14. Autonomous Underwater Vehicle Navigation

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This chapter surveys the problem of navigation for autonomous underwater vehicles (AUVs). Navigation is critical for the safety and effectiveness of AUV missions. The unavailability of global positioning system (GPS) underwater makes AUV navigation a challenging research problem. Recent years have seen considerable improvements in performance and reduction in the cost and size of the various sensor devices available for ocean vehicle navigation. In concert with these developments, advances in algorithms such as simultaneous localization and mapping, and cooperative navigation have enabled dramatic improvements in the navigation capabilities of AUVs. These improvements in AUV navigation have contributed to the successful deployment of AUVs for a wide variety of applications over the past decade.

This chapter surveys the problem of navigation for autonomous underwater vehicles (AUVs). We review the major types of sensors available for underwater navigation, and then describe some of the key techniques employed, including long baseline (LBL) navigation and simultaneous localization and mapping (SLAM) algorithms. Subsequently, we describe several example navigation systems utilized in recent AUV systems. Figure 14.1 shows some examples of the wide range of AUVs that are in use today. The selection of appropriate navigation sensors and algorithms, based on cost, power, size, and mission constraints, is a key element of AUV system design [14.1].

Navigation is an important requirement for any type of mobile robot, but this is especially true for AUVs. Good navigation information is essential not only for the safe operation and recovery of the AUV, but also for the data gathered by an AUV to be of value. For many types of AUV missions, such as seabed mapping and mine countermeasures, the quality of the data acquired by the vehicle depends critically on the accuracy of the vehicle's navigation system. Cost can be a major factor in AUV navigation system design. This is especially true for applications that involve the coordinated operation of multiple vehicles.

The absence of global positioning system (GPS) measurements underwater makes AUV navigation a difficult challenge. Without an external reference in the form of acoustic beacons at known positions, the vehicle has to rely on proprioceptive information obtained through a compass, a Doppler velocity logger (DVL) and/or an inertial navigation system (INS) to perform dead reckoning (DR). Independent of the quality of the sensors used, the error in the position estimate based on

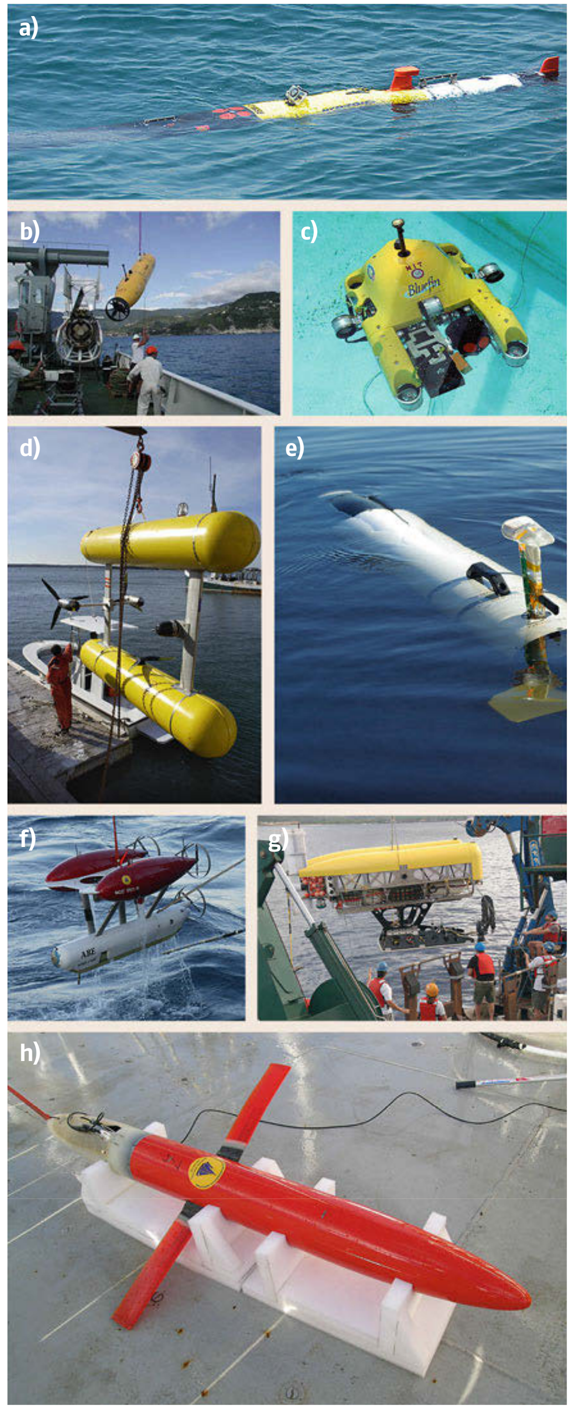

Fig. 14.1a–h The AUV systems that employ the diverse range of navigation sensors and algorithms described in this chapter include the REMUS [14.2], Bluefin 21 [14.3], HAUV [14.4], Seabed [14.5], Iver2 [14.6], ABE [14.7], and Nereus [14.8], AUVs and the Spray glider [14.9]. Photos **(a–c, e)** by MIT; **(f,h)** by WHOI; **(d)** Tom Kleindinst, WHOI; **(g)** Christopher Griner, WHOI ►

DR information grows without bound. Typical navigation errors are 0.5–2% of distance traveled for vehicles traveling within a few hundred meters of the sea floor such that their DVL has a lock on the bottom. Errors as low as 0.1% can be obtained with large and expensive INS systems, but for vehicles relying only on a compass and a speed estimate, the rate of error can be as high as 10%. By surfacing the AUV can obtain a position update through its GPS, but this is impossible or undesirable for many applications. The use of static beacons in the form of an LBL array limits the operation area to a few km^2 and requires a substantial deployment effort before operations, especially in deep water.

As underwater vehicles become more reliable and affordable, the simultaneous use of several AUVs has become viable, and it is anticipated that multivehicle deployments will become standard in the upcoming years. This will not only make entirely new types of missions which rely on cooperation possible, but will also allow each individual member of the group to benefit from the navigation information obtained from other members. For optimal cooperative localization, a few dedicated Navigation Aid-AUVs (NAs), which maintain an accurate estimate of their positions through sophisticated DVL and INS sensors, can enable a much larger group of vehicles with less sophisticated sensor suites to maintain an accurate position.

Navigation (along with communications, power, and autonomy) has been one of the fundamental challenges in the development of AUV technology. Underwater vehicle navigation is a challenging problem for several reasons. Due to the absorption of electromagnetic radiation in the ocean, GPS is only available at the surface. Unfortunately, there is no *silver bullet* solution for the AUV navigation problem. There are five primary technologies that an AUV designer has to draw upon in selecting an AUV navigation system:

1. Proprioceptive sensing
2. GPS
3. Acoustic transponder navigation
4. Map-based navigation
5. Cooperative navigation of multiple vehicles.

