

Response to Reviewers' Comments

We would like to thank the editor and four reviewers for their valuable comments and suggestions. The comments and suggestions have significantly helped improve the quality of this manuscript. All the reviewers' comments are fully addressed in the new manuscript. Especially, we have combined two submitted files (the main manuscript and the supplemental material) into a single file for the purpose of completeness. We also emphasize the novelty and contribution of this work in the introduction. In the experiment section, we add a comparison between the proposed approach and other existing methods to demonstrate the effectiveness of our approach. We have also revised the manuscript to improve its clarity and conciseness. The revisions are highlighted by the texts in orange color in the revised manuscript. The following paragraphs detail our responses to each reviewer's comments.

Reviewer #1

The topics is interesting, but I have some problems to discuss with the authors.

1. What is the novelty of the paper? Please specify in the paper.

Response:

The authors would like to thank the reviewer for this important comment. The previous version of the paper has obscured the novelty and contribution of our work. In the revised version, we have emphasized the contribution and features of the proposed distributed Bayesian filter. Here, we'd like to include a paragraph for your convenience.

"In this work, we propose a novel measurement dissemination-based distributed Bayesian filtering approach for target localization using networked UGVs. The main contributions of this paper include: (a) Different from existing works that assume full connectivity of the communication topology, each UGV only needs to broadcast the sensor measurements to its neighbors via single hopping and then implements individual Bayesian filter locally using its own measurements and the ones transmitted from neighbors. (b) We introduce the Latest-In-and-Full-Out (LIFO) protocol to reduce the communication burden, with the transmission data scaling linearly with the UGV number. (c) The proposed LIFO-based DBF has the following properties: For a fixed and undirected network, LIFO guarantees the global dissemination of measurements over the network in a non-intermittent manner. The corresponding DBF ensures the consistency of estimated target position, i.e., the estimate converges in probability to the true value when the number of measurements tends to infinity."

2. Whether the length of paper could be shorten or not? In this case, a part of supplementary material could be added in the paper considering the supplementary material could not be read by readers.

Response:

Thank you for the suggestion. We have added the supplementary material to the paper (section V) as the reviewer suggested.

3. Whether the definition of several typical sensors on page 2 can be reduced or not?

Response:

Thank you for the suggestion. We have trimmed unnecessary sentences in the definition of these typical sensors while maintaining the core parts. Please refer to section II.A for the updated version.

4. Please specify the measurement issue existed in the measurement for networked unmanned vehicles.

Response:

Thank you for the comment. The measurement issues mainly come from the sensors and the communication network of networked unmanned vehicles. For the sensors, the measurement noise, bias, and measurement quantization can affect the performance of sensors. For the communication network, the common issues include the asynchrony of the clock, the transmission delay, the changing network, and the packet loss. In the revised paper, we have mentioned some of these issues to be considered in our future work:

“We plan to extend the current LIFO-DBF to deal with some common issues in the measurement for networked unmanned vehicles, including the asynchronous clock, communication delay, dynamically changing network, and packet loss.”

Reviewer #2

The paper is well written and its objective is clearly presented. However, the originality of the paper needs to be further clarified.

Response:

The authors would like to thank the reviewer for this important comment. The previous version of the paper has obscured the novelty and contribution of our work. In the revised version, we have emphasized the contribution and features of the proposed distributed Bayesian filter. Here, we'd like to include a paragraph for your convenience.

“In this work, we propose a novel measurement dissemination-based distributed Bayesian filtering approach for target localization using networked UGVs. The main contributions of this paper include: (a) Different from existing works that assume full connectivity of the communication topology, each UGV only needs to broadcast the sensor measurements to its neighbors via single hopping and then implements individual Bayesian filter locally using its own measurements and the ones transmitted from neighbors. (b) We introduce the Latest-In-and-Full-Out (LIFO) protocol to reduce the communication burden, with the transmission data scaling linearly with the UGV number. (c) The proposed LIFO-based DBF has the following properties: For a fixed and undirected network, LIFO guarantees the global dissemination of measurements over the network in a non-intermittent manner. The corresponding DBF ensures the consistency of estimated target position, i.e., the

estimate converges in probability to the true value when the number of measurements tends to infinity.”

