Underwater Navigation Systems for Autonomous Underwater Vehicle

Sachi Choudhary(✉), Rashmi Sharma, Amit Kumar Mondal, and Vindhya Devalla

University of Petroleum and Energy Studies, Dehradun, Uttarakhand, India
sachi.choudhary1617@gmail.com

Abstract. Over the past few decades, researchers, navy of different countries and different organizations related to maritime archaeology, underwater mines & pipelines etc. had paid considerable attention towards underwater surveying & inspection by autonomous robot or vehicle. Considerable improvements for better AUV navigation have seen in different sensors in recent years. The sensors are available with not only improved performance but lesser cost and reduced size as well. In addition to these developments, huge improvements in path planning of AUVs have also seen with advanced navigation techniques & algorithm such as SLAM. This paper presents a survey on some important navigation systems for AUV. These techniques can be used to calculate the current position or to localize the robot/vehicle underwater.

Keywords: Autonomous Underwater Vehicle (AUV) · Inertial navigation
Acoustic navigation · Geophysical navigation

1 Introduction

Underwater divers & archaeologist have to dive underwater for information collection previously. As human body is not physiologically and anatomically well adapted to the underwater environmental, divers have to face lots of challenges like immersion, exposure, breath hold limitation, ambient pressure change etc. To overcome the problems of underwater divers lots of equipment have been developed which also helps in increasing depth range as well as time. Again diving activities are restricted to depths range even after wearing atmospheric suits and to conditions which are not extremely risky.

So to explore the underwater area, development & enhancement of unmanned underwater vehicles (UUV) have been a major area of research from past few decades. UUVs are classified into two categories as mentioned in Sect. 2 of this paper. This paper more focuses on AUV navigation & localization.

AUV navigation & self-localization is a challenging task due to penetration of radio waves & GPS signals underwater [6]. Radio waves can be used for communication at shallow depth. Acoustic based sensors perform better for underwater communication. The traditional sensors for navigation are magnetic compass, pressure depth sensors, acoustic navigation systems etc. From last few decades there is a huge development in

P. Bhattacharyya et al. (Eds.): NGCT 2017, CCIS 828, pp. 238–245, 2018.
https://doi.org/10.1007/978-981-10-8660-1_18

the navigation sensors such as Doppler sonars, optical gyrocompasses, and inertial measurement units (IMUs) etc. [2].

Navigating autonomously is the biggest challenge for any AUV, as opposed to a ROV whose location can be measured accurately relative to the surface vessel that is connected to it.

2 Unmanned Underwater Vehicles

Unmanned Underwater Vehicle (UUV) or underwater drone is any vehicle that can operate underwater without any human occupant. UUVs were developed to perform Intelligence, Surveillance and Reconnaissance, Mine Countermeasures, Anti-Submarine Warfare, Underwater Inspection/Identification, Oceanography/Hydrography, Communication/Navigation Network Nodes, Underwater Archaeologies etc. Unmanned Underwater vehicles are broadly categorized as Autonomous Underwater Vehicle (AUV) & Remotely Operated Underwater Vehicles (ROV).

Autonomous Underwater Vehicle (AUV) is UUVs without any human or remote interference. They are preprogrammed vehicles and operate autonomously. AUVs can be used to perform underwater inspection missions such as detecting and mapping submerged crashes, rocks, and obstructions that pose a hazard to navigation for commercial and recreational vessels. When a mission is complete, the AUV will return to a pre-programmed location to transfer the collected data during surveillance.

Remotely Operated Vehicle (ROV) is controlled by a remote human operator at sea/water surface. The main application areas of ROVs are in deep water industries such as offshore hydrocarbon extraction. They are linked to a surface vessel or host ship by a neutrally buoyant cable or, often when working in rough conditions or in deeper water, a load-carrying umbilical cable is used along with a tether management system (TMS).

