Cooperative Acoustic Navigation Scheme for Heterogenous Autonomous Underwater Vehicles

Xianbo Xiang[1,2], Lionel Lapierre[1], Bruno Jouvencel[1],
Guohua Xu[2] and Xinhan Huang[2]
[1]*CNRS - LIRMM – University of Montpellier II*
[2]*Huazhong University of Science and Technology*
[1]*France,*
[2]*China*

1. Introduction

Oceans cover 71% of the earth's surface and contribute the largest reservoir of life on the earth. With more and more concern about the abounding and valuable ocean resources, these years have witnessed a remarkable growth in the wide range of underwater commercial activities for ocean survey, especially focusing on undersea exploration and exploitation, and even extensively for salvage operations related with disastrous accidents occurred undersea (Lapierre, 2006).

There are three main kinds of vehicles recruited for underwater activities. Manned Submersibles and Manned Underwater Vehicles with good abilities of directly manoeuvring and in-situ observation, have been widely utilized in commercial activity and scientific research, and reached the zenith in the late 1960s and early 1970s. However, this critical systems with vital importance of crew aboard and complex handling system significantly cost so much. Then, Remotely Operated Vehicles (ROVs) still with human in the loop but not in the vehicle are successful substitutes, being low-cost vehicles piloting in deep water greater than 1000ft. Today, ROV becomes a well-established technology frequently used in the offshore industry, most notably in the commercial offshore oil and gas, nuclear, pipeline and cable industries. Nevertheless, the long umbilical cable, linked with the mother ship, greatly inhibits the speed of the ROV, requiring the mother ship equipped with deck gear capable of winding up this cable and significantly restricting ship movement while deployed. More recently, with the development of advanced underwater technology, Autonomous Underwater Vehicles (AUVs) are steadily becoming the next significative step in ocean exploration due to their freedom from the constraints of an umbilical cable. Nowadays there has been gradually growth in the AUV industry worldwide which would be on an unprecedented scale and AUVs will carry out interventions in undersea structures in the future (Whitcomb, 2000). Moreover, recent applications using Intervention Autonomous Underwater Vehicles (IAUVs), have demonstrated the feasibility of autonomous underwater manipulations (Xu et al., 2007), controlled via acoustic links, thus removing the parasite effects of the umbilical cable (http://www.freesubnet.eu). With

Source: Underwater Vehicles, Book edited by: Alexander V. Inzartsev,
ISBN 978-953-7619-49-7, pp. 582, December 2008, I-Tech, Vienna, Austria

further research results and technological advances, AUVs have the potential for supplementing or even substituting ROVs for deep water operations, and AUVs in a team hold considerable potential for challenging scientific and commercial mission at sea.

As a group of coordinated multiple robots dealing with tasks provides flexibility, robustness and efficiency beyond what is possible with single robot, there is one attractive scenario for underwater activities--the AUV team concept, which could be a mix of several low-cost specific purpose AUVs, guided and controlled by one or two higher cost AUVs (Xiang et al., 2008). The employment of multiple AUVs has significant advantages for both military and commercial applications (Bourgeois et al., 1999). A team of underwater vehicles could survey large ocean areas more rapidly and economically than that could be accomplished with a single AUV or ship (McDowell et al., 2002). The key point to the operation of AUVs is the availability of accurate navigation and positioning systems, which provide the measurement of the angular and linear positions of each underwater vehicle in the team and is therefore crucial to control and stabilize the platform. Unfortunately, one of the major problems that prevents the commercial application of AUVs, or at least mitigate their efficiency, is just that of vehicle navigation. On board navigation systems, as inertial navigation systems (INS), can not maintain the requested accuracy over the long time vehicle manoeuvring and are highly expensive as well as the inconvenient calibration for different AUV systems due to its vehicle-specific characteristic (Caiti et al., 1999).

There are several positioning and navigation systems currently employed by AUVs researchers. The traditional acoustic navigation methods will be reviewed in section 2, and the main non-acoustic approach, which is also a dominant approach for AUVs, is combining a GPS receiver and an INS in one AUV (INS/GPS). That is, the vehicle mainly depends on the INS to be navigated, but periodically comes to surface to receive the GPS signal and to recalibrate the INS (Yun et al., 1999).When one group of AUVs is traveling to the area of interest, inter-vessel communications could also be used to provide the information of position and navigation, and then the team of AUVs relies on machine learning techniques for creation and maintenance of loose formation. But there is an important assumption that still at least one vehicle has an accurate positioning system on board, typically with the INS combined with GPS. That means at least one of the AUVs must periodically come to the surface to calibrate the position which would severely disturb or even deteriorate the whole strategy of the team coordination and formation, besides the unwanted energy consumed to heave up to the surface and the high cost of INS.

Accounting for the disadvantage of currently positioning and navigation approach for coordinated AUVs team mentioned above, another promising scheme is the heterogenous autonomous vehicle team concept to overcome the navigation problem, which would be a mix of several low-cost specific purpose vehicles which typically are AUVs, guided and controlled by one or two higher cost control vessels which typically are ASVs. Benefited from the underwater GPS concept combining the DGPS technology, a dedicated novel cooperative underwater acoustic navigation approach is suitable for this heterogenous vehicle team. The central control ASV can get high precise positions of AUVs without INS/GPS on board, allocates the waypoints to the AUVs as well as provide the navigation information via acoustic modem and also move above the central of mass of the AUVs, so that the whole team with heterogenous vehicles could conveniently implement the coordinated search or rescue scenario as a whole (Xiang et al., 2007).