1. Please do not use abbreviation in title.

Response:

Thank you for the suggestion. We have changed our title to remove the abbreviation. The new title is *“Measurement Dissemination-based Distributed Bayesian Filter using the Latest-In-and-Full-Out Exchange Protocol for Networked Unmanned Vehicles”*.

2. Please give the Index terms after abstract part.

Response:

Thank you for this important suggestion. We have added the following Index terms after the abstract part: *“Bayesian filter, Distributed estimation, Networked vehicles, Nonlinear filter, Unmanned vehicles.”*

3. In the section V, experiment is not demonstrated clearly, especially how the method the authors proposed is verified.

Response:

We appreciate the reviewer for this comment. In the previous version of the paper, we did not clearly present the procedure of the experiment. Our analysis of the experiment results was also insufficient. In the revised paper, we provide more complete description of the experiment and add a new experiment result that compares our approach (LIFO-DBF) with two other commonly used methods (the centralized filter and the consensus-based filter). Please refer to section VI for the updated experiment section. As the experiment results show, the probability density concentrates to the true position of the target (Fig. 9(e)), even though the initial probability density is widely dispersed (Fig. 9(a)). This suggests that by using LIFO-DBF the networked unmanned vehicles can successfully localize the target. In addition, the comparison (Fig. 9(f)) shows that the LIFO-DBF achieves comparable performance as the centralized filter and better performance than the consensus-based filter. This verifies the superior performance of LIFO-DBF over traditionally used distributed filters.

We have added the following sentences to explain the experiment procedure:

“Each robot is equipped with an onboard sonar sensor to measure the target (a small cardboard box) position.”
“The robots locally run the LIFO-DBF to estimate the target position. Each robot’s probability map is constructed on an evenly spaced grid with 0:1m interval on each axis. In the experiment, robots move to different locations to measure the target position. We manually measure the robot positions where the sensor measurements are obtained to reduce the effects of localization error.”

We have added the following sentences to illustrate the effectiveness of the proposed approach in the revised paper:

“Similar to previous simulations, we compare our method with CbDF and CF. All three approaches achieve accurate position estimation. However, they differ in the uncertainty reduction, as shown in Figure 9f. The CF

has the fastest entropy reduction and the LIFO-DBF achieves comparable performance, while the CbDF shows the slowest entropy reduction. These experiment results validate the consistency of LIFO-DBF and demonstrate its effectiveness for distributed filtering.”

4. Please explain how the distributed Bayesian filter can be used in real world.

Response:

The authors would like to thank the reviewer for this important comment. We realize that, in spite that we showed the use of the distributed Bayesian filter for target localization in both the simulation and experiment, we did not discuss about the efficient numerical implementation alternatives to the histogram filter that we used in the paper. We also did not provide examples of the potential applications of this approach. So in the revised paper, we added several sentences in section VII. We include them here for your reference:

“The LIFO-DBF is promising for a wide range of applications using multiple robots, such as the environment monitoring, precision farming, and vehicle localization and mapping.”

“Second, LIFO-DBF provides a general framework for distributed nonlinear filtering. In our future work, we plan to develop computationally efficient implementation of LIFO-DBF by using particle filters and Unscented Kalman filters. Lastly, we will combine the distributed filtering with path planning approaches [34] so that multiple robots can actively localize and track targets, which can be applied to search and rescue and the navigation of autonomous vehicles.”

Reviewer #3

The proposed method is clearly elucidated with rigorous mathematics. Some experimental results are given. The following comments must be addressed before its final acceptance.

1. Please avoid abbreviations in the title.

Response:

Thank you for this comment. We have changed our title to remove the abbreviation. The new title is *“Measurement Dissemination-based Distributed Bayesian Filter using the Latest-In-and-Full-Out Exchange Protocol for Networked Unmanned Vehicles”*.

