Real-Time Underwater Localization System Based on Position-Keeping USVs for Multiple AUVs

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Abstract: *With the advancement of Autonomous Underwater Vehicles (AUVs), the demand for evaluating autonomy and navigation performance has increased significantly. However, real-time localization in underwater environments remains a major challenge due to the infeasibility of GPS and conventional wireless communication. In many countries, localization is typically performed using fixed seabed infrastructure or drifting buoys. However, in Korean coastal waters, securing dedicated test ranges is difficult due to dense maritime traffic and intensive fishing activity, limiting the feasibility of such infrastructure-based approaches. To overcome these limitations, we propose a rapidly deployable localization system utilizing Unmanned Surface Vehicles (USVs) equipped with position-keeping capabilities. The system consists of acoustic transmitters mounted on AUVs, acoustic receivers onboard USVs, and an operation control unit located on a mothership. It enables simultaneous tracking of multiple AUVs using up to nine USVs and six auxiliary drifting buoys, depending on the operational scenario. Acoustic signals transmitted by each AUV are detected by USV-mounted hydrophones at ranges up to 5 km. The received signals and operational data are transmitted to the mothership for integrated control and monitoring. Real-time positioning is performed using Time of Arrival (ToA) and Time Difference of Arrival (TDoA) techniques. Field experiments conducted at a depth of 1,000 m demonstrated an average localization accuracy of approximately 15 m at*

distances of 1, 3, and 5 km, confirming the system's effectiveness and operational reliability in dynamic marine environments.

INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have increasingly emerged as critical tools in various marine applications, including ocean exploration, environmental monitoring, and underwater defense operations [1], [2]. Accurate real-time localization of AUVs is fundamental to successful mission execution, particularly given the complexities of underwater environments. Due to the impracticality of Global Positioning Systems (GPS) underwater, acoustic-based localization methods are predominantly employed [3], [4].

Conventional acoustic localization systems commonly utilize fixed seabed infrastructure or drifting buoys equipped with acoustic sensors [5], [6]. Although effective, these approaches encounter significant challenges in regions characterized by intense maritime traffic or extensive fishing activities, such as Korean waters. Establishing permanent or semi-permanent localization infrastructure in such dynamic marine areas is often infeasible due to operational constraints, environmental regulations, and the high risk of damage or loss.

Addressing these challenges, recent research efforts have explored alternative, flexible approaches that utilize mobile platforms for underwater localization. Particularly, Unmanned Surface Vehicles (USVs) equipped with precise station-keeping capabilities have demonstrated potential in providing dynamically adaptable localization solutions [10].

In this paper, we propose a novel real-time underwater localization system leveraging multiple position-keeping USVs, designed explicitly for dynamic and complex marine environments. The proposed system integrates acoustic transmitters mounted on AUVs, USV-based acoustic receivers, and a centralized operation control unit located on board a mothership. This configuration allows simultaneous real-time tracking of multiple submerged vehicles utilizing acoustic-based Time Difference of Arrival (TDoA) and Time of Arrival (ToA) localization techniques combined with advanced tracking algorithms for enhanced accuracy [2], [7].

To validate the effectiveness of our proposed system, we conducted extensive simulations and field trials at depths of approximately 1,000 m. The experimental results demonstrate reliable tracking capabilities, achieving positional accuracy within 15 m for targets at distances up to 5 km. These outcomes validate the proposed USV-based localization framework as a viable and robust alternative, capable of addressing the limitations posed by traditional methods in highly dynamic marine operational environments.

UNDERWATER LOCALIZATION SYSTEM DESIGN

This section provides an overview of the system architecture and outlines key design considerations. Specific implementation details have been omitted or anonymized due to

technical confidentiality and security restrictions. The proposed real-time underwater tracking system consists of four main components: an acoustic transmitter, an acoustic receiver, an operation control unit, and a ground control station. A conceptual diagram of the system operation is illustrated in Fig. 1.

Fig. 1:Real-Time underwater localization system concept diagram

2.1 Acoustic Transmitter

The acoustic transmitter is mounted on the AUV and emits signals detectable by the acoustic receivers. All system components are synchronized to a common GPS time reference to ensure temporal alignment. Transmitted signals are detected by receivers onboard USVs using matched filtering techniques, and the demodulated results are forwarded to the operation control unit on the mothership. The control unit integrates information from multiple receivers to estimate the position of the AUV and transmits the estimated location to the ground station via satellite communication.

