Unmanned Aerial Underwater Vehicle (UAUV) in the Ocean Sensor Network

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Abstract. Human exploration of the ocean has never stopped. A large number of sensors are placed in the ocean to establish ocean sensor networks to obtain more information about the marine environment, crustal dynamic changes and so on. With the development of science and technology, autonomous underwater vehicle (AUV) emerges as the times require. As an underwater sensor acquisition system, it has been widely used in ocean sensor networks. Due to the complex and changeable marine environment, the AUV can not travel accurately, resulting in a lot of resources waste of time and energy, even the loss of AUV, so the information can not be timely and effective collected. In this paper, the Unmanned Aerial Underwater Vehicle (UAUV) is introduced into the ocean sensor network, and the advantages and disadvantages of the UAUV in the ocean sensor network are compared objectively from multiple dimensions. Through the ergodic search algorithm, the optimal water entry point for the UAUV to complete the task in the shortest time and the minimum power consumption is found, and the performance of the underwater vehicle's cross domain mode and underwater mode ocean sensor data acquisition task is compared and analyzed. The results show that compared with the traditional underwater mode, the cross domain mode saves 74.7% of the time and 24.34% of the energy consumption, which proves the feasibility, stability and High efficiency of introducing the air submersible into the ocean sensor network.

Keywords: Ocean sensor network · AUV · Unmanned aerial underwater vehicle · Ergodic search algorithm

1 Introduction

Ocean sensor network is more and more attention from scholars in recent years, with the development of The Times, the progress of science and technology, the potential of human exploration of the unknown sea have been digging, a large amount of mature machinery type sensor is arranged in the ocean environment information collection, the

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earth's crust, Marine species, Marine dynamic change information of military intelligence, etc. It provides necessary data support for the further research of Marine science, and also provides reliable support for the exploration of the unknown world in the future. Over a wide area of ocean, mechanical sensors can be distributed in a variety of ways. Luo et al. [1] summarized three kinds of sensor network topologies, namely two-dimensional static underwater sensor network, three-dimensional static underwater sensor network and three-dimensional underwater sensor network with AUV. Among them, the data exchange process of each sensor network cannot be separated from wireless communication. Due to different media, the environment of wireless communication is relatively complex in sea water than on land, and accompanied by a series of experimental problems, material problems and energy problems, its development speed is relatively slow, the communication rate is low, and the transmission distance is close. At present, there are three kinds of underwater wireless communication commonly used, namely underwater electromagnetic wave communication, underwater optical communication and underwater acoustic communication. Electromagnetic wave in seawater has weak penetration and extremely serious attenuation [2], so it cannot be used as an effective way of long-distance communication in seawater environment [3]. For optical communication, due to the high available bandwidth of optical communication [4], it can reach a high speed transmission of about 100 m. Research data shows that LED-based visible light communication can establish a communication link as long as 500 m in pure water. However, compared with the vast ocean area on Earth, the communication distance of 500 m is far from enough to meet the communication needs of ocean sensor. Therefore, in the ocean communication system, the communication mode with acoustic wave [5] as the carrier appears. Its transmission distance can vary from several hundred meters to several thousand meters, and it is the only widely used and the most mature underwater remote communication mode at present. Even so, regardless of the energy, for underwater acoustic communication of several thousand meters, it is still unable to effectively transmit the sensor data from tens or even hundreds of kilometers away from the coast to the coastal server. Therefore, AUVs is introduced into the third topology above, that is, a three-dimensional underwater sensor network with AUVs is introduced to solve the problem of sensor information collection and data exchange between nodes. As the carrier of data information of sensor nodes, the AUVs shuttles between sensor nodes and is responsible for collecting a large amount of information and sending it back to the shore server.

