

# Designing an Embedded Communication System for Underwater Asynchronous Localization

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**Abstract**— The majority of underwater acoustic sensor network (UASN) applications depend on accurate position data. We offer an embedded communication system for underwater asynchronous localization in this letter. Asynchronous localization protocol is created and encoded for the real embedded communication system implementation. Specifically, the embedded communication system consists of four acoustic modems, one control center, and four transducers. The direct-sequence spread-spectrum (DSSS) technology is used in modem design to lessen the impact of multipath interference. In the meantime, the position is estimated using the iterative least squares method. Lastly, experimental findings are presented to confirm the efficiency of the suggested system. It has been shown that asynchronous clock impacts are well-eliminable.

## I. INTRODUCTION

**D**URING the past decades, underwater acoustic sensor networks (UASNs) have attracted significant attention (see [1] and references therein). Most applications of UASNs demand accurate locations of sensor nodes. This critical importance arises from its fundamental role in the discovery of vast unexplored ocean volume, because monitoring command is valid only when the localization information is accurate.

Nevertheless, the weak characteristic of acoustic communication makes underwater localization more challenging as compared with terrestrial sensor networks. For instance, radio waves are strongly absorbed in water, and the global positioning system (GPS) technology is not available for UASNs. As a result, the clocks in water are always asynchronous [2]. Meanwhile, the man-made (e.g., pumps and reduction gears) and ambient (e.g., tides and current) noises cannot be ignored in underwater environment [3], which increase the uncertainty of localization. In order to solve these issues, some asynchronous localization algorithms have been proposed. For

instance, an on-demand asynchronous localization approach was developed in [4], where the exhaustive search strategy was implemented to estimate the positions. However, the duration time of exhaustive search is long because a large amount of computation is required. Meanwhile, the accuracy of exhaustive search is highly related with the amount of computation. In order to reduce the duration time and improve the localization accuracy, a joint solution to localization and synchronization was presented in [5], wherein the iterative least squares method was given to find the optimal position. Gong *et al.* [6] attempted to use an autonomous underwater vehicle to aid the localization process. In [7], a unified framework was developed for sensor nodes. In our previous work [8], [9], a mobility prediction-based asynchronous localization algorithm was presented. It is noted that, the iterative least squares-based algorithms in [5]–[9] are verified by simulation results. Per our understanding, how to present an embedded communication system that encodes the localization algorithm to verify the theoretical results is largely unexplored.

On the aspect of experimental verification, some embedded communication systems have been presented. In [10], a range-based underwater localization system was provided. Also of relevance, a low-cost underwater acoustic modem which includes transducer, analog transceiver, and digital signal processor was designed in [11]. Meanwhile, an adaptive acoustic modem was presented in [12], whose aim is to provide reliable and energy efficient communication in UASNs. Nevertheless, the experiments in [10]–[12] rely on the assumption of synchronous clock, and they cannot be directly applied to verify the asynchronous localization algorithm.

This letter develops an embedded communication system for the underwater asynchronous localization. With consideration of asynchronous clock and strong-noise characteristics, we first present an asynchronous localization protocol for sensor node. Then, an embedded communication system which includes transducers, control center, and acoustic modems is designed. Main contributions lie in two aspects.

- 1) We employ an asynchronous localization protocol to achieve the information interaction process. Compared with the exhaustive search method [4], the localization approach in this letter can improve the localization accuracy and reduce the localization time.
- 2) An embedded communication system is designed and implemented, while the direct-sequence spread-spectrum (DSSS) technology is applied to reduce the influence of noises. Instead of clock synchronization in [10]–[12], asynchronous clock is considered in this letter.

