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Development and path planning of a novel unmanned surface vehicle system and its application to exploitation of Qarhan Salt Lake

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Qarhan Salt Lake is rich in mineral resources, such as sodium chloride, potassium, and magnesium [1]. At present, liquid mine exploiting is the main exploitation form for the Qarhan Salt Lake. Salt mining ships with mining equipments are widely used to exploit carnallite which is located at the bottom of pools. Conventionally, workmen utilize rude ferric sampler to collect carnallite samples and estimate their thickness, providing guidance to the salt mining ship [2]. However, the turbid brine and uneven carnallite reduce the efficiency of exploitation, which could no longer meet the rapid mining requirements. Furthermore, the salt mining ship is equipped with the differential global positioning systems (DGPS) to achieve precise position and navigation. How to yield an optimal path rapidly is a real-world topic worthy of further study [3–5].

In order to solve the above problems, this study presents an unmanned system-based precise exploitation and meticulous production solution for the Qarhan Salt Lake. A modularized and multifunctional unmanned surface vehicle (USV) system is firstly developed. Different devices of the USV are customized to meet the various needs of different applications, such as topographic mapping, online ion concentration detection, automatic carnallite sampling, as well as navigation guiding. Secondly, the path planning algorithm is the core function and key technology of location and navigation system [4, 5]. To satisfy the demand of fast path planning, an improved rapidly exploring random tree (RRT) algorithm is employed to generate paths with faster convergence rate and better stability. Finally, both simulation and field experiments are conducted to verify the effectiveness of the proposed planner and the developed platform.

Overview of the modular USV. The prototype of the modularized and integrated USV for Qarhan Salt Lake is depicted in Figure 1(a). The shell is made of fiber reinforced polymer (FRP), which is well suited to the corrosive environment and long-span light-weight structures. A host computer on the shore is used as a console, which is responsible for remote control. Besides, according to the processed GPS data, the console plans paths for the USV and the salt mining ship to achieve automatic cruise. The propellers are anti-crystallized by a zinc-plating technique in response to harsh environments.

The multi-functional USV system adopts the

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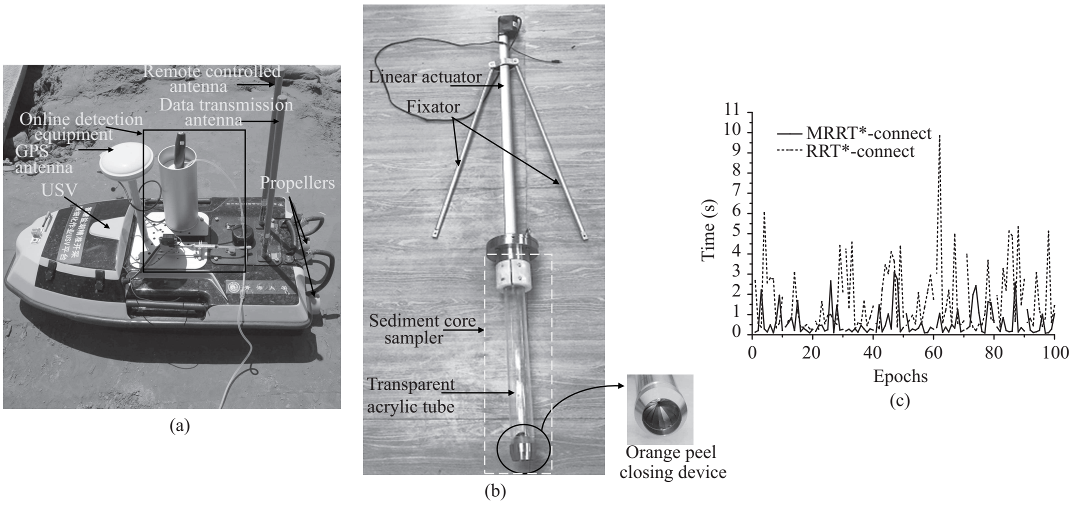

Figure 1 (a) The USV with online ion concentration detection equipment; (b) the USV with the automatic carnallite sampling equipment; (c) simulation results for two planners.

modularity concept for meeting different requirements. The main functions of the USV involve underwater topographical surveying, online ion concentration detection, and automatic carnallite sampling. The single beam echo sounder is mounted at the bottom of the USV, which is utilized to complete topographical surveying of the brine by transmitting sound waves into it.

The online ion concentration detection equipment consists of a multi-ion analyzer and an automatic brine suction device. The analyzer allows for rapid, easy, and simultaneous measurement of up to six ions in a brine solution. It is noteworthy that the concentration of some ions exceeds the full-scale value of the analyzer. An available solution is to dilute with pure water and expand detection results, then it is essential to sample brine accurately. The pure water must be the deionized water to ensure the accurate results. Through collection, dilution, detection, and amplification, the result of ion concentration can be obtained. The automatic brine suction device is composed of a microcontroller, a servo, a syringe, and a hose with check valves. The microcontroller is controlled by the console through a radio frequency wireless transceiver module. The servo is connected to the syringe with a movable connecting rod, which drives the piston to execute linear reciprocating motion. Thus, brine suction and extrusion are achieved. Furthermore, the syringe needle connects with the hose, and the end of the hose stretches into the brine. The device can hence accurately collect samples at different depths and in different regions through accurately controlling the swing number of servo.