At present, the researches of the AUV has made great progress, as well as there has been a mature AUV data acquisition system, which can the sensor at the bottom of the sea and the coast between reciprocating transmission more information. AUV is widely sought after in ocean sensor networks due to its advantages of flexibility, reliability, low cost and labor saving. In order to improve the collection efficiency of water column data, Luo et al. [6] designed an AUV data collection system based on wireless grid network, the AUV data acquisition system is composed of multiple AUVs, were completed in a set of grid data collection work, and then focus on the main AUV for data fusion, due to the method of wireless mesh networks for AUVs provides a relatively reliable communication environment, at a lower cost greatly improve the efficiency of the data acquisition of underwater robot. Lee and Yu [7] designed an AUV with single propeller motion to collect water column data in shallow water. AUV using deformable buoyancy system provides steering function, by reducing the number of propeller, improve the utilization efficiency of the energy of the AUV, which battery life for 9 h, can perform 15 times data acquisition tasks. Huang et al. [8] put forward a realization method based on clustering matrix (ACMC) of AUV auxiliary data collection scheme. By improving K-means algorithm, a two-stage AUV trajectory optimization mechanism based on greedy algorithm is introduced. AUV reduces the time delay and energy consumption of data collection of cluster nodes by about 4 times compared with the original scheme, reduces the energy consumption of nodes by more than 30%, and greatly improves the network life. In order to balance the energy consumption and prolong the service life of sensor networks, Yan et al. [9] expressed the energy optimization problem as minimizing the sum of the side lengths of a specific graph, and proposed a topology optimization scheme and local routing decision algorithm for sensor deployment based on minimum weighted grid graph. At the same time, a path planning strategy based on dynamic value was designed for AUV, making the performance of the whole ocean sensor network has been improved.

In addition, except a lot of work on improving the performance of AUVs data collection and reducing energy consumption, many studies also involve the underwater positioning of AUVs, the collaborative work of AUVs groups, AUVs path planning and other directions, so that AUVs can complete underwater work more efficiently as collecting information from sensors. Miller et al. [10] obtained the information from the seafloor profile by acoustic method, formed a series of seafloor acoustic images to estimate the speed and position of the AUV, and completed the underwater positioning of the AUV. Simulation results show that the algorithm is effective and good estimation quality is obtained. Ferri et al. [11], under the leadership of collaborative autonomy and data fusion of the AUV colony, developed a track management module integrated into the independent software of the AUV to realize information sharing and improve the overall performance of the AUV colony through data-driven collaboration among the AUVs, the average packet transfer rate between AUVs increased to around 50%. Willners et al. [12] proposed a method of using autonomous surface ships (ASVs) as AUV communication and navigation AIDS (CNA). A combination of search tree-based priority expansion and random sampling based exploration was used to locate CNA in strategic locations. At the same time, in order to reduce the position error and uncertainty of the AUV and realize the precise positioning of the AUV, the strategic path point and the best ranging information transmission time of the CNA were sought. Lim et al. [13] proposed 12 algorithms based on particle swarm intelligence (PSI) and applied them to the performance evaluation of AUV optimal path planning problem under underwater obstacles and non-uniform flow environment. The algorithm considers the physical limitations and practicability of AUV, meanwhile the advantages and disadvantages of each algorithm are analyzed comprehensively, and the most appropriate optimization method is selected from a variety of methods.

In the process of the gradual development of the AUV, the ocean sensor network based on the AUV has also made great progress. However, there are many unavoidable physical limitations in the underwater motion of AUV, such as very slow motion speed, poor flexibility, unable to position itself accurately, single communication mode and high energy consumption, which make it still have a great space for development. To solve the inevitable series of problems, a new approach is on the way. In recent years, the unmanned aerial underwater vehicle (UAUV), which combines AUV with UAV, appears in people's vision and gets rapid development. Its high speed flight and underwater movement as well as the ability to work across the field can solve more problems for the ocean sensor network.

Related concepts of UAUV appeared early, but due to the limitations of energy, materials, power and other aspects, the development of UAUV was relatively slow in the early stage. However, with the gradual conquer of related technical problems, the emergence of UAV has once again aroused the extensive interest of many marine and underwater researchers, meanwhile officially entered the human stage.

