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Frequency of arrival-based state estimation and trajectory optimization for the navigation of autonomous marine vehicles

Key words: Frequency of arrival; Rolling horizon estimation; Trajectory optimization; Unmanned surface vehicles; Autonomous underwater vehicles; Navigation

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Motivation

1. Robust navigation for AUVs: Accurate navigation is essential for AUVs in deep-sea exploration, which is challenging with traditional methods.

2. Limitations of existing systems: GPS and acoustic systems have limitations, especially with single-sensor setups.

3. Advantage of FOA: FOA-based methods enable simultaneous position and velocity estimation without time synchronization between the AUV and the USV.

4. Trajectory optimization: Optimizing the USV trajectory enhances AUV observability and state estimation accuracy.

Main idea

1. FOA-based estimation: A single surface sensor estimates the AUV position and velocity using FOA of acoustic signals.

2. Dynamic trajectory optimization: The USV trajectory is adjusted to ensure the best measurement geometry for state estimation.

3. Key innovation: A CRLB-driven cost function is proposed which optimizes observability through distance and angle adjustments.

4. Cost function: CRLB improves accuracy, while distance and angle optimize the USV's position relative to the AUV.

Method

1. FOA-based state estimation: The USV continuously measures the FOA of acoustic signals transmitted by the AUV, which helps estimate the AUV's position and velocity.

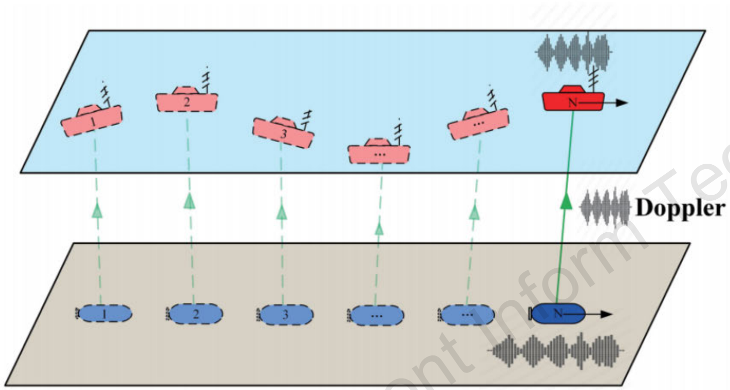

Fig. 1 Illustration of the FOA-based state estimation problem for USV–AUV. A USV (red vehicle) moves on the water surface, while an AUV (blue vehicle) moves underwater at a slowly varying speed. The green line represents the propagation path of the acoustic signals emitted by the AUV and received by the USV. The light-colored vehicles with dashed lines represent the historical states, whereas the dark-colored vehicles with solid lines represent the current states. References to color refer to the online version of this figure

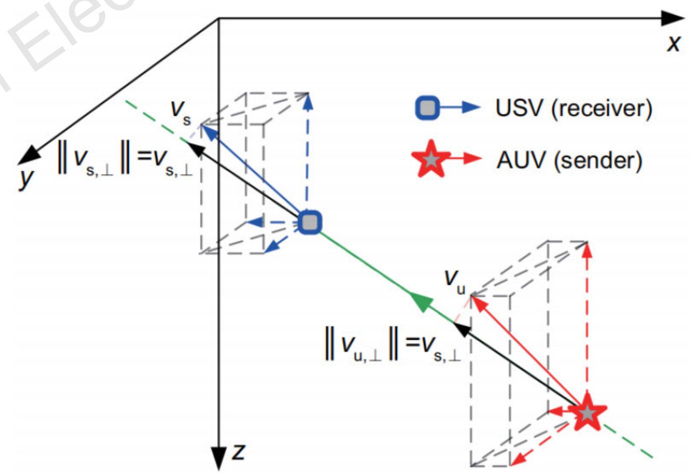

Fig. 2 Decomposition of velocities. The pentagram represents the AUV that sends the acoustic signal with a radial velocity of $v_{u,\perp}$ in the direction of signal propagation. The box represents the USV that receives the signal, and the radial velocity in the direction of signal propagation is $v_{s,\perp}$

Method

2. Rolling horizon AUV state estimation and solution: The particle swarm optimization (PSO) algorithm is used to minimize the combined cost function, adjusting the USV trajectory for optimal geometry in rolling horizon.