## II. DESIGN OF THE LOCALIZATION PROTOCOL

A network architecture that comprises of two types of nodes is considered. Particularly, *surface buoys* act as

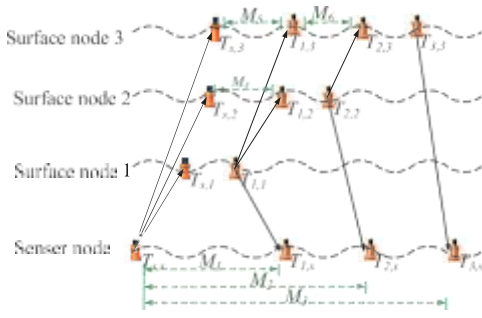


Fig. 1. Asynchronous localization process.

“satellites,” whose clocks are well synchronized and the locations are accurately preknown. *Sensor nodes* can make direct contact with surface buoys, and their locations are required to be calculated. The clocks between sensor and surface buoys are asynchronous. Without loss of generality, only one sensor node is considered here. The position of sensor node is denoted by  $(x_o; y_o; z_o)$ , and the position of surface buoy  $n$  is denoted by  $(x_n; y_n; z_n)$  for  $\forall n \in \{1, 2, 3\}$ . The depth (i.e.,  $z_o$ ) can be acquired through depth units, thus three buoys are required.

Particularly, the sensor node has a hardware clock, which is calculated by counting pulses of its hardware oscillator running at a particular frequency. Similar to [4], we ignore the clock skew and only deal with the clock offset. Based on this, the following asynchronization clock model is considered, i.e.,  $T = t + \beta$ , where  $T$  is the measured time (i.e., the hardware clock) of the sensor node.  $t$  denotes the real time, and  $\beta \neq 0$  is the clock offset. Accordingly, the following localization process is presented (see Fig. 1).

- 1) At time  $T_{s,s}$ , sensor node sends out an initiator message to surface buoys. The initiator message includes the sending orders for the surface buoys, indexed by 1, 2, 3. Subsequently, sensor node goes into the listening mode, waiting for the replies from surface buoys.
- 2) At time  $T_{s,n}$ , surface buoy  $n$  receives the initiator message from sensor node. Upon receiving the initiator message, surface buoy 1 sends out its localization message at time  $T_{1,1}$ , while surface buoys 2 and 3 switch into the waiting mode. For surface buoy 2, the arrival time from surface buoy 1 is denoted by  $T_{1,2}$ , while the arrival times for surface buoys 3 are  $T_{1,3}$  and  $T_{2,3}$ . Subsequently, surface buoys 2 and 3 send their localization messages to sensor node at times  $T_{2,2}$  and  $T_{3,3}$ , respectively.
- 3) At time  $T_{3,s}$ , sensor node receives the reply from surface buoy 3. The timestamp measurements are  $M_1 = T_{1,s} - T_{s,s}$ ,  $M_2 = T_{2,s} - T_{s,s}$ ,  $M_3 = T_{3,s} - T_{s,s}$ ,  $M_4 = T_{1,2} - T_{s,2}$ ,  $M_5 = T_{1,3} - T_{s,3}$ , and  $M_6 = T_{2,3} - T_{1,3}$ .
- 4) With collected measurements, an iterative least squares method is given to estimate position  $\eta = (x_o; y_o; z_o)$ .

### III. DESIGN OF EMBEDDED COMMUNICATION SYSTEM

This section provides the design of embedded communication system. We first design a buoy localization module that can provide accurate location reference for sensor node. Next, the modem is presented to provide ubiquitous communication capability for three types of wireless links, i.e., sensor-to-buoy,

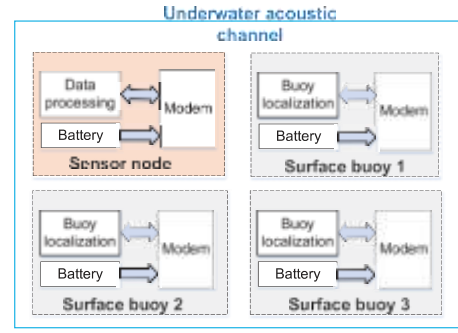


Fig. 2. Major components of the embedded communications system.

