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Self-localization of autonomous underwater vehicles with accurate sound travel time solution[☆]

Jing Li[a], Han Gao[a], Shujing Zhang[b], Shuai Chang[a], Jiaxing Chen[b], Zhihua Liu[c,*]

[a] College of Mathematics and Information Science, Hebei Normal University, Shijiazhuang 050024, Hebei, China
[b] College of Vocational Technology, Hebei Normal University, Shijiazhuang 050024, Hebei, China
[c] College of Information Technology, Hebei Normal University, Shijiazhuang 050024, Hebei, China

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ABSTRACT

In underwater acoustic sensor networks, long baseline localization for autonomous underwater vehicles (AUVs) requires distance estimation that always encounters severe problems: (a) Time-synchronization is hard to achieve in underwater environment, which baffles ranging methods based on the synchronized time. (b) Long propagation delay of acoustic signals and the impact of AUVs' mobility make it rash to use the round trip ranging (RTR) technology. (c) Sound speed uncertainty enlarges the inaccuracy of distance estimation. This work addresses those problems above and proposes an AUVs self-localization algorithm with accurate sound travel time solution (SL-STTS), which is time-synchronization free and ranging optimization based. Simulation results show that under the measurement noise of time and angles, the root mean square error of SL-STTS is decreased by about 8–79% compared with the counterparts. In addition the average distance estimation error of SL-STTS is declined by 42% compared with RTR.

1. Introduction

In underwater acoustic sensor networks (UASNs), autonomous underwater vehicles (AUVs) have been increasingly gaining concerns, as they make it accessible to those untouchable areas for human beings and assist with complex and arduous ocean tasks. AUVs are untethered and intelligent mobile platforms [1]. In many scenarios like target tracking [2], AUV-aid localization [3], and demining etc., AUVs need accurate localization for the accuracy of the gathered data [4]. And due to tough underwater conditions and technical restrictions, to localize a moving AUV is still challenging and needs more complementary researches.

Since the global position system (GPS) cannot work underwater because of bad attenuation of radio frequency (RF) signals, the inertial navigation system (INS) is mostly applied on AUVs. INS suffers from error accumulation. High-quality INS is however greatly expensive and can only provide relative locations. Overall, it is a better and available scheme to take advantage of acoustic communication for AUVs self-localization [5].

Acoustic localization system for AUVs includes long baseline (LBL), short baseline (SBL) and ultra-short baseline (USBL). Compared with SBL and USBL, LBL is more cost-effective [4]. In LBL, AUVs communicates with one or more transponders fixed on the seabed to measure range information and achieve self-localization. One-way ranging is mostly based on time of arrival (ToA) and time difference of arrival (TDoA). ToA needs strict time-synchronization, which is energy-intensive and hard to achieve. Multiple-node cooperation in TDoA [6,7] increases cost and is computationally complex. The round-trip ranging (RTR) technology [8] is

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[*] Corresponding author. Tel.:+86 13930194955, +86 15227865118.
E-mail addresses: sayqie@aliyun.com (J. Li), 13930194955@163.com (J. Chen), hebtuliuzhihua@163.com, liuzhihua@mail.hebtu.edu.cn (Z. Liu).

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frustrated by the long propagation delay and AUVs' mobility. In RTR, the two-way travel time (TWTT) between the AUV and a transponder is halved as the one-way travel time (OWTT), which is the propagation delay of acoustic signals traveling from the AUV to a transponder or the opposite case. Consequently the ranging error is increased since the AUV has sailed away from where it signals. But many approaches ignored this e.g. [6,7,9]. Moreover, the underwater sound speed is no constant but varies with salinity, temperature and depth [10], which adds uncertainty of location estimates.

To solve these problems stated above, we propose a self-localization algorithm with accurate sound travel time solution (SL-STTS) for AUVs in shallow water (depth $<$ 500 m). SL-STTS is time-synchronization free. The ranging accuracy relies on precise time measurement. It is accessible in microsecond resolution with seabed transponders [11] whose locations are known in advance with some technologies e.g. [12]. Orientation for the AUV and angle of arrival (AoA) for acoustic signals from transponders are analyzed to calculate the OWTT. As we know, the error of OWTT estimation in milliseconds may cause error of distance estimation in meters, which weakens localization accuracy. So it's indispensable to work out a high performance sound travel time solution. We model the function relating the distance estimates to the location vector of AUV. The Levenberg–Marquardt algorithm (LMA) [13] is utilized to optimize the distance estimates.