3 Challenges with Underwater Autonomous Vehicles

3.1 Unstructured Environment

Underwater surveillance is more complex than surface or land surveillance using mobile robot or autonomous vehicles. The navigation & obstacle avoidance in unstructured underwater environment is very difficult due to low visibility & more penetration of light. It is challenging for autonomous vehicles to explore & navigate without any knowledge of environment, geophysical landmarks, obstacles & environmental factors like turbidity, water current, tide level, etc.

3.2 Unavailability of Satellite Based Navigation or GPS

GPS is a space based radio frequency signal used for navigation at surface. GPS is unavailable after a certain range as radio frequency cannot penetrate sea water. Very low frequency radio waves i.e. 3–30 kHz can penetrate sea water but not more than range of 20 m. So for underwater navigation, vehicles have to depend on different acoustic based sensors. Section 4 of this paper focuses on different techniques that can be used to locate the vehicle's current position underwater.

3.3 Underwater Communication

Communication among the underwater vehicles or in between underwater vehicle & surface vehicle is still a broad area of research. As radio waves can't be used underwater, vehicles have to depend on acoustic signals. In case of ROV, communication is possible because vehicle is tide to surface vehicle via a cord. In this case the noise level may be high due to physical disturbance transmitted along the cable to surface (Fig. 1).

4 Underwater Navigation Systems

To solve the navigation problem different sensors can be used which can locate the AUVs current position. The different AUV navigation techniques/methods can be classified into three categories [5, 6]:

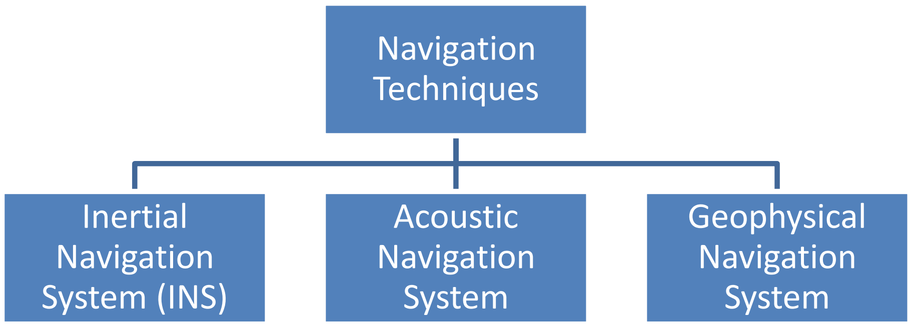


Fig. 1. Underwater navigation techniques

4.1 Inertial Navigation System (INS)

AUV can estimate its position at sea by estimating the distance & direction travelled called as **Dead reckoning.** Dead reckoning (DR) is the method of calculating AUV's positon at sea autonomously without help of any positioning support or landmarks.

In DR AUV can estimates its position based upon its previous orientation & velocity or acceleration vector.

INS uses onboard sensors & no other external resources for positioning. The initial position of AUV is set by GPS or any other positioning system. The position of AUVs get updated underwater using on-board sensors. To update the position of AUV on-board sensor are used along with previously stored position. On-board sensors measure acceleration, change in velocity along with time.

DR is the oldest & low cost method of navigation. DR uses inertial sensors such as gyroscopic sensor or gyrocompass and an accelerometer, to estimate the orientation and distance traveled by the AUV with respect to a reference coordinate system. The disadvantage of DR is the measurement error due to noise from gyroscopes which affect navigation [11]. The source of error also includes inaccurate knowledge of start position & time varying effects of on-board sensors. The AUV's motion is affected by ocean waves. A neural network based DR method (DR-N) was proposed in [11] to overcome these problems.

INS uses gyroscopic and/or accelerometers to calculate the current position of AUV. It can be used with Doppler Velocity Log (DVL) feature and Acoustic Doppler Current Profiler (ADCP) [5]. INS can be combined with DVL to use bottom tracking feature for better navigation. The current position of AUV can be calculated by combining velocity of vehicle with previous position & data from accelerometer. Kalman filter (KF) is used to reduce the uncertainty of the position estimated [5]. Extended Kalman Filter (EKF) can be used for state estimation.