Proprioceptive navigation refers to using measurements of the vehicle's self-motion to deduce the vehicle's position. There are two major categories, based on price: (a) INS combined with DVL, and (b) magnetic compass/attitude heading reference systems. Integrated INS/DVL systems typically cost up to \$ 100 000 and have been integrated on many large-scale, high-cost AUV systems. In the past two decades, the cost and size of proprioceptive navigation sensors have reduced dramatically, making them available to smaller and lower-cost AUV systems. The performance claims of better than 0.1% of distance traveled have been made in the literature [14.10].

Regardless of sensor cost and quality, the problem with exclusive reliance on proprioceptive sensing is that the position error increases without bound as the distance traveled by the vehicle increases. The rate of increase will be a function of ocean currents, the vehicle speed, and the quality of dead reckoning sensors. If a vehicle can surface, then GPS can be used for a position fix. Indeed, many AUVs have demonstrated this capability. However, frequent surfacing is impractical for deep-water missions and is undesirable for other types of missions.

In acoustic navigation, transponders serve as *beacons* to constrain INS/DR error growth without the need for resurfacing. Two types of systems have been primarily employed [14.11–13]: LBL and ultra-short baseline (USBL). Both systems employ external transducers or transducer arrays as aids to navigation. Acoustic navigation is a well-established and widely used technique. However, in littoral waters, a number of sources of error occur. These include: multipath, drop-outs, fading, and reverberation. Further development is required to attain better outlier rejection and improve robustness for autonomous operations [14.14]. A longer term goal is to fully integrate navigation, communications, and tomography [14.15].

For many applications, deployment of acoustic beacons is undesirable, and map-based navigation presents an alternative. If an accurate a priori map of the environment is available, one approach to globally-referenced position estimation is to use measurements of geophysical parameters, such as bathymetry, magnetic field, or gravitational anomalies [14.16, 17]. In practice, an up-to-date, high-quality map may be unavailable in the operating area of interest. This motivates research into the problem of SLAM, in which the goal is for the AUV to build a map of its environment and to use that map to navigate in real time.

The structure of this chapter is as follows. Section 14.1 describes available sensors for measuring depth, heading, velocity, acceleration, acoustic range and bearing, and GPS. Section 14.2 describes the main navigation algorithms including DR and inertial navigation, LBL and USBL navigation, geophysical and map-based navigation, and cooperative localization. Section 14.3 summarizes the performance of several typical types of AUV systems in use today, and provides an outlook for future developments in this area.

14.1 Sensors

14.1.1 Depth

All submersible vehicles are outfitted with a pressure sensor [14.18] that allows an accurate determination of absolute depth using the known properties of sea water [14.19]. As a result, all other underwater navigation systems are only used to resolve the two-dimensional (2-D) position, (i. e., longitude and latitude) and underwater-vehicle-related localization problems are typically stated in 2-D. Quartz crystal pressure sensors can typically attain accuracies of 0.01% or better, but achieving full accuracy requires careful calibration and thermal compensation [14.1].

14.1.2 Compass

Like the pressure sensor, a compass is part of the basic navigation sensor suite of most underwater vehicles, as it is an inexpensive and low-power device. It provides the three-dimensional (3-D) vector of the local magnetic field. Before computing the heading from the magnetic field vector, it is necessary to carefully calibrate the compass each time the vehicle's area of operation changes, as the difference between the orientation of the 3-D magnetic field vector and the direction of true north (called *variation*) depends on the geographic location. In addition to the spatially slow variation, there are highly localized *magnetic anomalies*. The compass output is also affected by its position in the vehicle as electrical currents create magnetic fields which cannot be discerned from the earth's magnetic field. On-line compass calibration algorithms [14.3, 20] can substantially improve performance.

14.1.3 Gyroscopes

Gyroscopic systems measure changes in vehicle orientation by exploiting physical laws that have predictable effects under rotation [14.21]. Available sensors include mechanical gyrocompasses, ring laser gyroscope (RLG), fiber optic gyroscope (FOG), dynamically tuned gyroscope (DTG) and micro-electromechanical (MEMS) devices [14.22]. Optical gyroscopes have become popular as an accurate angular rate sensor, and operate on the SAGNAC principle [14.23]. However, sensible DR navigation requires high gyroscope performance increasing the associated costs significantly.

The power consumption and size of common optical gyroscopes have limited their use to larger and more expensive AUVs [14.1].

14.1.4 Attitude Heading Reference Systems

An attitude-heading reference system (AHRS) unit typically consists of a 3-axis gyroscope as well as a 3-axis linear acceleration sensor and a heading sensor (magnetic or gyrocompass). Combining the measurements from these sensors, the AHRS maintains a common algorithmic orientation estimate between the sensor cluster and the global world navigation frame. The orientation is maintained through integration of the gyroscope measured rotation rates. Long term pitch and roll stability of the orientation estimate is achieved through selective use of earth's gravity vector, which is measured by a triad of accelerometers. The long-term heading accuracy is maintained from either magnetic compass sensor readings or direct measurement of the earth rotation through the gyroscopes.

14.1.5 Inertial Navigation Systems

The sensors of an INS are the same as those of the AHRS described earlier. In addition to the AHRS, measured accelerations are rotated to the common navigation frame, as discussed above, and then double integrated to compute a position estimate for the vehicle. The initial position of the INS is obtained from an absolute position sensor (such as GPS or LBL). The process of inertial navigation is discussed in more detail in Sect. 14.2.1.

14.1.6 GPS

Almost all underwater vehicles today are equipped with a GPS receiver as it can be used to get a position fix before the start of the mission or during intermittent surfacings. GPS measurements obtained at different points during a mission can be used to constrain the error growth of position estimates derived from inertial and Doppler sensors [14.3]. Farrell provides a comprehensive summary of the mathematical techniques for integrating GPS measurements with high-rate inertial and acoustic sensors [14.24].

Fig. 14.2 **(a)** Doppler velocity log (DVL); **(b)** REMUS AUV with DVL

14.1.7 Doppler Velocity Log (DVL)

A DVL (Fig. 14.2) is a device which typically has four transceiver units that emit acoustic pulses. When a DVL is used for navigation purposes, it is usually mounted on a vehicle such that the transceivers are facing downward. If the DVL is close enough to the bottom, the transceiver will receive the reflected pulses (*bottom lock*) and as the transceivers are mounted at an angle with respect to the sea-floor plane, the received pulses will be subject to a Doppler shift if the vehicle is moving. Combining the measured Doppler shifts from all four sensors with the built-in roll, pitch, and heading sensors the DVL can then compute the vehicle's 3-D-speed vector $\boldsymbol{v}_v = (\dot{x}, \dot{y}, \dot{z})$ in a world-referenced frame.

The maximum distance between the DVL unit and the sea floor depends on the operating frequency of the transceivers. A low-frequency (150 kHz) DVL can obtain bottom-lock for ranges up to 500 m, while a high-frequency DVL (1200 kHz) can obtain bottom-lock up to 30 m.

