SUPPLEMENTARY MATERIAL
UACOF: A USV-AUV Collaboration Framework for Underwater Tasks under Extreme Sea Conditions

In this supplementary material, we mainly describe the system model of the multi-AUV data collection task employed in this research. Then we further present the code implementation of the UACOF.

1 System Model of The Multi-AUV Data Collection Task

In this paper, we utilize the multi-AUV data collection task as an illustrative example [1]. In this section we present an overview of the AUV communication model, AUV energy consumption model and node selection model of the task.

1.1 Underwater Data Collection Model

The system model of the multi-AUV data collection task utilized in this study is illustrated in Fig. 1. Consider an environment containing N task-performing AUVs and λ IoUT sensor nodes, where the AUVs are denoted by set $AUVs = \{AUV_1, AUV_2, \ldots, AUV_N\}$. These AUVs receive status information of IoUT device nodes from the base station on the sea surface, which enables them to identify the nodes requiring data collection. The IoUT nodes are represented by set $\Phi = \{\Phi_1, \Phi_2, \ldots, \Phi_\lambda\}$, comprising μ ordinary nodes $\Phi_k^{\mathrm{N}} = \{\Phi_{k_1}^{\mathrm{N}}, \Phi_{k_2}^{\mathrm{N}}, \ldots, \Phi_{k_\mu}^{\mathrm{N}}\}$ and ν data-collecting nodes $\Phi_j^{\mathcal{F}} = \{\Phi_{o_1}^{\mathcal{F}}, \Phi_{o_2}^{\mathcal{F}}, \ldots, \Phi_{o_\nu}^{\mathcal{F}}\}$. The components of the system are described as follows.

Ordinary Nodes: The underwater nodes equipped with fundamental functions including signal reception, data storage, and signal transmission. These nodes do not have data backlog and do not require data collection capabilities.

Data-Collecting Nodes: Underwater nodes that require data collection due to a certain degree of data backlog.

AUVs: AUVs equipped with communication devices, sensors, mechanical arms, and charging/storage equipment. In this work, the role of the AUV is to locate nodes within the IoUT network and perform data collection tasks.

Surface Base Stations: Information transmission and storage centers located on the sea surface or on land, responsible for the overall coordination of multi-AUV underwater data collection task.

During data collection operations, AUVs work collaboratively to locate nodes that require data collection. Considering that ocean turbulence significantly impacts the movement and energy consumption of AUVs, they must avoid turbulent areas during operation to optimize their trajectories.

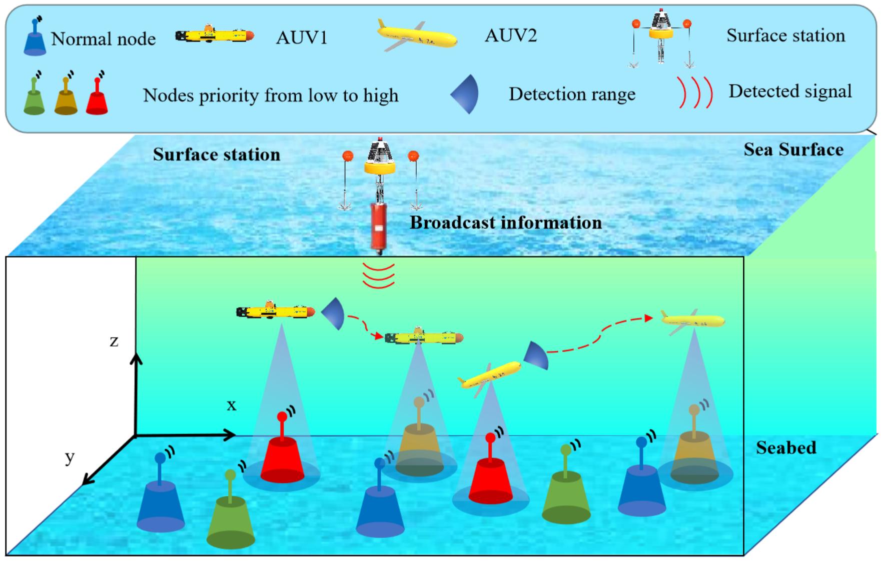

Fig. 1: The system model of the multi-AUV data collection task.

