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Design of a dual-mode AUV for crawling and swimming under Arctic ice

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ABSTRACT

We propose a new concept AUV which equips with the capability of crawling, swimming under the Arctic ice and a variety of underwater operations. The AUV adopts the biomimetic shape of the stingray and employs multiple thrusters and buoyancy adjustment hybrid drive to realize the dual work of crawling and agile swimming under Arctic ice. Meanwhile, the AUV adopts advanced modular design idea and intelligent control strategy, and has the ability of rapid load reconstruction. It meets various operational requirements such as large-scale under-ice scanning, under-ice mesoscale high-precision acoustic stereo imaging, local fined-grained time-series observations, in-situ sampling of ice algae under Arctic ice. Based on the AUV, we utilize an underwater non-contact adsorption technology based on fluid vortex motion, and combine this technology with the underwater crawling dual-mode AUV, which can greatly improve the stability of the AUV crawling and sampling operations under Arctic ice. In addition, the highly reliable autonomous hybrid control technology for the dual-mode AUV under ice climbing and swimming is proposed, which solves the difficulty of constructing a high-precision six-degree-of-freedom hydrodynamic model of the AUV. In summary, the proposed techniques and methods have a great impact on further research on the Arctic ice and seabed environment, resource exploration and other fields.

KEY WORDS: Autonomous underwater vehicle; Crawling and swimming; Vortex-based suction cup; Underwater non-contact adsorption.

INTRODUCTION

The response of the Arctic subglacial ecosystem to the rapid change of sea ice is a hot topic and frontier of polar ocean research (Boetius et al., 2015). The earliest AUVs for polar ocean exploration appeared in the 1990s (Wallis et al., 2010). Today, there are dozens of polar AUVs. According to different scientific research missions, each platform size, weight, load, and other design parameters are not the same.

Autosub series AUVs (Autonomous Underwater Vehicles) developed by UK National Marine Center are the representative of the application of AUV in polar areas (Furlong et al., 2012). In 2000, AUI (Autosub Under Ice) project used Autosub to explore the ice-sea interaction in polar regions and the impact of ice on the ecosystem. Developed by Woods Hole Oceanographic Institution in collaboration with Johns Hopkins University, The Nereid Under Ice (NUI) is a Remotely Operated Arctic ice observation vehicle that uses a fiber-optic tether for remote control and acoustic modem communication. Besides, it is equipped with inertial navigation and Doppler Velocity Log for under-ice navigation and imaging sonar for under-ice collision avoidance (German et al., 2014). Autonomous and Remotely Operated Polar ARVs (Autonomous and Remotely Operated Vehicles), developed by the Shenyang Institute of Automation of the Chinese Academy of Sciences in 2008, are mainly used for under-ice investigation in the Arctic. Polar ARVs have on-board power and fiber-optic technology to survey autonomously within a range or to be guided to a fixed target point (Yoerger et al., 2007). Fan et al. (2022) present a climbing AUV which uses a vortex-based suction cup to provide adhesion for AUV climbing motion.

