A SURVEY OF UNDERWATER VEHICLE NAVIGATION: RECENT ADVANCES AND NEW CHALLENGES

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Abstract: The paper surveys recent advances in underwater vehicle navigation and identifies future research challenges. Improvements in underwater navigation sensor technology and underwater navigation algorithms are enabling novel underwater vehicles and novel underwater vehicle missions. This paper first reviews advances in underwater navigation sensor technology. Second, advances in deterministic and stochastic underwater navigation methodologies and algorithms are reviewed. Finally, future challenges in underwater vehicle navigation are articulated, including near-bottom navigation, vehicle state estimation, optimal survey, environmental estimation, multiple-vehicle navigation, and mid-water navigation. Advances in vehicle navigation will enable new missions for underwater vehicle (commercial, scientific, and military) which were previously considered impractical or infeasible.

1. INTRODUCTION

This paper reviews recent advances in underwater vehicle navigation sensing and algorithm research, and identifies future challenges in underwater vehicle navigation. Within the last ten years, the development of commercially available, precise, high update rate navigation sensors such as Doppler sonars, optical gyrocompasses, and inertial measurement units (IMUs), have served to complement traditional underwater sensors such as acoustic positioning systems, magnetic compasses, and pressure depth sensors. Data from these sensors, along with data from scientific sensors such as bathymetric sonars and optical cameras, have served as a catalyst for the development of novel navigation methodologies. Many of these methodologies supplement sensor data with information from dynamic or kinematic models. This paper concludes with a discussion of current research problems that will improve our ability to navigate oceanographic submersibles and increase the value of these vehicles to the oceanographic community.

The motivation for improving underwater vehicle navigation arises from the need to expand the capabilities of these vehicles and further increase their value to oceanography. All classes of oceanographic vehicles have progressed remarkably and the data collected with these vehicles contributes to our knowledge of the oceans. For example, over the last decade the Autonomous

[1] The Authors gratefully acknowledge the support of the National Science Foundation.

Benthic Explorer (ABE), an autonomous underwater vehicle (AUV), has conducted 191 benthic surveys at mid-ocean ridge sites at an average depth of 2000 meters and a navigation precision on the order of a few meters (Yoerger *et al.*, 2006). These surveys have provided bathymetric and magnetic maps of the seafloor, photographed biological and geological features, and mapped hydrothermal plumes (Karson *et al.*, 2006; Kelley *et al.*, 2005). A critical factor in ABE's success, and that of other oceanographic submersibles, had been continued research in underwater vehicle navigation. For example, improvements in the precision and update rate of navigation have *(i)* enabled closed-loop feedback control of underwater robotic vehicles; and *(ii)* allowed oceanographers to more fully exploit quantitative data from high-resolution sensors such as high-frequency bathymetric sonars and optical cameras. Future improvements in underwater vehicle navigation will enable us to optimize the infrastructure necessary for navigation and enable submersibles to optimally achieve specific objectives. These improvements will increase the value, quantity, and cost-effectiveness of scientific data obtained with these vehicles.

This paper is organized as follows: Section 2 reviews advances in navigation sensors and methodologies that primarily employ data from a single sensor. Section 3 surveys state estimators that employ kinematic or dynamic models along with sensor data to estimate the vehicle state (position and velocity). Section 4 identifies current research problems that have the potential to further advance underwater vehicle navigation, and, in consequence, improve oceanographic submersibles and the value of scientific data collected with these platforms.

None of the techniques reported within is a perfect solution to the challenges of underwater vehicle navigation, and in practice it is common for a vehicle to employ a combination of these methods. The selection of sensors and techniques that are employed on a specific vehicle depends on numerous factors including the required precision and update rate of navigation and scientific measurements, sensor cost, power, depth, range, and time necessary to setup and calibrate requisite infrastructure.

2. NAVIGATION SENSOR SYSTEMS

Table 1 lists navigation sensors commonly used aboard oceanographic submersibles. Depth, heading, pitch, and roll are instrumented with strapdown high update rate sensors which provide direct measurement of the state (position and velocity) of these four degrees of freedom (DOF). The lack of a single equivalent sensor for the XY horizontal degrees of freedom complicates navigation in this plane. This lacuna is apparent in the experimental reports of undersea robotic vehicle tracking controllers e.g. (Yoerger and Slotine, 1991; Choi and Yuh, 1996; Whitcomb and Yoerger, 1996; Fossen, 1994), which have historically focused primarily on heading, altitude, depth, or attitude control. Less common is the experimental reports of XY controllers in the horizontal degrees of freedom. However, recent improvements in commercially available sensors, particularly Doppler sonars and IMUs, have enabled significant improvements in XY navigation.

This section reports a survey of recent advances in navigation sensor technology. Navigation technologies surveyed in this section include depth sensing (Sections 2.1), orientation sensing (Section 2.2), time-of flight acoustic navigation (Section 2.3), Doppler navigation (Section 2.4), inertial navigation (Section 2.5), and satellite navigation (Section 2.6).

