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Localization in Underwater Sensor Networks

Springer

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Preface

The ocean covers 70.8% of the Earth's surface, and it plays a significant role in supporting the system of life on Earth. Nevertheless, more than 80% of the ocean's volume remains unmapped, unobserved, and unexplored. With regard to this, underwater sensor networks (USNs), which incorporate ubiquitous computation, efficient communication, and reliable control, have emerged as a promising solution to understand and explore the ocean. The deployment of USNs can enhance the monitoring capacity for various applications such as intrusion surveillance, marine resource protection, navigation, geographic mapping, and petroleum exploration. In order to support these applications, accurate location information of sensor nodes is required for correctly analyzing and interpreting the sampled data. However, the openness and weak communication characteristics of USNs make underwater localization much more challenging as compared with the terrestrial sensor networks.

In this book, we focus on the localization problem of USNs with consideration of the unique characteristics of USNs. The localization problem is of great necessary and importance since fundamental guidance on design and analysis on the localization of USNs is very limited at present. We first introduce the network architecture and briefly review the prior arts in localization of USNs. Then, we consider the asynchronous clock and node mobility during the localization procedure, through which a mobility prediction-based least squares estimator is developed to seek the locations of sensor nodes. Note that the first-order linearization is required for least squares estimator to calculate the Jacobian matrix; however, it can introduce large model errors. In view of this, we further design a consensus-based unscented Kalman filtering (UKF) localization estimator to relax the linearization requirement and improve the localization accuracy. In addition, we also employ the reinforcement learning (RL) to relax the linearization requirement and avoid the local minimum during the least squares-based localization procedure, such that an RL-based localization algorithm is provided. Besides that, we investigate the privacy-preserving localization issue for USNs. To this end, three privacy-preserving localization protocols are designed to hide the position information of reference nodes. Accordingly, the least squares and deep reinforcement learning (DRL) based localization estimators are developed, respectively, to jointly achieve privacy preservation, asynchronous localization, and stratification compensation for USNs. Finally, rich implications from the book provide guidance on the design for future localization schemes on USNs.

The results in this book reveal from the system perspective that the underwater localization accuracy is closely related to the communication protocol and optimization estimator. Researchers, scientists, and engineers in the field of USNs can benefit a lot from this book. As such, the valuable knowledge, useful methods, and practical algorithms can provide the guidance on understanding and exploring the ocean. To use this book for underwater applications, knowledge of wireless communication and signal processing is needed.

The book is organized as follows.

Chapter 1 provides the network architecture of USNs and briefly reviews the prior arts in localization of USNs. Besides that, the weak communication characteristics of USNs, including asynchronous clock, stratification effect, and node mobility, are also summarized in this chapter.

Chapter 2 considers the asynchronous clock and node mobility. A hybrid network architecture including autonomous underwater vehicles as well as active and passive sensor nodes is constructed. Then, an asynchronous localization solution with mobility prediction is developed for USNs, where iterative least squares estimators are conducted to seek the position information.

Chapter 3 presents a consensus-based UKF localization algorithm. Compared with the results in Chap. 2, the stratification effect is incorporated into the developed localization protocol in this chapter, and more importantly, the model error can be significantly reduced since the first-order linearization is not required by the localization algorithm in Chap. 3.

Chapter 4 covers an RL-based localization algorithm for USNs in weak communication channel. Note that the least squares-related localization estimators are adopted in Chaps. 2 and 3. However, the least squares-related estimators can easily fall into local minimum. In view of this, Chap. 4 employs the RL to seek the global optimization localization solution.

Chapters 2–4 assume the monitoring area is safe and the position privacy is ignored. However, USNs are usually deployed in open environment, and it is necessary to utilize the information-hiding technology to develop a privacy-preserving localization protocol for USNs. In view of this, Chap. 5 presents a privacy-preserving solution for the asynchronous localization of USNs, in which the asynchronous clock and node mobility are also considered.

Chapter 6 further considers the stratification effect and the forging attack in underwater environment, through which a privacy-preserving localization estimator is developed for USNs. It is worth mentioning that the malicious attacks can be detected and the straight-line localization bias can be compensated in this chapter, which are not available in Chap. 5.

Chapters 5–6 employ the least squares-based estimators to seek the position information of sensor nodes, which can easily fall into local minimum. In order to solve this issue, Chap. 7 develops DRL-based privacy-preserving localization protocol and estimator for USNs. Per knowledge of the authors, this is the first work that incorporates DRL and stratification compensation into the privacy-preservation localization of USNs.

Chapter 8 provides the future research direction on the localization of USNs. We have tried to provide complete instructions for the underwater localization and meanwhile share insights into the underwater localization from the system perspective. We hope this book has reached our goal.

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Acronyms

AOA	Angle of arrival
AUVs	Autonomous underwater vehicles
CRLB	Cramér-Rao lower bound
DRL	Deep reinforcement learning
DVL	Doppler velocity log
FOG	Fiber optic gyroscope
GPS	Global positioning system
HAPs	High-altitude platforms
LBL	Long-baseline
LS	Least squares
ML	Maximum likelihood
PPDP	Privacy-preserving diagonal product
PPS	Privacy-preserving summation
RF	Radio frequency
RL	Reinforcement learning
RMSE	Root mean square error
RSS	Received signal strength
SBL	Short-baseline
TDOA	Time difference of arrival
TOA	Time of arrival
TOF	Time of flight
UAVs	Unmanned aerial vehicles
UKF	Unscented Kalman filtering
USNs	Underwater sensor networks
UWB	Ultra-wideband

Symbols

$\mathcal{R}$	Field of real numbers
$\mathcal{R}^n$	n-Dimensional real Euclidean space
$\mathcal{R}^{n\times m}$	Space of $n \times m$ real matrices
$\mathbf{I}$	Identity matrix
$\mathbf{A}$	System matrix
$\mathbf{A}^{-1}$	Inverse of matrix $\mathbf{A}$
$\mathbf{A}^{\mathrm{T}}$	Transpose of matrix $\mathbf{A}$
$\operatorname{argmin} f$	Value of the variable that minimizes function f
$\operatorname{argmax} f$	Value of the variable that maximizes function f
$\operatorname{tr}(\mathbf{A})$	Trace of matrix $\mathbf{A}$
$\operatorname{rank}(\mathbf{A})$	Rank of matrix $\mathbf{A}$
$\\|\cdot\\|$	Euclidean norm
$\bigtriangledown f$	The gradient of function f
$\forall$	For all
$\in$	Belong to
$\sum$	Sum
$\mathbf{E}\{\cdot\}$	Mathematical expectation operator
$\mathbf{var}\{\cdot\}$	Mathematical variance operator
$(\mathbf{A})_{\mathrm{s}}$	The sth column of matrix $\mathbf{A}$
$L_f\mathbf{A}$	Lie derivative of $\mathbf{A}$ to f
$\lceil\cdot\rceil$	Ceiling function
$\lfloor\cdot\rfloor$	Floor function
ϕ	Empty set
$\operatorname{diag}\{\cdot\}$	Diagonal matrix