As early as 2014, Yao et al. [14] introduced a kind of flying and diving submarine "flying fish", which is an early UAUV. By simulating the morphological characteristics of biological flying fish and the variable density method of waterfowl, "flying fish" realized the trans medium conversion of air and water, and finally verified the feasibility of this method through experiments. Weisler et al. [15] described the concept of fixed wing UAUV and developed a fixed wing UAUV to verify its feasibility and analyze its performance. The UAUV adopts the structure of single motor and single propeller, and uses passive inflow and drainage wings to achieve cross domain function. The UAUV combines the advantages of the aircraft's speed and long range, as well as the durability, diving ability and stealth ability of the submersible, this allowed it to avoids a series of shortcomings of the underwater robot, and makes a qualitative breakthrough in the efficiency of underwater related work on the physical level. In the actual test, the UAUV can complete 12 full cycle cross domain tasks at a time. Maia et al. [16] successfully completed the design and implementation of a full working multi rotor UAUV. The dynamic model of an eight-rotor quadcopter was established by Newton Euler method. The results show that the UAUV has achieved good results in both media and can realize seamless transition between the two media. Lu et al. [17, 18] proposed a new solution, which solved the problem of poor durability of the existing UAUV. The scheme combines the design ideas of fixed wing UAV, multi rotor and underwater glider(UG), and adds a new light aerodynamic buoyancy control system. The experiment shows that the UAUV is very suitable for moving in different media and can achieve long-distance endurance in the air or water. Based on the concept of the quadcopter, Kasno et al. [19] constructed a long-distance amphibious UAUV, which can hover in the air at 200 cm height and dive depth in water about 20 cm, which proves the feasibility and effectiveness of the four axis UAV cross motion. In addition, the UAUV is simulated and tested, and its good withstand voltage performance is verified. Wang et al. [20] designed a hybrid aerial aquatic vehicle based on underwater obstacles crossing background to collect water column data. When underwater obstacles are encountered, it can switch to flight mode to cross obstacles and turn on GPS for real-time navigation. At present, the UAUV has been developed and tested. The test results show that the UAUV can sail in shallow water environment, and verify its maneuverability of underwater takeoff and underwater glide.

UAUV, with its multiple advantages of high-speed in the air, accurate positioning, low energy consumption per 100 km, underwater diving, stability, concealment, and cross media avoidance of obstacles and dangers, can improve the data acquisition efficiency of large ocean sensor networks by an order of magnitude. The main research work of this paper is as follows.

1) Scene construction. Firstly, the ideal ocean environment is simulated, the ocean sensor scene is established, and the sensor position and communication distance are set. Then the UAUV is constructed, its initial position and flag state are set, and its related physical parameters are set.
2) Performance comparison of UAUV and AUV. According to the above scene, the time consumption and energy consumption of UAUV data acquisition efficiency under underwater motion and cross-domain motion are compared. It will be proved that the performance of UAUV is much better than AUV, indicating the necessity of introducing UAUV into ocean sensor networks. At the same time, the maneuverability data of UAV underwater movement and cross-domain movement are presented intuitively, so as to guide the further research and development of UAUV.
3) Performance analysis. Through the ergodic search algorithm, the effectiveness and reliability of the UAUV in the ocean sensor network are verified in terms of time and energy consumption. It will be proved that UAUV can effectively improve the overall stability of ocean sensor networks, save a lot of time cost and energy consumption.

2 Scenario Model

UAUV has the ability of high-speed air operations, can reach many large ocean sensor nodes in a short time, and complete a large number of data acquisition work in time. This paper studies a ideal ocean sensor network scenario, and selects an ocean environment with seamounts as the background. The topography of the sea floor is complex. There are many mountains. The top of the mountain is higher than the sea level. The specific scene is shown in Fig. 1. At the same time, sensors are arranged in the key areas of the ocean to collect marine environmental data. Each sensor has a certain communication range. When the UAUV enters the range, it broadcasts the search signal and establishes a connection with the sensor to collect the sensor data. In this scenario, the scale of sensor network is large, and the distance between each two groups of sensors is far. The data information collected in the ocean is collected by the UAUV and sent to the coastal server regularly. For UAUV, in addition to the superiority of air and underwater, it has dual communication system carrying underwater acoustic communication and electromagnetic communication simultaneously. When operating in the air, UAUV can interact with the cloud server or transmit data information to the shore server through electromagnetic wave communication, meanwhile obtain real-time positioning information through the global navigation system, and correct the accumulated underwater positioning error. The data acquisition process of UAUV in underwater sensor network can be divided into two ways: cross domain flight path acquisition of sensor data and full underwater path acquisition of sensor data.