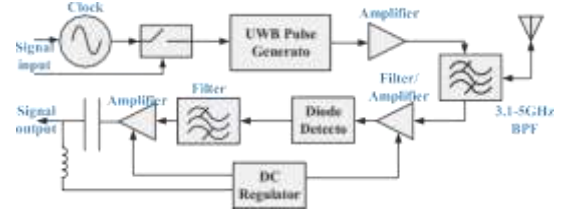


Fig. 3. Schematic of transmitter and receiver with UWB technology.

buoy-to-sensor, and buoy-to-buoy. Finally, the data processing module is given to run the iterative least squares method, through which the localization protocol is encoded. Major components of this system are shown in Fig. 2.

#### A. Buoy Localization Module

Ultrawideband (UWB) technology is applied by buoys to acquire their positions. The UWB technology uses the narrow-pulse signal of nanosecond to transmit data, which can provide the UWB signal with high time resolution and low power consumption. Particularly, the Federal Communications Commission (FCC) defines UWB as any signal that occupies more than 500-MHz bandwidth in the 3.1–10.6 GHz band and that meets the spectrum mask [13]. It is assumed that four Readers are connected to each buoy, where the Readers play the role of base stations. Besides, a localization tag is mounted on each buoy. After receiving the localization request, the localization tag transmits a stream of UWB pulses to the Readers. Subsequently, these pulses are received by the Readers and down-converted into baseband pulses. Particularly, the UWB pulse generator is triggered by the clock, and then the pulse is amplified by a 3.1–5 GHz band-pass filter. The schematic of transmitter and receiver is shown in Fig. 3.

Let  $(x_{R,j}; y_{R,j}; z_{R,j})$  be the position of Reader  $j$ , for  $\forall j \in \{1, 2, 3, 4\}$ . At time  $\hat{t}_{n,j}$ , buoy  $n$  sends out a message to Reader  $j$ , and the time of receiving the reply from Reader  $j$  is denoted by  $\check{t}_{j,n}$ . Based on this, the relative distance between Reader  $j$  and surface buoy  $n$  can be represented by  $\check{d}_{n,j} = (1/2) \rightarrow c(\check{t}_{j,n} - \hat{t}_{n,j})$ , where  $\rightarrow c = 3 \times 10^8$  m/s denotes the speed of light. Thereby, the position of buoy  $n$  is obtained by solving the following equation, i.e., for  $i = 1, 2, 3, 4$ :

$$(x_n - x_{R,i})^2 + (y_n - y_{R,i})^2 + (z_n - z_{R,i})^2 = \check{d}_{n,i}^2 \quad (1)$$

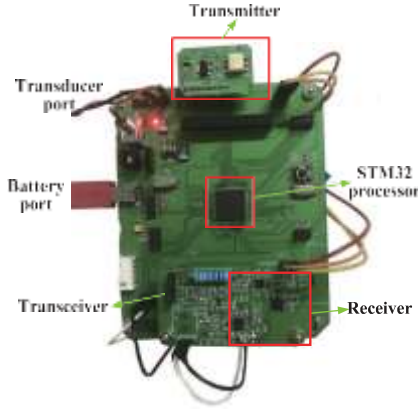


Fig.4.Illustrationoftheacousticmodemmodule.

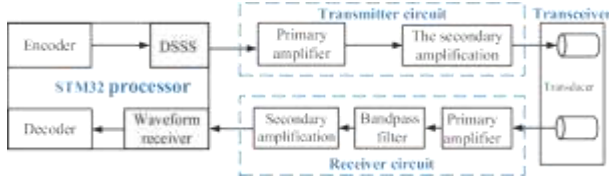


Fig.5.Blockdiagramoftheacousticmodemmodule.