The acoustic transmitter is installed on the AUV and is responsible for emitting signals that can be tracked by the receivers. The transmitted signal consists of three components: a tracking signal, an identification (ID) signal, and a depth information signal, as shown in Fig. 2.
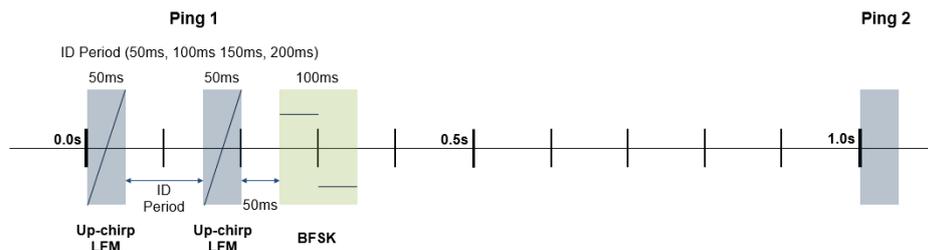

Fig. 2:Transmitted signal concept

The tracking signal is implemented as a linear frequency modulated (LFM) waveform of OOO ms duration, optimized for tracking fast-moving AUVs. Although Doppler effects may cause detection errors, the waveform is tailored to meet the requirements of high-speed underwater platforms. Before AUV deployment, GPS modules are used to synchronize the signal with GPS Pulse Per Second (PPS) timing, enabling Time of Arrival (ToA)-based ranging upon signal reception at the USVs.

The ID signal is introduced to resolve ambiguities arising from the geometry and spacing of the receivers, which may cause time-delay overlaps during detection. In practical scenarios, identifying which combination of detected signals should be used for position

estimation becomes computationally expensive, especially when signals are intermittently detected. To address this, four ID-coded versions of the tracking signal are generated by applying predefined delays to the same waveform. This approach enables unambiguous signal identification at distances of up to 6 km, while also reducing the computational burden of signal matching.

Finally, to compensate for the degraded accuracy in depth (Z-axis) estimation due to the planar geometry of the receiver array, an additional depth signal is incorporated. This signal is implemented as a binary frequency shift keying (BFSK) waveform occupying two sub-bands within the tracking signal spectrum. The total duration of the signal is 000 ms, divided into N bits for BFSK encoding.

2.2 Acoustic Receiver

The acoustic receivers are mounted on twin-hull unmanned surface vehicles (USVs), as illustrated in Fig. 3. This configuration facilitates the integration of a winch system, which is advantageous for deploying and retrieving sensors. Additionally, the physical separation between the signal processing and communication modules and the propulsion unit minimizes the impact of potential water ingress caused by hull damage and provides additional buoyancy.
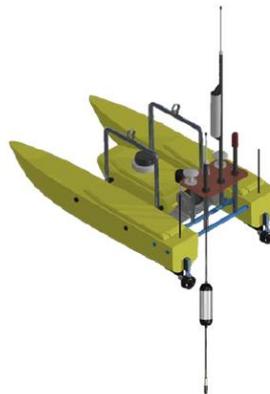

Fig. 3: Position keeping unmanned surface vehicle with acoustic receiver

Each USV is equipped with a navigation controller, which receives commands from the operation control unit and executes them accordingly. The USV travels to the designated position at a limited speed and maintains its location upon arrival. Since the thruster operates intermittently during station-keeping, the detection of acoustic signals is not significantly affected.

A 16-bit analog-to-digital converter (ADC) is used for data acquisition, and a B&K 8106 hydrophone is installed to ensure high-sensitivity acoustic reception. To reduce the influence of ambient noise and enable signal detection over a wide area, analog filters targeting specific frequency bands are applied. The overall signal processing flow is shown in Fig. 4.
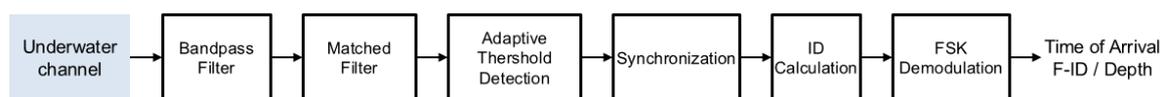

Fig. 4: Signal processing flow chart

For each received signal, a band-pass filter is applied based on the frequency band assigned to each target, followed by detection using a matched filter. When applied to LFM signals, the matched filter yields a signal-to-noise ratio (SNR) gain and enhances

detection performance even under Doppler conditions. The ID and depth information are then demodulated from the detected signals and transmitted to the operation control unit on the mothership.

2.3 Operation Control

The operation control unit is installed on the mothership and communicates with all station-keeping USVs to receive their data. It has the capability to simultaneously control all USVs, including navigation, signal processing, and mechanical actuation.

When an acoustic signal is detected by a USV, the corresponding detection result is transmitted to the operation control unit. The unit integrates the received information from multiple USVs and performs real-time localization of the AUV. The localization algorithm primarily relies on the Time of Arrival (ToA) method and applies correction using dynamic filters such as the Kalman filter.