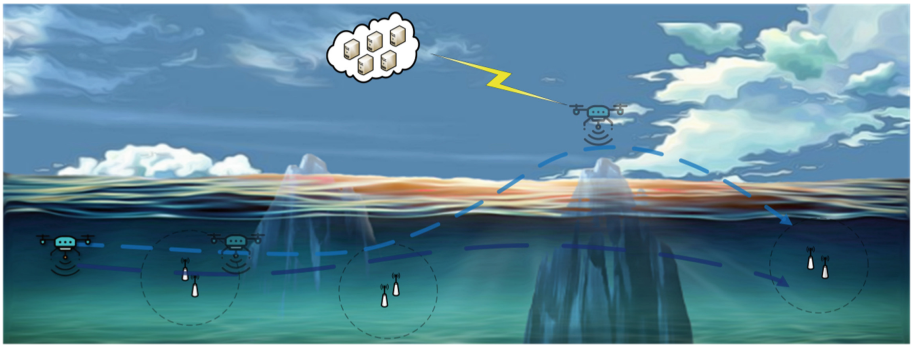

Fig. 1. UAUV data acquisition in ocean sensor networks.

In view of this situation, this paper thinks that the problems to be solved are as follows: In the ideal environment, the best water entry point of UAUV in the cross domain mode is found by traversal search algorithm, and the advantages and disadvantages of cross domain flight path and all underwater path in ocean sensor network data acquisition are compared, which shows that UAUV has high acquisition efficiency and energy saving effect, as well as highlights the necessity and innovation of introducing UAUV.

For this problem, the main parameters to be compared between the two paths are the time required to collect underwater sensor information and the energy consumed to complete a task. This is an ideal model, which does not consider too many complex factors, such as wind speed, water flow, water temperature, air temperature (the consumption and damage of temperature to battery), underwater obstacles, energy consumption of UAUV in and out of the ocean, etc. It is assumed that wind speed and water flow have no effect on UAUV speed, water temperature and air temperature are normal, there is no bad environment in ideal environment, and there is no obstacle in UAUV path planning.

In order to simplify the complexity of the problem, a single sensor is selected as the target point of UAUV data acquisition. As shown in Fig. 2, a two-dimensional ocean plane model from UAUV to single sensor is constructed. Set the UAUV at sea level, and set the starting position of the UAUV coordinate (x_U, h_U) as the origin, set the speed in the air as v_{Air}, and the flight power in the air as P_{Air}. Assuming that P_{Air} does not change with v_{Air}. the flight speed v_{Air} should meet the requirements

$$0 \leq v_{Air} \leq v_{Air}^{\max}, \tag{1}$$

at the same time, the velocity of UAUV in underwater is set as v_{water}, and the power of UAUV in underwater is set as P_{water}. Assuming that P_{water} does not change with the magnitude of v_{water}, the velocity of UAUV in underwater should meet the requirements

$$0 \leq v_{water} \leq v_{water}^{\max}, \tag{2}$$

the communication system of UAUV is a dual communication system, which includes underwater acoustic communication with communication distance r and wireless electromagnetic wave communication with line of sight. The UAUV can choose any communication mode according to its own environment. When the UAUV is underwater, it can use underwater acoustic communication, while in the air, it can use wireless electromagnetic wave communication.