### B. Acoustic Modem Module

A modem is required to ensure reliable acoustic communication. As shown in Fig. 4, the acoustic modem consists of three main components: 1) STM32 processor; 2) transmitter; and 3) receiver. The block diagram of an acoustic modem is depicted in Fig. 5. Different from the previous work [14], the modem in this letter is implemented on a small and low-cost platform named STM32. Particularly, the STM32 processor is based on Cortex-M3 ARM kernel [15], which is widely used in the application of embedded system due to its high-performance, low cost, and low power consumption. The source data is amplified through transmitter, and then it is sent out in the form of acoustic signal through transducer. For the receiver, the acoustic signal is converted and processed into electrical signal. Besides, the frequency and bandwidth for the four transducers are 35-KHz and 4-KHz, respectively. Of note, the material of transducers in our design is piezoelectric ceramics.

1) *STM32 Processor*: The structure of a data frame can be divided into three parts, i.e., the preamble, the space time, and the data payload. Especially, the preamble is a short sequence, which is used for detection. The role of space time is to ensure that the preamble does not affect the data payload due to multipath channels. In order to transmit and receive the data, the DSSS technology is employed for the STM32 processor. Inspired by this, we denote  $A$  as the amplitude of carrier wave,  $\omega_c$  as the angular frequency,  $g(t)$  as the spreading sequence, and  $\phi_c$  as the phase of the carrier signal. With DSSS technology, the information sequence  $a(t)$  is modulated as

$$S(t) = A a_n(t) g(t - nT) \sin(\omega_c t + \phi_c). \quad (2)$$

2) *Transmitter*: The source data is encoded by linear hamming code. Moreover, the cyclic redundancy check (CRC) is utilized to ensure the correctness of the data. Subsequently, the

### Algorithm 1 Iterative Least Squares Method

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**Input:** Time stamp measurements from buoys  
**while**  $k < k_{max}$  **do**  
  1. Calculate Jacobian matrix  $J$ , and acquire increment  $\zeta$   
  2. Update the position estimation, i.e.,  $\tilde{\eta}_{k+1} = \tilde{\eta}_k + \zeta$   
  **if**  $\|\tilde{\eta}_{k+1} - \tilde{\eta}_k\|$  is less than a small value **then**  
    break  
  **end if**  
**end while**  
**Output:** The position estimation  $\tilde{\eta}$  for sensor node.

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encoded data is modulated in the STM32 by the DSSS technology. It should be emphasized that, the upsampling and digital to analog converter (DAC) are essential to make the transmitted signal fit in the effective bandwidth. Next, a two-stage amplifying circuit, including current amplifying and voltage amplifying are redesigned to transmit signal through transducer.

The detailed parameters can be given as follows: the amplification factor of current amplification is 50–75 $\times$ , the current amplification is 1.5 A, the amplification factor of the voltage amplifier is 1.5 $\times$ , and the amplified voltage is 5 V. Based on this, the passband signal can be transmitted to the underwater sound channel at the power of about 7.5 W.

3) *Receiver*: The receiver amplifies and filters the signal from transmitter. Next, the received signal is demodulated in the STM32, whose process is contrast with the one in transmitter. Under cross-correlation, the preamble is used as the starting point. Then, the preamble is found out by maximizing the correlation value. As a result, the detection algorithm [16] is utilized to decode the received data from transmitter. The detailed parameters are given as follows: the preamplification factor is 100–130 $\times$ , the central frequency of the bandpass filter is 35 KHz, and the bandwidth is 18 KHz.

### C. Data Processing Module

In our design, the position of sensor node is calculated in data processing module. Particularly, the sensor node sends its measurement back to control center, with the assistance of surface buoys. For the nonlinear measurement, an iterative least squares estimator, which is a standard approach in regression analysis to approximate the solution of over determined systems [17],[18], is employed in our system. Based on this, we denote  $\tilde{\eta}$  as the estimation of  $\eta$ , and the increment  $\zeta$  in the  $(i + 1)$  iteration is updated as  $\zeta = -[J^T J]^{-1} J^T D$ . Of note, the first-order linearization is applied to compute the Jacobian matrix  $J$ , through which linear measurements can be obtained. Meanwhile,  $D$  denotes the measurement error. The overall operations of the iterative least squares method are outlined in Algorithm 1, where  $k_{max}$  denotes the total time step. Due to page limitation, please see [8],[18] for the detailed results of iterative least squares estimator.

