location estimation algorithm. To know the size of an underwater target, Liang and Cheng (2009) proposed an estimation algorithm based on maximum likelihood, but an entire tracking solution is still not available. Huang et al. (2008) presented two tracking algorithms that are based on a distributed particle filter (PF) for cluster-based underwater sensor networks, one of which provides a more precise tracking result, while the other focuses on dramatic reduction of energy consumption and tracking efficiency. Wang et al. (2012) combined PF with an interactive multiple model to solve nonlinear and maneuvering target tracking problems in three dimensions, but they did not consider the energy consumption problem, and thus their algorithm is not practical for UWSNs. Isbitiren and Akan (2011) presented a target tracking algorithm in three-dimensional UWSNs. First, the distance from a node to its target was calculated with the echo time of arrival (TOA) from the target after transmitting acoustic pulses from the sensors, and the trilateration method was used to obtain the target's location. Then the location and calculated velocity of the target were exploited to achieve tracking. As we know, energy consumption is also a critical issue for target tracking in UWSNs. To extend the lifetime of the system, Yu et al. (2008) used a wake-up/sleep scheme to select a number of nodes to track the underwater target at each sampling interval. However, the target-node geometry and fusion weights of selected nodes were not considered. Baumgartner et al. (2009a) derived an integral objective function representing the quality of the service of a sensor network performing cooperative tracking detection over time using a geometric transversal approach. Then optimal control was used for cooperative target tracking in UWSNs. To improve the service quality of a sensor network for cooperative tracking detection, Baumgartner et al. (2009b) proposed a novel approach comprising placing sensors in the region of interest based on their future displacement.

To the best of our knowledge, target-node geometry affects the accuracy of target tracking in UWSNs, and our previous study provided some solutions to select the optimal target-node geometry for target tracking (Zhang Q et al., 2014, 2015; Liu et al., 2016; Zhang et al., 2016). The relationship between the posterior Cramer-Rao lower bound (PCRLB) and the target-node geometry was derived, and a node selection scheme was designed by minimizing the PCRLB. As we know, the information from different nodes varies due to node differences such as position and distance to the target (Chen et al., 2010; Javadi and Peiravi, 2015), but the fusion weights of selected nodes are equal; it is not a precise approach for practical tracking tasks. Therefore, it is important to consider the fusion weights of selected nodes for tracking. To overcome this limitation, we study fusion weights of selected nodes and present a novel scheme to design fusion weights. This scheme has more precise tracking results than our previous study. The main contributions of this paper can be summarized as follows:

1. We derive the mutual information (MI) between a node's measurement and the target state in an underwater environment. It considers the effect of the node's location uncertainty due to mobility.

2. We propose a novel scheme to design fusion weights by using MI, which can quantify information about the target by the node's measurement.

3. We present a novel multi-sensor weighted particle filter (MSWPF). Combined with a node selection scheme based on the PCRLB, we offer a more precise and energy-efficient target-tracking solution to UWSNs.

2 Problem formulation

In this section, we formulate the problem of single target tracking in UWSNs. The relevant issues include the network model, the target state model, and the measurement model.

2.1 Network model

As an example (Fig. 1), sensor nodes in UWSNs are anchored to the ocean bottom to perform the target tracking task. Sensor nodes are deployed at known positions along the ocean floor. Different from terrestrial sensor networks, underwater nodes move due to the effect of water flow. Therefore, the true locations of the nodes are not fixed; we know only the estimated locations of nodes. If a moving target is within the sensing range of a node, the node will wake up, participate in the tracking task, measure the target, and send quantized measurements to the fusion center. Otherwise, it remains dormant for energy efficiency. After receiving measurements from all selected nodes, the fusion center will estimate the

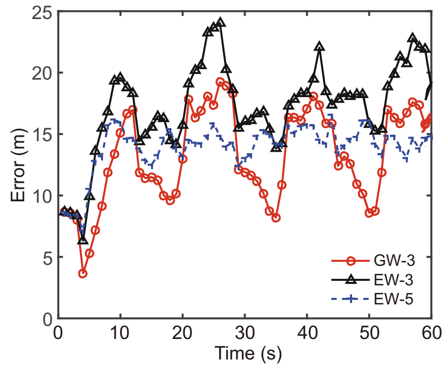

Fig. 15 3D scenario: tracking errors for GW-3, EW-3, and EW-5 (over 100 MC runs)

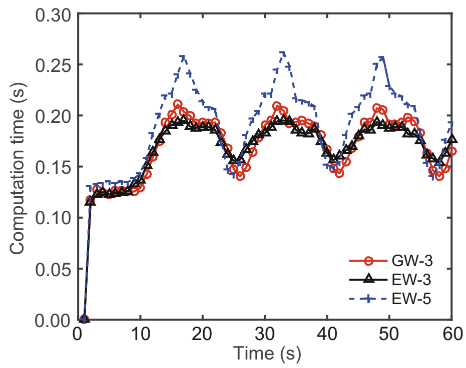

Fig. 16 3D scenario: average computation time for GW-3, EW-3, and EW-5 (over 100 MC runs)

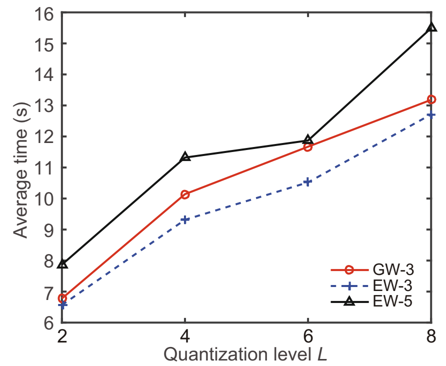

Fig. 17 3D scenario: average time of one MC for GW-3, EW-3, and EW-5 with different quantization level L (over 100 MC runs)

6 Conclusions and future work

We have studied a weighted fusion scheme for target tracking in UWSNs. We have presented a novel multi-sensor weighted particle filter (MSWPF) and a corresponding tracking scheme. To find a proper solution to determine fusion weights, the mutual information (MI) between a node's measurement and the target state was calculated. To verify the effectiveness of our scheme, 2D and 3D simulation scenarios have been carried out. The results showed that with fusion weights determined by MI, our scheme achieved better tracking performance than existing schemes.

However, there are many problems for target tracking in a real sea environment, such as clock synchronization and channel fading. Further work will focus on these problems and extend the algorithms to multiple target-tracking problems to develop an experimental platform in a real sea environment.

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