2.1 Depth

Vehicle depth is computed from the direct measurements of ambient sea water pressure via standard equations for the properties of sea water, e.g. (Fofonoff and Millard Jr., 1983). The two most common pressure sensors technologies for deep ocean applications are *(i)* strain gauges and *(i)* quartz crystals. Strain gauge pressure sensors employ metal alloys (e.g. constantin) or silicon crystal sensing elements whose resistance changes linearly with total strain, mounted on an elastic pressure diaphragm in a Wheatstone Bridge. Strain gauges pressure sensors can typically attain overall accuracies of up to about 0.1% of full-scale and resolutions of up to about 0.01% of full-scale. Attaining full accuracy requires calibration and compensation for thermal variation in sensor gain and offset. Quartz crystal pressure sensors employ quartz crystals whose resonant frequency varies with stress induced by being subject to ambient ocean pressure. Quartz crystal pressure sensors can typically attain overall accuracies of about 0.01% of full-scale and overall resolution of up to about 0.0001% of full-scale — i.e. a resolution of one part per million. Attaining full accuracy requires calibration and compensation for thermal variation in gain and offset. The computation of geodetic vehicle altitude from depth is complicated by variation (due to tide, weather, or other factors) of the ocean's free-surface.

2.2 Orientation

Rapid innovation in the the technology of attitude sensing over the past two decades has resulted in new families of attitude sensors that offer dramatic improvement in accuracy, size, power consumption, interfaces, and operational lifetime. This section briefly reviews some of the technologies commonly employed for attitude sensing of underwater vehicles.

Table 1. Commonly Used Underwater Vehicle Navigation Sensors

INSTRUMENT	VARIABLE	UPDATE RATE	PRECISION	RANGE	DRIFT
Acoustic Altimeter†	Z - Altitude	varies: 0.1-10Hz	0.01-1.0 m	varies with frequency	—
Pressure Sensor†	Z - Depth	medium: 1Hz	01% - .01%	full ocean depth	—
Inclinometer†	Roll, Pitch	fast: 1-10Hz	0.1° - 1°	$+/-45°$	—
Magnetic Compass†	Heading	fast: 1-10Hz	$1-10°$	360°	—
Gyro: (mechanical)†	Heading	fast: 1-10Hz	0.1°	360°	$10°/h$
Gyro: Ring-Laser and Fiber-optic†	Heading	fast: 1-1600Hz	0.1° - 0.01°	360°	$0.1-10°/h$
Gyro: North Seeking†	Heading, Pitch, Roll, $\ddot{x}$,ω	fast: 1-100Hz	0.1° - 0.01°	360°	—
12 kHz LBL	XYZ Position	varies: 0.1-1.0 Hz	0.1-10 m	5-10 Km	—
300 kHz LBL	XYZ Position	varies: 1.0-10.0 Hz	+/-0.007 m	100 m	—
IMU†	$\ddot{x}, \omega, \dot{\omega}$	fast: 1-1000Hz	0.01m	varies	varies
Bottom-Lock Doppler†	$\dot{x}_{body}$	fast:1-5Hz	0.3% or less	varies: 18 - 100 m	
Global Positioning System	XYZ Position	fast: 1-10 Hz	0.1-10 m in air	In water: 0 m	—

† — Internal Sensor

2.2.1. Two-Axis and Three-Axis Magnetic Sensors A great variety of commercially available single-axis (heading only) and three-axis flux-gate magnetometers provide heading accuracies (when properly calibrated) on the order of 1°–3° with respect to local magnetic North, update rates on the order of 1–10 Hz, and power consumption typically less than 1 W. Many of these units employ the flux-gate magnetic sensing method originally developed in World War II for magnetic anomaly detection, while others employ magneto-resistive and magneto-inductive magnetic sensing methods. Most modern navigation magnetometer units incorporate an on-board microprocessor to provide a serial digital data output. These units are low-cost and highly reliable, yet studies have shown the accuracy of magnetic heading sensors can be a principal error source in the overall navigation solution, e.g. (Whitcomb *et al.*, 1999; Kinsey and Whitcomb, 2004). A variety of systematic errors can vitiate the accuracy of these magnetic sensors, including the following:

(1) Errors due to the magnetic disturbance of the vehicle itself can be significant. To address this error source, most available navigation compass units provide on-board facilities to calibrate and compensate the unit for static errors induced by the vehicle's magnetic signature.
(2) Errors due to gravity-based roll-pitch compensation methods can result in significantly degraded accuracy in the presence of induced acceleration (e.g. heave, surge, and sway).
(3) Errors due to geographic, local magnetic anomalies can be significant — a common occurrence near hydrothermal vents on mid-ocean ridges.
(4) Errors due to the orientation of the compass unit's mounting on the vehicle. As with any orientation sensor, the orientation of the sensor's angular position with respect to the vehicle's frame-of-reference must be calibrated.