The rest of this chapter is organized as follows. In section 2 the traditional underwater acoustic navigation system and the underwater GPS concept are reviewed, and the hardware implementation of DGPS intelligent sonobuoys as well as the novel cooperative navigation architecture for heterogeneous autonomous vehicle is presented in section 3. Section 4 includes a detailed description of the cooperative navigation algorithm for coordinated underwater vehicles. Section 5 provides the simulation results of the acoustic navigation. Section 6 draws conclusions. Section 7 makes acknowledgement for the support from co-authors and related scientific research projects.

2. Traditional navigation methods for AUVs

In this section, two kinds of navigation systems currently employed by AUVs will be reviewed here. One is acoustic navigation system, the other is non-acoustic navigation system, especially the underwater GPS navigation system.

2.1 Acoustic navigation

The simple transition from available navigation techniques based on electromagnetic signals for mobile robots or flying robots to underwater vehicles, is not applicable due to the peculiarities and constraints of the underwater environment, as the electromagnetic signals do not penetrate below the sea surface. The good propagation characteristics of sound waves in water makes acoustic positioning and navigation as a feasible candidate, and the related study of the implications of such methodology for the underwater vehicles has been conducted for a long time.
As fig. 1 illustrated, classic acoustic approaches for underwater vehicle positioning, include Long Baseline (LBL), Short Baseline (SBL), Ultra-short Baseline (USBL) Systems, and Long & Ultra Short Baseline (LUSBL), etc.

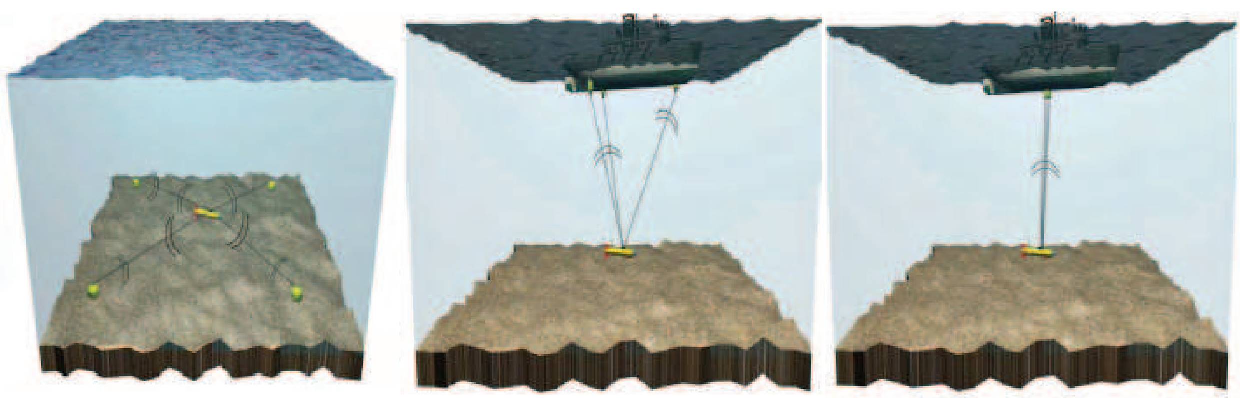


Fig. 1. Classic underwater acoustic positioning systems: LBL system(left), SBL system(central), USBL system(right).

The application and performance of this challenging area have been investigated by many researchers (Vickery, 1998). In the LBL case, a set of acoustic transponders is pre-deployed on the seafloor with the geometry of interested vehicles centered. The vehicle position is achieved by the basis of the acoustic signal returns detected by the transponders with the required accuracy (Collin, 2000). In the SBL side, a dedicated ship follows the underwater vehicle at short range with a set of three hydrophones to determine the AUV position, and the AUV can also get its absolute position via the bidirectional communication among the

AUV and the mother ship (Storkensen, 1998). USBL systems are very similar to SBL principles except that the transducers are built into a single transceiver assembly or an array of transducer elements in a single transceiver. The distances are measured as they are in an SBL system but the time differences are replaced by the "time-phase" of the signal in each element with respect to a reference in the receiver. The "time-phase differences" between transducer elements are computed by subtraction and then the system is equivalent to an SBL system. The LUSBL system is a special case of a USBL system. It utilizes USBL hardware in a configuration similar to the one described for the LBL system. Range and bearing in an LUSBL system are still measured as described for a basic USBL system. However, because a larger number of beacons are deployed on the seabed, a considerable improvement in accuracy may be achieved.

Although all these classic acoustic methods have been used for a long time, there are still some disadvantages existed in practical utilization. LBL systems require long time with associated costs for deployment and comprehensive calibration at each deployment. SBL systems is installed on a dedicated ship so that they are in poor signal to noise ratio due to ship’s self noise and the accuracy of acoustic positioning can only be achieved in calm weather and without ship motion which also lies on USBL and LUSBL systems.

2.2 Underwater GPS navigation

As mentioned above, traditional acoustic solutions for AUV navigation present some installation, calibration constraints and operational limitations. Their performances may be over estimated and in some cases not fully satisfying, and then non-acoustic solutions will be considered here.