The ranges indicated above can only be obtained under ideal conditions. A soft sea floor or vegetation can absorb most of the energy of the incoming pulse and thereby significantly decrease the maximum range. Another option is to mount the DVL in an upward-looking configuration such that the acoustic pulses are reflected at the water/air interface (*surface-lock*). Then, the vehicle measures its speed relative to the water surface, but this strategy may introduce errors in the case of significant surface currents. Figure 14.2 shows a REMUS 100-AUV with a double-DVL configuration. If bottom-lock cannot be obtained with the downward-looking DVL the vehicle tries to determine its speed using the upward looking unit. Recent developments greatly increased the accuracy of DVL-systems and errors as low as 0.2% (1200 kHz) or 1% (150 kHz) of distance traveled can be obtained.

In deeper waters, where the distance from the seabed is beyond the range of a DVL, an alternative is to use a correlation speed log sonar [14.25]. Whereas a DVL employs four angled beams, a correlation sonar utilizes a single widebeam transducer, pointing straight downward toward the seabed. By cross-correlating the received waveforms on two closely separated transducers, the displacement of the crosscorrelation peak provides a measure of the vehicle velocity. Correlation sonar navigation has been demonstrated by *Griffiths* and *Bradley* for performing long-distance under-ice excursions in deep water in polar regions with the Autosub AUV, achieving ranges greater than 1000 m [14.26].

14.1.8 Acoustic Ranging Methods

The most commonly used way to obtain absolute position information underwater is through the use of beacons. These beacons are at known locations and the AUV obtains the range and/or bearing to several of these and then calculates its position through trilateration or triangulation. Based on the location of the transceivers, we can identify three different baseline systems.

Electromagnetic energy cannot propagate appreciable distances in the ocean except at very low frequencies. Acoustic energy, however, propagates well in the ocean, and hence acoustic transponders can be used as *beacons* to guide the motion of an AUV without the need for resurfacing. Two types of system have been primarily employed [14.11–13]: LBL and USBL. Both systems employ external transducers or transducer arrays as aids to navigation.

Standard LBL

A typical LBL-configuration is shown in Fig. 14.3a. Two or more beacons are deployed around the perimeter of the area in which the AUV will operate. These beacons are anchored and float on the surface or, particularly in deeper water, a few meters above the sea floor. Each unit listens to acoustic query pings on a common receive channel. After receiving a query ping from an AUV, each unit waits for a unique turn around time (TAT) t^{TAT} and then sends out a reply ping on its individual transmit channel. The AUV then receives the reply pings. The transmit channel as well as the TAT are different for each unit. A unique TAT ensures that two beacons will not interfere by transmitting at the same time and by using different transmit frequencies the beacons provide a way for the AUV to identify from which unit a reply ping was sent. The time difference Δt_i between sending out the query ping and receiving a reply can then be used to determine the one-way travel-time (OWTT) t_i^{owtt}.

$$t_i^{\mathrm{owtt}} = \frac{\Delta t_i - t_i^{\mathrm{TAT}}}{2}$$

The distance d_i between a beacon i and the AUV is then given by

$$d_i = \frac{c}{t_i^{\mathrm{owtt}}} \,,$$

where the speed of sound c is either a pre-programmed value or measured on-board. Using range measurements to several beacons and the beacon positions stored in the vehicle before deployment, the AUV can now trilaterate its position.

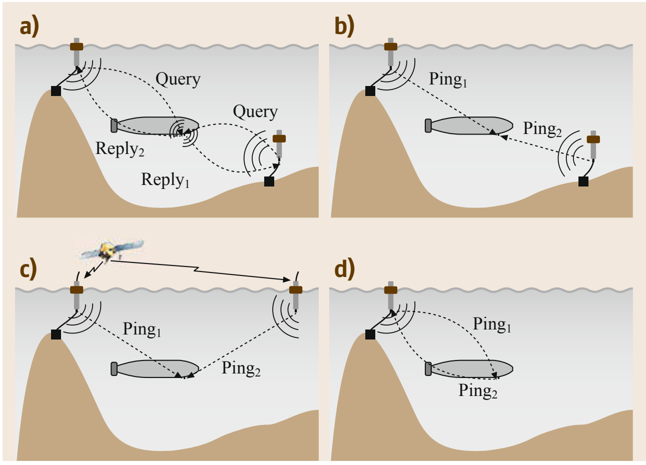

Fig. 14.3a–d Beacon-based underwater localization techniques. **(a)** Conventional (two-way) Long Baseline (LBL) navigation; **(b)** time-synchronized (one-way) LBL; **(c)** GPS-buoy navigation [14.27]; **(d)** ultra-short baseline (USBL) navigation

The maximum possible distance between the AUV and a beacon as well as the localization accuracy depends on the the frequency band used for query and reply pings. Long-range LBL-systems using the 12 kHz band work over distances as long as 10 km [14.28] and can provide an absolute position with an error between 1 and 10 m. Short-range LBL systems using frequencies up to 300 kHz band can achieve subcentimeter precision, but the maximum range is limited to 100 m [14.28]. The indicated errors assume that large outliers have been filtered out. These outliers, which can be seen in Fig. 14.4, are due to multipath and other acoustic propagation effects.

LBL Variants

Standard LBL systems such as the one described earlier are not well suited for large groups of AUVs because only one vehicle at a time can query the beacon network and get a position update. Thus, the position update interval increases with the number of vehicles. Newer LBL systems, like the one developed by ACSA [14.27, 30] and shown in Fig. 14.3b, have synchronized clocks in the beacons and the AUV transceiver units. The beacons broadcast a ping containing a unique identifier at fixed time intervals. When the AUV receives this ping, the beacon's known broadcast schedule and the synchronized clock's time ensure that the vehicle knows when a ping was sent and can directly compute the OWTT. The synchronized clocks thereby eliminate the need for query pings and allow all vehicles within the range of the beacons to get a range to the broadcasting beacon. As a result, the ping interval is independent of the number of vehicles relying on the beacon network.

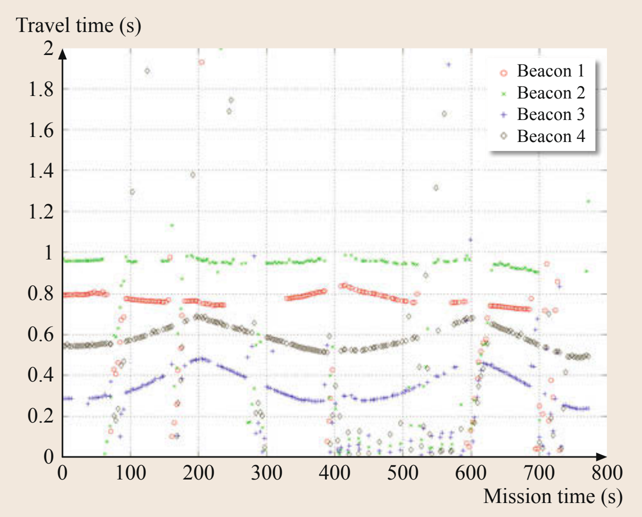

Fig. 14.4 Time-of-flight measurements obtained from four LBL beacons at the GOATS 2002 experiment (after [14.29]). The plot shows significant outliers for all beacons, particularly between 400 s and 600 s. This data illustrates the importance of techniques for outlier rejection in autonomous operations (after [14.7, 14])

Another improvement over conventional LBL is the system depicted in Fig. 14.3c. Building on the setup in Fig. 14.3b, beacons now transmit their GPS position along with the unique identifier. As with the system described previously, the vehicles do not need to query the beacons. With the position of the beacons embedded in the ping the beacons can float freely and it is not necessary to store their coordinates in the AUV before deployment.