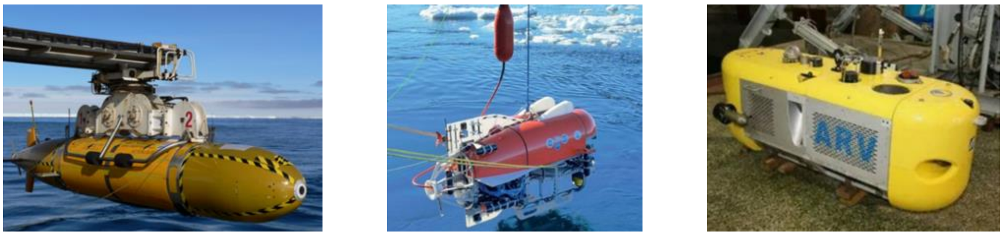


Figure 1. Autosub series AUV, Nereid Under Ice observation vehicle and Polar ARV

In general, AUVs have become a mainstream tool in the exploration of polar scientific problems, and various maritime powers in the world have developed several AUVs for polar regions. However, due to the harsh natural conditions in polar regions, the current technology can not guarantee the absolute safety of AUV under Arctic ice. There is a lack of AUVs suitable for complex ice bottom crawling and in situ operation. The application of advanced intelligent autonomous control technology in polar AUVs needs further exploration. The Arctic Ocean is covered by a vast expanse of ice. Limited by the harsh natural conditions such as high latitude, low temperature, and thick ice (Adumene et al., 2022), routine operations of AUV such as mobile sea observation and terrain and landform mapping are increasingly difficult, which puts forward high requirements for the structural design and working performance of AUV. In addition, most of the lower surface and sides of the polar region in contact with the ocean show extremely irregular forms, which brings great challenges to the close-range observation and operation of Arctic ice, and often requires the ability of diving equipment to attach to Arctic ice. The study of subglacial ecosystem has put forward higher requirements for large-scale observation under Arctic ice, and it is urgent for AUV with two operating modes of subglacial crawling and underwater agile swimming to carry out high-quality and efficient operations under the polar ice.

It can be seen from the survey that some AUVs in the past need to be improved. For example, some existing AUVs lack advanced design concepts and the latest control technology, resulting in a lack of mobility, autonomy, intelligence and stability in under-ice operations. At the same time, some AUVs are limited by size and structure, so it is difficult to realize the dual working modes of crawling and agile swimming under Arctic ice. Therefore, a kind of AUV with strong maneuverability, which can adapt to the polar working environment, and has two working modes of crawling under the ice and swimming in the water, named Arctic dual-mode AUV, is proposed. The key technologies of the multidisciplinary optimization of the AUV, such as the overall design and autonomous control, are realized.

GENERAL STRUCTURE DESIGN

After comparing the resistance coefficients and layout space of various shapes, we designed a AUV with near ellipsoid shape. Figure 2 shows different shape schemes and corresponding resistance coefficients, which were obtained through simulation of the standard k-ε turbulence model with 3 million grids, and shapes 8 was ultimately used. Using a hybrid propulsion system of multiple thrusters and buoyancy control, it can both crawl under Arctic ice and swim nimbly. Modular design concept and advanced intelligent control strategy are adopted in the design, enabling the AUV to quickly reconstruct various loads. There are four operating modes: large-scale under-ice scanning, under-ice mesoscale high-precision acoustic stereo imaging, locally refined time series observations, in-situ sampling under Arctic ice. Each operation mode has different requirements on the motion ability of AUV.

The AUV's modular design allows for rapid installation and reconfiguration of a variety of functional loads, including a manipulator, camera, irradiance meter, image sonar and CTDs, which can be restructured to enable no less than four subsea exploration operation modes. The overall structure of the dual-mode AUV is shown in Figure 3.