The traditional non-acoustic approach, is a set of INS on board combining with a GPS receiver, which is also a dominant approach for AUVs. Due to the accumulated error from INS, the AUV must periodically come to the surface to calibrate the position with the help of GPS. In the case of a team of multiple AUVs, at least one AUV, providing accurate navigation information for others, have to come to the surface for position calibration, which would deteriorate the whole strategy of the team coordination and formation, besides the extra energy consumed to come to the surface and high cost of INS set in each AUVs.

Since there some drawbacks of the non-acoustic INS combined with GPS navigation approach for coordinated underwater vehicles, we should seek alternative solutions. Unfortunately, it seems there is no way to directly utilize GPS for underwater navigation, as the electromagnetic signals do not penetrate below the sea surface making the GPS unsuitable for directly underwater navigation. However, more recently, several new ideas about underwater “reproducing” GPS have been proposed in order to improve the accuracy of underwater positioning and navigation, making such system easily used. The ideas of “reproducing” the GPS in the underwater environment which getting the merits of both non-acoustic and acoustic approaches, can be classified in three different groups summarized as follows.

The first type is so-called “false” underwater GPS. A GPS receiver mounted on a buoy is towed on the surface by the underwater targets such as underwater vehicles. A cable or fiber is used to send the GPS position to the underwater target. This technique does not give the true position of the target but the false position even in few tens of meters around the surface buoy, so that it is named as false underwater GPS.

The second type is a "direct" underwater GPS solution. In 1992, Youngberg inspired a direct transposition of GPS signal to underwater world. Acoustic waves but not radio electric signals, directly go from surface buoys replacing satellites to the underwater mobiles (receivers). Then, the underwater platform receives these acoustic messages from the buoys equipped GPS receptors and computes its own position locally. This solution has been presented by M. Youngberg of the US-AIR FORCE and patented (US Patent N°: 5.119.341).
The third type is very similar to the second type solution, but it is a "reverse" underwater GPS solution. This method has been recently investigated by Thomas (Thomas, 1998) and is available commercially: the so-called GPS Intelligent Buoy (GIB) system, developed by ACSA in 1999. This system is designed to track the position of an underwater target equipped with an acoustic emitter, by measuring the times of arrival of the acoustic signals at a set of surface buoys equipped with submerged hydrophones and GPS receivers. As fig. 2 illustrated, it is a standard GIB buoy system (http://www.underwater-gps.com). The minimum number of buoys deployed is 2 if there are only 2 unknown parameters X and Y, as the depth (Z) of the target could be known using a telemetry channel. Technology of Time, Frequency or pseudo-random code diversity could be employed when tracking multiple underwater targets.

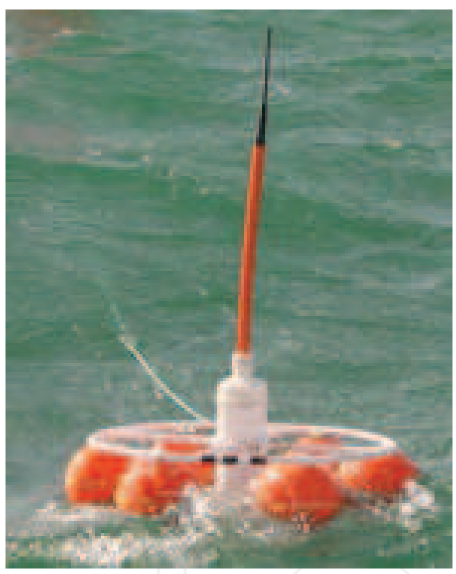


Fig. 2. GIB standard buoys

As we can see, in the direct type 2 solution, the information fusion is done on board the vehicle which uses downwards acoustic flow of data. In the reverse type 3 solution, the fusion is done on the remote control station which uses upwards acoustic flow of data.

3. Cooperative acoustic navigation scheme for AUVs

Inspiration of new techniques allows the underwater usage of DGPS, that is "Underwater DGPS" concept, to develop advanced underwater robotics system. Because of its special characteristics, the "reverse" type 3 is selected as the representative acoustic navigation system for heterogenous autonomous vehicles, and with which the heterogenous vehicles in a team could benefit a lot from the cooperative acoustic navigation. Before referring to the cooperative acoustic navigation scheme for heterogenous vehicles, the DGPS Intelligent Sonobuoy (DIS) navigation system will be firstly introduced here.

3.1 DIS navigation system

A prototype of such acoustic navigation system proposed in this chapter consists of a set of light surface buoys usually more than three of them. The physical characteristics of the buoys with acoustic module(hydrophone), in terms of size, weight and autonomy, will tend to those of a standard sonobuoy, with however the capability of micro-controller, processing of acoustic signals, local data storage, and online transmission by a radio modem. The most peculiar characteristic is a DGPS receiver integrated on board, the hydrophone and the ARM CPU is synchronized before deployment with the DGPS clock datum. One possible simplified schematic of a sonobuoy with DGPS is shown on fig. 3. We call it as a DGPS Intelligent Sonobuoy system.