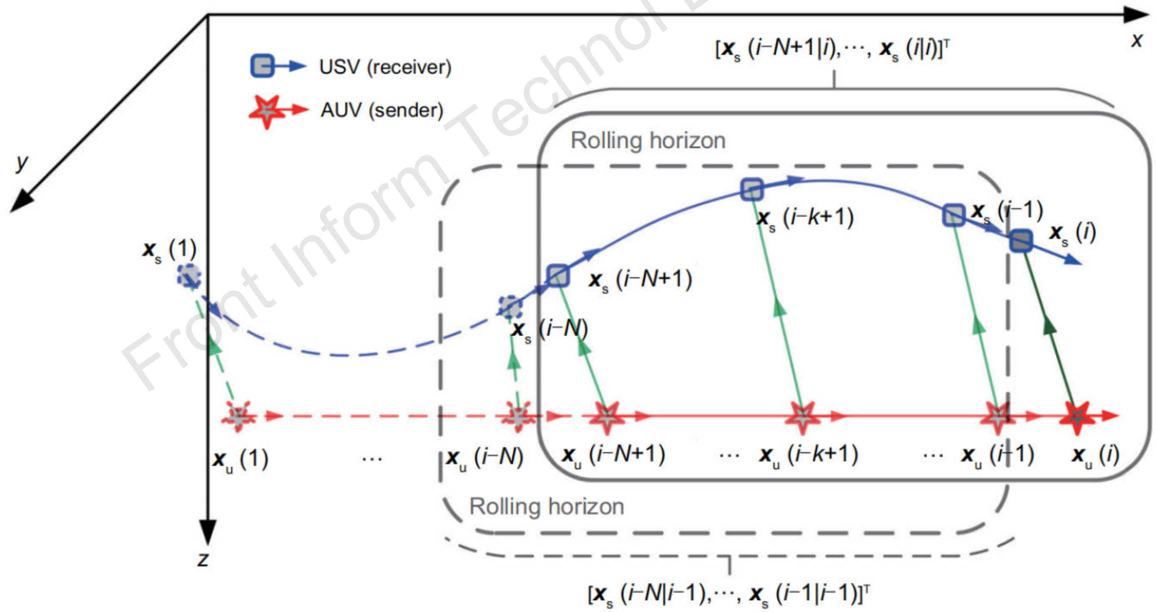

Fig. 3 For each step i, the historical N FOA measurements and USV state measurements $x_s(i-k|i)$ for $k=0,1,\ldots,N-1$ are used to estimate the current AUV state. At step $i+1$, the set of historical measurements is shifted one step forward, and the estimation process is repeated, accounting for the rolling horizon estimation

Method

3. Dynamic trajectory adjustment: The USV trajectory is optimized over time to ensure the best geometry for the AUV's state estimation, which helps maintain good tracking performance.

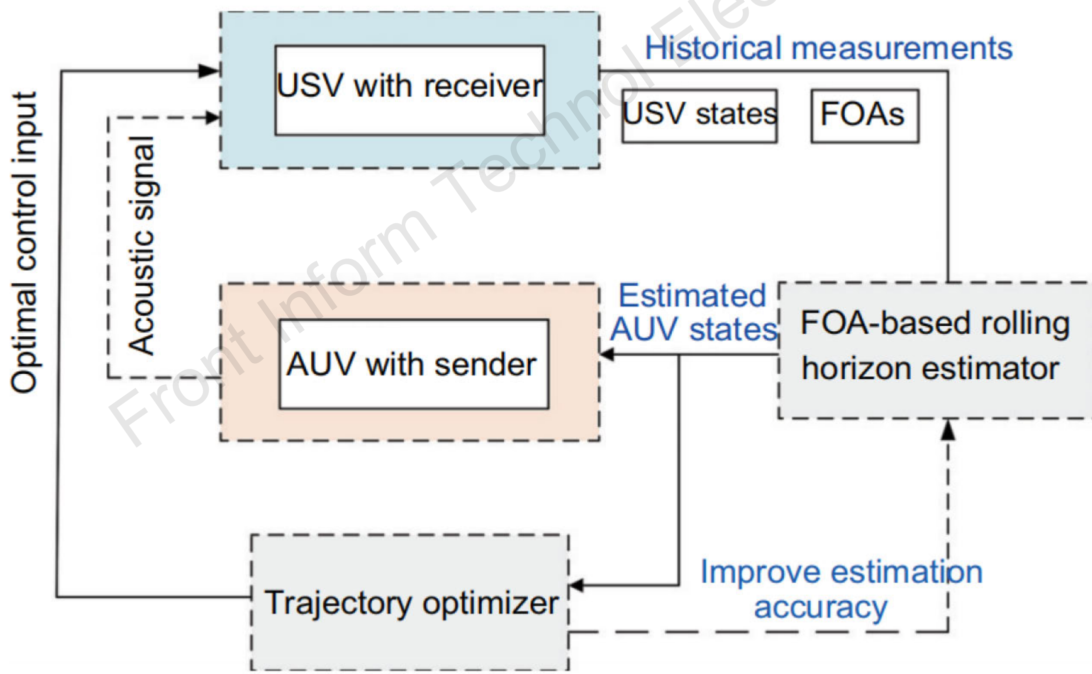

Fig. 5 Closed-loop FOA-based USV–AUV navigation

Major results

Improved estimation performance: The proposed method achieves significantly better AUV state estimation accuracy compared to traditional methods, especially with optimized USV trajectories.