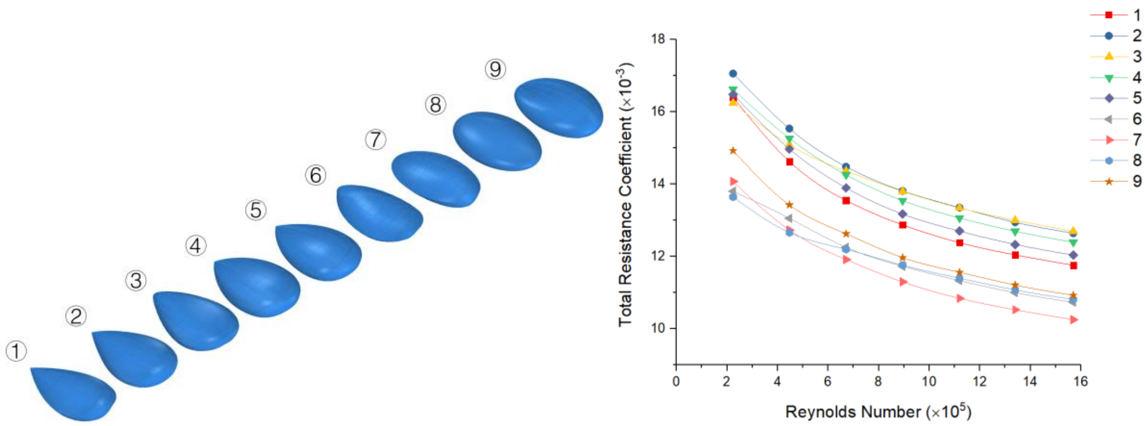


Figure 2. Various shape schemes and corresponding resistance coefficients

Figure 3. Overall structure of the AUV

Firstly, the structure layout design and hydrostatic design of the AUV were carried out, and the three-dimensional modeling of the AUV is completed. Due to the limitation of the distribution and recovery conditions in polar regions, AUVs are small and require compact layout. The layout dynamic optimization design technology and modular design technology based on multi-input conditions are adopted to realize multi-load cooperative distribution. Figure 4 shows the AUV structure layout.

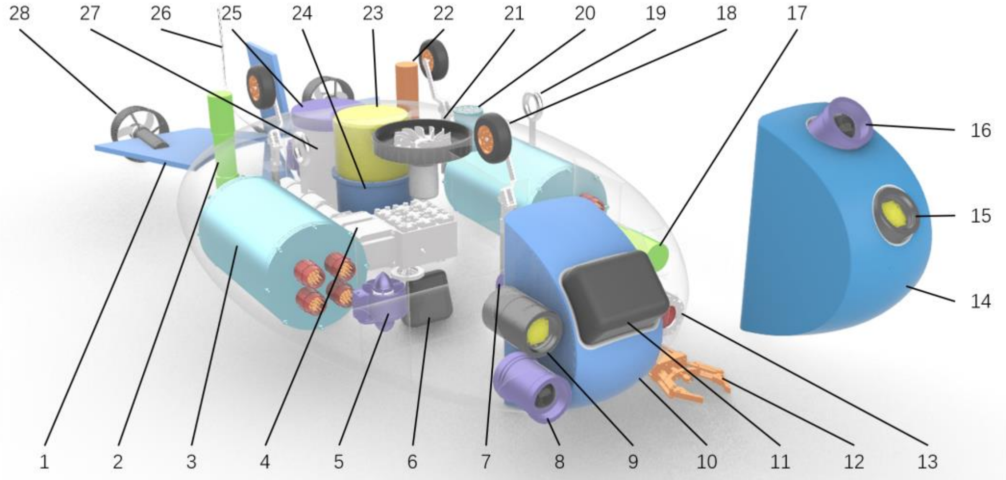


Figure 4. Structure layout of the AUV

Each part of the figure indicates the structure as follows: (1)Stabilizer tail; (2)Height and depth meter; (3)Electronics cabin; (4)Buoyancy adjustment mechanism; (5)Vertical thruster; (6)Jettison iron; (7)Lateral thruster; (8)Forward camera; (9)Forward lighting; (10)Replaceable load module; (11)Image Sonar; (12)Manipulator; (13)Optical communication module; (14)Replaceable load module; (15)Upward lighting; (16)Upward camera; (17)Obstacle avoidance sonar; (18)Crawling caster; (19)Lifting ring; (20)Irradiance meter; (21)Vortex-based suction cup; (22)Conductivity-Temperature-Depth meter; (23)Doppler Velocity Log; (24)Inertial navigation system; (25)Charging coil; (26)Optical fiber; (27) Ultra Short Base Line system; (28)Main thruster.