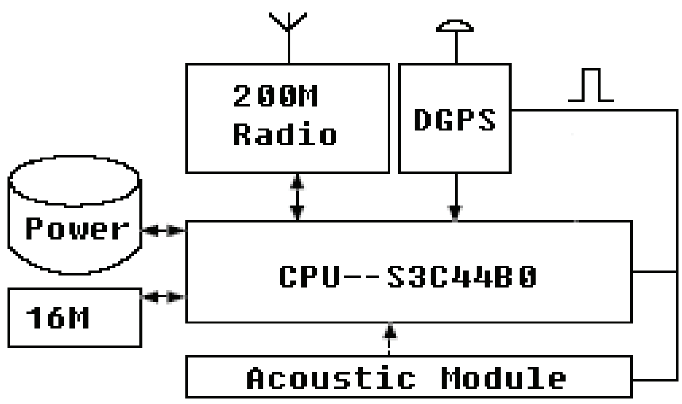


Fig. 3. Block scheme representing DGPS Intelligent Sonobuoy

The core of the DIS is ARM7 CPU named as S3C44B0. An extended 16M memory is for data storage as well as a data buffer. An acoustic module based on MOTOROLA DSP. A two way radio link with 200M Radio Frequence (RF) allows for communication within ranges up to 40/50 km. The DGPS board for 1us precision timing and localization of the buoy. The system was designed to be deployed switch off and auto-activate in order to avoid electronic equipment damage by severe deck and banging during deployment and recover.

The DIS system usually consists of four surface buoys which use the hydrophones to receive the acoustic impulses and record their times of arrival (TOA). The pinger onboard the vehicle emits two successive acoustic pulses during each emission cycle so that the pinger/vehicle depth is proportional to the time delay between the two pulses. The ranges or distances between the buoys and the pinger/vehicle can be translated into the times of arrival, and the value of sound speed in the water is assumed to be known. The buoys transmit the information of the DGPS position and the time of arrivals to the a Autonomous Surface Vehicle as a central station via radio link, where the true position of underwater target is computed by triangulation or by using more sophisticated algorithms. However, the dropouts and outlier of the acoustic positioning system should be carefully dealt with due to acoustic path screening, partial system failure, and multipath effects. See (Vagannay et al., 1996)for a treatment and discussion on this challenging topic, and (Alcocer et al., 2004) also gives an intensive study to deal with the dropouts and outliers in real time.

3.2 Cooperative navigation architecture for heterogenous AUVs

With the underwater DGPS concept and the underwater acoustic navigation approach, the position of the AUV can be achieved with high precise given a set of range measurement from the AUV to known sonobuoys locations. In the set-up adopted for vehicle positioning the underwater pinger of an AUV carries a high precision clock that is synchronized with those of the sonobuoys (and thus with DGPS) prior to AUVs deployment. The pinger emits an acoustic signal every T seconds, at precisely known instants of time. As the underwater positioning of AUVs is done on the remote control station which uses upwards acoustic flow of data, one natural strategy for the undersea exploration is to use an Autonomous Surface Vessels (ASV) to control multiple AUVs motivated by the "reverse" underwater GPS method. With this method, the ASV can conveniently get all of the AUVs' positions in a heterogenous coordinated AUV team, because the pre-deployed four sonobuoys as a set transmit the DGPS positions themselves and the TOA of AUVs in a team to the central control ASV via radio link, and then generate and allocate the waypoints to the AUVs to implement the coordinated search or rescue scenario. As fig. 4 illustrated, a typical description of such heterogenous vehicle team is a ASV as a central control vehicle combined with three types low-cost AUVs based on DIS to provide navigation information. One type of them may be a vehicle with side-scan sonar to build maps of the ocean bottom and get rough list of interested objects with on-board computer-aided detection and classification. It will be followed by another vehicle with forward-looking high resolution sonar or camera for further identification of the object. The last type of vehicle with a dexterous underwater manipulator maybe intended to perform some sampling inspection operations.

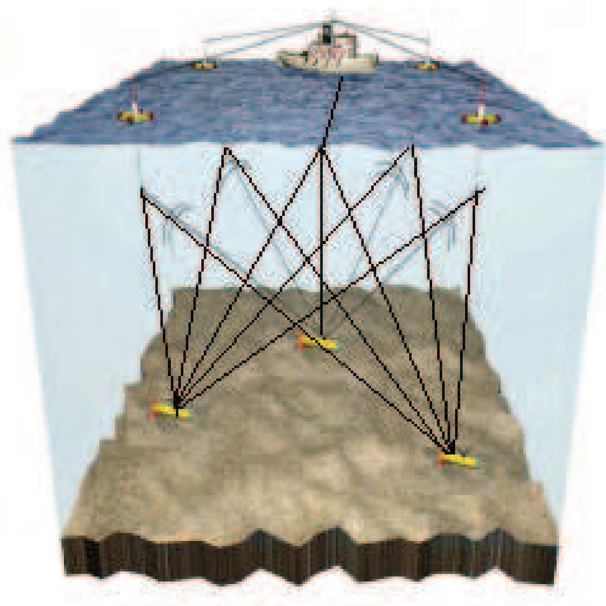


Fig. 4. DIS for coordinated control of heterogeneous vehicles

The ASV communicates with AUVs via 3~5 kHz acoustic modem for long range bi-directional communication. Communications from the ASV to the AUVs in the heterogeneous team will support navigation and control information. Control commands include performing wide-scale mapping, making detailed acquisition or further identification over targets, drilling and sampling of interested objects, and so on. Navigation messages include the waypoint generated by the ASV as well as the positioning information for the specific AUV which will be accurately provided by the acoustic modem. AUVs will upload useful sensor information and compressed high resolution segments of data to the central ASV, and this function will be unnecessary if the vehicles are to be retrieved with all datum transferred on shore.

