Development and Path Planning of a Novel Unmanned Surface Vehicle System and Its Application to Exploitation of Qarhan Salt Lake

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Outline

- Introduction
- Modular and Multifunctional USV
- Path Planning
- Simulation and Field Tests
- Conclusion and Future Work

Introduction

Salt Lake exploitation

◆ **Abundant mineral resources**

Qarhan Salt Lake is rich in mineral resources, such as sodium chloride, potassium, and magnesium.

◆ **Malpractice of the traditional mining**

The turbid brine and uneven carnallite reduce the efficiency of exploitation, which could no longer meet the rapid mining needs.

Introduction

Path planning

◆ **Precise position and navigation**

Path planning that is defined as yielding a collision-free path from the start point to the goal, is the prerequisite and foundation of navigation.

◆ **Major drawback of traditional algorithms**

High computational cost for the explicit representations of the configuration space

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- **Modular and Multifunctional USV**
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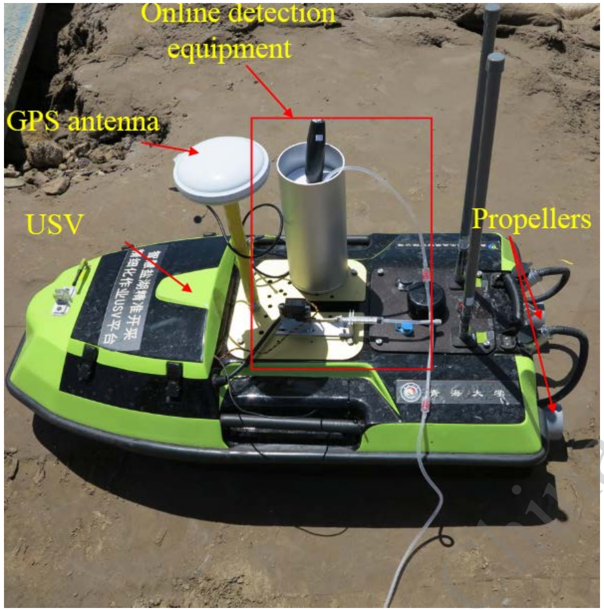
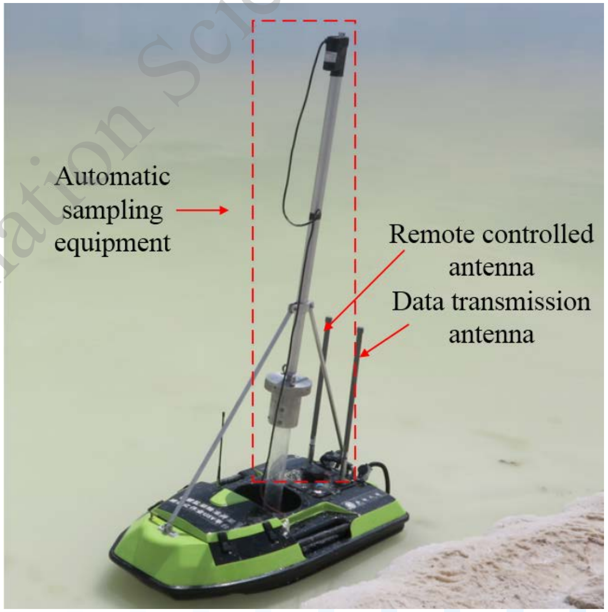
Modular and Multifunctional USV

Overview of the modular USV



The USV with the online ion detection equipment.



The USV with the automatic carnallite sampling equipment.

- **Underwater topographic mapping, online ion concentration detection, automatic carnallite sampling, as well as navigation guiding.**

Modular and Multifunctional USV

Overview of the modular USV

Technical specification of the developed USV

Item	Characteristics
Size (L×W × H)	~1050×550×270 mm3
Total mass	14 kg
Maximum speed	4.5 m/s
Turning radius	0.5 m
Operation time	~5 h
Operation mode	DC 24V
Power supply	Remote control, autonomous
Drive mode	Propeller
On-board sensors	GPS, single beam echo sounder
Carrying capacity	20 kg

- Fiber reinforced polymer is used to deal with the corrosive environment and long span light weight structures .
- A host computer on the shore is used as a console.
- The differential global positioning systems (DGPS) is employed to achieve precise position.
- The propellers are anti-crystallized in response to the harsh environment.