The stability and structural strength of the AUV structure are analyzed, including the statics and dynamics analysis of joint joint mechanisms such as the AUV support structure, operation module fixing mechanism and chassis-body fixing mechanism, and the vibration modal research of the robot structure is carried out to analyze the natural frequency, damping ratio and mode shape of the mechanical structure, to accurately identify the modal parameters of the system structure. Finally, for the miniaturization and lightweight requirements of the robot, the structural strength analysis and optimization were carried out. Aluminum alloy, titanium alloy and carbon fiber materials were comprehensively used to reduce the weight of the AUV and enhance the carrying capacity.

For the agile parade of the AUV under ice, we carried out the overall design and optimization of the AUV's shape. It adopts a near ellipsoid shape with good rapidity, stability, floatability and low manufacture cost. The computational fluid dynamic simulation analysis, the towing test of the scale model and the system parameter identification of the principle model were carried out to obtain the first-order and second-order hydrodynamic coefficients of the AUV and construct a complete dynamic model of the AUV. According to the establishment of the dynamic model, a complete kinematics simulation model is further established to realize the estimation and optimization of motion performance of the AUV.

In addition, in view of the complex working environment under the polar ice, the hydrodynamic characteristics of the AUV near the under-ice surface are studied in order to achieve stable adsorption and crawling. In this case, the under-ice surface will significantly affect the hydrodynamic performance, and the traditional hydrodynamic analysis in infinite flow field will be distorted. Based on the traditional hydrodynamic analysis, the specific influence parameters of under-ice surface on AUV are obtained by simulating different distance between AUV and under-ice surface. Figure 5 shows the hydrodynamic simulation analysis result of the AUV model near with under-ice surface.

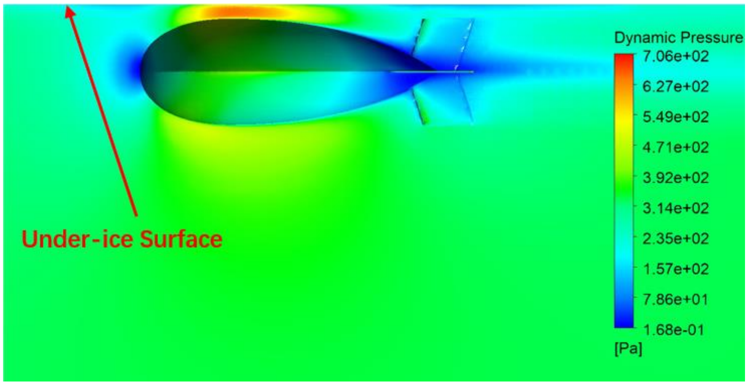


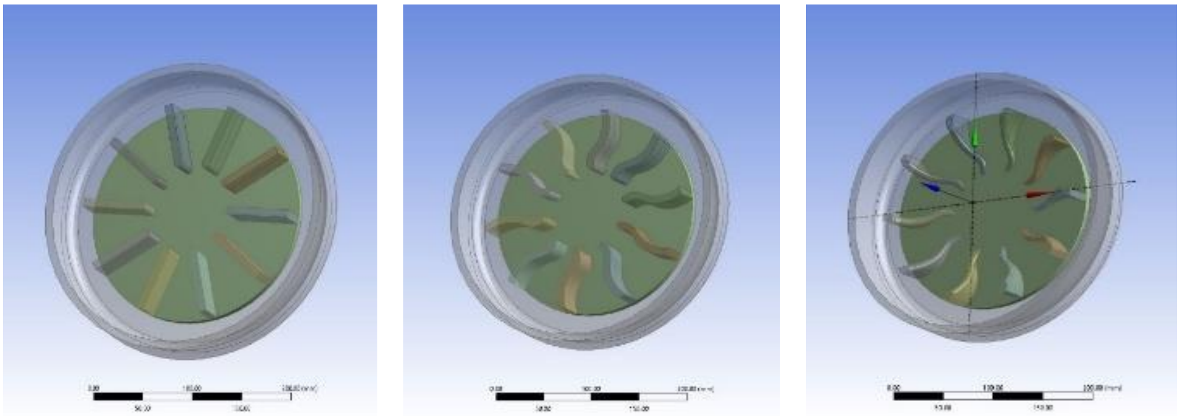
Figure 5. Pressure nephogram of the AUV at 0.2m away from under-ice surface by CFD simulation

BUOYANCY ADJUSTMENT AND NON-CONTACT VORTEX ADSORPTION

The dual-mode AUV is equipped with crawling casters at the top to achieve stable crawling under Arctic ice in a positive buoyant state. Non-contact adsorption technology is used to enhance the adhesion under Arctic ice for stable sampling operations.