Without the INS/GPS onboard, the AUV with DIS need not periodically come up to the surface to calibrate their positions however seriously disturb the underwater vehicle team coordination and existed formation. In the side of underwater vehicles for navigation, just a good flux gate compass is the most important requirement, and a Doppler velocity sensor associated with a high quality attitude sensor can improve the overall system accuracy. From time to time, the AUVs will receive new heading settings via an acoustic link. The central control ASV will also move above the central of mass of the AUVs in order to keep a desirable distance between the ASV and AUVS to ensure the high quality acoustic communication. Thus the whole team with heterogenous vehicles could conveniently implement the coordinated search or rescue scenario as a whole base on the novel acoustic navigation scheme. Compared with traditional acoustic positioning methods, the high precision could also be conveniently achieved by the DIS without installation and calibration constraints and operational limitations. With this novel acoustic navigation scheme, it is possible for us to easily handle with heterogeneity in coordinated control task for underwater activities.

4. Cooperative navigation algorithm

Problem statement: Given the simultaneous information of sonobuoys positions and the TOAs at different sonobuoys, and assuming the measurement performed each time affected by a bounded error accounting for all the uncertainties, then the simultaneous Least Squared (LS) navigation algorithm could be proposed for cooperative navigation for heterogenous AUVs, and the observation equations could be made. The Taylor-series will give a Least Squared error solution to a set of simultaneous nonlinear algebraic position equations, and the position of AUV will be achieved via the iterative refinement scheme.

When Time of Arrivals from the pinger on-board the vehicle to the sonobuoys combined with the DGPS positions of the sonobuoys themselves are used to identify the position of an AUV, it is possible for the sonobuoys to get the positions of multiple underwater vehicles within different time slots, namely the time-multiplexed navigation. Then, the central control ASV can collect all the positions of underwater vehicles via radio link to sonobuoys. It gives a clear understanding that the navigation algorithm for acoustic navigation in coordinated underwater vehicles regresses to the navigation algorithm of a single target. The detailed algorithm will be shown as follows.

Consider an absolute earth fixed reference system {O}:={X, Y, Z} with the Z-axis pointing upward from the sea surface, and n sonobuoys(usually n is equal to four) at the sea surface with hydrophones at DGPS positions given by vector $P_i=[x_i, y_i, z_i]^T$; $i=1,2,\ldots n$. Let $P_0=[x\ y\ z]^T$ denote the position of one of the interested underwater vehicles with respect to the reference frame. The navigation problem considered in this chapter can then be concisely stated as follows: obtain estimates of the AUVs position based on information provided by the sonobuoys, which compute the flight time of the acoustic signals emitted periodically by a pinger installed on-board the underwater vehicle. It belongs to a passive acoustic navigation system but not an active navigation system according to (Freitag et al., 2001). Further let $f=[f_1 \ldots f_i]^T$; $i=1,2,\ldots n$, denote the ranges between the dedicated underwater vehicle and the sonobuoys.

Before formulating the measurement, there are three assumptions based on practical but also reasonable principle.

1. Each sonobuoy position will be known at differential GPS accuracy, and the uncertainty of the DGPS position can be treated as an additional uncertainty in the totally measurement.
2. The sonobuoys freely drift at the sea surface due to waves and current and are assumed with a much slower drifting speed compared with the instantaneous flight time of the acoustic signals, which means the sonobouy position is relatively static and the movement of the sonobuoy can be treated again as an additional uncertainty in the totally measurement.
3. The sound speed $c(z)$ in the area of interest is assumed known and the sound speed is assumed to vary only with depth in the area of interest is considered in the most common situation. Although the different sea temperature do affect the sound speed in different water column, the slightly varied sound speed due to heterogeneous temperature in different current layers can be treated again as an additional uncertainty in the totally measurement.

With the simultaneous information of sonobuoys positions and the TOAs at different sonobuoys, the simultaneous Least Squared (LS) navigation algorithm can be followed as:
The n equations describing the distance between the unknown position of the AUV and the sonobuoy location are:

$$f_i = \| p_0 - p_i \| = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} \quad (1)$$

The underwater pinger carries a high precision clock that is synchronized with those of the sonobuoys with DGPS prior to AUV deployment. Assuming the measurement s_i of the one-way travel time of the emitted signal by the pinger of the underwater vehicle is available to the ith sonobuoy, the distances between the AUV and the sonobuoys can be simply computed as

$$f_i = s_i \cdot c(z) \quad (2)$$

The sound speed is not a constant and varies with depth of the sea. Practically the weighted average speed is used to evaluate the sound speed propagating under the sea where the profile of the sound speed is divided as m layers, is shown on fig. 5. Then the sound speed considered in the central control ASV can be defined as

$$c(z) = \frac{1}{H}\sum_{i=0}^{m-1}(c_i + c_{i+1}) \cdot (z_{i+1} - z_i) / 2 \quad (3)$$

Assuming the measurement performed each time affected by a bounded error e_i, which accounts for all the uncertainties, such as synchronization errors, noisy signals, DGPS accuracy, buoy/vehicle motion between transmission and reception of the same ping, multi-path effect, etc. Then the observation equations with uncertainties can be written as

$$\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} = s_i c(z) - e_i \quad (4)$$

As the Taylor-series estimation (also Gauss or Gauss-Newton interpolation) gives a Least Squared error solution to a set of simultaneous nonlinear algebraic position equations (Foy, 1976). If x_g, y_g, z_g are initial guesses of the true vehicle position, f_i can be expanded in a Taylor-series keeping only terms below second order as

$$f_{ig} + \frac{\partial f_{ig}}{\partial x}\delta x + \frac{\partial f_{ig}}{\partial y}\delta y + \frac{\partial f_{ig}}{\partial z}\delta z \cong s_i c(z) - e_i \tag{5}$$

