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A robust method for underwater wireless sensor joint localization and synchronization

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ABSTRACT

Nowadays underwater wireless sensor networks (UWSNs) have gained a lot of attention. Among the services of UWSNs, localization and time synchronization have special importance. Usually localization and synchronization can be solved jointly. This could save energy of sensors which is a vital requirement in UWSNs. In this paper, a new robust iterative method based on least squares (LS) is proposed for joint localization and synchronization in UWSNs. In this method the stratification effect of underwater environment is considered and compensated. Indeed, the assumption of the straight line transmission in water medium could lead to considerable bias in the range estimation. Furthermore, by compensating the stratification effect, the sound speed can be calculated from a linear relationship; and this is one of the contributions of this article. The linear relationship for calculating the propagation speed is common in terrestrial networks, whereas the proposed method generalized it for underwater medium. In addition, as another contribution, iterative method is used to improve the accuracy of localization and time synchronization. The iteration process will continue until the position, skew and offset errors reached to the convergence. The proposed method has been compared with other benchmark joint localization and synchronization methods as well as the Cramér Rao Lower Bound (CRLB). The results show that the proposed method outperforms the benchmark methods and exhibits performance close to the CRLB.

1. Introduction

Underwater wireless sensor networks (UWSNs) have recently attracted significant attention due to their potential benefits for marine monitoring. While other change detection systems such as satellite marine observation are also applicable (Arsanjani et al., 2015); UWSNs works have wide applications in data collection, water pollution monitoring, navigation and undersea exploration (Kavoosi et al., 2015). Moreover, in spite of SONAR systems (Javidan et al., 2008) which are so costly, UWSNs are cost effective. However, in UWSNs, the transmission medium is water which has many challenges including: limited bandwidth, variability of sound speed with depth, temperature and salinity, long propagation delay, sensor mobility and multipath (Kim and Yoo, 2014). These unique features of underwater acoustic communications put many challenges to almost every layer of network protocol stack (Mohammadi et al., 2014; Liu et al., 2012; Cui et al., 2006; Mohammadi and Javidan, 2014; Pu et al., 2012).

Localization and time synchronization are two important services in UWSNs, because most UWSNs applications require these two services together. For example, Time Division Multiple Access (TDMA) that is an important medium access control (MAC) protocol often requires accurate time synchronization between sensor nodes. Furthermore, most geographic routing algorithms and Autonomous Underwater Vehicle (AUV) navigation systems rely on the availability of location information (He et al., 2014; Liu et al., 2015). Although a variety of protocols have been proposed for node positioning or time synchronization for terrestrial sensor networks, these protocols can't be used in underwater environment due to the limitations medium. Hence, techniques are needed to develop the terrestrial localization techniques for underwater sensor networks.

Localization and time synchronization depend on each other and most localization algorithms rely on synchronization services. Localization algorithms usually use the distance measurements, time of arrival (TOA) and time difference of arrival (TDOA) that are synchronization services. On the other side, time synchronization algorithms rely on localization techniques; because for estimating the propagation delay, node locations should be known. Therefore, based on these dependencies and the advantage of energy saving, performing joint localization and time synchronization has been became an interested problem.

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Many algorithms have developed for localizing underwater sensor networks (Misra et al., 2015; Carroll et al., 2014; Ramezani and Leus, 2012; Berger et al., 2008; Frampton, 2006). In general, localization algorithms are divided into two categories: range based and range free algorithms. Here, the focus is on range based algorithms that they are either: communication based or connectivity based. Cheng et al. (2008) proposed UPS (underwater positioning scheme); a TOA based silent underwater positioning scheme for underwater acoustic sensor networks. UPS consists of two steps: The first step is to derive TDOA from four anchor nodes. These time differences then are transformed into range measurements; which describe the distance from the underwater sensor to the anchor nodes. In the second step, the location of unknown node is estimated by the trilateration. UPS doesn't need any time synchronization and uses silent positioning for self-positioning of sensors. Thus, the energy can be saved. Computation overhead of this scheme is low because it is based on simple operations. In this method, for positioning a node, it is necessary to calculate the distance with four reference anchor nodes; while in our proposed method in this paper we need to know just three distances. This scheme is a localization algorithm; while our method used localization and synchronization together which can improve the accuracy of both of them.

In spite of communication based methods mentioned above, there is no communication between anchor and ordinary nodes in connectivity based methods. Zhou et al. (2011) introduced a scheme called Scalable Localization with Mobility Prediction (SLMP) for UWSNs. In SLMP, anchor nodes communicate with the surface buoys and perform self-localization by using existing GPS approaches. While, ordinary nodes predict their locations by utilizing the spatial correlation of underwater object mobility pattern. This scheme considers node mobility and works for large scale networks, but because the use of prediction based on temporal and spatial correlations, it works only in dense networks; while our method can work in large scale network which has been planned for our future work.