An acoustic Doppler current profiler (ADCP) is a hydro acoustic current meter, uses Doppler Effect of sound waves. It can measure velocity of water current. ADCP can measure water current over ranges of about 1000 m.

4.2 Acoustic Navigation System

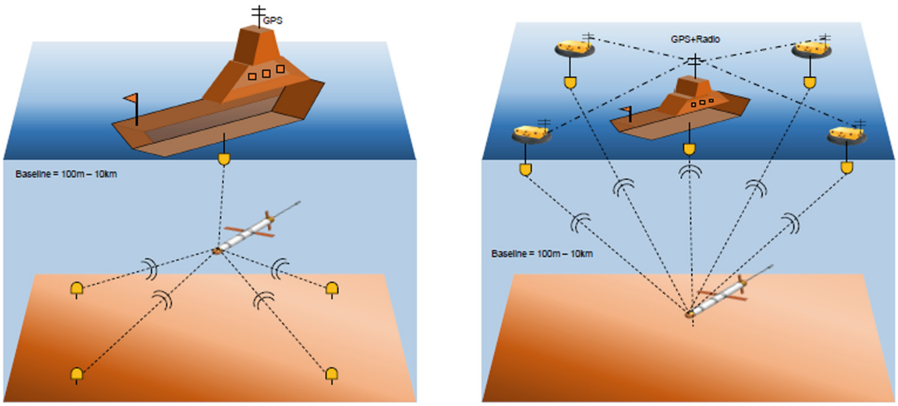
Acoustic navigation system works with the help of acoustic beacons placed in navigation area. It is used to improve the efficiency of navigation of large mission. The main approaches of acoustic navigation are Long baseline (LBL), Short baseline (SBL) & Ultra short baseline (USBL) [5, 12] (Table 1).

Table 1. Acoustic baseline is the distance between active sensors.

Acoustic system	Acoustic baseline length
LBL	100 m–10 km
SBL	20 m–50 m
USBL	<10 cm

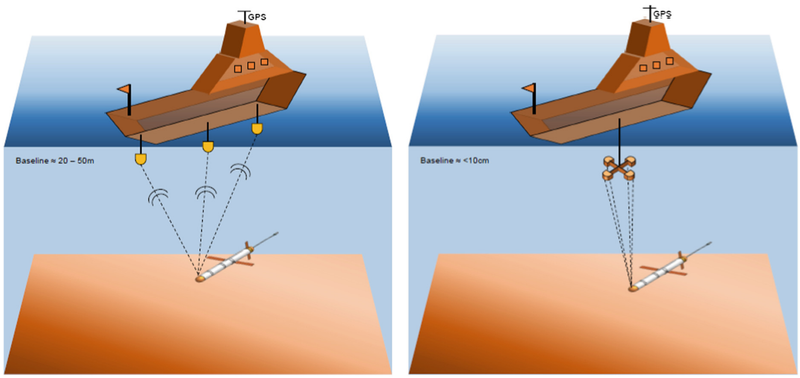
In classical Long-Baseline (LBL) transponders are placed in sea floor or sea bed separated by a long distance that is why it is called Long baseline [12]. The other LBL system available is Mobile LBL which has beacons (GIBs) at water surface & transponders submerged in the water at a specified depth. It is not portable (Fig. 2).

The SBL has acoustic baseline of range 20 m–50 m. SBL uses single beacon at AUV & multiple acoustic transponders on the ship (the accuracy can be increased by increasing distance between the transponders) [12]. The position of AUV is calculated by acoustic signals travel time from different transponders placed on ship to AUV. It is not used because of low accuracy (Fig. 3).