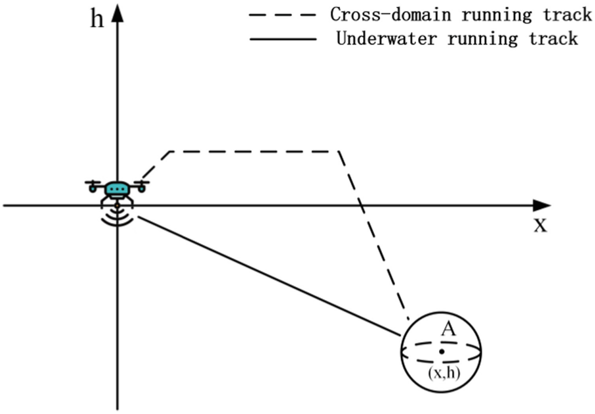

Fig. 2. UAUV with a two-dimensional plane model of a single sensor.

In the study of this problem, the energy of the UAV is not considered, and the total energy of the UAV is expressed as C, C should meet the requirements

$$C \to \infty. \tag{3}$$

In this paper, the coordinate of a sensor node A is (x, h), and the underwater acoustic communication distance of the sensor is the same as r. This paper objectively compares the two modes of cross-domain and underwater motion, and intuitively gives the speed, power and more intuitive data. It is assumed that the R value is fixed and the influence of the underwater channel environment on the communication distance is not considered.

In order to analyze the velocity model of the UAUV in more detail, the air acceleration a_{Air} and the underwater acceleration a_{water} of the UAUV are considered in the model, and it is assumed that the values of a_{Air} and a_{water} are fixed. Due to the acceleration and deceleration process of the UAUV in motion, the relationship between the time t_{water} required for the UAUV to complete a task in the underwater diving mode and the path distance $(l_{water} - r)$ required for the UAUV's current position to move to the vicinity of sensor A can be expressed as

$$t_{water} = \begin{cases} \frac{l_{water}-r}{v_{water}^{\max}} + \frac{v_{water}^{\max}}{a_{water}}, & l_{water} \geq \frac{(v_{water}^{\max})^2}{a_{water}} \\ \sqrt{\frac{2 \cdot (l_{water}-r)}{a_{water}}}, & 0 \leq l_{water} < \frac{(v_{water}^{\max})^2}{a_{water}} \end{cases} \tag{4}$$

where, l_{water} is the Euclidean distance between UAUV and sensor node A, which is expressed as

$$l_{water} = \sqrt{(x - x_U)^2 + (h - h_U)^2}, \tag{5}$$

similarly, the relationship between the time t_{Air} required for UAUV to move in the air and the path distance required for UAUV to move into the location of water entry point x_{Air} can be expressed as

$$t_{Air} = \begin{cases} \frac{l_{Air}}{v_{Air}^{\max}} + \frac{v_{Air}^{\max}}{a_{Air}}, & l_{Air} \geq \frac{(v_{Air}^{\max})^2}{a_{Air}} \\ \sqrt{\frac{2 \cdot l_{Air}}{a_{Air}}}, & 0 \leq l_{Air} < \frac{(v_{Air}^{\max})^2}{a_{Air}} \end{cases}, \tag{6}$$

however, sensor A is installed underwater. the UAUV needs to be converted from air mode to underwater mode on the water surface after flying in the air, therefore t_{Air} cannot be directly expressed as the time t_{cross} needed to travel from UAUV to sensor A. Assuming that the velocity of UAUV from the air to the water is 0, the UAUV mode conversion time and the flight altitude in the air are ignored, and the diving time t_{water} of UAUV is considered on the basis of t_{Air}. Therefore, the cross-domain motion t_{cross} time can be expressed as the sum of t_{Air} and t_{water}, t_{cross} can be expressed as