Despite the noted limitations in accuracy and precision, most underwater vehicles employ a magnetic heading sensor either as a primary or secondary heading sensor.

2.2.2. Roll and Pitch Low-cost roll and pitch sensors are most commonly based upon measuring the direction of the acceleration due to gravity with either pendulum sensors, fluid-level sensors, or accelerometers. Pendulum tilt sensors typically employ one or two pendulums equipped with angle sensors to determine roll and pitch. Fluid tilt sensors employ a variety of techniques (e.g. resistive, capacitive, inductive) to detect the tilt of the free-surface of a captive fluid. Accelerometer tilt sensors employ two or three DC-accurate accelerometers to determine roll and pitch. The accuracy of most low-cost tilt sensors degrades significantly in the presence of time-varying vehicle acceleration (e.g. heave, surge, and sway). Medium-cost roll and pitch sensors employ additional gyroscopic design elements to stabilize the attitude measurement in the presence of non-uniform vehicle acceleration. The above technologies can provide static roll/pitch accuracies on the order of of 0.1°, and the gyro-stabilized versions can attain dynamic roll/pitch accuracies typically on the order of 1°–5°.

2.2.3. Angular Rate First-generation angular rate sensors, which were based on rotating mechanical gyroscopes, are rarely used in non-military underwater vehicles due to their high size, cost, and power as well as their limited operational lifetime. A wide variety of vibrating gyroscopes (either macro-machined or micro-machined) are commonly employed on underwater vehicles to measure angular rate information with accuracies on the order of 1–5 degrees per second. This level of accuracy is adequate for many underwater vehicle angular rate sensing tasks, but is insufficient for use of angular position determination. Micro-machined angular rate gyroscopes providing low cost, low power consumption, and small size are widely used as stand-alone units and are widely employed within 3-degree-of-freedom (DOF) attitude systems to provide gyro-stabilization and compensation for vehicle acceleration.

Optical gyroscopes remain the most accurate available angular rate sensors, yet their comparatively high cost and power consumption has limited their use in small and low cost underwater vehicles. Fiber-optic (FOG) and ring-laser (RLG) gyroscopes can provide angular drift rates typically on the order of 0.1–10° per hour. Low-end FOG motion units employ FOGs, accelerometers, and flux-gate compasses to estimate angular position, angular velocity, and translational acceleration.

2.2.4. True North-Seeking Three-Axis Gyrocompasses North-seeking gyrocompasses employ the earth's rotation and earth's gravitational field to determine directly the direction of local vertical and true North. Mechanical North-seeking gyrocompasses — the direct descendents of the Sperry Gyroscope Company of 1910 (Hughes, 1993) — are still widely employed on large ocean-going vessels, but their size, power consumption, and cost precludes their use on non-military underwater vehicles. A number of manufacturers offer optical-gyroscope based North-seeking gyrocompasses which employ fiber-optic FOGs or RLGs together with precision accelerometers to provide true North heading, true-vertical referenced pitch and roll, and angular rates. Available units provide dynamic heading accuracy on the order of 0.1° and dynamic roll/pitch accuracy of 0.01°. Recent improvements in the cost, size, and power consumption of these FOG and RLG based North-seeking gyrocompasses have made them feasible for use on non-military underwater vehicles. North-seeking optical gyrocompasses are now commonly utilized in underwater vehicles employed in high-precision survey operations. Full inertial navigation systems, discussed in Section 2.5, include the full North-seeking gyroscope function as part of their capability, and thus obviate the need for a separate North-seeking gyroscope.

2.3 Time of Flight Acoustic Navigation

Acoustic time-of-flight navigation methods pioneered in the 1960's and 1970's continue to be employed today. Long Baseline (LBL), in which a vehicle triangulates its position from acoustic ranges within a network of surveyed transponders, and Ultra-Short Baseline (USBL) acoustic navigation, in which a sonar array is employed to determine the range and bearing to the vehicle, are routinely used today. This section reviews previously reported work in LBL and USBL navigation, and discusses recent advances in single range navigation.

2.3.1. Long Baseline Navigation At present, the best method for obtaining sub-centimeter XY position sensing is to employ a high-frequency (typically 300 kHz or greater) LBL system. Experiments show that these systems are capable of sub-centimeter precision and update rates up to 10 Hz (Kinsey *et al.*, 2003). Unfortunately, due to the rapid attenuation of higher frequency sound in water, high frequency LBL systems typically have a very limited maximum range.

The standard method for full ocean depth XYZ acoustic navigation is 12 kHz Long Baseline (LBL) acoustic navigation (Hunt *et al.*, 1974). 12 kHz LBL typically operates at up to 10 km ranges with a range-dependent precision of 0.1–10 m and update rates periods as long as 20 seconds or more (Hunt *et al.*, 1974; Milne, 1983). The range, precision and update rate of LBL position fixes 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 or other filtering techniques (Vaganay *et al.*, 1998; Jakuba and Yoerger, 2003; Bell *et al.*, 1991; An *et al.*, 1997). Bingham and Searing report a methodology for improving LBL navigation using hypothesis grids and report results from data collected with an AUV (Bingham and Seering, 2006).

