Autonomous Underwater Vehicle Navigation

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Abstract

This paper surveys the problem of navigation for autonomous underwater vehicles (AUVs). Marine robotics technology has undergone a phase of dramatic increase in capability in recent years. Navigation is one of the key challenges that limits our capability to use AUVs to address problems of critical importance to society. Good navigation information is essential for safe operation and recovery of an AUV. For the data gathered by an AUV to be of value, the location from which the data has been acquired must be accurately known. The three primary methods for navigation of AUVs are (1) dead-reckoning and inertial navigation systems, (2) acoustic navigation, and (3) geophysical navigation techniques. The current state-of-the-art in each of these areas is summarized, and topics for future research are suggested.

1 Introduction

Autonomous underwater vehicles (AUVs) have the potential to revolutionize our access to the oceans to address critical problems facing the marine community such as underwater search and mapping, climate change assessment, marine habitat monitoring, and shallow water mine countermeasures. Navigation is one of the primary challenges in AUV research today. The goal of this paper is to survey previous work in AUV navigation and to make suggestions for future research in this area.

Navigation is an important requirement for any type of mobile robot, but this is especially true for autonomous underwater vehicles. Good navigation information is essential for safe operation and recovery of an AUV. For the data gathered by an AUV to be of value, the location from which the data has been acquired must be accurately known. Some of the important concerns for AUV navigation, such as the effects of acoustic propagation [25], are unique to the ocean environment.

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Other aspects of the problem, such as managing uncertainty, are generic to mobile robotics research. New techniques for AUV navigation have potential to be useful for mobile robots operating in natural and dynamic environments on land and in space.

The structure of this paper is as follows. Section 2 summarizes the current state of AUV technology. Section 3 describes methods for AUV navigation based on the use of dead reckoning, inertial navigation systems (INS), and Doppler velocity sonar (DVS) systems. Section 4 describes methods for positioning based on the use of acoustics beacons, such as the use of a Long baseline (LBL) array. New methods that integrate navigation with acoustic tomography and communications are described. Section 5 describes methods for geophysical navigation, in which the goal is to use sensor measurements of geophysical parameters or environmental features to estimate the position of the robot. This section also discusses the problem of concurrent mapping and localization (CML), in which the goal is for the robot to build a map of an unknown environment while simultaneously using that map to navigate. Finally, Section 6 summarizes the paper and makes suggestions for future research.

2 Autonomous Underwater Vehicles

The capabilities of marine robot systems have improved dramatically in recent years. Many autonomous underwater vehicle (AUV) systems have moved from the prototype stage to become important field assets for difficult scientific, commercial, and military missions. The research community has expended considerable effort in defining the most appropriate applications for the introduction of AUV technology [5]. To make sense economically, an AUV must provide a cost-effective alternative to other available technologies, such as manned submersibles [27], remotely operated vehicles (ROVs) [3], and towed instruments sleds. The benefits offered by autonomous data gathering have to be weighed against the difficulties faced by AUVs in power, sensing, information processing, navigation, and control. Untethered operations impose a severe restriction on power consumption and present challenging problems in intelligent control. Acoustic modem technology can enable remote control of AUVs, but communications bandwidth and reliability are restricted by challenging acoustic propagation conditions [11].

Under-ice and covert surveillance missions have provided the motivation for the development of large, long-endurance AUV systems. Examples include the Theseus AUV, developed by International Submarine Engineering [10], the DARPA UUVs, developed by Draper Laboratories [42, 43], and the LDUUV and 21UUV developed by the Naval Undersea Warfare Center in Newport [32].

These vehicles possess high performance navigation sensors and high capacity battery systems, and are designed to operate for long duration missions at high speeds. For example, the Theseus vehicle has performed an autonomous under-ice run of more than 300 kilometers [10].