The mechanism of automatic carnallite sampling is depicted in Figure 1(b). A waterproof linear actuator with approximately one-meter length is fixed with a sediment core sampler, which is installed along both sides of the USV. The sampled carnallite is visible through the transparent acrylic sample tube. The bottom of the tube holds an orange peel closing device (core catcher), which will prevent the sample from exiting. The linear actuator drives the sediment core sampler into the brine via wireless communication.

Path planning. Rapid and effective path planning strategy for the USV lays a solid basis for underwater topographical mapping [5]. The guider ship moving back and forth on the lake will be the moving obstacle for the USV. During the in-situ test, there may be abnormal status, e.g., deviation from the predetermined trajectory owing to the waves. All these factors will be considered as threats to the planned path. Rapid and effective path planning ability is thereby crucial. The RRT*-connect algorithm is a combination of the classic RRT* and bidirectional search RRT-connect algorithms. It has been verified that the algorithm has a better asymptotic optimality and well known narrow-passage passing performance [3]. The proposed MRRT*-connect algorithm is a modified heuristic strategy from the RRT*-connect. The operation process of the MRRT*-connect is described as follows.

In the initial phase, the start point x_{init} and the end point x_{goal} are set as root nodes for two trees (i.e., G_a and G_b). The two trees alternate between moving towards the other root node in search space until an obstacle is met. In the extension process, if obstacles are encountered along the solution paths, a new state node x_{rand} is randomly sampled from the C-space. The newly sampled node is added to the corresponding tree and treated as the root node of the trees G_a or G_b to guide the direction of exploration of the two trees. At each iteration, both trees are incrementally extended towards each other. Two trees are maintained at all times until they become connected, and a solution is found. The more detailed path planning process can be referred to the supporting information. The extended way is different from the RRT*-connect.

Simulation and field tests. In order to verify the effectiveness of the proposed algorithm, a simulation comparison between the two schemes was performed by using MATLAB. After about 100 trials, the simulation result of the two algorithms is depicted in Figure 1(c). The average computation time of the RRT*-connect was 1.732 s, which is more than three times than the MRRT*-connect (0.57 s). The convergence rate of the proposed algorithm was about three times as fast as the RRT*-connect method. Furthermore, the standard deviation of the MRRT*-connect is 0.67, and the RRT*-connect is 1.69. A lower standard deviation revealed that the MRRT*-connect had better stability and convergence property than the RRT*-connect. It was apparent that the proposed algorithm sped up the overall planning efficiency.

To demonstrate the feasibility of the developed multifunctional USV, in July 2018, some field experiments were conducted in a salt pond whose dimensions were 18 m×50 m at Qarhan Salt Lake, Qinghai province, China. It involved underwater topographical mapping, automatic carnallite sampling, and online brine ion concentration detection.

The single beam echo sounder was utilized to survey the topography of the salt pond. The thickness of carnallite layer could be estimated through the relative benchmark of topography. As for the same area, a topographic map is firstly drawn. With the growth of carnallite, the updated topography can be mapped after a couple of weeks. In such a case, the thickness of carnallite layer could be calculated through the difference between them. For details of other experimental results, please refer to the attached videos and supplemental documents.

Discussion. The proposed path planner is a variant of the RRT*-connect that is a combination of the classic RRT* and RRT-connect algorithms. Simulation results show that the presented method has a faster convergence rate and better stability, indirectly verifying the asymptotic optimality and better narrow-passage passing performance of the proposed path planner.

Despite successfully implementing field experiments, there are other issues should be mentioned. The major disadvantage of the single beam echo sounder is that it illuminates only a narrow portion, the depths between survey lines will be omitted from the bathymetric data, while multibeam echo sounder can provide continuous coverage. Consequently, accurate modeling bathymetric models are crucial to interpolate the depths and fill the gaps between the survey lines. Furthermore, the measurement accuracy is affected by stained water and stormy waves. This is a crude way to estimate the thickness of carnallite layer through a relative benchmark method. To ensure precise and convincing analysis of online brine ion concentration detection, the diluent without interference ions should be afforded.

Conclusion. We have developed a modularized USV system based detection solution for the Qarhan Salt Lake. Its modularized design offers a solid guarantee for functional expansion. Then, a path planner based on the MRRT*-connect algorithm is created. Both simulations and field experiments are conducted to validate the effectiveness of the proposed scheme. The developed unmanned system based detection scheme sheds light on the automatic and intelligent exploitation of Qarhan Salt Lake, which can be expanded to other extreme aquatic environments.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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