Traditionally, LBL transponders have been moored on the sea-floor (Hunt *et al.*, 1974; Whitcomb *et al.*, 1998), on the hull of a surface ship (Milne, 1983), or on sea-ice (Bellingham *et al.*, 1994). Recently researchers have reported using a network of surface buoys equipped with a global positioning system (GPS) unit and a LBL transponder to track underwater vehicles (Thomas, 1998). In (Alcocer *et al.*, 2004), the authors report a system that employs a network of these buoys to estimate the position of an AUV and employ an Extended Kalman Filter to compensate for latencies resulting from the finite propagation speed of sound in water.

2.3.2. Ultra-Short Baseline Navigation The modest infrastructure required for USBL navigation (i.e., a hull mounted transducer) has resulted in its widespread utilization in a variety of scientific, industrial, and military underwater vehicles (e.g., (Peyronnet *et al.*, 1998; Jalving *et al.*, 2004)). USBL systems require alignment calibration of the transponder and ship's positioning system (typically GPS), although the recent development of USBL transponders with integrated GPS systems could minimize this error (Audric, 2004). Supplementing the vehicle range and bearing measurements with range and bearing measurements from a fixed sea floor transponder has been shown to improve the precision of USBL navigation (Parthiot and Denis, 1993; Opderbecke, 1997). In addition to vehicle tracking, USBL navigation systems have been employed for the task of docking a vehicle to a transponder-equipped docking station (Singh *et al.*, 1996; Smith and Kronen, 1997).

2.3.3. Acoustic Modems The development of acoustic modems that provide both range measurements and data telemetry (Catipovic and Freitag, 1990; Singh *et al.*, 1996; Kilfoyls and Baggeroer, 2000) has enabled research in which multiple vehicles (typically AUVs) can share navigation data. In (Singh *et al.*, 1996), the authors propose establishing one AUV as a master that uses a conventional LBL system to compute its position. The slave vehicles employ USBL to estimate their position relative to the master vehicle using an acoustic modem to transmit the position measurement of the master AUV to the slaves. Baccou and colleagues propose having the slave vehicles employ dead reckoning with position corrections provided from the master vehicle via an acoustic modem (Baccou *et al.*, 2001). The development of acoustic modems has enabled research in one-way travel time (OWTT) navigation, as discussed in Section 2.3.4.

2.3.4. Single Range Navigation Within the last decade, an increasing number of single-range navigation systems have been proposed as a practical method for bounded-error XY navigation. This growing interest is due largely in part to improved dead-reckoned (DR) vehicle capabilities, such as the advent of Doppler sonars which allows for the possibility of computing a "running-fix". A majority of the published work in single-range navigation systems deals with two-way time-of-flight range measurements as obtained from interrogating a single standard LBL beacon moored to the sea floor. For example, the work of (Scherbatyuk, 1995; Larsen, 2000; Vaganay *et al.*, 2000; Baccou and Jouvencel, 2002; Gadre and Stilwell, 2005; Ross and Jouffroy, 2005) analyzes the navigation performance and feasibility of such systems. The impetus behind this approach is its reduced infrastructure requirements, which allows for more rapid deployment, calibration, and recovery. However, like LBL, navigation update rates decrease proportionally with the number of vehicles, due to a time division multiple access (TDMA) interrogation scheme, which makes this approach less desirable when dealing with more than a few vehicles in a multiple vehicle environment.

Alternatively, work in single-range navigation systems have explored the use of synchronous-clocks strategies for the direct measurement of one-way time-of-flight from an acoustic source. The constant update rates of XY position with these systems, when used in a master/slave architecture, is superior to those for multiple vehicle two-way time-of-flight systems. Early work in synchronous-clock one-way travel time (OWTT) ranging has been reported by (Hunt *et al.*, 1974) for the "in-hull navigation" of the manned deep-submergence vehicle Alvin. In (Singh *et al.*, 2001), Singh reports synchronous-pinger OWTT navigation using integrated range-rate positioning for AUV docking using a early predecessor of the modern WHOI Micro-Modem. More recently, other work using acoustic modems and synchronous-clock navigation has been reported in (Curcio *et al.*, 2005) for autonomous surface-craft; in that work each vehicle was equipped with a GPS receiver to provide a common time base for synchronous ranging.

Recent work by the Authors (Eustice *et al.*, 2006) explores a synchronous-clock acoustic navigation framework that employs Micro-Modems developed by the Woods Hole Oceanographic Institution (WHOI), (Freitag *et al.*, 2005*b*; Freitag *et al.*, 2005*a*; Singh *et al.*, 2006), in conjunction with low-power stable clocks to yield a navigation system capable of submerged inter-vehicle communication and OWTT ranging. The use of precision clocks allows for a synchronous modem communication/navigation system whereby navigation data packets can encode time of origin information as well as local ephemeris data (e.g., XYZ positional data and error metric). Our methodology is to use the above capabilities in the context of a surface-ship acting as a moving transponder navigating a fleet of AUVs over length scales of $\mathcal{O}(100\text{ km})$. In this scenario, the ship maneuvers with the vehicle fleet tending to vehicle launch/recovery support, while also acting as a global navigation aid by broadcasting GPS-derived ship-transducer position to the vehicle network. All vehicles within listening range of the ship that passively receive the GPS ephemeris can then use this knowledge to compute a running position fix and correct any accumulated dead-reckoning error.