AUVs designed for scientific applications tend to be much smaller and cheaper than vehicles designed for surveillance applications. Examples include the Autonomous Benthic Explorer (ABE) [51] and Remus [63] vehicles developed at Woods Hole Oceanographic Institution, the Odyssey II vehicles developed at MIT Sea Grant [7], the Ocean Explorer vehicles developed at Florida Atlantic University [54], and the MARIUS AUV being developed by a team of European partners [17]. High performance INS systems typically cannot be integrated into small AUVs because of size, cost, and power restrictions. Hence, these vehicles typically rely on acoustic navigation systems and/or GPS navigation resets for shallow water operations [1]

Autonomous oceanographic sampling networks (AOSN) represent a new ocean sampling concept that promises to increase the deployment possibilities for AUVs [13]. The idea behind AOSN is to deploy multiple AUVs with communications and power-recharging moorings in a remote location to enable long-term, large-scale oceanic data gathering. The motivation for this type of system comes from the difficulty that oceanographers face in obtaining enough data to understand ocean processes and to develop predictive ocean models. The technology to realize these capabilities is currently in development. Components of the AOSN have been tested recently in the Haro Strait Experiment [48], which studied tidal front mixing, and the Labrador Sea Experiment [62], which measured oceanic deep convection.

3 Dead Reckoning and Inertial Navigation Systems

The most obvious and longest established navigation technique is to integrate the vehicle velocity in time to obtain new position estimates [35]. 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 knots. Consequently, dead reckoning for power-limited AUVs, operating at small speeds (3-6 knots), involving water-relative speed measurements can generate extremely poor position estimates.

In inertial navigation systems, the accelerations of the vehicle are integrated twice in time to derive the updated position [31]. Position drift rates for high quality commercial grade INS units are on the order of several kilometers per hour. Initialization of the INS system 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.

For operations near the seabed, Doppler Velocity Sonar (DVS) 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 performance. For example, the DARPA UUV has achieved navigation performance of 0.01% of distance traveled using an integrated INS/DVS system [42].

The problem with exclusive reliance on dead reckoning or inertial navigation is that 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. 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 dead reckoning/inertial navigation accuracy. Poor quality dead reckoning 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 bottom are very unfavorable. Finally, surfacing is impossible in ice-covered oceans.

4 Acoustic Navigation

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 [21, 22, 38]: long baseline (LBL) and ultra-short baseline (USBL). Both systems employ external transducers or transducer arrays as aids to navigation. In LBL navigation systems, an array of transponders is deployed and surveyed into position. 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 [61]. 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 rejection of outliers becomes a key issue. 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 [61].

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 [6]. 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 [2].

Most LBL systems work at a frequency of approximately 10 kHz and provide position accuracy to within a few meters with a maximum range on the order of a few kilometers. Alternative systems operating at 300 KHz have been created that can provide positioning repeatability down to 1 centimeter resolution in a triangular operating area that is 100 meters to a side [23].

In USBL navigation, the vehicle has a multi-element 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 [24]. 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 distance and direction to the beacon allows for local navigation [55]. 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 [8] and autonomous ocean sampling network [50] 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 time-of-flight 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.

To address this issue, Deffenbaugh has developed a technique for long-range LBL navigation in complex and dynamic acoustic environments, such as the Arctic [15, 16]. The approach uses the extra information provided by the multipath arrivals to invert for sound speed profile variations in space and time, and in the process provide a more accurate position estimate. This technique was motivated by the particularly challenging conditions of the Arctic, which is characterized by an upwardly refracting sound speed profile [25].

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 [40]. These techniques are being investigated from scales of a few kilometers [48] to the global scale [66]. 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 [40]. This same information (effectively, knowing the channel impulse response of the environment) is vital for providing effective acoustic communications [11]. Hence, the problems of acoustic tomography, communication, and navigation are closely intertwined. The development of integrated methods for performing these tasks concurrently in dynamic environments presents a challenging and exciting topic for future research.

5 Geophysical 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 [20, 36, 57, 59]. 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 [64]. 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 nanoTeslas per 1 km of depth, depending on location [41]. Additionally, there are small but predictable variations in the earth's magnetic flux from day to night, and large arbitrary changes during magnetic storms (which are approaching the height of their 11 year cycle at this time); 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 [56].

