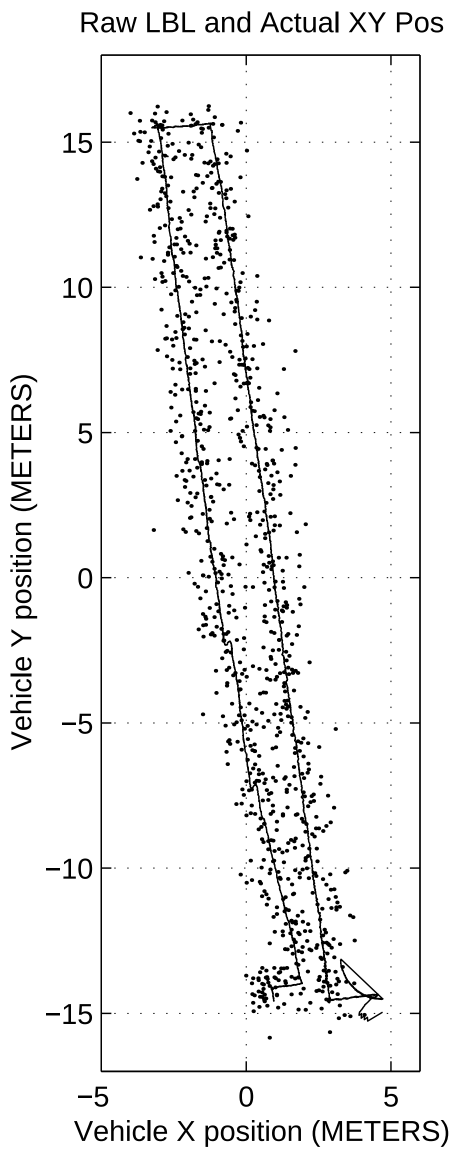


Figure 3: X-Y Plot of 12 kHz LBL Jason position fixes (dot cloud) fixes and 300 kHz LBL X-Y fixes (solid line). Data collected during a closed-loop sea-floor survey at approximately 850 meters depth, Jason dive 222, 24 June 1997.

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.

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