2.3.5. Error Sources in Acoustic Navigation All acoustic time of flight navigation methods require *(i)* careful placement of transponders fixed or moored on the sea floor (Hunt *et al.*, 1974; Whitcomb *et al.*, 1998), on the hull of a surface ship (Milne, 1983), or on sea-ice (Bellingham *et al.*, 1994); *(ii)* accurate knowledge of the sound velocity; and *(iii)* are fundamentally limited by the speed of sound in water — about 1500 m/s. Deeply submerged vehicles employing USBL or surface LBL systems are especially challenged by *(ii)* as sound velocity can vary significantly due to ambient factors such as water temperature and density.

2.4 Doppler Navigation

The development of high-frequency, multi-beam Doppler sonars that provide bottom velocity measurements with a precision of 0.3% or less and update rates up to 5 Hz provide researchers with velocity measurements for near-bottom (18–100 m) navigation. This has enabled the development of a wide variety of Doppler-based navigation techniques. This section reviews reported work in Doppler-based navigation systems. In addition to these techniques, Doppler velocity measurements are employed to improve state estimates in Inertial Navigation Systems (INSs) (Section 2.5) and state estimators (Section 3).

2.4.1. Reported Doppler Navigation Techniques In (Spindel *et al.*, 1976) Spindel and colleagues report an acoustic navigation system combining LBL navigation techniques with transponder-based Doppler velocity sensing. In (Brokloff, 1994) Brokloff reports a bottom-lock Doppler-based dead-reckoning system combining GPS, a 300 kHz Doppler, and an inertial navigation unit (for vehicle heading and attitude data) to obtain relative navigation errors of 0.4% of distance traveled over long (five hour) high-speed (five knot) missions, and a general least-squares technique for estimating the alignment error in Doppler navigation. Brokloff extends the previous results to employ water-lock Doppler tracking when the vehicle altitude exceeds bottom-lock range (Brokloff, 1997). The preliminary results of the deployment of a combined LBL/Doppler navigation system are reported in (Whitcomb *et al.*, 1998). The development of an integrated Doppler navigation program for oceanographic submersibles, DVLNAV, is reported in (Kinsey and Whitcomb, 2004). McEwen and colleagues report the utilization of a Doppler navigation system aboard an AUV during an under ice deployment (McEwen *et al.*, 2005).

2.4.2. Error Sources in Doppler Navigation Previously reported studies by the Authors and others identify two principal error sources arising in the Doppler navigation of underwater vehicles. The first error source is heading, both in terms of attitude sensor accuracy and precision (Whitcomb *et al.*, 1999; Kinsey and Whitcomb, 2004). The recent availability of relatively low-cost, true North-seeking, 3-axis optical gyrocompasses reported in Section 2.2.4 effectively ameliorates this problem.

The second error source is sensor calibration alignment errors between the Doppler sonar and the attitude sensor (Brokloff, 1994; Joyce, 1989; Kinsey and Whitcomb, 2004; Münchow *et al.*, 1995; Pollard and Read, 1989; Whitcomb *et al.*, 1999; McEwen *et al.*, 2005). The analytical development of least-squares (Kinsey and Whitcomb, 2006*b*) and adaptive identifier (Kinsey and Whitcomb, 2006*a*) methodologies for the *in-situ* estimation of the Doppler alignment. These techniques use data commonly available to deeply submerged vehicles (Doppler velocities, gyrocompass attitude, and LBL position measurements) and can utilize, but do not require, GPS position measurements. Data from laboratory and field deployed underwater vehicles demonstrate that alignment estimates obtained from these techniques significantly improve the precision of Doppler navigation (Kinsey and Whitcomb, 2006*b*; Kinsey and Whitcomb, 2006*a*).

All navigation methodologies that employ Doppler measurements require *(i)* accurate knowledge of the Doppler alignment; *(ii)* accurate sound velocity estimates; and *(iii)* attitude measurements from gyrocompasses for accurate position estimates.

2.5 Inertial Navigation

Inertial measurement units (IMUs) offer excellent strap-down navigation capabilities, but their power consumption (ranging from 12–30 V) and cost (often in excess of $100,000 U.S.) has, until recently, precluded their widespread use in civilian oceanographic vehicles. Numerous papers have reported the deployment of IMUs on underwater vehicles over the last decade — examples include (Uliana *et al.*, 1997; Trimble, 1998; Thorleifson *et al.*, 1997; Larsen, 2002; Alameda Jr., 2002; Ura and Kim, 2004; Huddle, 1998; Asada *et al.*, 2004; Griffiths *et al.*, 2003; Stokey *et al.*, 2005; McEwen *et al.*, 2005). Typically, IMUs employ Doppler velocity measurements and position measurements from GPS or acoustic navigation systems to correct for errors in the IMU state estimate. IMUs are often employed in high-precision surveys and when vehicles are deployed under ice-caps or in the mid-depth zone.