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, 65]. These variations are due to a variety of factors, especially the effects of local topography [18] and density inhomogeneities [58]. 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 [26][1]. Gravity maps were originally gathered on behalf of the US Navy for the purposes of inertial navigation system calibration [47]. To an INS, the effects of a change in the local gravitational field are indistinguishable from accelerations of the vehicle itself. Gerber [19] proposed the use of a gravity gradiometer as an aid to inertial navigation systems. Jircitano *et al.* extended this idea to the AUV community, performing navigation simulations using a model of the Bell Aerospace Textron Gravity Gradiometer System [26] 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 [35]. 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 [29, 28]. Lucido *et al.* have also investigated the segmentation and registration of of bathymetric profiles [33]. Tuohy has investigated geophysical navigation using maps of multiple geophysical parameters based on contour intersection methods [57]. 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 [9]. 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.

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 concurrent mapping and localization. The goal of concurrent mapping and localization is for the AUV to build a map of its environment and to use that map to navigate in real time. A seminal technique for concurrent mapping and localization, called

[1] $1 milligal = 1 mgal = 10^{-5} m/sec^2$

the stochastic map, was published by Smith, Self, and Cheeseman [53]. The stochastic map consists of a single state vector that represents the estimates of the vehicle and feature locations and an associated covariance matrix. As the vehicle moves around its environment, taking measurements of environmental features, the stochastic map is updated using an extended Kalman filter. Moutarlier and Chatila [39], Rencken [44], and Chong and Kleeman [12] have implemented variations of the stochastic map using land robots. To our knowledge, CML has not been implemented with an underwater vehicle.

As an illustration of a stochastic map approach to CML, a stochastic map has been implemented to post-processing of field data from the Naval Undersea Warfare Center (NUWC) high resolution array (HRA) forward-look imaging sonar [37]. Figure 1 shows the sonar returns using the HRA and the result of the stochastic map applied to this data set.

The major problems encountered by the stochastic map are the failure of the extended Kalman filter to properly track the highly nonlinear transformations involved in geometric estimation and the fact that the technique scales (at best) quadratically with the number of features present. Also, Smith, Self, and Cheeseman ignored errors which may arise from ambiguity in the source of sensor data. Some of these drawbacks have recently been considered by Uhlmann [60] in a theoretical investigation of concurrent mapping and localization. However, there are many important issues to address in future research to realize this capability on-board an AUV.

A new multiple hypothesis approach to concurrent mapping and localization (MHCML) is currently in development at MIT [52]. MHCML has potential to provide a general framework for integrated mapping and localization that incorporates navigation error, sensor noise, data association uncertainty, and physically-based sensor models. MHCML is both an extension of multiple hypothesis tracking to incorporate vehicle position uncertainty and an extension to the stochastic map to incorporate data association uncertainty and model uncertainty. Work is in progress to apply the new algorithm to perform CML using data from the US Navy's High Resolution Array sonar sensor [37].

A basic problem with CML based AUV navigation systems, is the identification and recognition of natural features in the environment. Sonar data can be notoriously difficult to interpret. Spurious measurements due to multiple reflections are common. Considered in isolation, an individual sonar return yields insufficient information to determine the shape of an object. The fundamental capability required is to combine the information provided by multiple sonar returns obtained from different sensing location. However, motivated by the abilities of bats [4, 30, 49] and dolphins [46] to navigate in cluttered environment using sonar, new sonars and processing techniques have