1.2 AUV Communication Model

During the multi-AUV data collection task, AUVs detect sensor nodes using their onboard sonar systems. Concurrently, communication between AUVs is also facilitated through sonar equipment. These processes can be uniformly modeled using the underwater environment sonar equation

$$EM = SL + TS + DI - NL - DT - 2TL(d, f), \tag{1}$$

where SL, TS, DI, NL, and $TL(d, f)$ represent the source level, target strength, directivity index, ambient noise level, and transmission loss, respectively. DT and EM denote the active sonar detection threshold and the echo excess, respectively. $TL(d, f)$ is related to the detection radius d and the center frequency f, satisfying the following equation:

$$TL(d, f) = 20\log(d) + \frac{d\kappa(f)}{1000}, \tag{2}$$

where $\kappa(f)$ represents the absorption coefficient, calculated according to the Thorp formula

$$\kappa(f) = 0.11\frac{f^2}{1 + f^2} + 44\frac{f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003. \tag{3}$$

In the underwater environment, the total noise N_l consists of turbulence noise N_t, shipping noise N_s, wind noise N_w, and thermal noise N_{th}. These noises can be represented by Gaussian statistics, and the total power spectral density (PSD) of N_l is

$$N_l(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{4}$$

The noise component in Equation 8 can be expressed as

$$\begin{cases} 10\log N_t(f) = 17 - 30\log f, \\ 10\log N_s(f) = 30 + 20s + \log\left(\frac{f^{26}}{(f+0.03)^{60}}\right), \\ 10\log N_w(f) = 50 + 7.5\omega^{\frac{1}{2}} + 20\log\left(\frac{f}{(f+0.4)^2}\right), \\ 10\log N_{th}(f) = -15 + 20\log f, \end{cases} \tag{5}$$

where $s \in (0,1)$ represents the activity factor, and ω is the wind speed with the unit of m/s.

1.3 AUV Energy Consumption Model

The energy consumption of the AUV arises from two primary sources: the hovering energy consumption $\mathcal{M}_j^h$, and the traveling energy consumption $\mathcal{M}_j^m$. According to classical fluid dynamics, the drag experienced by the AUV while hovering underwater can be expressed as

$$\tau_j^h = \frac{\rho_s \|v_c(\nabla_j^t)\|_2^2 C_a \mathcal{U}_d}{2}. \tag{6}$$

The resistance during navigation can be expressed as

$$\tau_j^m = \frac{\rho_s \|v_k(\nabla_j^t)\|_2^2 C_a \mathcal{U}_d}{2}, \tag{7}$$

where ρ_s represents the density of seawater, while C_a and $\mathcal{U}_d$ denote the drag coefficient and frontal area of the AUV, respectively. And ∇_j^t is the position vector of the AUV j at time t. Additionally, $v_c(\nabla_j^t)$ and $v_k(\nabla_j^t)$ represent the flow velocity and relative velocity at position ∇_j^t, respectively. Therefore, the power consumption of the AUV j hovering at the $\hbar$-th node can be calculated as follows:

$$P_j^h[\hbar] = \frac{\tau_j^h[\hbar] \|v_c(\nabla_j^{\hbar})\|_2^2}{\vartheta}, \tag{8}$$

where ϑ is the electrical conversion efficiency.