2.6 Global Positioning System

The U.S. global positioning system (GPS) provides superior three-dimensional navigation capability for both surface and air vehicles, and is widely employed by oceanographic research surface vessels. The GPS system's radio-frequency signals are blocked by sea water, thus GPS signals cannot be directly received by deeply submerged ocean vehicles. However, GPS commonly aides a variety of underwater vehicle navigation techniques, including surveying of acoustic transponders, position correction for IMUs, alignment calibration of Doppler sonars (Kinsey and Whitcomb, 2006*b*), and surface LBL systems (Thomas, 1998; Desset *et al.*, 2003).

3. NAVIGATION STATE ESTIMATORS

This section reviews previously reported work on the analytical development and experimental implementation of state estimators in underwater vehicle navigation. While many of the techniques reported within employ data from sensors discussed in Section 2, the methodologies discussed in this section differ in that they supplement these measurements with information from a kinematic or dynamic model. This survey focuses on techniques that are independent of a specific sensor, such as those commonly available with inertial measurement units (e.g., (Napolitano *et al.*, 2004)). To date, most research has focused on the development of stochastic state estimators such as the Extended Kalman Filter (EKF) (Section 3.1), however there is an increasing amount of reported results on Simultaneous Localization and Mapping (SLAM) and nonlinear deterministic observers (Sections 3.3 and 3.4, respectively).

3.1 Stochastic Model-Based State Estimators

Stochastic state estimators, specifically optimal unbiased estimators such as the Kalman Filter and the EKF, are increasing employed in underwater vehicle navigation. To date, most implementations of these estimators have employed kinematic plant models. Typically, these estimators utilize data from many, if not all, of the sensors discussed in Section 2. The estimators discussed in this section differ from the deterministic estimators reviewed in Section 3.4 in that they employ knowledge of process and measurement noise to compute optimal gains. A growing number of vehicles employ this class of estimators for vehicle navigation — recently reported implementations include (Blain *et al.*, 2003; Di Massa and Stewart, 1997; Eustice *et al.*, 2005*a*; Gade and Jalving, 1998; Roman, 2005; Yun *et al.*, 2001).

Rarer is the development of stochastic state estimators employing knowledge of the vehicle's dynamics (e.g. hydrodynamic coefficients, buoyancy, etc.) and control inputs (e.g. actuator forces, control surface angles, etc.). Jakuba and Yoerger report the implementation of a Rauch-Tung-Striebel (RTS) smoother (Rauch *et al.*, 1965) to post-process AUV navigation data using heuristic estimates of the vehicle model parameters, and utilization of this technique on data from bathymetric surveys has been shown to reduce track line artifacts (Jakuba and Yoerger, 2003).

More recent developments in general nonlinear stochastic state estimators include Unscented Kalman Filters (i.e. Sigma-Point Kalman Filters), as reported in (Julier and Uhlmann, 1996; Wan and van der Merwe, 2000; van der Merwe, 2004), and Monte Carlo Methods (i.e., Particle Filters), as described in (Gordon *et al.*, 1993; Arulampalam *et al.*, 2002; Doucet *et al.*, 2001). Both of these numerical estimation techniques rely upon a sampling strategy to avoid linearizing the plant/observation models, which is a known source of approximation error in EKF-based methods. Instead, these methods rely upon numerically approximating the state-estimate distribution. Application of these estimation techniques within the underwater navigation community, to the best our knowledge, has been slow to be adopted, though, appears to be nascent.

3.2 Terrain Based Navigation

Terrain relative, or landmark relative navigation uses real-time sensing and a terrain or landmark map (typically of topographic, magnetic, gravitational, or other geodetic data) to determine vehicle position. These methodologies employ data from scientific sensors, reducing the need for dedicated navigation sensors. Authors have addressed the problem *(i)* where an *a-priori* map is available, e.g. (Di Massa and Stewart, 1997; Moryl *et al.*, 1998; Vajda and Zorn, 1998; Williams, 2003; Eustice *et al.*, 2005*c*); *(ii)* where *a-priori* landmark maps are not available, but are constructed incrementally from sensor data, e.g. (Newman and Durrant-Whyte, 1998; Feder *et al.*, 1998; Williams *et al.*, 2000; Eustice *et al.*, 2005*a*; Roman, 2005); and *(iii)* where a task is achieved (e.g., altitude control, obstacle avoidance) without explicit maps, e.g., (Yoerger *et al.*, 1998). In typical underwater scientific missions, *a-priori* maps are seldom available. Although most terrain relative navigation techniques employ time-of-flight sonars as the principal navigation sensor, a few reported studies, e.g. (Fleischer, 2000; Negahdaripour *et al.*, 1998; Tena Ruiz *et al.*, 2001; Williams and Mahon, 2004; Eustice *et al.*, 2004; Eustice *et al.*, 2005*b*), employ optical sensing. These methodologies are limited by the range of the sensors, which are typically $\mathcal{O}(10\text{–}100 \text{ m})$ for bathymetric sonars and $\mathcal{O}(< 10 \text{ m})$ for optical cameras.