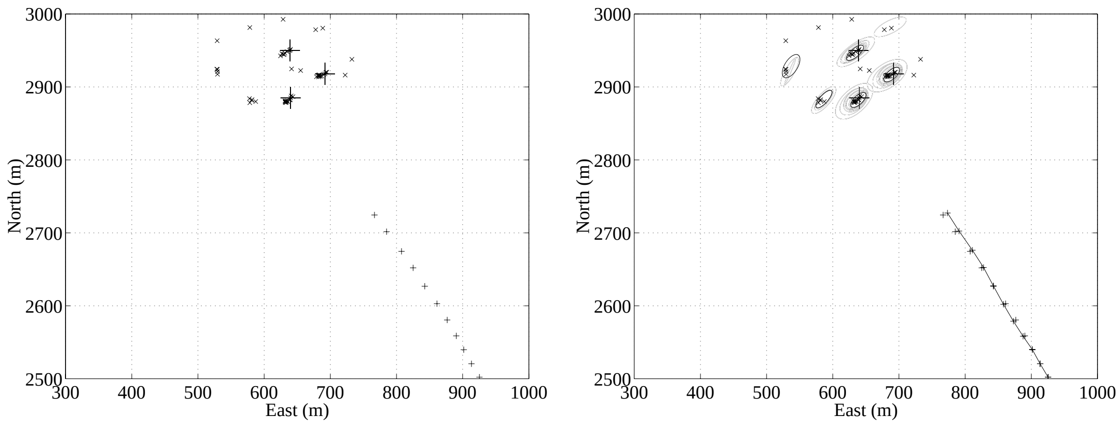

Figure 1: Left figure: Data collected by the NUWC HRA sensor in Naragansett Bay, RI, USA [37]. The crosses represent the sonar returns that passed a given threshold. The large plus signs indicates the position of three known targets. The small plus sings represents the assumed vehicle position. The data set contains 88 sonar returns above the threshold and 11 vehicle position. Right figure: Post processing of the sonar returns given in the left figure using a stochastic map and a delayed nearest neighbor approach for track initiation and data association. The symbol convention is the same as in the left figure. The solid line connects the vehicles estimated true position. The ellipses shows the 95% confidence region. The algorithm has managed to map the known features as well as two more natural features and is able to use this map to update the vehicles position. (Data provided courtesy of M. Medeiros, R. Carpenter, V. Greco, and C. Shaw of NUWC.)

been developed to mimic the performance of bat and dolphin sonar systems and object detection capabilities. The use of these systems for CML presents an interesting topic for future research.

AUVs have a limited range due to limited power consumption and tend to have dynamical constraints, such as loss of controllability at low speeds, that require fast access to information about the environment for safe navigation. An interesting research area is to adaptively choose a sensing and motion strategy to obtain the most information about the environment. Such adaptive strategies are seen in the way dolphins use sonar to localize and navigate by moving their heads from side to side. Bats adaptively increases the number of sound pulses emitted as they approach a target. Further, due to the low rate of information obtained from sonar, adaptive strategies are especially beneficial.

6 Conclusion

This paper has reviewed the literature relating to the problem of autonomous underwater vehicle navigation. Current practice in AUV navigation is limited primarily to dead-reckoning, INS, and acoustic systems. High performance, tactical-sized AUVs have demonstrated positioning accurate to 0.01% of distance traveled using a coupled INS and DVS system. Smaller, low-cost vehicles generally rely on compass and speed sensors for dead-reckoning, with correspondingly poorer performance. However, this performance can be expected to improve as commercial, off-the shelf sensors become smaller and more affordable.

Long baseline navigation is the most frequently used technique for scientific AUV missions, and ultra-short baseline homing systems will take on new importance as autonomous ocean sampling network systems continue to be developed. Integrated acoustic navigation, communication, and tomography represents an extension of LBL navigation which incorporates the transmission of data packets to and from the vehicle and inversion of acoustic data to estimate physical parameters of the environment. This field has many exciting prospects for future research, as it combines field experimentation with advances in acoustics, signal processing, estimation theory, and oceanographic modeling and prediction. Integrated navigation, communications, and tomography is one instance of the problem of ocean data assimilation, which is the process of integrating real data with models of ocean processes [34, 45, 66].

Geophysical navigation techniques continue to be an interesting topic for research. To our knowledge, these techniques have been limited to bathymetric approaches, in large part due to the requirement that accurate *a priori* maps be available. If a vehicle can build a map of an unknown environment and use that map to navigate, the range of feasible applications for AUVs would increase greatly. The realization of this capability using sonar will require advances in our ability to extract features from sonar data, to manage uncertainty, and to model and represent dynamic environments.

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