Modular and Multifunctional USV

Underwater topographical surveying

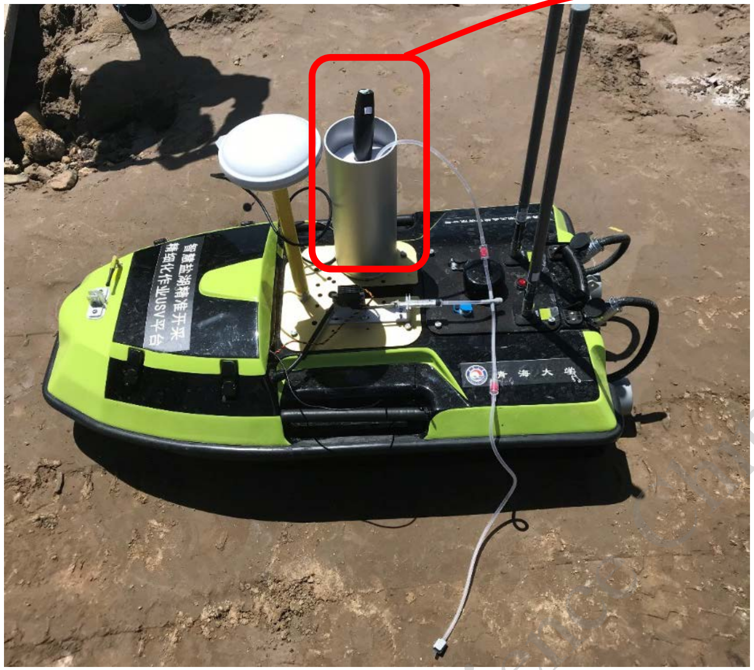
The single beam echo sounder.

- The single beam echo sounder is mounted at the bottom of the USV to determine the depth of the brine by transmitting sound waves into it.
- The brine concentration is one of the most important items which have influence on the sound wave's propagation speed.

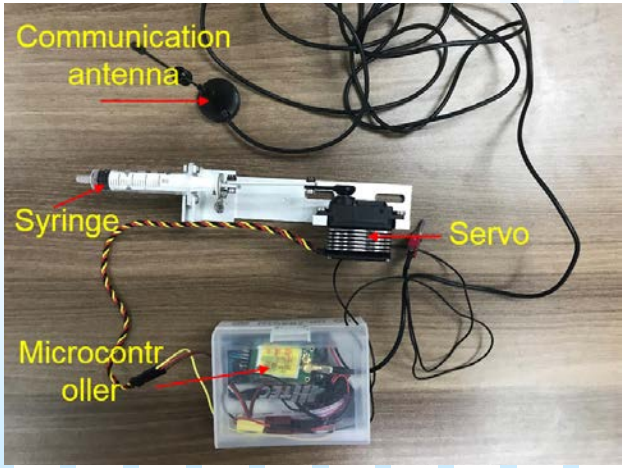
Modular and Multifunctional USV

Online ion concentration detection

Online ion concentration detection equipment



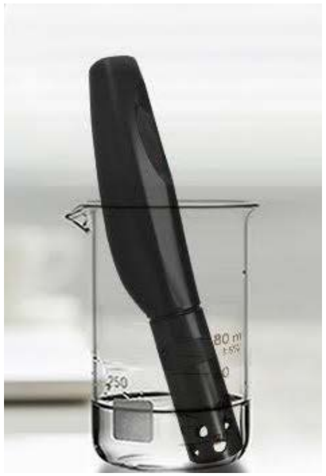
Multi-ion analyzer.