2. The novelty and contributions could be more explicit in the introduction section.

Response:

We appreciate the reviewer for this important comment. The previous version of the paper has obscured the novelty and contribution of our work. In the revised version, we have emphasized the contribution and features of the proposed distributed Bayesian filter. Here, we’d like to include a paragraph for your convenience.

“In this work, we propose a novel measurement dissemination-based distributed Bayesian filtering approach for target localization using networked UGVs. The main contributions of this paper include: (a) Different from existing works that assume full connectivity of the communication topology, each UGV only needs to broadcast

the sensor measurements to its neighbors via single hopping and then implements individual Bayesian filter locally using its own measurements and the ones transmitted from neighbors. (b) We introduce the Latest-In-and-Full-Out (LIFO) protocol to reduce the communication burden, with the transmission data scaling linearly with the UGV number. (c) The proposed LIFO-based DBF has the following properties: For a fixed and undirected network, LIFO guarantees the global dissemination of measurements over the network in a non-intermittent manner. The corresponding DBF ensures the consistency of estimated target position, i.e., the estimate converges in probability to the true value when the number of measurements tends to infinity.”

3. In my mind, the analysis results should be richer, in addition to the only Fig. 5. How about a comparison with other existing methods?

Response:

The authors would like to thank the reviewer for this important comment. In the previous version of the paper, the analysis of the experiment results was insufficient. In the revised paper, as the reviewer suggested, we add a new experiment result that compares our approach (LIFO-DBF) with two other commonly used methods (the centralized filter and the consensus-based filter). Please refer to section VI for the updated experiment section. Especially, the comparison (Fig. 9(f)) shows that the LIFO-DBF achieves comparable performance as the centralized filter and better performance than the consensus-based filter. This verifies the superior performance of LIFO-DBF over traditionally used distributed filters.

We have added the following sentences to illustrate the effectiveness of the proposed approach in the revised paper:

“Similar to previous simulations, we compare our method with CbDF and CF. All three approaches achieve accurate position estimation. However, they differ in the uncertainty reduction, as shown in Figure 9f. The CF has the fastest entropy reduction and the LIFO-DBF achieves comparable performance, while the CbDF shows the slowest entropy reduction. These experiment results validate the consistency of LIFO-DBF and demonstrate its effectiveness for distributed filtering.”

4. A hint on likely future work is welcome.

Response:

Thank you for this suggestion. We have added contents to delineate our future work in section VII. Here we would like to include a paragraph for your convenience.

“This work has opened up several directions for future work. First, we plan to extend the current LIFO-DBF to deal with some common issues in the measurement for networked unmanned vehicles, including the asynchronous clock, communication delay, dynamically changing network, and packet loss. Second, LIFO-DBF provides a general framework for distributed nonlinear filtering. In our future work, we will develop computationally efficient implementation of LIFO-DBF by using particle filters and Unscented Kalman filters. Lastly, we will combine the distributed filtering with path planning approaches [34] so that multiple robots can actively localize and track targets, which can be applied to search and rescue and the navigation of autonomous vehicles.”

Reviewer #4

This paper is well written. The reviewer suggests to further highlight the main contributions of this work.

Response:

The authors would like to thank the reviewer for this important comment. The previous version of the paper has obscured the novelty and contribution of our work. In the revised version, we have emphasized the contribution and features of the proposed distributed Bayesian filter. Here, we'd like to include a paragraph for your convenience.

“In this work, we propose a novel measurement dissemination-based distributed Bayesian filtering approach for target localization using networked UGVs. The main contributions of this paper include: (a) Different from existing works that assume full connectivity of the communication topology, each UGV only needs to broadcast the sensor measurements to its neighbors via single hopping and then implements individual Bayesian filter locally using its own measurements and the ones transmitted from neighbors. (b) We introduce the Latest-In-and-Full-Out (LIFO) protocol to reduce the communication burden, with the transmission data scaling linearly with the UGV number. (c) The proposed LIFO-based DBF has the following properties: For a fixed and undirected network, LIFO guarantees the global dissemination of measurements over the network in a non-intermittent manner. The corresponding DBF ensures the consistency of estimated target position, i.e., the estimate converges in probability to the true value when the number of measurements tends to infinity.”