3. RESULTS AND CONCLUSION

To validate the system's multi-target tracking functionality, analog signals generated by a signal generator were injected into the receiver under near-realistic conditions. This pre-test, performed in the absence of multiple AUVs due to infrastructure limitations, confirmed that signals transmitted over three distinct frequency bands could be independently detected and tracked without interference shown in Fig. 5-(a)

Subsequent sea trials were conducted in deep-sea conditions in the East Sea of Korea, at depths exceeding 1,000 meters. Three USVs were deployed in a triangular formation, and the system was evaluated at target distances of 1 km, 3 km, and 5 km. Fig. 5-(b) shows that even without applying tracking filters, the system achieved an average localization error of approximately 4 m when the target was centered within the USV array. As the distance increased, the average error grew to 11 m at 3 km and 30 m at 5 km, demonstrating effective long-range tracking performance.
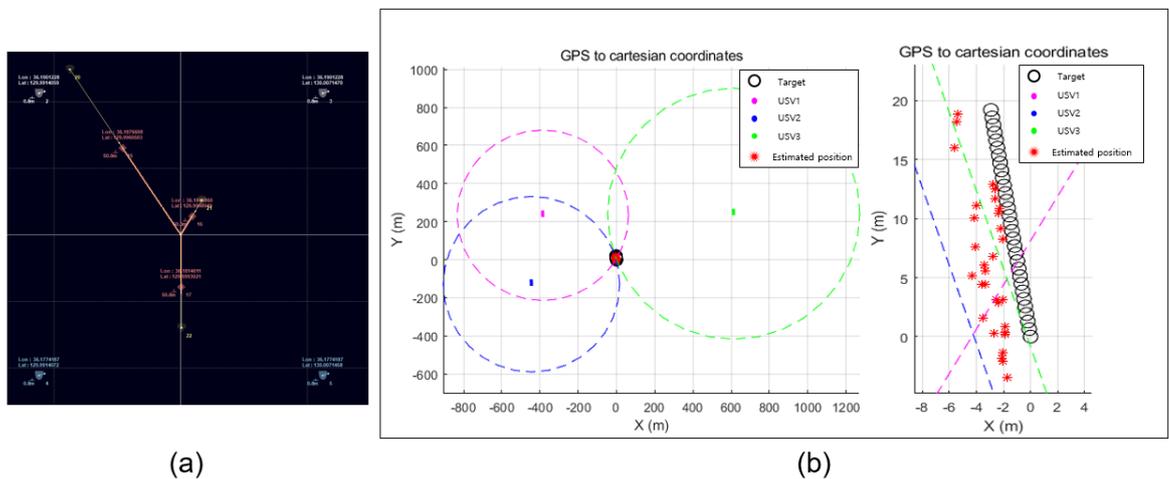

(a)   (b)

Fig. 5:Localization results a) multi-target simultaneous tracking result using a signal generator b)sea trial result of the target positioned at the center of the USV array

The signal of the ID and BFSK depth signal decoding results, evaluated at 3 km and 5 km, are shown in Fig. 6. ID decoding achieved perfect accuracy in both scenarios, verifying the reliability of the coded ID system under real oceanic conditions. In contrast, BFSK depth decoding exhibited occasional bit errors at the final position, resulting in

depth estimation errors of up to 1 m. This degradation is attributed to synchronization jitter caused by doppler-induced distortions in the reference tracking signal.
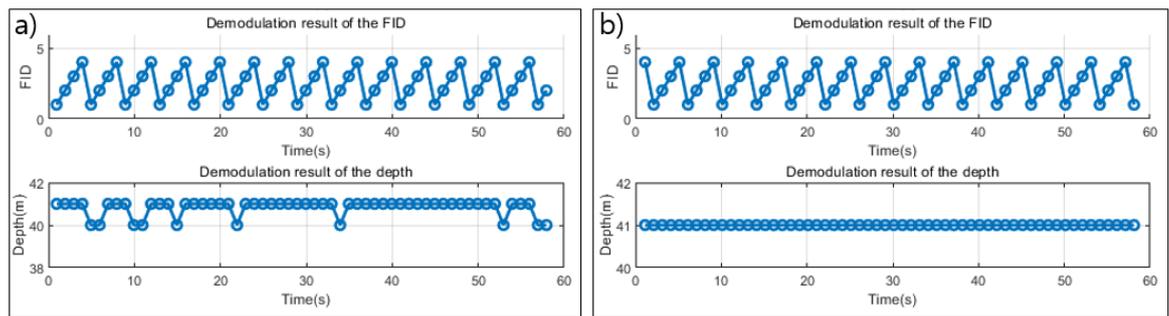

Fig. 6: Signal ID and BFSK demodulation results a) at 3km, b) 5km

Overall, the results confirm that the proposed system enables robust and simultaneous tracking of multiple AUVs, and that its ID and BFSK decoding modules are viable for practical deployment in long-range marine operations. Future work will focus on Doppler-resilient signal design and adaptive filtering to further improve performance under high-speed doppler conditions.

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