USBL

Another variant of beacon-based navigation systems is USBL (Fig. 14.3d). Here the beacon is of the same kind as in a standard LBL system, but the transceiver on the AUV contains several receiving elements which are very close to each other. After querying the beacons, the reply ping is captured by all receiving elements. The phase difference between the signals coming from the different receiving elements allows the AUV to compute a bearing to the beacon. Combined with the beacon position stored in the AUV and the distance d obtained from the OWTT, the vehicle can compute its absolute position using only a reply from a single beacon.

Modern beacon-based systems, such as the ones shown in Fig. 14.3, significantly decrease the pre-deployment effort when compared to early beacon-based systems such as the standard LBL. However, all beacon-based systems confine the operating area of the vehicles to a polygon of beacons or, as in the case of USBL, to the coverage radius of a single beacon. Thus, beacon-based navigation is only feasible for operating areas of $\mathcal{O}(10\,\mathrm{km}^2)$ in size.

14.2 Algorithms

We now review some of the basic algorithms employed in AUV navigation. These are divided into:

1. Dead-reckoning and inertial navigation
2. Acoustic navigation
3. Map-based navigation
4. SLAM.

14.2.1 Dead-Reckoning and Inertial Navigation

The most obvious and the longest established navigation technique is to integrate the vehicle velocity in time to obtain new position estimates [14.31, 32]. This process is called DR. For low-cost vehicles, the measurement of the velocity components of the vehicle is usually accomplished with a compass and a water speed sensor. The principal problem is that the presence of an ocean current will add a velocity component to the vehicle which is not detected by the speed sensor. In the vicinity of the shore, ocean currents can exceed 2 km. Consequently, DR for power-limited AUVs, operating at small speeds (3–6 km), integrating water-relative speed measurements can generate extremely poor position estimates.

In inertial navigation, rotation rate measurements from gyroscopes are integrated to estimate the vehicle attitude, and measurements from accelerometers are integrated twice in time to compute the change in the vehicle position from a known initial location [14.33]. Inertial navigation is a widely studied field with a fascinating history [14.22]; *Titterton* provides a comprehensive description of inertial sensors and algorithms [14.34].

Position drift rates for current high-quality commercial grade INS units are of the order of several kilometers per hour. Initialization of the INS system for marine systems can be difficult. Cost and power consumption have historically made INS systems unattractive for small AUVs; however, this may change as systems get smaller and cheaper in the future.

As the linear and angular acceleration sensors are subject to noise, the position derived from these sensors in the absence of GPS or LBL is subject to a cumulative error and the obtained position will drift with respect to the true position. The drift (error) e between the vehicle's true position x_{true} and the position obtained with DR x_{DR} are expressed as *drift over time* or *drift over distance traveled*

$$e = \frac{\|x_{\text{true}} - x_{\text{DR}}\|_2}{\Delta t} \quad \text{or} \quad e = \frac{\|x_{\text{true}} - x_{\text{DR}}\|_2}{\Delta x} .$$

Typically the heading and rate sensors of an INS are less noisy than those of a comparably inexpensive AHRS, which reduces the effect of accumulated drift. An INS that fits into the hull of a typical AUV shows typical drift rates of 1 km/h [14.35]. The exact performance of the most precise INS available are those developed for nuclear submarines; the drift rates for these sensors are not published but are expected to be $\mathcal{O}$ (0.01 km/h) [14.22].

For operations near the seabed, DVL sensors can be used to measure the vehicle's velocity relative to the ground. The integration of this information in the navigation Kalman filter can greatly improve the performance. For example, the DARPA Autonomous Minehunting and Mapping UUV developed in the early 1990s achieved a navigation performance of 0.01% of distance traveled using an integrated INS/DVL system [14.10]. The MARPOS system developed by Mariden A/S and the Technical University of Denmark for the MARIDAN series of AUVs represents a recent state-of-the-art commercially available AUV system, achieving 0.02% accuracy for site surveys and 0.10% accuracy for straight-line transits [14.36].

The problem with exclusive reliance on DR or inertial navigation is that the position error increases without bound as the distance traveled by the vehicle increases. The rate of increase will be a function of ocean currents, the vehicle speed, and the quality of DR sensors. Radio and satellite navigation systems can provide an accurate position update provided the vehicle can travel at or near the surface periodically for a position fix. The maximum vehicle travel time between surfacing for a position update will be governed by DR/inertial navigation accuracy. Poor quality DR will dictate an unacceptably high frequency of surfacing. Also, vehicles operating close to the coast are in appreciable danger of collision with surface vessels if they need to frequently approach the surface for position fixes. For deep water applications, the time and energy needed by a small AUV for transiting to the surface from near the bottom are very unfavorable. Finally, surfacing is impossible in ice-covered oceans.

14.2.2 Acoustic Navigation

When acoustic transponder measurements are available, a variety of algorithms are possible. Most techniques are based on recursive least-squares estimation, often with an extended Kalman filter. As described above, in an LBL navigation system, an array of transponders is deployed and surveyed into position. The array is usually calibrated through use of an additional acoustic transponder that is hung from a surface ship and interrogates the array from various locations.

The vehicle sends out an acoustic signal which is then returned by each beacon as it is received. Position is determined by measuring the travel time between the vehicle and each beacon, measuring or assuming the local sound speed profile, and knowing the geometry of the beacon array. With this information, the relative distances between the vehicle and each array node can be calculated. The two primary techniques are (1) to compute position fixes by locating the intersection point of spheres of appropriate radii from the beacons in the array, and (2) to integrate the raw time-of-flight (TOF) measurements into an appropriate Kalman filter.

The basic solution for computing a fix from spherical ranges to three transponders is as follows [14.14]. The local earth frame origin is at the surface. The x-axis points north, the y-axis points east, and the z-axis points down. The vehicle position in this frame is (x, y, z) and the coordinates of beacon i are (x_i, y_i, z_i). The measured round-trip travel times between the vehicle and the beacons are t_i and the associated distances are d_i. The distances are computed from the travel times by the approximate relation: $d_i = c(t_i - \tau_i)/2$, where c is the average speed of sound (Note: spatial variations in the speed of sound can be significant, especially variations with depth [14.11]).