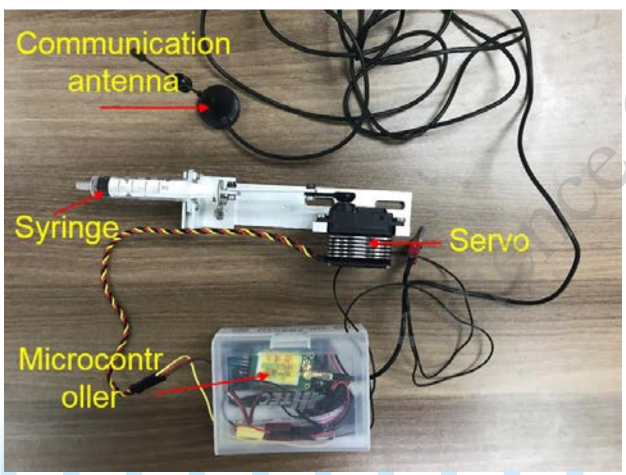
Automatic brine suction device.

Modular and Multifunctional USV

Online ion concentration detection



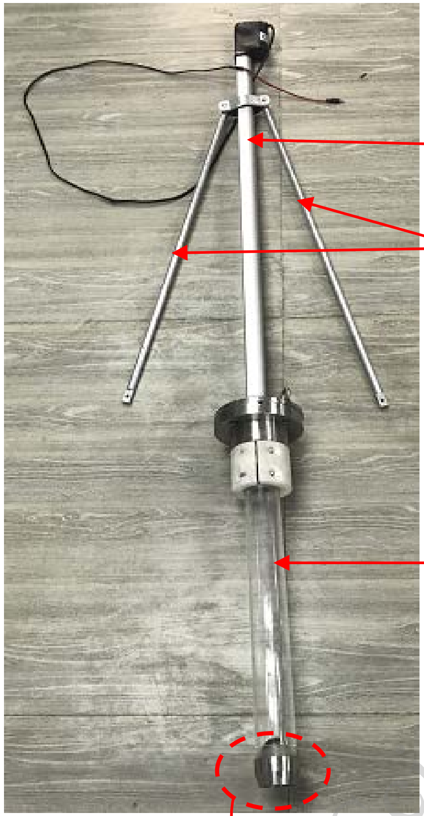
- Rapid, easy and simultaneous measurement of up to six ions
- Diameter: 35 mm, length: 180 mm



- The microcontroller is controlled by the console.
- Through the reciprocating motion of the piston to achieve brine suction and extrusion.
- The device can accurately collect samples of different depths and different regions through accurately controlling the swing number of servo.

Modular and Multifunctional USV

Automatic carnallite sampling



Linear actuator: waterproof

Fixator

Transparent acrylic tube: the sampled carnallite is visible

Orange peel closing device: prevent the sample from exiting

The linear actuator is controlled by console.

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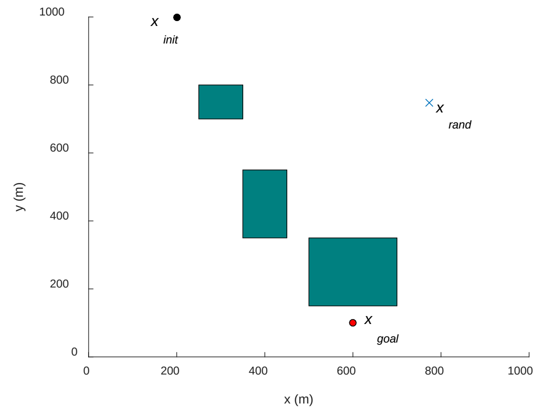
Path Planning

Rapidly-exploring Random Tree

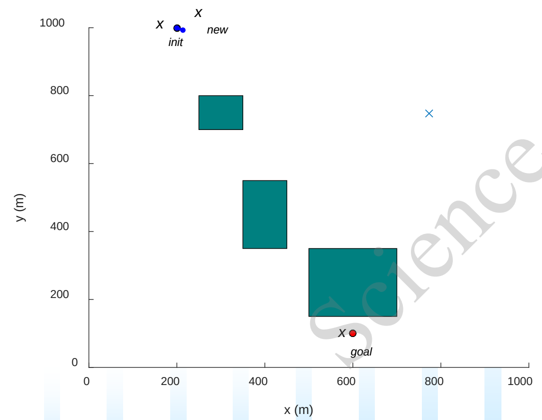
- Rapidly-exploring random tree (RRT): Randomly chosen nodes are used to incrementally generate paths satisfying motion and collision constraints of the robot.
- The most fascinating feature of this strategy: Simplicity, fast convergence, and meeting high-dimensional continuous domains .
- The RRT*-Connect 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.
- The MRRT*-Connect is a modified heuristic strategy from the RRT*-Connect.