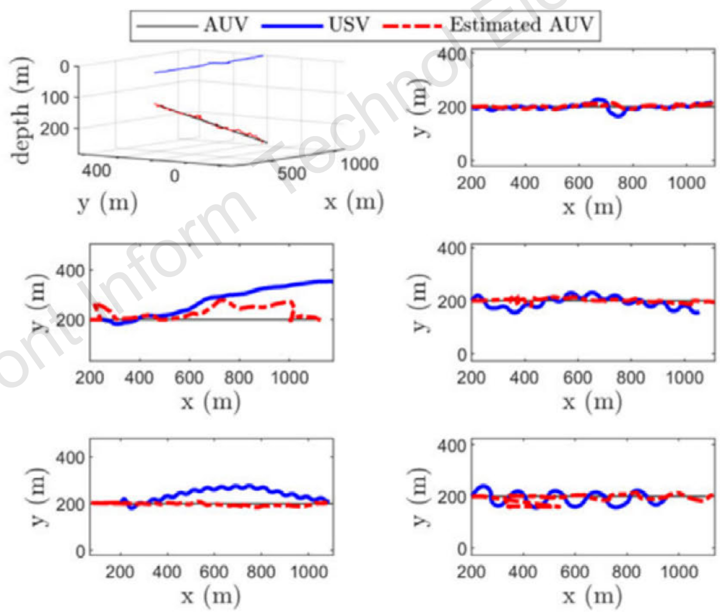

Fig. S7 USV moves along the optimized trajectory and the four specific trajectories in Case 1. The thin black line represents the AUV, the thick blue line represents the USV, and the dashed red line represents the estimated AUV trajectory. The first subfigure shows the 3D trajectories for the optimized USV. The remaining five subfigures, arranged from left to right and top to bottom, display the 2D optimized, LinearFollow, SinFollow 1, SinFollow 2, and SinFollow 3 trajectories, respectively

Major results

Impact of optimization: The optimized trajectory provides superior results in terms of both AUV position and velocity estimation, demonstrating the importance of dynamic trajectory adjustment.