$$t_{cross} = \left\{ \begin{array}{l} \left. \begin{array}{l} \frac{l_1}{v_{Air}^{\max}} + \frac{v_{Air}^{\max}}{a_{Air}}, l_1 \geq \frac{(v_{Air}^{\max})^2}{a_{Air}} \\ \sqrt{\frac{2 \cdot l_1}{a_{Air}}}, 0 \leq l_1 < \frac{(v_{Air}^{\max})^2}{a_{Air}} \end{array} \right\} t_{Air} \\ \left. \begin{array}{l} \frac{l_2 - r}{v_{water}^{\max}} + \frac{v_{water}^{\max}}{a_{water}}, l_2 \geq \frac{(v_{water}^{\max})^2}{a_{water}} \\ \sqrt{\frac{2 \cdot (l_2 - r)}{a_{water}}}, 0 \leq l_2 < \frac{(v_{water}^{\max})^2}{a_{water}} \end{array} \right\} t_{water} \end{array} \right. , \tag{7}$$

where, l_1 is the flying distance in the air during the UAUV's cross-domain movement, and l_2 is the distance from the sea surface to the vicinity of sensor A during the UAUV's cross-domain movement. The sum of the two represents the total distance l_{cross} of the UAV from air and underwater cross-domain movement to the vicinity of sensor A, i.e.

$$l_{cross} = l_1 + l_2. \tag{8}$$

The whole process of UAUV moving from the starting point to sensor a and then collecting data can be regarded as completing a task, the total energy consumption W_{cross} can be expressed as

$$W_{cross} = P_1 \cdot t_1 + P_2 \cdot t_2 + \cdots, \tag{9}$$

that is, the sum of the product of the power corresponding to the UAUV motion mode and its motion time.

3 Analog Simulation

Through the establishment of the corresponding model of the problem, the system variable planning, and according to the results of the objective analysis of UAUV. The data acquisition method of UAUV underwater motion mode is simple and refined, while the data acquisition method of cross domain mode is relatively complex. In this paper, the best entry point of UAUV is searched by traversal, so as to choose the most effective path and save time and energy as much as possible.

According to the objective data of UAUV given by Wang et al. [20], we may reasonably assume the specific performance parameters of UAUV in this scenario, as shown in Table 1.

Table 1. Performance parameters of UAUV in simulation test.

Parameter	Meaning and value
$v_{Air}^{\max}$	The maximum speed of the UAUV in the air is 20 m/s
a_{Air}	The maximum acceleration of the UAUV in the air is 5 m/s^2
p_{Air}	The operating power of the UAUV in the air is 180 W
$v_{water}^{\max}$	The maximum speed of the UAUV in the sea is 5 m/s
a_{water}	The maximum acceleration of the UAUV in the sea is 1 m/s^2
P_{water}	The operating power of the UAUV is 60 W when submerged in the sea
r	The maximum distance of UAUV and sensor underwater acoustic communication is 1000 m

In the simulation test, given the specific location coordinates (10^5, 10^3) of sensor A, the unit is m, that is, sensor A is placed 1 km under the sea, 100 km horizontally from the starting point of UAUV.

According to the model, the algorithm idea was determined, and the time and power consumption needed to complete the data collection of UAUV underwater motion mode were obtained. The traversal method was used to search the optimal entry point of UAUV cross-domain motion mode, and the shortest time and minimum power consumption to complete the task were calculated respectively.

Algorithm 1: Search algorithm for the best water entry point based on traversal

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1: Calculate the time and power consumption of underwater mode
2: Cycle
3: for L1 = 0:5:$10^6$
4: Calculate and record the minimum time $t_{cross}$ and power consumption $W_{cross}$ of cross domain mode
5: Compare the minimum update time $t_{cross}$ and power consumption $W_{cross}$
6: Record the best water entry point L1 for the shortest time and minimum power consumption respectively
7: end for
8: Until the end of the loop, traverse the optimal results
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4 Performance Analysis

In order to verify the advantages of the UAUV described in this paper, the following results are obtained through simulation. Firstly, the data acquisition time of two motion modes is analyzed. It can be seen that in the underwater navigation mode, the time t_{water} for UAUV to collect data from the initial point to the sensor A is 19806 s, while in the cross domain mode, the time t_{cross} for UAV to complete data collection is only 5002.65 s. From Fig. 3, we can see the relationship between the two modes. Compared with the traditional AUV, the time of the cross domain mode UAUV saves nearly 74.7%. According to the simulation results, the water entry point L1 is the water surface at 9.974×10^4 m from the starting point of UAUV, which is the coordinate point (9.974×10^4, 0), with the shortest time as the leading factor.