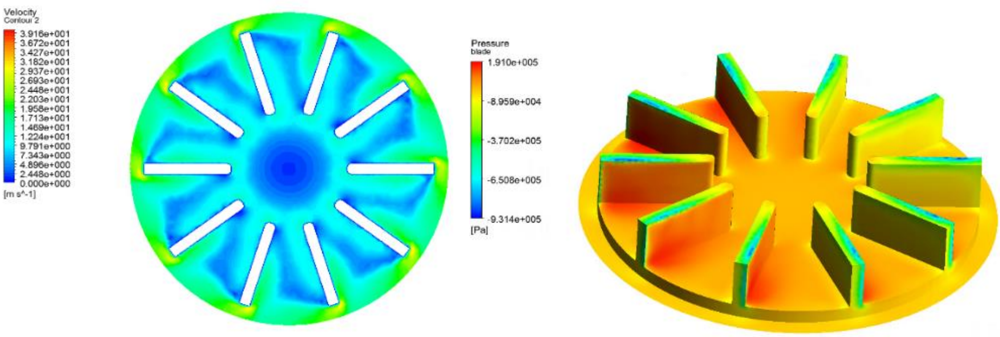
In order to achieve the conversion of swimming and crawling mode, the AUV should have the ability of mass buoyancy adjustment. However, the AUV has light weight and small volume, and the traditional oil-sac buoyancy regulation module is heavy and can not meet the requirements. Therefore, the principal design of seawater buoyancy regulation system was carried out, and the high reliability direct seawater buoyancy regulation system was built. The limited weight/space occupancy was greatly reduced by using the seawater pump and wet seawater control valve suitable for polar environment, and the prototype of seawater buoyancy adjustment device was formed.

Aiming at the requirements of adsorption and wall climbing under polar ice, steady-state flow field characteristics and internal pressure field distribution characteristics of water media vortex generator were analyzed, to clarify the mapping relationship among the adsorption force, working distance, blade rotation speed and adsorption Angle and posture of deep-sea vortex-based suction cup (Xinzhe Yu, 2018). In order to obtain the maximum adsorption force, maximum working stroke range and minimum energy consumption, the structure form of vortex generator, blade curve and structural parameters of vortex flow field were optimized, and the principle prototype of vortex-based suction cup was designed. The dynamic and static adsorption characteristic test bed of the scroll sucker was built, and the dynamic and static adsorption characteristic experimental research of the scroll sucker was carried out respectively to test the pressure field distribution on the adsorbed surface, reveal the variation law of the adsorption force of the scroll sucker, and realize the optimal design of the structural parameters of the scroll sucker.