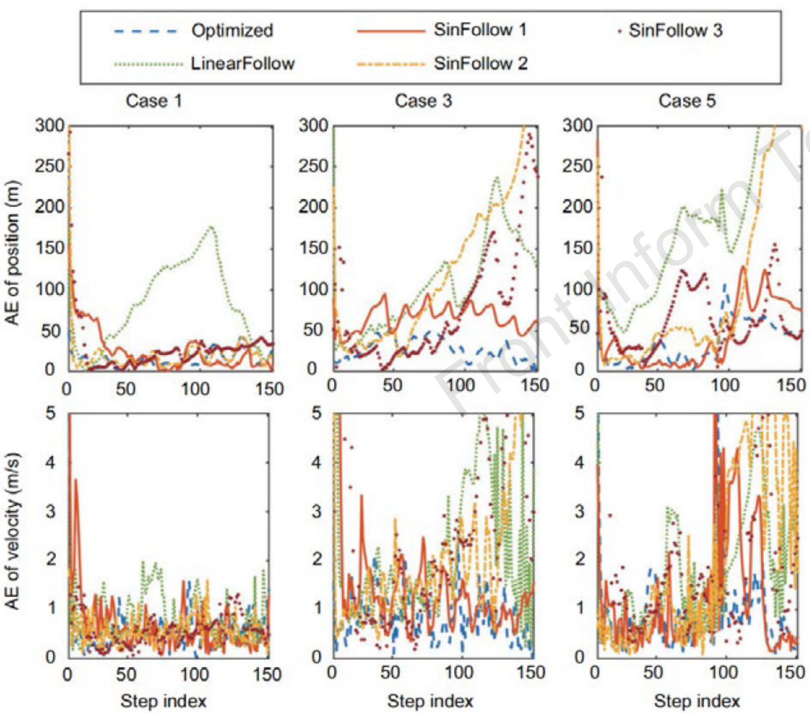

Fig. 6 AE of the estimated position and velocity

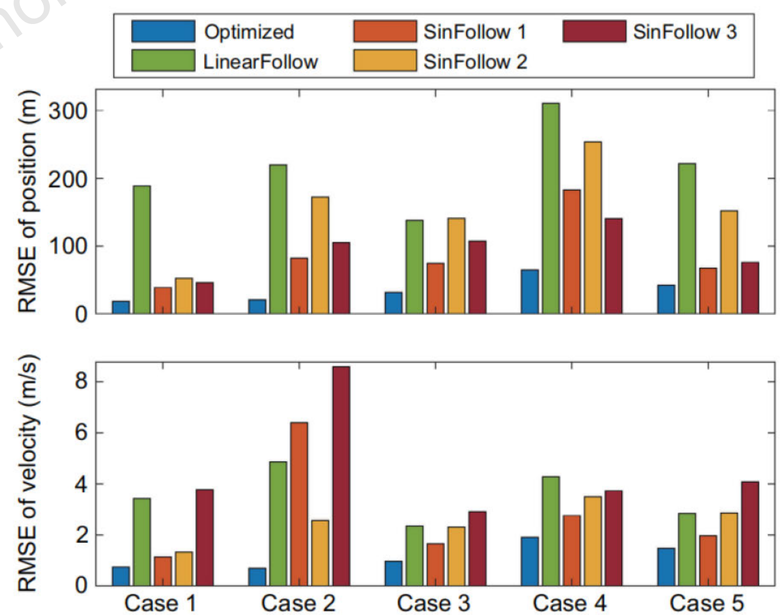

Fig. 8 RMSE of the estimated position and velocity

Major results

Robustness to different configuration factors: The method demonstrates robustness in varying configurations with different AUV depths, etc.

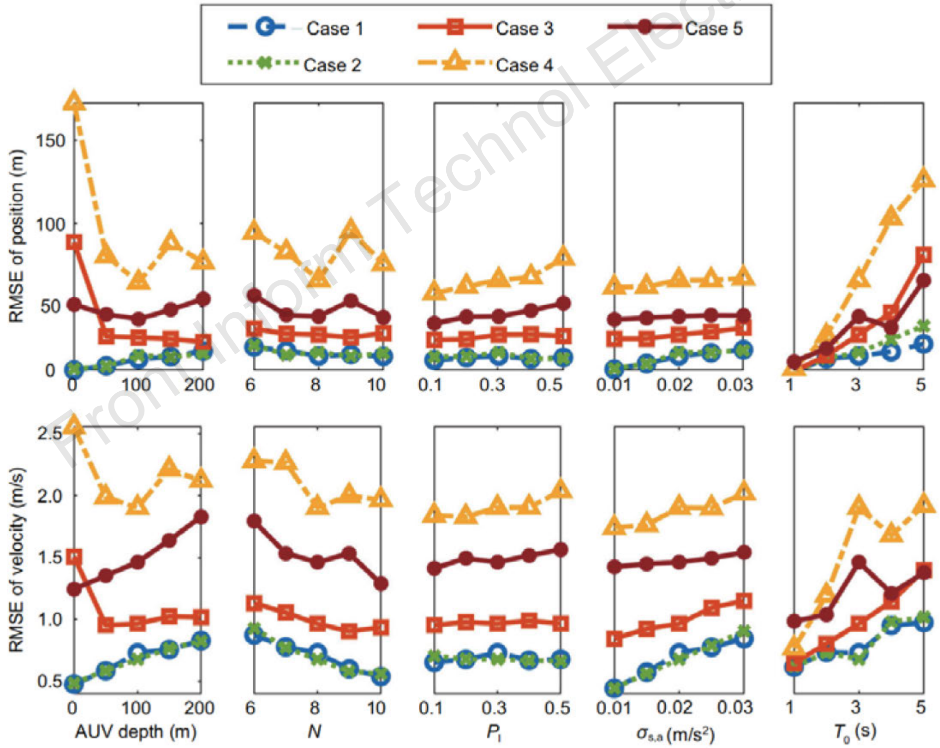

Fig. 10 RMSE of AUV state estimation across different factors

Conclusions

1. Key contribution: A novel FOA-based navigation framework for AUVs is proposed which uses a single USV for state estimation, eliminating the need for time synchronization.

2. Observability and estimation performance: The method improves AUV observability by dynamically optimizing the USV trajectory, leading to better estimation accuracy.

3. Practical implications: This work contributes to advancing real-time, efficient navigation systems for AUVs in underwater environments, with potential applications in marine exploration and monitoring.

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