3.3 Simultaneous Localization and Mapping

Over the past decade, a significant research effort within the terrestrial mobile robotics community has been to develop environmentally-based navigation algorithms that eliminate the need for additional infrastructure and bound position error growth to the size of the environment — a key prerequisite for truly autonomous navigation. The goal of this work has been to exploit the perceptual sensing capabilities of robots to correct for accumulated odometric error by localizing the robot with respect to landmarks in the environment. The question of how to use such a methodology for navigation and mapping was first theoretically addressed in a probabilistic framework in the mid 1980's with seminal papers by (Smith *et al.*, 1990) and (Moutarlier and Chatila, 1989). Since that time, this general problem has become known as the Simultaneous Localization and Mapping (SLAM) problem.

One of the major challenges of the SLAM problem is (a) defining fixed features from raw sensor data and (b) establishing measurement to feature correspondence (i.e., the problem of data association (Neira and Tardos, 2001)). Both of these tasks can be nontrivial — especially in an unstructured underwater environment. In man-made environments, typically composed of planes, lines and corners primitives, features can be more easily defined, as discussed in (Tardos *et al.*, 2002). However, natural, unstructured environments such as the sea floor pose a more challenging task for feature extraction and matching.

One SLAM methodology that has seen recent success in the near-sea-floor underwater realm is to apply a view-based scan-matching approach, as reported in (Fleischer, 2000; Garcia *et al.*, 2001; Eustice *et al.*, 2005*c*; Roman, 2005). View-based SLAM approaches do not require an explicit representation of features and instead use a data-driven approach based upon pose-graphs. This technique has seen good success when applied to a unstructured sea floor environment. The main idea behind this methodology is that registering overlapping perceptual data, for example optical imagery as reported in (Eustice *et al.*, 2005*c*) or bathymetry as reported in (Roman, 2005), introduces spatial drift-free constraints into the pose-graph. These spatial constraints effectively allow the robot to close-the-loop when revisiting a previously visited place thereby resetting any accumulated dead-reckoning error.

The application of feature-based SLAM frameworks have also been reported for an underwater environment, but so far with less real-world success than view-based approaches. Notable exceptions include (Williams and Mahon, 2004) who reports an optical camera system that tracks point feature targets initialized by a pencil-beam sonar within the camera's field of view; demonstrated results include mapping of a natural coral reef environment. Other reported feature-based SLAM applications include sonar-based target mapping as reported by (Tena Ruiz *et al.*, 2001; Newman *et al.*, 2003) and range-only LBL network self-calibration as reported in (Olson *et al.*, 2004).

3.4 Deterministic State Estimators

The deterministic state estimator problem addresses exact (non-stochastic) plant and measurements models, and focuses on the development of exact asymptotically stable estimators. Lohmiller and Slotine reported a deterministic non-linear dynamic model-based velocity estimator for underwater vehicles in (Lohmiller and Slotine, 1998) that uses contraction mapping to show stability of the estimator. An advantage of this estimator over the stochastic estimators presented in Section 3.1 is that it exploits exact knowledge of the vehicle's nonlinear dynamics. Jouffroy refines Lohmiller and Slotine's stability condition and further discusses this estimator in (Jouffroy, 2003).

The analytical development and experimental evaluation of a deterministic non-linear dynamic model-based full-state (i.e., position and velocity) estimator is reported in (Kinsey, 2006). This observer exploits exact knowledge of the vehicle's nonlinear dynamics, the forces and moments acting on the vehicle, and disparate data from navigation sensors to estimate position and velocity. The stability of the observer is shown using Lyapunov techniques and the Kalman-Yakubovich-Popov Lemma. The observer is experimentally evaluated using data from single degree-of-freedom experiments with a laboratory remotely operated vehicle (ROV), with a 300kHz LBL acoustic positioning system providing high-precision position measurements. The observer provides position estimates whose errors possess a standard deviation significantly lower than the those for 12kHz LBL positioning systems and comparable to those computed by an Extended Kalman Filter.

While the above-mentioned techniques employ knowledge of the vehicle's dynamics, Jouffroy and Opderbecke use a kinematic model to derive diffusion-based trajectory estimators in (Jouffroy and Nguyen, 2004). The observer is evaluated on data from a field-deployed ROV and these experiments illustrate the potential benefits of this method. This estimator estimates an entire trajectory of the state as opposed to the state at a given instance, and consequently, must be used off-line, after the trajectory has been completed.