(a) Classical LBL (b) Mobile LBL (GIBs)

Fig. 2. Long baseline (LBL) navigation system



a. **b.**

Fig. 3. (a) Short baseline (SBL) navigation system (b) Ultrashort baseline (USBL) navigation system

The third is ultra-short baseline (USBL) positioning have a single multi-element transducers or transducer array (minimum 3 transducer in an array) called trans-receiver on AUV and a single beacon at sea bottom [12]. The distance between transducer in array is <10 cm i.e. ultra-baseline. The transducers in AUV pings the trans-receiver by acoustic signal & receive the response. The round trip time along with angle & direction are used to calculate the position of AUV in an inertial frame. USBL is easy to deploy than above mention acoustic navigation systems, that is why it is most widely used. But USBL is less accurate than other two as the baseline is small.

Source of error in acoustic navigation system are:

I. Deployment of transponders on the sea bed & beacons at AUV [2].
II. Information of sound velocity as sound velocity is dependent on water temperature & density [2].

4.3 Geophysical Navigation

DR cannot be used for long mission & cost of INS & acoustic baseline system is high for multipurpose AUVs. Therefore researches have more focus on cost effective systems which can use AUVs surrounding data to position it without help of GPS and any other external system [9]. It is based on the physical features captured/observed by onboard sensors like sonar & optical sensors [5]. The difficulties faced by AUVs using geophysical navigations are to identify & process gathered features/data.

Different Geophysical Navigation Systems are:

4.3.1 Optical

Optical navigation system uses camera images to find the position of robot. The cameras used for this type of navigations are either monocular or stereo cameras [6].

A **monocular camera** passes light through a series of lenses or primes to magnify the images of distant objects. Stereo cameras have full six degree-of-freedom transformations between consecutive image pairs [6]. The optical navigation is dependent on the available features, so it can be used for small maps.

4.3.2 Sonar

Sonar system uses sound propagation to navigate underwater. Sonar emits sound energy and analyses the echo from underwater object or sea floor. The Sonar is categorized as passive & active sonar. Passive sonar relies on sound made by vessels while active sonar emits pulses of noise & then listen for echoes. Sonar is designed to work at specific frequency depending on the required range & resolution [6]. This section contains a brief description of (a) imaging sonar and (b) ranging sonar [6] (Tables 2 and 3).

Table 2. Sonar imaging devices used for underwater navigation

Sonar	Description
Side-scan Sonar	Sonar towed in surface vessel emits sounds energy in conical or fan-shaped pulses towards sea bed continuously & analyses the return echo to create a picture of sea floor or underwater object. The sound frequencies used in side-scan sonar usually range from 100 to 500 kHz; higher frequencies yield better resolution but less range. The side scan sonar can be used with single beam & multi-beam sonar system for better results [6]
Forward look sonar	The working is similar to side scan sonar only beams are in forward direction of vessel [6]
Synthetic aperture sonar	It uses multiple pulses to create a large synthetic array (or aperture). It has more resolution than advanced side scan sonar i.e. hundreds of meters. It combines multiple echoes to form an image
Mechanical scanned imaging sonar	It scans 2D horizontal plane by rotating a mechanically actuated transducer head at pre-set angle [13]

Table 3. Sonar imaging devices used for underwater navigation

Sonar	Description
Echo sounder	It measures depth by emitting sound pulses into water. The calculation depends on difference between time of emission, echo arrival and speed of sound
Profiler	It gives cross sectional profile of seabed or object. Profilers operate by rotating a transducer attached to a stepper motor through a number of angular ping positions within a defined scan width
Multi beam	Similar to other sonar it also uses sound pulses except it uses beamforming by which it can find the information of direction from returning echoes

5 Conclusion

Different underwater navigation techniques have been reviewed. The navigation techniques for autonomous underwater vehicles are inertial navigation system (INS), acoustic navigation & geophysical navigation system. Along with navigation techniques the different state estimation techniques such as Kalman Filter (KF), Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), Extended Information Filter (EIF), Particle Filter (PF) ect can be combined for better estimation & accurate results. To improve the efficiency of different techniques, localization techniques can be used such as SLAM.

SLAM (Simultaneous localization & mapping) is a robot mapping technique used by autonomous vehicle to construct & update map of unknown environment and it maintains the track of vehicle's current location.

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