The analytical solution based on measurements from three beacons consists of solving the following nonlinear system of equations for the vehicle coordinates

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = d_i^2 , \quad i = 1, 2, 3 . \tag{14.1}$$

In order to make the computations easier, we first compute the solution in an intermediate frame obtained by shifting the local earth frame at the location of beacon 1. The beacon coordinates in this frame are (x'_i, y'_i, z'_i) and the vehicle position is (x', y', z'). The intermediate solution is then transformed back to the local earth frame. Advantage is also taken of the accurate knowledge of the vehicle depth, leading to a linear over-constrained problem (three equations known and two unknowns). The vehicle position is then

$$x = \frac{b_1 c_2 - b_2 c_1}{a_1 b_2 - a_2 b_1} + x_1 , y \quad = \frac{a_2 c_1 - c_2 a_1}{a_1 b_2 - a_2 b_1} + y_1 , \tag{14.2}$$

Part B | 14.2

with

$$
\begin{aligned}
a_1 &= -2x'_2\,,\\
b_1 &= -2y'_2\,,\\
c_1 &= x_2'^2 + y_2'^2 + z_2'^2 - 2z'z'_2 - d_2^2 + d_1^2\,,\\
a_2 &= -2x'_3\,,\\
b_2 &= -2y'_3\,,\\
c_2 &= x_3'^2 + y_3'^2 + z_3'^2 - 2z'z'_3 - d_3^2 + d_1^2\,.
\end{aligned}
$$

When measurements from four beacons are available, least-squares minimization can be performed [14.37].

In more difficult acoustic environments, such as in shallow water or in the Arctic, it becomes difficult to distinguish between the direct arrival and multipath interference, and the rejection of outliers becomes a key issue, as shown in Fig. 14.4. In a fix computation scheme, one can rule out spurious fixes, whereas in a Kalman filter-based system, one can gate the raw TOF values [14.14].

A variant of this system is *hyperbolic navigation*, in which the vehicle does not actively ping but instead listens to an array of beacons whose geometry is known [14.38]. Each beacon pings in a specific sequence relative to the others at its specified frequency. By knowing which beacon pings when and the geometry of the array, the vehicle can reconstruct where it must be in space in order to hear the ping sequence as recorded. This system has the advantage of saving the vehicle the power expenditure of active pinging, and is especially useful for multiple AUV operations. With an active (spherical) LBL system, multiple AUV operations require careful sequencing of the pings between vehicles [14.39].

Most LBL systems work at a frequency of $\approx 10\,\mathrm{kHz}$ and provide position accuracy to within a few meters with a maximum range of the order of a few kilometers. Alternative systems operating at $300\,\mathrm{kHz}$ have been created that can provide positioning repeatability down to $1\,\mathrm{cm}$ resolution in a triangular operating area that is $100\,\mathrm{m}$ to a side [14.40].

In USBL navigation, the vehicle has a multielement receiver array that enables it to measure the angle as well as the range to an acoustic beacon. This system is a variant of a popular system for tracking an underwater vehicle from a surface ship [14.41]. By measuring the arrival time (phase) difference of a single sonar ping between two or more hydrophones, the bearing from the vehicle to the beacon can be determined. If the beacon responds to vehicle interrogation, then the time delay (and hence distance, as with an LBL array) can be calculated. Knowing the distance and direction to the beacon allows for local navigation [14.42]. Knowing the latitude/longitude of the beacon allows for geodetic navigation. This type of system is especially effective for homing and docking operations, which are important for Arctic [14.43] and autonomous ocean sampling network [14.44] deployments.

Errors in both LBL and USBL arrays come from many sources. The key sources of error can be broken down into two primary categories: errors in the assumed array geometry and errors in the assumed sound speed profile. Positioning error comes from inadequately or improperly surveying the relative and/or geodetic positions of the array beacons. In the event that only local navigation is desired, then only relative beacon positions are relevant. If the navigation is to be geodetic-referenced, then the beacons must be located globally as well. Sophisticated software packages are available for accomplishing this. Self-calibrating beacons simplify the task by reducing the surveying task to only one beacon with the others determining their own positions relative to the first. However, this raises the possibility of relative position errors due to errors in the assumed local sound speed.

A significant difficulty in acoustic navigation can be caused by an error in the assumed sound speed profile. An inaccurate sound speed profile will appear as a distance bias in the calculations. Reflection or multipath errors will result in incorrect TOF values and hence erroneous position fixes. Typically, LBL works well in deep water and with array separations of a few kilometers. Over longer distances in shallower water, more complex propagation effects come into play and increase the frequency of bad position fixes. If the topography is sufficiently severe, beacons may be occluded by rocks or other seabed formations. Even if the sound speed profile is known at the start of an AUV mission, the acoustic propagation environment can change during the mission [14.45].

Acoustic tomography refers to the goal of using travel time information between one or more vehicles and vertical hydrophone arrays to estimate the sound speed profile and other information at various places in the intervening water column [14.46]. These techniques are being investigated from scales of a few kilometers [14.47] to the global scale [14.48]. To perform moving source acoustic tomography with an AUV, one needs to know the location of the vehicle to a high precision. In addition, one needs to be able to identify the different propagation paths of the different arrivals received by each hydrophone [14.46]. This same information (effectively, knowing the channel impulse response of the environment) is vital for providing effective acoustic communications [14.49]. Hence, the problems of acoustic tomography, communication, and navigation are closely intertwined. An interesting idea for future research may be to employ techniques from acoustic time reversal [14.50] to achieve higher accuracy in range estimation while concurrently estimating ocean acoustic propagation conditions.

14.2.3 Geophysical Map-Based Navigation

For some applications of AUVs, the use of acoustic beacons is undesirable or impractical. If an accurate a priori map of the environment is available, one approach to globally-referenced position estimation is to use measurements of geophysical parameters, such as bathymetry, magnetic field, or gravitational anomaly [14.16, 17, 51, 52]. These approaches are based on matching sensor data with an a priori environment map, under the assumption that there is sufficient spatial variation in the parameter(s) being measured to permit accurate localization.

All forms of map-based navigation are motivated by the desire to operate at an arbitrary location without the additional expense or problems associated with the installation of artificial beacons. In principle, the process appears straightforward: gather information about the surrounding terrain and match that information to an on-board map or database of terrain information. When the vehicle has a match to the database, then it knows its location on the map. This is analogous to the method which humans use to navigate; we find our way to our destination by locating and identifying landmarks which are familiar to us – either from past experience or via a map which has been constructed for our benefit.

In practice this form of navigation is not so simple. The vehicle is attempting to navigate by matching a set of sensed data with an a priori map or dataset of stored data. Two key problems are the cost and difficulty of generating the a priori maps and the computational complexity of searching for a peak in the n-dimensional correlation surface, where n is the number of dimensions in the map or sensor data set. Typically, map making expense is governed by both the type of data being collected and the desired resolution of that data. Determining the map resolution has a direct effect on the size and level of detail of the search needed to locate the vehicle in space. Since the vehicle could be in any of a large number of possible orientations relative to the original dataset, the search must be performed over all possible locations and orientations. This is a potentially large search space, necessitating some simplifications and/or simplifying assumptions in order to make the search more tractable. Typical simplifications are: restricting the types of map data stored (what sensor values, how many different sensors), lowering map resolution, *patchy* maps (maps of key areas only), restricting vehicle orientations (to reduce the correlation problem), and using inertial navigation or dead reckoning systems to limit the valid search area.