## IV. EXPERIMENTAL RESULTS

Experimental results are given to verify the effectiveness (see Fig. 6), and the embedded communication system is shown by Fig. 7. It is noted that, ten static points are required to be localized, i.e., sensor node is sequentially located at ten different positions. Besides, the total time step  $k_{max}$  and the threshold  $\epsilon$  are set as 20 and 0.01 s, respectively.

The top of Fig. 6(a) depicts the received signals in time by the DSSS modulation. These analog signals are converted

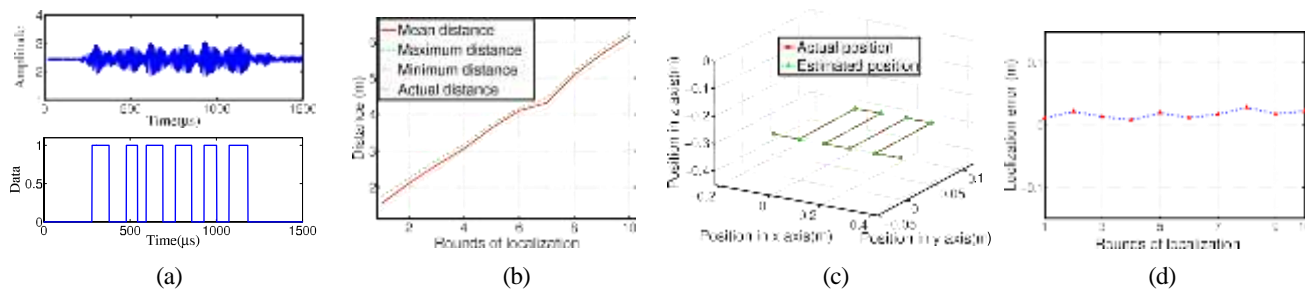


Fig. 6. Simulation results for the embedded communications system. (a) Received signals with the modem. (b) Distance measurements. (c) Actual and estimated positions. (d) Localization error.

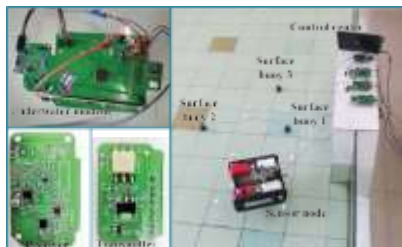


Fig. 7. Experimental setup of the embedded communications system.

to digital signals by ADC circuitry, as shown in the bottom of Fig. 6(a). Clearly, the transmitted preamble and the guard interval can be well identified, which indirectly verifies the effectiveness of the designed acoustic modem in this letter.

The experimental data for distance measurements are shown in Fig. 6(b). It is clear that, the measured distance can capture the actual value. Accordingly, the actual and estimated positions of the ten different points are shown in Fig. 6(c).

To show more clearly, we define the localization errors as  $d_{\text{error}} = (\tilde{x}_o - x_o)^2 + (\tilde{y}_o - y_o)^2 + (\tilde{z}_o - z_o)^2$ , where  $\tilde{x}_o, \tilde{y}_o, \tilde{z}_o$  and  $x_o, y_o, z_o$  are the estimations of  $x_o, y_o$ , and  $z_o$ , respectively. Based on this, the localization error is shown in Fig. 6(d). From Fig. 6(c) and (d), it is known that the localization task can be achieved, because the localization errors converge uniformly to zero. These results reflect that the embedded communication system in this letter is meaningful and necessary.

## V. CONCLUSION

We present the underwater asynchronous localization design, implementation, and experiment of an embedded communication system. An asynchronous localization protocol is given, taking strong-noise characteristics and asynchronous clock into account. Specifically, the position is estimated using the iterative least squares method. Lastly, tests are conducted to assess the suggested system.

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