Considering the practical situation, the relative velocity at different positions varies as the AUV moves from the $\hbar$-th node to the $(\hbar+1)$-th node. Hence, it is inappropriate to use the velocity at a single fixed point to calculate the energy consumption of the AUV during its movement. To address this issue, we use the average relative velocity at the starting point, midpoint, and endpoint of the trajectory to calculate the energy consumption. Taking the process of the AUV moving from the $\hbar$-th node to the $(\hbar+1)$-th node as an example, the average relative velocity is expressed as follows:

$$\overline{\boldsymbol{v}_k}(\nabla_j^{\hbar}) = \frac{\boldsymbol{v}_k(\nabla_j^{\hbar}) + \boldsymbol{v}_k(\nabla_j^{\hbar m}) + \boldsymbol{v}_k(\nabla_j^{\hbar+1})}{3}, \tag{9}$$

where $\nabla_j^{\hbar m}$ denotes the position vector of the intermediate point of the trajectory. Therefore, the power consumption of the AUV in this motion trajectory is

$$P_j^m[\hbar] = \frac{\rho_s \|\overline{v_k}(\nabla_j^{\hbar})\|_2^2 C_a \mathcal{U}_d \|\overline{v_k}(\nabla_j^{\hbar})\|_2^2}{2\zeta}. \tag{10}$$

Based on the above analysis, the total energy consumption of AUV j can be concluded as follows

$$E_j = \sum_{i=1}^{M} \sum_{\hbar=1}^{\Phi_o^{F_j}} \chi_{j,i}[\hbar] P_j^h[\hbar] \pi_{j,i}[\hbar] + \sum_{\hbar=1}^{\Phi_o^{F_j}} P_j^m[\hbar] t_j^m[\hbar], \tag{11}$$

where M represents the set of all nodes, while $\chi_{j,i}[\hbar] = 1$ denotes the event that the AUV j hovers over node i for the $\hbar$-th time, and conversely, $\chi_{j,i}[\hbar] = 0$. $\pi_{j,i}[\hbar]$ represents the hovering time over the node, $\Phi_o^{F_j}$ denotes the set of hovering points of AUV j, and $t_j^m[\hbar]$ represents the time required to move from the $\hbar$-th node to the $\hbar + 1$-th node.

1.4 Node Selection Model

Before the AUV initiates data collection from IoUT nodes, it is essential to determine the priority based on the urgency of data collection required by each node. The priority $\mathcal{Q}_{\hbar}^j(t)$ of data collection from a node is defined as follows:

$$\mathcal{Q}_{\hbar}^j(t) = \frac{\mathcal{C}_{\hbar}(t)}{\mathcal{C}_{max}(\mathcal{N}_{\hbar}(t) + \varepsilon)} - \xi d_{\hbar}^j(t), \tag{12}$$

where $\mathcal{N}_{\hbar}(t) \in [0, \mathcal{N}_{\hbar}^{max}]$ is the channel capacity of node $\hbar$ at time t, $\mathcal{C}_{\hbar}(t) \in [0, \mathcal{C}_{max}]$ represents the data storage amount, and $\mathcal{C}_{max}$ denotes the maximum data storage capacity of the node. $d_{\hbar}^j(t)$ represents the relative distance between AUV j and node $\hbar$ at time t, ε denotes a constant to prevent calculation errors when $\mathcal{N}_{\hbar}(t)$ equals zero, and ξ is a penalty factor. By calculating $\mathcal{Q}_{\hbar}^j(t)$, the AUV can prioritize collecting data from nodes with higher urgency while considering the relative distance, thereby improving the system's operational efficiency.

2 Code Implementation

To accelerate relevant research in this field, we have made the simulation codes available as open-source. The source code associated with this article is available at the following GitHub repository: https://github.com/360ZMEM/USV-AUV-colab.

References

1. Zhang, Z., Xu, J., Xie, G., Wang, J., Han, Z., Ren, Y.: Environment- and energy-aware auv-assisted data collection for the internet of underwater things. IEEE Internet of Things Journal **11**(15), 26406–26418 (2024). https://doi.org/10.1109/JIOT.2024.3395568