Evidence exists that geomagnetic navigation is employed by birds, fish, and other animals for migration and general navigation [14.53]. The magnetic flux density of the earth varies according to latitude, the presence of man-made and natural anomalies, and even one's depth in the ocean, increasing from 6 to 30 nT/km depth, depending on location [14.54]. Additionally, there are small but predictable variations in the earth's magnetic flux from day to night, and large arbitrary changes during magnetic storms; magnetic maps can be rendered useless for the duration of such storms. Useful magnetic maps, generated by satellites or surface ships, can be employed by underwater vehicles by accounting for the daily field variations and by calculating the effective magnetic field at depth using a Laplace field equation, setting the boundary conditions at the ocean surface [14.55].

Research into the nature of the earth's gravitational field has demonstrated that it is far from uniform and indeed possesses a varied topography [14.56, 57]. These variations are due to a variety of factors, especially the effects of local topography [14.58] and density inhomogeneities [14.59]. Variations in the earth's gravitational field on the ocean's surface relative to a regular ellipsoidal model have been measured to be on the order of 30–50 mgal [14.60]. Gravity maps were originally gathered on behalf of the US Navy for the purposes of INS calibration [14.61]. To an INS, the effects of a change in the local gravitational field are indistinguishable from accelerations of the vehicle itself. *Gerber* [14.62] proposed the use of a gravity gradiometer as an aid to INS. *Jircitano* et al. extended this idea to the AUV community, performing navigation simulations using a model of the Bell Aerospace Textron Gravity Gradiometer System [14.60] with good preliminary results. The drawbacks to such a system are the size, expense, and complexity of a gradiometer. In addition, the gradiometer must be mounted on an inertially stabilized and vibrationally isolated platform, making its use difficult on small, low-cost scientific AUVs.

Geophysical navigation algorithms have origins in techniques of navigating at sea using depth soundings that have been in use for centuries [14.31]. *Kamgar-Parsi* has developed techniques for performing geophysical navigation that are based on fitting contour lines to sensor data and matching these curves to an a priori map using matching techniques from computer vision [14.63, 64]. *Lucido* et al. have also investigated the segmentation and registration of bathymetric profiles [14.65]. *Tuohy* et al. have investigated geophysical navigation using maps of multiple geophysical parameters based on contour intersection methods [14.17]. The reliability of any of these approaches will depend on the accuracy of the a priori map.

AUV navigation based on bathymetric data has been successfully achieved by *Bergem* [14.66]. In this system, depths are measured at different angles using a multibeam sonar. This gives an accurate profile of the sea floor, and the absolute position is determined by matching this profile against an a priori known detailed bathymetric map of the actual area. This idea is motivated by the successful employment of this technique to missile guidance systems.

14.2.4 Simultaneous Localization and Mapping

In practice, an up-to-date, high-quality map may be unavailable in the operating area of interest. This motivates research into the use of SLAM to enable an AUV to build a map of its environment while concurrently using that map to navigate in real time [14.67]. SLAM is a probabilistic estimation problem in which noisy sensor measurements are combined into a probabilistic representation of the state of the sensor and the observed surroundings. This model needs to be updated and extended sequentially by integrating new sensor measurements as they become available.

The variables to be estimated and the sensor measurements can be described in a graph [14.68] that captures their relation. We use a factor graph [14.69] as a general graphical model representation of the SLAM problem. Formally, a factor graph is a bipartite graph $G = (\mathcal{F}, \Theta, \mathcal{E})$ with two node types: *factor nodes* $f_i \in \mathcal{F}$ and *variable nodes* $\theta_j \in \Theta$. Edges $e_{ij} \in \mathcal{E}$ are always between factor nodes and variable nodes. A factor graph G defines the factorization of a function $f(\Theta)$ as

$$f(\Theta) = \prod_i f_i(\Theta_i) , \tag{14.3}$$

where Θ_i is the set of variables θ_j adjacent to the factor f_i, and independent relationships are encoded by the edges e_{ij}: each factor f_i is a function of the variables in Θ_i. Our goal is to find the variable assignment Θ^* that maximizes (14.3)

$$\Theta^* = \arg\max_{\Theta} f(\Theta) . \tag{14.4}$$

The general factor graph formulation of the full SLAM problem is shown in Fig. 14.5, where the landmark measurements m, loop closing constraints c and odometry measurements u are the examples of factors. Note that the factor graph formulation supports general probability distributions or cost functions of any number of variables, allowing, for example, the inclusion of calibration parameters.

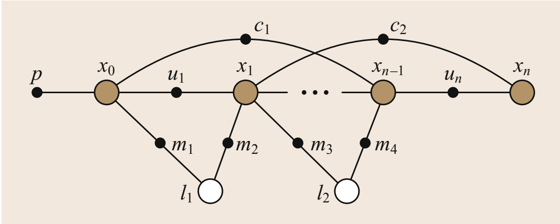

Fig. 14.5 Factor graph for the pose graph formulation of the SLAM problem

It is standard in the SLAM literature [14.70, 71] to assume Gaussian measurement noise models

$$\begin{aligned} f_i(\Theta_i) &= \mathcal{N}(h_i(\Theta_i); z_i, \Sigma_i) \\ &\propto \exp\left(-\frac{1}{2}\,\|h_i(\Theta_i) - z_i\|^2_{\Sigma_i}\right) \end{aligned} \tag{14.5}$$

because the factored objective function to maximize (14.4) reduces to a nonlinear least-squares problem

$$\begin{aligned} &\arg\min_{\Theta}\,(-\log f(\Theta)) \\ &\quad = \arg\min_{\Theta} \frac{1}{2} \sum_i \|h_i(\Theta_i) - z_i\|^2_{\Sigma_i} \end{aligned} \tag{14.6}$$

for which efficient solutions are available. Here, $h_i(\Theta_i)$ is a measurement function and z_i a measurement, and $\|e\|^2_{\Sigma} \triangleq e^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}e$ is the squared Mahalanobis distance with the covariance matrix $\boldsymbol{\Sigma}$.

Recently, least-squares solutions to the full SLAM problem dominate, but many other solutions have been proposed in the past, mostly aimed at making computational complexity manageable. For example, Kalman filter solutions to SLAM achieve greater computational efficiency by keeping only the most recent robot pose (through marginalization of previous poses). However, this approach has been shown to be inconsistent [14.72] when applied to the inherently nonlinear SLAM problem, i. e., the estimate is biased and the error covariance is smaller than the actual one. State-of-the-art approaches achieve better performance by estimating the entire robot trajectory, which is known as full SLAM. The first solution to the full SLAM problem has been presented in [14.68] and a range of iterative least-squares solvers have been applied including relaxation [14.73], gradient descent [14.74], conjugate gradient [14.75], multilevel relaxation [14.76], and loopy belief propagation [14.77]. Exploiting the sparsity of the information form [14.78], Gauss–Newton type solvers using sparse matrix factorization have since become very popular [14.37, 79–81] because of their faster convergence rate. Full SLAM incurs a computational burden that grows in time with the duration of the mission. Strategies to mitigate this are discussed in *Johannsson* et al. [14.82].