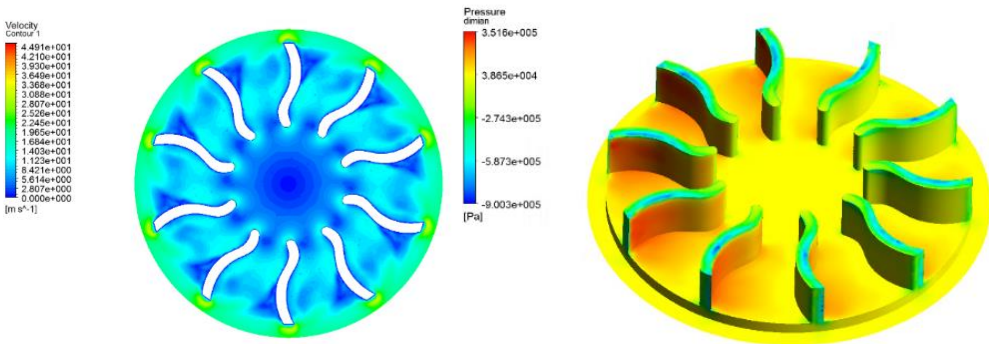


(a) Model 1: Rectangular vane (b) Model 2: S-shaped vane (c) Model 3: Inward tapered S-shaped vane

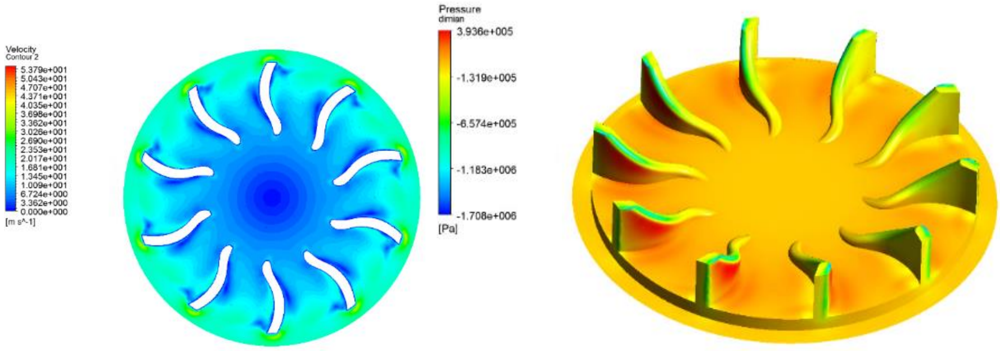
Figure 6. Three kinds of impeller models.



(a) Velocity and pressure distribution of Model 1



(b) Velocity and pressure distribution of Model 2



(c) Velocity and pressure distribution of Model 3

Figure 7. Fluid velocity and pressure distribution inside suction cup of different impeller models

RESEARCH ON MULTI-CONTROLLER CONTROL SYSTEM

When AUV is crawling or swimming under the Arctic ice, the non-linearity and complexity of the six-degree-of-freedom motion and the complex environment of Arctic ice surface will affect the real-time and stability of the motion control, so the conventional AUV control algorithm cannot be adopted. In order to solve this problem, we adopt the crawling and swimming dual motion mode, fiber optic remote control/autonomous cruise hybrid control and multi-scale adaptive modular design control for AUV. In the process of in-situ observation and operation of the AUV adsorbed on Arctic ice floor, the fuzzy control algorithm with low model dependence is also adopted to control the buoyancy regulation system, and the water injection is changed so that the buoyancy of the AUV is greater than gravity and floats to the near Arctic ice floor, and the position of the target on Arctic ice floor is detected according to the fusion of sonar and camera information. Fast online path replanning is realized according to the dynamically adjusted target position, and the attitude of the submarine is adjusted and controlled in real time according to the target position, to guide the AUV to arrive at the target attitude accurately, quickly, and safely and stably adsorb at the set observation point. Crawling under Arctic ice floor relying on non-contact adsorption technology mainly relies on the coordination of two main thrusters at the tail to realize forward, backward, and steering motion control under Arctic ice floor, as shown in Figure 8. When the AUV uses the scroll sucker to adsorb Arctic ice floor for local refinement, the suction sensor can sense the resultant force of Arctic ice bottom adsorption generated by the buoyancy regulation system and the scroll suction in real time.