A significant shortcoming of deterministic non-linear state estimators is the absence of analytical methods for selecting optimal gains. In consequence, heuristic or numerical simulation approaches must be employed.

4. CONCLUSION AND FUTURE CHALLENGES

The past decade of advances in both the technology and the algorithms of underwater navigation have significantly improved existing navigation methodologies and, moreover, resulted in entirely novel navigation methods. This Section briefly reviews some of the interesting current and future challenges in this rapidly evolving field of research. As navigation research rises to meet these challenges, improved navigation will continue to enable new missions for underwater vehicles which were previously considered impractical or infeasible.

4.1 Improvements in Near-Bottom Navigation

While the precision and update rate of many near-bottom navigation techniques is sufficient for dynamic positioning, these characteristics are still inferior to those of high-resolution science sensors. Further improvements in near-bottom navigation will close this lacuna, and, in consequence, allow scientists to more fully exploit scientific data of near-bottom processes.

4.2 State Estimation Research

The development of model-based state estimators reviewed in Section 3 demonstrates the growing interest in employing these methodologies in underwater vehicles. To date, most work has focused on analytical development and experimental evaluation in post-processing — necessary steps for real-time implementation. The implementation of estimators *in-situ* has the potential to significantly advance underwater vehicle navigation. The wide variety of outstanding issues in this area ensures that state estimators will remain a fertile research topic in the coming years.

4.3 Optimal Survey and Environmental Estimation

Navigation is comprised of two tasks: *(i)* determining the current position of a vehicle and *(ii)* selecting a set of trajectories necessary to achieve an set of prescribed goals. Traditionally, the oceanographic engineering community has focused on developing *in-situ* techniques for the former task, determining position, and relied upon trajectories defined *a-priori* for the latter task. While *a-priori* defined trajectories have been suitable for tasks such as underwater bathymetry, such trajectories are inappropriate for tasks such as finding thermoclines or hydrothermal vents. The resources (e.g., time and power) necessary to achieve these latter tasks might be significantly reduced by selecting trajectories based on data measured by quantitative science sensors during the mission.

The development of methodologies that evaluate scientific data collected during a mission to determine sites of interest have been reported for a number of scientific tasks, including physical oceanography (Willcox *et al.*, 1996; Willcox *et al.*, 2001; Fiorelli *et al.*, 2004), bathymetry (Burian *et al.*, 1996), and hydrothermal vents (Jakuba *et al.*, 2005). The coupling of these "environmental state estimators" with navigation state estimators could enable vehicles to plan optimal trajectories *in-situ*, thus allowing for more efficient completion of objectives.

Perhaps the most interesting aspect of these studies is that they begin to directly address the environmental estimation problem in a holistic formulation. These studies seek to unify the time-honored but artificial distinction between *(i)* vehicle navigation accuracy and trajectory planning and *(ii)* scientific sensor data obtained from sensors carried as vehicle payload. The idea is that the methodologies of vehicle navigation, vehicle trajectory planning, and scientific sensor data collection should be analyzed holistically to determine how these disparate design parameters effect the overall accuracy of the environmental process. Researchers are beginning to investigate the analytical properties of systems that estimate environmental parameters — for example, existence and uniqueness of solutions, observability, unbiased estimation, asymptotic behavior, stochastic lower bound analysis.

4.4 Multiple Vehicle Navigation

Advances in acoustic modems and one-way travel time (OWTT) navigation techniques enable researchers to consider navigation methodologies that employ data from multiple vehicles. In these techniques, a vehicle employs sensor and state information from other vehicles, in addition to data it possesses from on board sensors and navigation systems. The deployment of multiple vehicles to sites of scientific interest (e.g., thermoclines or hydrothermal vent fields) coupled with improved environmental and navigation state estimation techniques increases our ability to effectively search, locate, and study scientific processes. The ability of vehicles to operate in the same region and share information could allow for reductions in the resources (e.g. LBL transponders, high-resolution bathymetry sonars, gyro compasses) necessary for ocean exploration. These advances would significantly advance our abilities to use underwater vehicles in oceanography, and potentially alter ocean exploration strategies.

4.5 Navigation in the Mid-depth Zone

Three-dimensional surface navigation has been effectively solved by GPS, and Doppler sonars and landmark navigation have significantly improved near-bottom navigation. However, acoustic time of flight systems and IMUs are the only effective sensors for XY state measurements in the mid-depth zone (the water column far from the sea surface and far from the sea-floor). This vitiates our ability to precisely navigate in this region of the ocean. At present, these techniques are sufficient for oceanographic research, however the continually increasing interest in quantitative biological and physical oceanography in the mid-depth zone motivates developing improved navigation systems. The limited amount of sensors measurements available at these depths implies that model-based state estimators will be pivotal in these advances. In the case of vehicles operating in the mid-depth zone being simultaneously deployed with vehicles operating near the surface or at the sea-floor, advances in multiple vehicle navigation may contribute to improvements in the navigation in this region.

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