SLAM techniques have been used successfully on a wide range of AUVs, using sonar and image measurements. A key requirement for SLAM is to be able to extract and match features from measurements obtained from different vantage points, to extract constraints that can be used to constrain error growth. Figures 14.6 and 14.7 show an illustration of the constraint matching process for features extracted from consecutive camera images in a seabed mapping task [14.83]. Visual SLAM has been successfully applied by a variety of researchers, using either sonar [14.67, 84–86] or camera data [14.87–89].

14.2.5 Cooperative Navigation of Multiple Vehicles

An exciting development over the past fifteen years has been the integration of ranging and communication capabilities in modern undersea acoustic modems, such as the WHOI micro-modem [14.90]. Given recent advances in AUV communications technology [14.64], the technology exists now for two or more AUVS to establish communication links with each other. This new capability allows the development of fundamentally new approaches to navigation based on multiple cooperating vehicles. Improved position estimation via collaboration enables the development of cooperative behaviors, permitting teams of AUVs to perform adaptive and more efficient survey missions. Ultimately, one can envision a system in which one AUV can direct other AUVs to revisit targets of interest, using complementary sensors. Two or more vehicles can be used to establish a mobile transponder network to provide positioning support for each other and for a fleet of other vehicles [14.91].

If more than one AUV is available to carry out a task and these vehicles are at least occasionally within communication range, both vehicles can cooperate in order to improve their navigation accuracy. Generally speaking, cooperative navigation relies on the fact that one vehicle may have a more accurate position estimate than another one. It then broadcasts it's own position estimate, possibly along with additional information such as the uncertainty associated with that estimate. Other vehicles, which are within the communication range of the broadcasting vehicle and receive this information, are able to obtain a relative position estimate to the broadcasting vehicle (range and/or bearing) and can incorporate this information in order to improve their own position estimate.

Systems

One key advantage of cooperative navigation is that most AUVs are already fitted with the necessary gear. In order to exchange information, a standard acoustic modem, found on most of today's AUVs, can be used. The only other information required – a range and/or bearing to the broadcasting vehicle can be obtained by slightly modifying existing modem hardware. By adding several transducers to a modem, it can determine the incident angle of an incoming transmission through the small differences in the arrival time. In addition, all vehicles can carry a very accurate clock

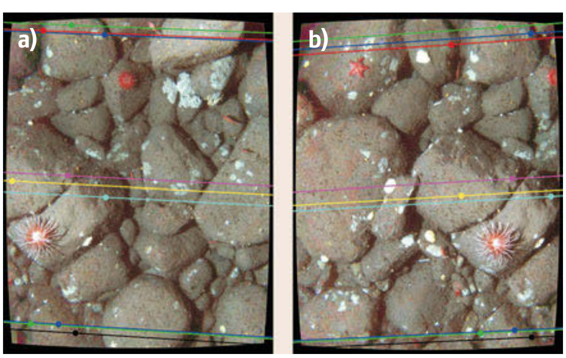

Fig. 14.6 Two consecutive pictures after being processed by the visually aided navigation (after [14.83]). From the several hundred features identified in each picture, only nine, marked by the *colored dots* have correspondences in both pictures and fit within the epipolar constraints (courtesy of R. Eustice)

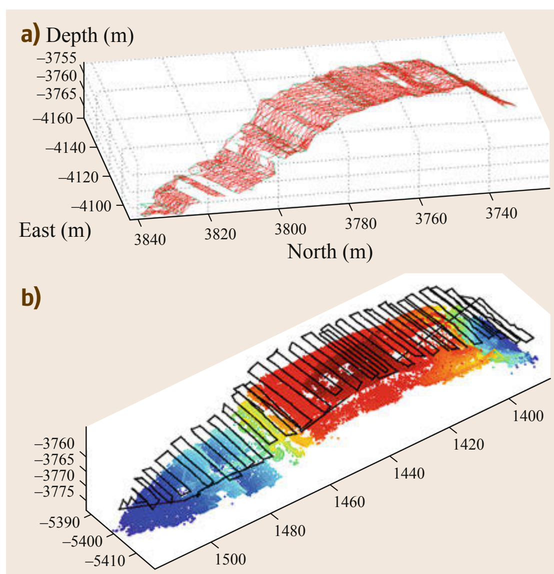

Fig. 14.7 Network of contraints **(a)** and estimated vehicle trajectory **(b)** for visual mapping of the RMS Titanic (after [14.87], courtesy of R. Eustice)

which is synchronized to a global clock via GPS on the surface [14.92–94].

Accurate time keeping has been central to precision navigation at sea throughout history [14.32]. Recent implementations of synchronous-clock one-way-travel-time acoustic navigation by *Eustice* et al. [14.92] and *Bahr* et al. [14.95] have been enabled by using a low-power temperature compensated crystal oscillator (TCXO), from SeaScan Inc., which has a typical drift of 20 ns/s, corresponding to a drift in position of approximately 2.6 m/day [14.96]. A common timebase and embedding a time-stamp indicating the broadcast time of each outgoing transmission allow a receiving vehicle to determine the time which the signal took to reach the receiver. With an accurate estimate of the speed of sound in water, the vehicle can then determine the distance to the broadcasting vehicle.

Strategies

Two different kinds of strategies can be employed for cooperative navigation. The first assumes a strict hierarchy where a group of AUVs acts as dedicated navigation aids (NAs). Their sole purpose is to provide navigation information to the mission AUVs (MAs). The NAs are thus equipped with very sophisticated sensors such that the drift of their position estimate is minimized. They may also operate very close to the surface such that they can easily surface to update their position using a GPS fix. In this scenario, only NAs broadcast navigation information and serve as mobile LBL-beacons to all MAs in communication range. As the sole purpose of the NAs is to maximize the MAs' navigation accuracy, their path can be adapted to best accomplish that goal [14.97].

The second strategy does not impose any particular hierarchy. Each vehicle occasionally broadcasts its position estimate and incorporates other overheard broadcasts. This approach does not require an extra set of dedicated vehicles, but due to the stochastic nature of received updates it is very difficult to predict, let alone guarantee, the performance of the navigation improvement of this cooperation strategy. In addition, the fact that each vehicle may transmit and receive navigation information may lead to cyclical updates. This occurs when a vehicle A incorporates information from a vehicle B and at a later point in time vehicle B then incorporates information from A. The dependencies arising between the position estimates may lead to overconfidence in the position estimate of each vehicle and must be carefully mitigated [14.98].