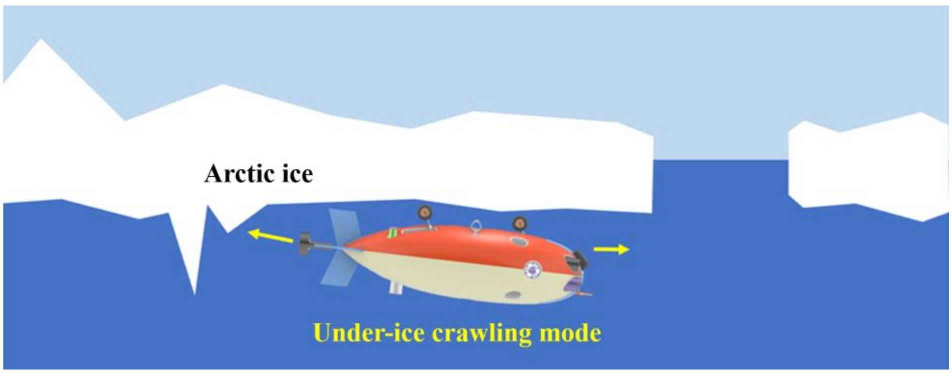


Figure 8. Under-ice AUV crawling main thruster system control

At the same time, the control system of the AUV supports the autonomous mode and the remote-control mode in the adsorption state. When the AUV is adsorbed on the bottom of Arctic ice for local refinement operations, the control system switches to the micro-optical fiber remote control mode. In remote control mode, the operator sends commands to the AUV via tiny fiber-optic cables to steer it to complete its tasks. With high-definition video from AUV, operators can get a clear view of conditions under ice. The controller translates the received control data into the driving signals of AUV thrusters, screw suckers and robotic arms according to the preset conversion format, to manipulate and execute the machinery to complete the corresponding operation tasks.

The Under-ice AUV obtains the flow site map of the operation area by combining the velocity sensor with the ocean current prediction model. For a specific scientific observation task, the optimal trajectory planning from the starting point to the target position is studied. Considering the timeliness of the task and the limited energy carried by the AUV, the trajectory time, energy consumption and path smoothness were designed as cost functions. The particle model of the AUV combined with the ocean current speed to establish a motion model, as the constraint condition of an optimization problem, the point-to-point path optimization problem was established, and the globally optimal path (three-dimensional path sequence) of the AUV was obtained. It relies on the camera and 3D sonar carried by the AUV to obtain the spatial position information of the obstacles under Arctic ice, and then input the information into the dynamic obstacle avoidance strategy neural network. The reward and punishment functions and constraints of the neural network are designed to obtain the local obstacle avoidance trajectory in real time, correct the global trajectory, and realize the motion synthesis to output the local path sequence of the AUV. To ensure the safe implementation of large, medium, and small-scale scientific observation and sampling missions in the complex subglacial environment.

APPLICATIONS

Finally, for the scientific problem of "the response of Arctic ecosystem to the rapid change of Arctic ice", four working modes are designed as follows:

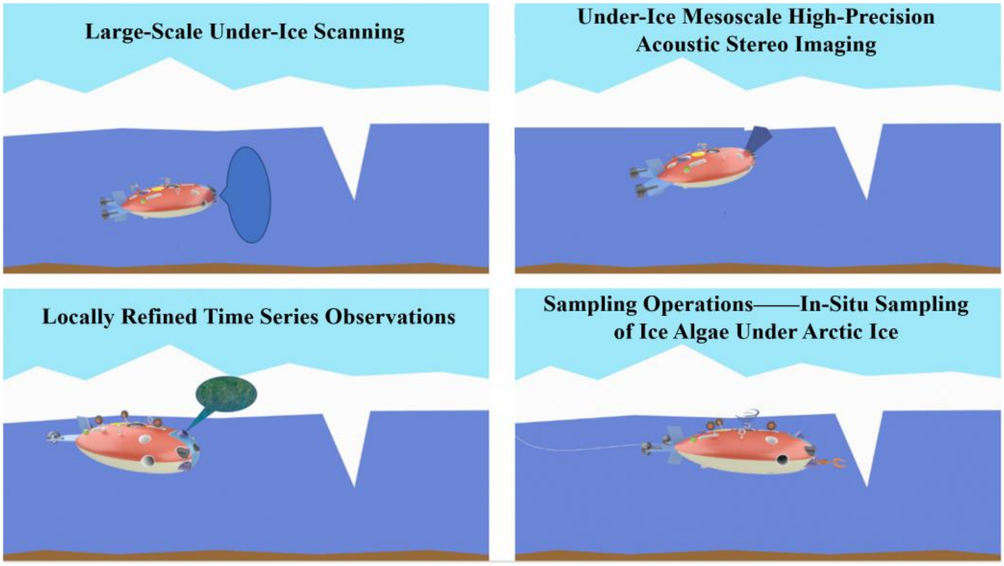


Figure 9. Schematic diagram of working modes

Large-Scale Under-Ice Scanning

In this working mode, CTD, PAR and Chl-a sensors will be deployed under Arctic ice, and the vehicle will sail independently within a radius of 1km from the deployment point, with a depth of 50-200m and a speed of less than 2kn. Large-scale continuous variation data of subglacial temperature, salinity, PAR and Chl-a were obtained to provide data support for subsequent research on subglacial water mass evolution, seawater stratification and primary productivity in the Arctic

Under-Ice Mesoscale High-Precision Acoustic Stereo Imaging

In this working mode, the AUV is deployed under Arctic ice with image sonar. Within a range of 500m of the distribution point as the center radius and a depth of 10m-20m from the underside of Arctic ice, the serpentine reciprocating motion is carried out at a speed of 2kn, and the coverage of the range area is achieved by image sonar scanning, to obtain a complete fine image of the area under Arctic ice. Furthermore, high-resolution spatial distribution patterns of subglacial ice algae in the long-term ice station area at high latitudes in the Arctic were obtained to provide auxiliary materials for further development of the Arctic ice coverage and structural changes.

Locally Refined Time Series Observations

After obtaining the high-resolution topography data of the subsurface ice surface in the presequencing test, the landing area was selected as flat as possible and with the distribution of subsurface ice algae. In this mode, the AUV, carrying CTD, PAR, and Chl-a sensors and cameras, moves autonomously or remotely under the area, adjusting its buoyancy to climb the wall, and climbing back and forth over the area to take high-definition digital images of Arctic ice algae in the area. At the same time, the time series changes of temperature, salinity, PAR and Chl-a were recorded to study the process of local sea ice ablation and ice algae release.

Sampling Operations——In-Situ Sampling of Ice Algae Under Arctic Ice

In this working mode, a mechanical arm grasping device is installed on the AUV, and in the optical fiber remote control mode, the AUV swims to the designated area (flat under-ice areas with the presence of ice algae identified by modes 2 and 3), adjusts the buoyancy and floats up to achieve wall climbing, and carries out accurate position control through reciprocating crawling. Finally, the scroll suction cups are opened to stabilize the AUV body. In addition, local sampling was realized by the manipulator in the adsorption crawling mode to capture, sample and store ice algae under the Arctic ice, which provided in situ sample support for the subsequent laboratory to analyze the biomass, community structure and dominant species of ice algae under the Arctic ice.

CONCLUSIONS

The proposed AUV can crawl and swim under Arctic ice with high mobility, long time and high resolution in extreme Marine environment. There are two motion modes of crawling and agile cruise under Arctic ice, and four working modes of scanning under Arctic ice, high precision stereoscopic imaging under Arctic ice, fine long time series observation and in situ sample sampling. It can realize the non-contact adsorption under Arctic ice of AUV, and then carry out local fine observation and in situ sample sampling. The modular design of the AUV can carry CTD, light irradiance meter, three-dimensional imaging sonar and other loads according to the operation requirements, and carry out large-scale scanning under Arctic ice and fine acoustic stereo imaging under Arctic ice in the Arctic ice region, filling the gap in the dual-mode crawling motion mode of the AUV under the polar ice.

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