Path Planning

RRT*-Connect



(a)



(b)

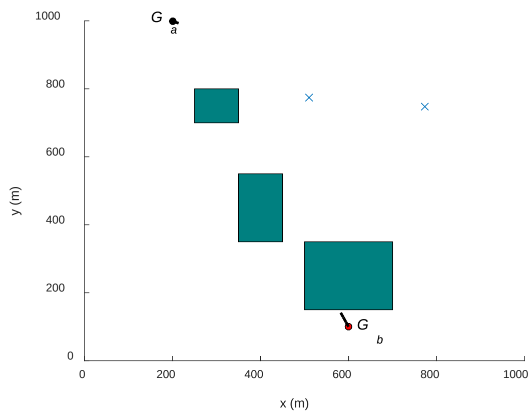
The process of the RRT*-Connect algorithm

The start state x_{init} and the end state x_{goal} are belong to two random tree G_a and G_b, a new state node x_{rand} is sampled through greedy strategy.

The x_{new} the steering procedure is used as a step to extend the distance η with the direction from the point can be got.

Path Planning

RRT*-Connect



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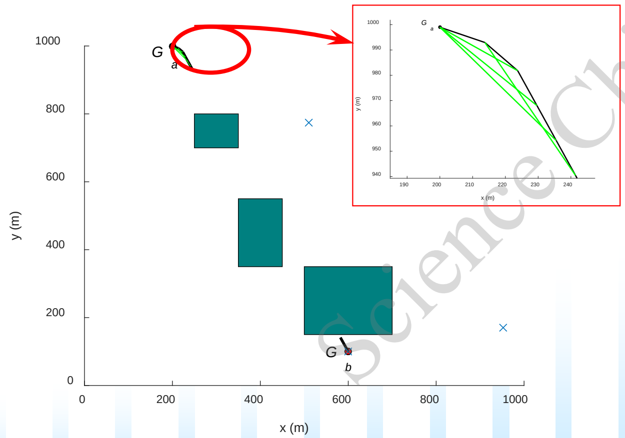


(d)

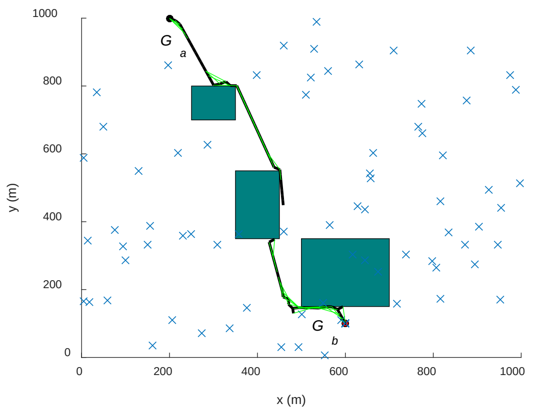
The process of the RRT*-Connect algorithm

The x_{new} can be regarded as x_{rand} to conduct the growth of G_b that is growing from the x_{goal}.

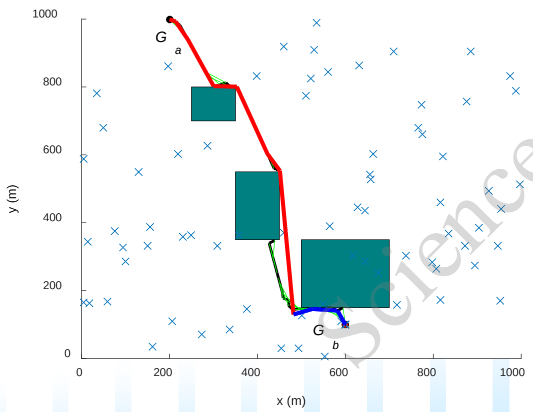
An evolutionary structure optimization function is used, The obtained new vertexes are used to compete the minimum "Cost", and the minimum cost path will asymptotically converge to an optimal solution