Algorithms

By treating the information received from a cooperating AUV as the noisy observation of landmark with an uncertain position, we can draw on a vast amount of algorithms and techniques developed by the SLAM community. Their work provides various frameworks to represent a state estimate (in this case a position) together with the uncertainty of this estimate. It also provides several methods to incorporate landmark observations, in this case received broadcasts from cooperating vehicles. Several of these SLAM techniques have been adapted for cooperative navigation [14.95, 99, 100].

14.3 Summary

Figure 14.8 shows typical navigation system performance for current AUVs based on five typical vehicle configurations. The sensor suite employed for an AUV depends on the navigation accuracy required for the mission as well as the available power, space, and the cost constraints.

14.3.1 Glider with Very Low Power Sensor Suite

Autonomous ocean gliders must operate for extended periods of time without being able to recharge their batteries [14.9, 101]. As a result, power consumption is the limiting factor for the selection of navigation sensors, and the navigation suite of a glider usually consists of a GPS, an AHRS, and a pressure gauge. While submerged the glider uses the AHRS combined with a vehicle model to estimate its heading and forward velocity and dead-reckon its position. The high noise and the unobservable variables in the vehicle model lead to a very high drift of 30% or even more if strong currents are present. On the surface, the vehicle resets its position estimate using GPS. The navigation accuracy achieved is typically more than adequate for providing data into ocean circulation models [14.102].

14.3.2 Low-Cost AUV Sensor Suite

A low-cost AUV such as the *IVER* uses a flow meter to obtain a measurement of their forward speed u_x^V. This information combined with an AHRS leads to a significant improvement of the navigation accuracy when compared to that of a glider.

14.3.3 Standard AUV Sensor Suite

The standard AUV adds a DVL to the list of sensors. When the DVL is able to obtain bottom lock a very accurate vehicle-referenced velocity vector $\boldsymbol{u}^V$ is available and the navigation accuracy improves by an order of magnitude. Drift rates as low as 1% of the distance traveled can be obtained with a well calibrated magnetic compass. Standard AUVs operating in a confined area are often outfitted with an LBL system. When operating within the polygon established by the position of the LBL beacons, the position drift will remain bounded.

14.3.4 High-End AUV

The dominant source of error in the standard AUV sensor suite described above is introduced during the transformation of vehicle-referenced velocities to world-referenced velocities as a result of errors in the heading measurements. Replacing the simple magnetic compass with an FOG improves the navigation by two orders of magnitude (0.1% of the distance traveled). When the DVL is not able to obtain bottom lock all of the vehicles described so far can only rely on the vehicle's linear acceleration sensors to obtain velocities. Due to the large noise introduced by these sensors the navigation accuracy decreases dramatically.

14.3.5 Special-Task AUV Using Visual SLAM

The special-task AUV has the same sensors as the standard AUV. Additionally, it uses a bottom-looking camera to take a series of pictures of the sea-floor. When revisiting a point it has taken a picture of before, it is able to recognize that fact and the navigation algorithm is able to reset the drift. As a result, the drift is bounded. An example, of this technique has been illustrated in Fig. 14.6. This method however requires the AUV to revisit points and stay close enough to the sea floor (< 10 m) to acquire the images.

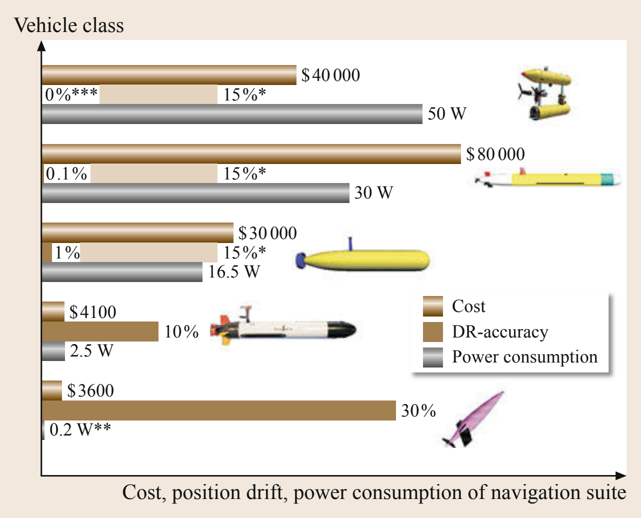

Fig. 14.8 Navigation accuracy, power consumption and price of various AUV sensor suites (*bottom to top*): (1) Glider with compass and attitude sensor; (2) low-cost AUV with compass, attitude sensor and flow meter; (3) medium-range AUV with INS, DVL and LBL; (4) high-end AUV with FOG-based INS, DVL and LBL; (5) special-task AUV with INS, DVL and SLAM. * Drift in mid water-column when DVL cannot obtain bottom or surface lock. ** Assuming a 10% duty cycle during which the navigation sensors are powered. *** Assuming that the vehicle was close enough to the sea floor throughout the entire mission to take pictures and revisit places.

14.4 Conclusion

In summary, the design of an AUV navigation system will depend on the mission requirements and cost constraints. For missions that are performed in shallow water, and for which frequent GPS surfacing is acceptable, a combination of GPS and dead-reckoning/inertial navigation will be acceptable in many situations. Cooperative navigation will become even more important in the future, as improved temperature compensated oscillators, and possibly even miniature atomic clocks, are anticipated to become widely available at low cost. This can greatly improve available options for hyperbolic and one-way time-synchronized AUV localization algorithms.

In deep water, the current state of the art is represented by the Nereus vehicle, whose sensor suite contains a Paroscientific pressure sensor, a Teledyne-RDInstruments 300 kHz Doppler sonar, an IXSEA Phins IMU, a WHOI LBL transceiver, a WHOI Micro-Modem, and a Microstrain gyro-stabilized attitude and magnetic-heading sensor [14.8]. Nereus navigates using the NavEst navigation software package developed by Woods Hole Oceanographic Institution and Johns Hopkins University, which integrates the DVLNav [14.103] package with the ABE LBL navigation suite [14.7]. This high-performance system embodies the current state of the art in deep ocean AUV navigation.

For further information on navigation sensor device performance, the reader is directed to a detailed survey by *Kinsey* et al. [14.1]. A tutorial introduction to SLAM is provided by the authors of [14.104, 105]. *Fallon* et al. gives a detailed presentation for several recent SLAM applications, including mine neutralization, real-time cooperative navigation, and ship hull inspection [14.106].

For future research in AUV navigation, a key challenge will be to develop techniques for Arctic and Antarctic operations. Polar regions pose major difficulties for AUV navigation including: high magnetic declination, inability to surface for GPS, infeasibility of deploying transponders, potentially moving ice canopy, and limited recovery options. Recent work in AUV navigation for polar regions includes the work of *Kunz* et al., who have deployed variants of the Seabed AUV in both the Arctic and Antarctic [14.107, 108].

Another ambitious goal for future research is to develop robust navigation techniques, combined with autonomous docking [14.44] and advanced communication networks [14.109], to enable long-term AUV deployments for persistent ocean sampling missions [14.110] using underice or deep ocean observatories [14.111, 112].

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