Where

$$\delta x = x - x_g, \delta y = y - y_g, \delta z = z - z_g$$

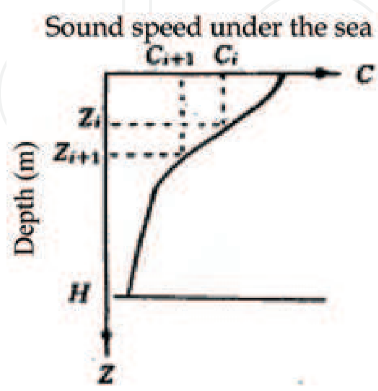


Fig. 5. Profile of the sound speed under the sea

Assuming errors e_i are stastistically distributed, the approximate relations of stacked equations (5) can be written as

$$A\delta \cong b - e \tag{6}$$

Solving (6) for δ while minimizing the least squared error with the terms in the sum weighted according to the covariances of the measurement errors gives

$$\delta = [A^T R^{-1} A]^{-1} A^T R^{-1} b \tag{7}$$

The matrixes and vectors are defined as:

$$\delta = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

$$A = \begin{bmatrix} \frac{x_g - x_1}{\rho_1} & \frac{y_g - y_1}{\rho_1} & \frac{z_g - z_1}{\rho_1} \\ . & . & . \\ . & . & . \\ \frac{x_g - x_n}{\rho_n} & \frac{y_g - y_n}{\rho_n} & \frac{z_g - z_n}{\rho_n} \end{bmatrix}$$

$$b = \begin{bmatrix} s_1 c(z) - f_1 \\ . \\ . \\ s_n c(z) - f_n \end{bmatrix}$$

Where

$$\rho_i = \sqrt{(x_g - x_i)^2 + (x_g - y_i)^2 + (x_g - z_i)^2}$$

With the computed δ x, δ y, δ z replace

$$x_g = x_g + \delta x, y_g = y_g + \delta y, z_g = z_g + \delta z$$

in (6), and repeat the computation to get a new estimate of $P_0=[x\ y\ z]^T$. The iterations will have converged when δ x, δ y, δ z are essentially zero, and the position of AUV is achieved via the iterative refinement scheme. The solution derived above can be easily simplified to the case where the target undergoes motions in two dimensional space with fixed depth z.
Considering the noise covariance matrix R= σ^2 I (i.e., the noise terms e_i are independent with the same variance), the covariance matrix of the LS estimation errors in the corresponding position can be calculated as

$$C = \left[A^T R^{-1} A\right]^{-1} = \left[A^T A\right]^{-1} \sigma^2$$

The system is computationally simple requiring inversion of n (sonobuoys as reference stations) by 3 matrix and it usually converges in several iterations, but the linearized estimator is sensitive to the geometry of the situation. For instance, sonobuoys were placed very clear each other and the AUV is in very deep depth, then even small measurement errors of TOA will lead to large position estimation errors due to the occurred ill-conditioned matrix.
On the other hand, the solved depth of the underwater target is very inaccurate when depth is small compared to the distance between transponders. In this case, a pressure sensor integrated in the mobile's pinger is one solution, and the telemetry technique used is of an external freedom for depth accuracy as the time delay between two pulses is proportional to the depth.
Within different time slots, all of the dedicated AUVs in the coordinated team can be calculated with this high precise navigation algorithm based on intelligent sonobuoys with DGPS. Benefited from all of the vehicle positions, The ASV can generate and allocate the waypoints to the AUVs as well as providing the navigation information so that the coordinated control of heterogenous vehicles including the ASV and AUVs could be possible. At the same time, the ASV with the collected AUV positions will follow the AUVs and move above the central of mass of the underwater vehicles to keep the heterogenous team as a whole (Xiang[a] et al., 2007).

5. Simulation results

The performance of the cooperative navigation proposed here could be examined by computing the trajectory-tracking error with noisy range measurements, which was with very good accuracy. The acoustic navigation system was tested as follows.
It was supposed that there were four sonobuoys pre-deployed in a given square geometry of 10x10 Km in the *X*-*Y* plane, and the AUV of interesting in the coordinated team was in the depth of 500m. The sonobuoys were separately located at (0, 10000, 500), (0, -10000, 500), (10000, 10000, 500), and (10000, -10000, 500), and the AUV was locate at (0, 0, 0). The performance of the navigation method could be examined by computing the trajectory-

tracking error with noisy range measurements. Assume that the range measurements in four sonobuoys had a standard deviation of σ_1^2 =0.5, σ_2^2 =4, σ_3^2 =1, and σ_4^2 =0.2. Assume also that the errors were independent. Thus the covariance matrix of the errors was *R*=[*0.5 0 0 0; 0 4 0 0; 0 0 1 0;0 0 0 0.2*]^T. In fig.6, the solid track was from the true trajectory of one AUV in coordinated team moving in a spiral cord in 3D space or projected in 2D space, and the asterisks represented the corresponding tracking position estimates for the acoustic navigation system, which were with very good accuracy. Using the simultaneous LS positioning algorithm, the estimates were typically within centi-metric accuracy in northing(*X*-axis) and easting direction(*Y*-axis) of the true position. The mean length of the overall errors was 0.014171m and 0.0013966m respectively in *X*-axis and *Y*-axis, and the mean length of correction vector values was 0.2215m. The small errors give accurate measurement of the AUV position, but we should also be aware of that the actual error might be different due to the variety of noise measurements and the DGPS accuracy.