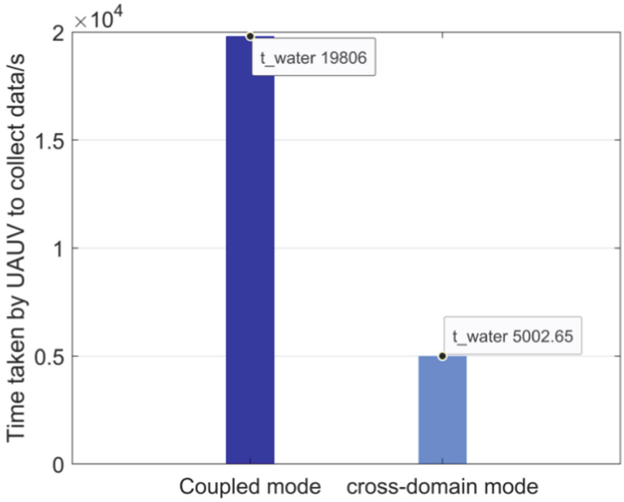

Fig. 3. Comparison of data acquisition time for different motion modes of UAUV.

From the analysis of energy consumption dimension, we can see that the energy consumption W_{water} of UAUV in underwater navigation mode is 330.1 Wh. In cross domain mode, the optimal water entry point L1 with the shortest time as the dominant search is (9.974×10^4, 0), and the energy consumption W_{cross} is 249.744 Wh. We can see from Fig. 4.

Among them, the energy consumption of cross domain UAUV is 24.34% lower than that of traditional AUV. However, with the shortest time as the dominant factor, its energy consumption is not the minimum. The minimum energy consumption W_{cross} of L1 coordinate (9.8865×10^4, 0) is 249.155 Wh, which is 24.52% lower than that of traditional AUV. The results show that the energy consumption based on the shortest time is basically the same as that based on the minimum energy consumption, but it is proved that the energy consumption of UAUV completing the task in the shortest time is not the minimum energy consumption.

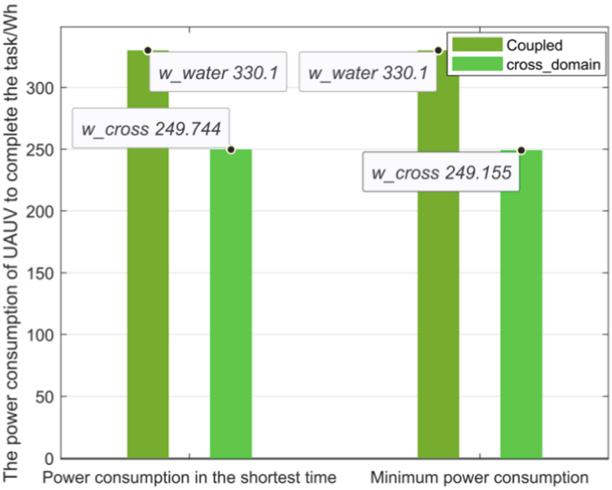

Fig. 4. Comparison of energy consumption for data acquisition in different motion modes of UAUV.