Compared to terrestrial networks, the research on time synchronization for UWSNs is relatively limited. Liu et al. Liu et al. (2013) presented a time synchronization scheme for mobile UWSNs called Mobi-Sync. They considered spatial correlation among the mobility patterns of neighboring UWSNs nodes. This feature makes Mobi-Sync to accurately estimate the long and dynamic propagation delays. Although sensor mobility and clock skew are considered in Mobi-Sync. It works better for dense networks as it is based on spatial correlation. Furthermore, this scheme assumes that the sound speed is constant; despite of our work which used variable sound speed. DA-Sync (Liu et al., 2014) is a pair-wise, cross-layer time synchronization scheme for mobile UWSNs. It uses a framework to estimate the Doppler shift through accounting the impact of the clock skew. Also, to improve the accuracy of propagation delay estimation in time synchronization, the Kalman filter is employed. DA-Sync solves the long propagation delay problem and considers clock skew and sensor node mobility. The disadvantage of DA-Sync compared to our method is assuming the constant sound speed; while it is variable with depth, temperature and salinity.

Chen et al. (2007) proposed the first localization and synchronization scheme for three-dimensional (3D) underwater acoustic networks. The anchor nodes are placed on the surface of the water and know their locations and time synchronization information. These nodes send time and location information to other sensors. If sensor nodes receive the synchronization messages from at least five anchor nodes, they can calculate their locations and time information. For estimating the location and time of sensor nodes, atomic multilateration and iterative multilateration techniques are used. The drawback of this scheme compared with our proposed method is that it ignores the clock skewness and the mobility of unknown node. Furthermore, despite our method, it assumes that the sound speed is constant.

Diamant and Lampe (Diamant and Lampe, 2013) proposed a sequential algorithm, STSL (Sequential Time Synchronization and Localization); for joint time synchronization and localization of underwater networks. STSL is a two-step approach: In first step, nodes are synchronized and then the location of nodes is estimated in second step. STSL uses directional navigation systems employed in nodes to obtain accurate short term motion estimates. This scheme allows self-evaluation of the localization accuracy and considers sensor node mobility and anchor node mobility. Furthermore, STSL assumes that anchor nodes are not time synchronized. The drawback of the STSL method compared with our method is that the stratification effect of sound is not considered.

Another method called JSL (Joint time Synchronization and Localization) (Liu et al., 2015) is a joint time synchronization and localization method for UWSNs. JSL consists of four phases: data collection, synchronization, localization and iteration. In JSL, time synchronization and localization are performed at different phases and iteration phase is continued until there is no message to be exchanged. During iterations, the output of synchronization is used as the input of localization, and the output of localization is used as the input of synchronization. In this scheme, sensor node mobility is also considered. Furthermore, JSL assumes that anchor nodes are synchronized and the other nodes are not. Additionally, an advanced tracking algorithm called Interactive Multiple Model (IMM) is used to predict sensor node mobility and thus the accuracy of localization is improved. JSL considers variable sound speed and compensates stratification effect of underwater medium. In comparison with our method, we also compensate the stratification effect using range estimation scheme. But JSL is based on reconstructing the slanted path using Fermat's principle. In that work, a constant which is defined by snell's law numerically is calculated. After that, by knowing this constant, the propagation delay which compensated the stratification effect can be estimated through integral equality. However, as explained in Liu et al. (2015), the algorithm may compute this constant with an ambiguity which is the main disadvantage of the work of JSL compared with our method for compensating the stratification effect.

In this paper, a new robust iterative joint localization and synchronization approach with considering the stratification effect for UWSNs is proposed which called RJLS (robust joint localization and synchronization). RJLS consists of five phases. Unlike many other proposed schemes that assume straight line transmission in water medium, this work compensates the stratification effect which can improve the propagation delay estimation. Furthermore, by compensating the stratification effect, the sound speed can be calculated from a linear relationship. The linear relationship for calculating the propagation speed for underwater medium is one of innovations in this paper. In addition, as another contribution, iterative method is used to improve the accuracy of localization and time synchronization. Finally, the performance of the RJLS scheme is analyzed and compared with other well-known methods to show the superiority of the proposed method. Cramér Rao lower bound (CRLB) is also formulated and Root Mean Square Error (RMSE) expression is derived for the proposed method to show the effectiveness of the method.

The rest of this paper is organized as follows: The proposed method, RJLS, is described in Section 2. In Section 3 the CRLB method is explained. In Section 4 simulation results are presented and discussed. Finally, conclusions are outlined in Section 5.

2. The proposed method (RJLS)

Since the water environment is inhomogeneous in terms of depth, temperature and salinity, the straight line propagation could not be assumed in UWSNs. To eliminate the bias caused by straight line propagation, in this work, a range estimation scheme is applied which compensates the stratification effect.

The procedure of the RJLS method consists of five phases: Message Exchange and Initial Position Estimation with TDOA, Estimating the Position, Clock Skew and Offset, Stratification Compensation,