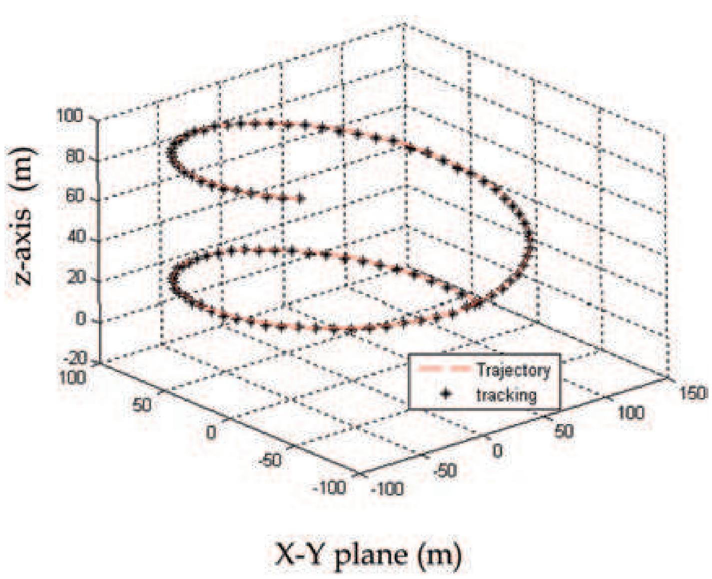


Fig. 6. (a) Trajectory-tracking of AUV moving in a spiral cord

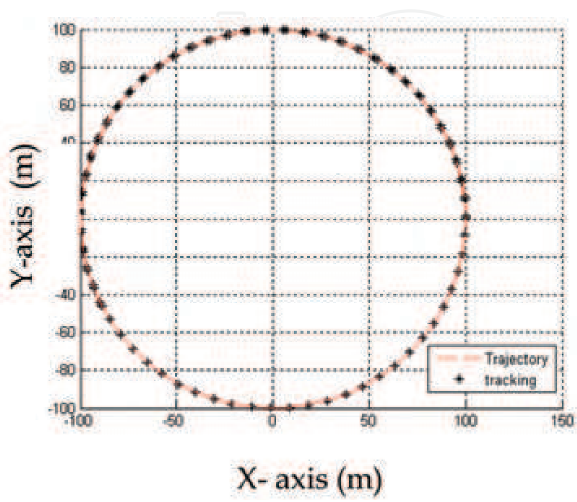


Fig. 6. (b) Trajectory-tracking of AUV projected in X-Y plane

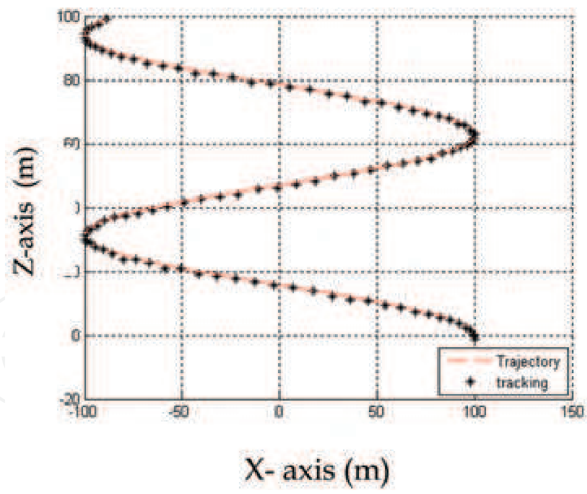


Fig. 6. (c) Trajectory-tracking of AUV projected in X-Z plane

6. Conclusion and future work

A new cooperative acoustic navigation concept based on intelligent sonobuoy with DGPS, that fits into coordinated control of hetergenous vehicles was proposed in this paper, which gives a great advantage to coordinate a team of heterogenous vehicles with provided position estimates in centi-metric accuracy. It is believed that the navigation method proposed may represent a significant alternative to the ones based on traditional navigation methods (such as LBL, SBL, USBL and INS/GPS, etc.), and the novel acoustic navigation method is especially suitable for the field of coordinated control of heterogenous vehicles including ASV and AUVs due to its characteristics of upwards acoustic flow of data.

Future work is to develop a robust acoustic navigation system that can perform reliably and also include a version of the system in the presence of multi-path effects, acoustic outliers and of course include in-water validation of the system.

7. Acknowledgement

The first author would like to acknowledge helpful discussion and solid support from the co-authors of the chapter.

The European Marie Curie Research Fellowship and the wonderful team in the research project FREESUBNET under grant 036186 give the first author a great support for the finalization of the chapter. This work was also funded in part by the National Natural Science Foundation of China under grant 69585003, and in part by the National 863 Hi-tech Research and Development Program of China under grant 2006AA09Z203.

8. References

Lapierre L. (2006). Underwater Robots Part I: current systems and problem pose, in *Mobile Robotics – Towards New Applications*, Edited by Pro Verlag & Advanced Robotic Systems International (ARS), ISBN: 978-3-86611-314-5, Germany.

Louis L. Whitcomb.(2000). Underwater Robotics: Out of the Research Laboratory and Into the Field, *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 709-716, April 2000, San Francisco, USA.