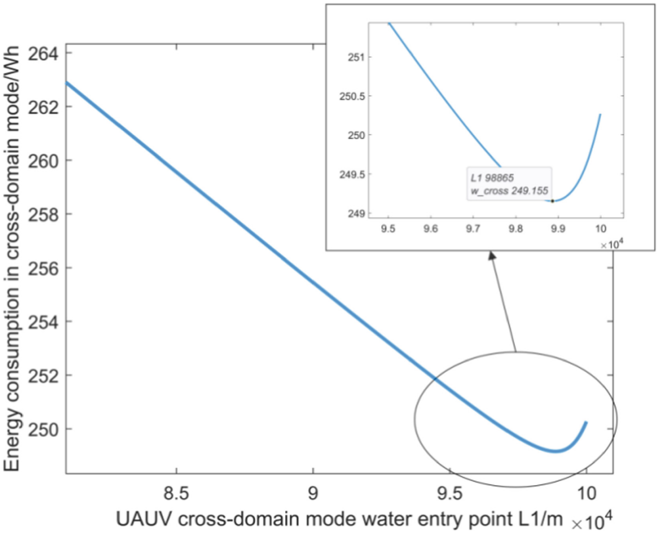

Fig. 5. Relationship between UAUV water entry point L1 and energy consumption.

Taking the water entry point L1 of UAUV cross-domain model as the analysis variable, it can be seen from Fig. 5 that when L1 is less than 9.8×10^4 m, the relationship between the water entry point and the energy consumption is approximately linear, that is, the energy required by UAUV to complete the task gradually decreases with the distance from the water entry point, while L1 increased from 9.8865×10^4 m to the horizontal distance of sensor A 10×10^4 m, the energy consumption shows a rapid upward trend. This indicates that the longer the flight time of UAUV in the air, the less energy is needed to complete the data acquisition task. At the same time, it also reflects the advantages of the UAUV in the air flight, and the necessity of introducing the UAUV into the ocean sensor network to replace the traditional AUV. The relationship between the time of UAUV entering the water point L1 and the time required to complete the task is shown in Fig. 6, and the trend is similar to that in Fig. 5, when L1 is greater than 9.974×10^4 m, the time consumption began to rise.

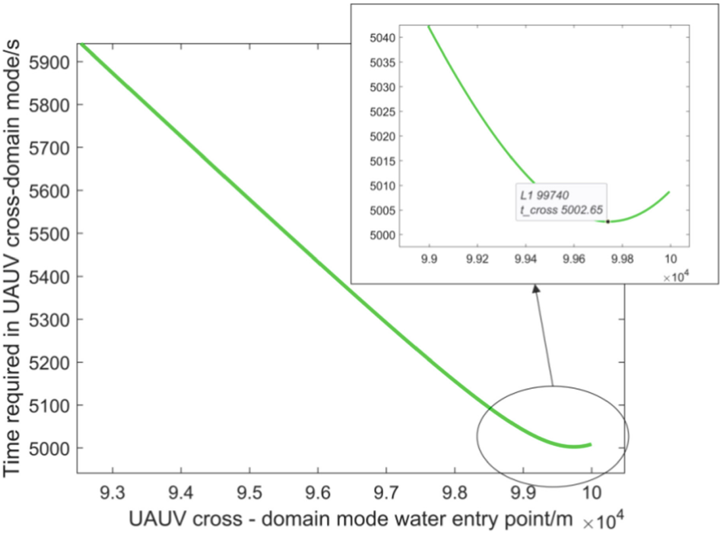

Fig. 6. Relationship between UAUV water entry point L1 and time.

5 Conclusion

This paper introduces the current situation of underwater robot in ocean sensor network and the development of UAUV, analyzes the advantages of UAUV, and proposes to introduce UAUV into ocean sensor network. Firstly, this paper makes a direct comparison between UAUV and traditional AUV in terms of speed and energy consumption. Through traversal search, find the best water entry point. The experimental results show that the running time of UAUV is 74.7% lower than that of AUV, and the energy consumption was reduced by 24.52%. At the same time, the influence of different water entry points on the time and energy consumption when the UAUV cross-domain motion collects sensor data is also shown. The simulation results show that the performance advantages of the UAUV, as well as the real-time performance and energy cost of data acquisition in the ocean sensor network are very good. The simulation results aim to provide intuitive data for further understanding of UAUV, show the advantages of UAUV in collecting ocean sensor data, and provide data support for guiding the next research and development of UAUV. UAUV not only shows advantages in the ocean sensor network, but also can carry servers, etc. Therefore, UAUV also can provide powerful data processing capacity and communication relay capacity for the ocean communication network.

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