Our main contribution is as follows. First, the time-synchronization free scheme is presented which saves energy used for frequent two-way packet exchange in the time-synchronization ones. Second, the accurate sound travel time solution is proposed which improves ranging and localization accuracy. Third, we analyze the mathematical expectation of underwater sound speed, employ it for distance estimation and further analyze the rationality in theory. Fourth, we employ the LMA in solving the non-linear least squares optimization problem and localizing the AUV. SL-STTS can also be used in recalibrating the INS without resurfacing.

A reminder of this paper presents as follows: the related work are reviewed in Section 2. Section 3 gives an overview of the proposed algorithm and expatiates on how an AUV localizes itself. The performance of our algorithm is discussed in Section 4. Next a conclusion and the future efforts are summarized in Section 5.

2. Related work

Recent years, problems of AUVs localization have been studied extensively. In this section algorithms concerning AUVs localization presented in recent works are briefly reviewed.

In underwater area, acoustic signal is an ideal information carrier for it is less attenuated and can travel longer distances [14]. All underwater acoustic localization systems suffer most from sound speed uncertainty. In [10] the relation between OWTT and AUV location was modeled on the isogradient sound speed profile and Snell's law. Based on this model, the extend Kalman filter (EKF) was used to localize the AUV. Kussat et al. [11] conducted a series of sea trails in shallow water. They investigated the sources (salinity, temperature and depth) leading to sound speed uncertainty. Sound propagation ray trace was studied in [15] to model depth-dependent sound speed profile.

Based on unknown-but-bounded uncertainty and distance estimates, Caiti et al. [16] calculated out the region where the AUV resides. Then the sound propagation ray path was analyzed to obtain how the varying sound speed affected such region. Liu et al. [5] studied coordinated localization for multiple AUVs based on TDoA technology. In [15] a non-linear least squares estimator using the Newton's method was performed to give location estimates based on the ToA measurements. Meanwhile a gradient descent algorithm was adopted to improve the estimates. Karimi et al. [17] adopted a two-loop decentralized data fusion method. EKF worked in both loops to estimate locations of the AUV with its information of velocity, orientation and depth. A decentralized information filter did the final fusion of the estimates produced in both loops. Eustice et al. [18] proposed a max likelihood sensor fusion method based on the OWTT information, but it needs synchronous clock and surface ships as GPS to assist underwater localization, which is not economical.

Those algorithms listed above well disposes the localization uncertainties caused by measurement noise by means of denoising. The ranging optimization in this work is motivated by this point, for the main challenge that confronts LBL is the ranging uncertainty.

However, the above methods solve the OWTT through mathematically analyzing RTR, ToA or TDoA, which meets limitations stated in Section 1. Especially the RTR technology may trigger large ranging error. One major difference between this work and the above methods is that this problem has been considered and addressed well by the proposed sound travel time solution. And in the above approaches, the sound speed uncertainty is either processed with complicated computation or not given enough consideration. However, this work proposes a more simple way to estimate the sound speed.

3. Algorithm design

In this work we focus on AUVs self-localization in shallow water (depth $<$ 500 m). The orientation of an AUV includes yaw angle, pitch angle and roll angle [17]. In this work we only need the information of yaw angle and pitch angle. All the locations and angles are computed in the global Cartesian coordinates. The AUV is equipped with sensors measuring its forward velocity, z-axis gyro and inclinometer measuring its yaw angle and pitch angle [2,17], and AoA antennas measuring AoA of received acoustic signals. Conductivity–temperature–depth (CTD) instruments [11] are preloaded onto the AUV and transponders to help estimate sound speed by measuring salinity, temperature and depth. We first take an overview on SL-STTS and afterwards demonstrate how SL-STTS works in detail.