Xu, G., Guo, Y., Xiang, X. and Xiao, Z (2007). Motion control and computer simulation for underwater vehicle-manipulator systems, *Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation*, pp. 1368-1373. Harbin, China.

http://www.freesubnet.eu.

Xiang, X., Huang, X., Zhang, Q., Xu, G. (2008). Prospective research on coordinated control of multiple AUVS. *Proceedings of the 2008 IEEE Chinese Control and Decision Conference, pp. 3306-3310. Yantai, Shangdong, China.*

Bourgeois,B., Martinez,A., Alleman,P., Cheramie,J., Gravley,J. (1999). Autonomous bathymetry survey system. *IEEE Journal of Oceanic Engineering,* vol.24, no. 4, pp. 414-423.

McDowell,P., Chen,J., and Bourgeois,B. (2002). UUV Teams, control from a biological perspective. *Proceedings of the Oceans 2002 MTS/IEEE Conference, Biloxi MS,* pp 331-337.

Caiti,A., Garulli, A., Livide,F., and Prattichizzo,D. (2005). Localization of autonomous underwater vehicles by floating acoustic buoys: a set-membership approach. *IEEE Journal of Oceanic Engineering,* vol.30, no. 1, pp. 140-152.

Yun, X., Bachmann, E. R., McGhee, R. B., Whalen, R. H., Roberts, R. L., Knapp, R. G..,Healey, A. J., and Zyda, M. J. (1999). Testing and evaluation of an integrated gps/ins system for small auv navigation. *IEEE Journal of Ocean Engineering.,* vol. 24, no. 3, pp. 396-404.

Xiang, X., Xu, G., Zhang, Q., Guo, Y. and Huang, X. (2007). A novel acoustic navigation scheme for coordinated heterogenous autonomous vehicles. *Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation*, pp. 2801-2806. Harbin, China.

Vickery,K. (1998). Acoustic positioning systems. A practical overview of current systems. *Proceedings of the 1998 Workshop on Autonomous Underwater Vehicles., Fort Lauderdale, FL, USA*., pp. 5-17.

Collin, L., Azou, S., Yao, K., and Burel, G.. (2000). On spatial uncertainty in a surface long base-line positioning system. *Proc. 5th Europ. Conf. Underwater Acoustics*, Lyon, France.

Storkensen, N., Kristensen, J.,Indreeide, A., Seim, J. and Glancy, T. (1998). Hugin—UUV for seabed survey. *Journal of Sea Technology.*

Thomas, H. G.. (1998). GIB buoys: An interface between space and depths of the oceans. *Proceedings of IEEE Autonomous Underwater Vehicles, Cambridge, MA, USA*, pp.181-184.

http://www.underwater-gps.com.

Alcocer,A., Oliveira,P., and Pascoal,A. (2006). Underwater acoustic positioning system based on buoys with GPS. *Proc. 8th European Conf. on Underwater Acoustics,* Carvoeiro, Portugal.

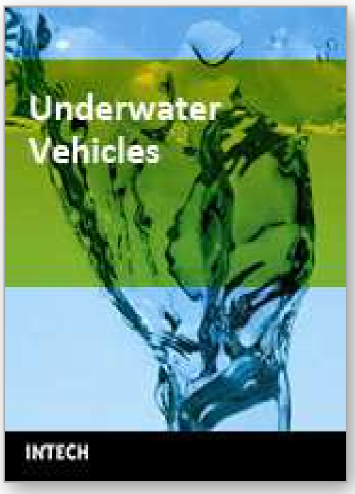
Vaganay, J., Leonard, J., and Bellingham, J. (1996). Outlier rejection for autonomous acoustic navigation. *Proceedings of IEEE International Conference on Robotics and Automation,Minneapolis, MN, USA*, pp. 2174–2181.

Alcocer, A., Oliveira P., and Pascoal A. (2004). Study and implementation of an EKF GIB-Based underwater positioning system. *Proceedings of the IFAC Conference on Control Applications in Marine Systems (CAMS'04)*, Ancona, Italy.

Freitag,L., Johnson, M., Grund,M., Singh, S. and Preisig,J. (2001). Integrated acoustic communication and navigation for multiple UUVs, *Proc. Oceans 2001,* pp. 2065-2070, Honolulu, HI.

Foy,W.H.. (1976). Position-location solutions by Taylor-series estimation. *IEEE Trans. Aerospace and Electronic Systems*, vol.12, no.2, pp.187-194.

Xiang[a], X., Xu, G., Zhang, Q., Xiao, Z. and Huang, X. (2007). Coordinated control for multi-AUV systems based on hybrid automata. *Proceedings of the 2007 IEEE International Conference on Robotics and Biomimetics*, pp. 2121-2126. Sanya, China.



Underwater Vehicles

Edited by Alexander V. Inzartsev

ISBN 978-953-7619-49-7
Hard cover, 582 pages
Publisher InTech
Published online 01, January, 2009
Published in print edition January, 2009

For the latest twenty to thirty years, a significant number of AUVs has been created for the solving of wide spectrum of scientific and applied tasks of ocean development and research. For the short time period the AUVs have shown the efficiency at performance of complex search and inspection works and opened a number of new important applications. Initially the information about AUVs had mainly review-advertising character but now more attention is paid to practical achievements, problems and systems technologies. AUVs are losing their prototype status and have become a fully operational, reliable and effective tool and modern multi-purpose AUVs represent the new class of underwater robotic objects with inherent tasks and practical applications, particular features of technology, systems structure and functional properties.