Path Planning

RRT*-Connect



(e)



(f)

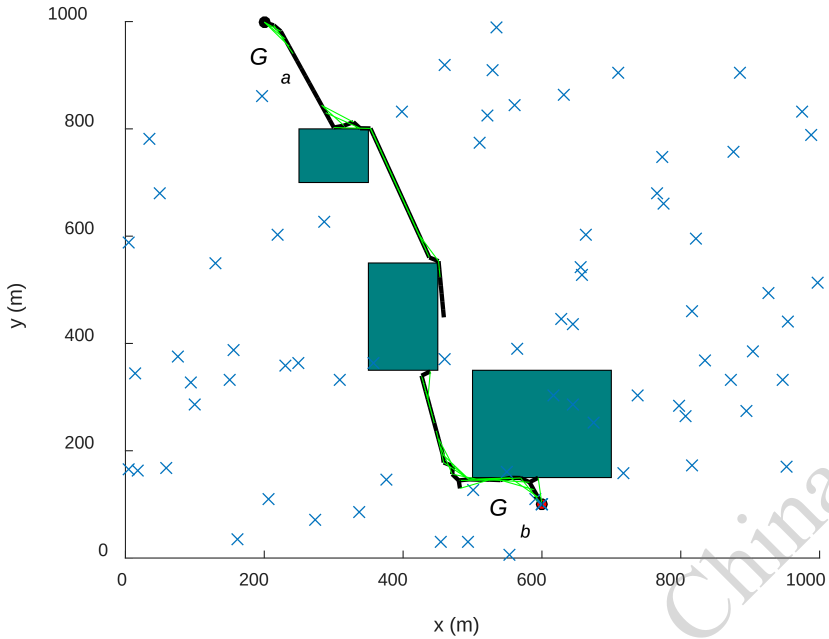
The process of the RRT*-Connect algorithm

The iteration will not stop until it arrives at an obstacle, after that a new state node x_{rand} through greedy strategy is sampled again.

Two trees are maintained at all times until they become connected, and a solution is found.

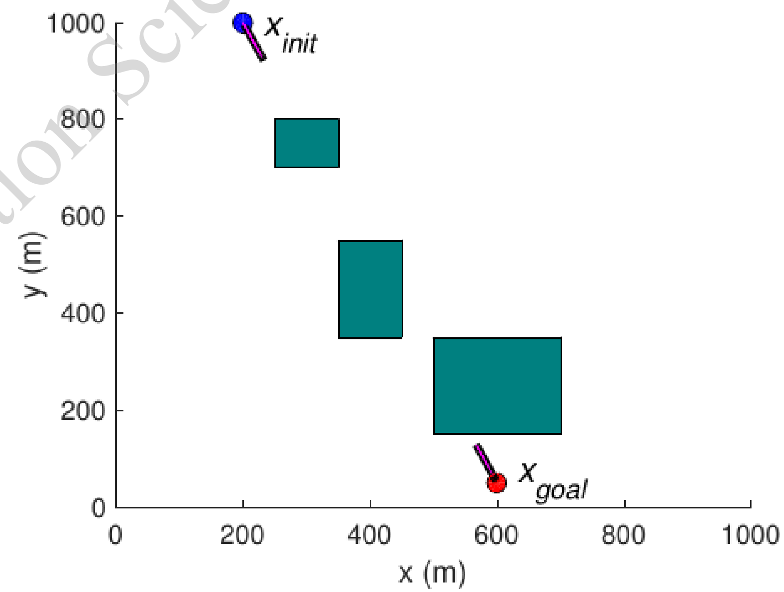
Path Planning

MRRT*-Connect



RRT*-Connect

Modify



MRRT*-Connect

If obstacles are encountered, x_{rand} is randomly sampled, and the greedy targets are x_{init} and x_{goal}, which are fixed.

The new sample is randomly selected as the latest sample point and selected as the root node of the trees

Path Planning

MRRT*-Connect

Algorithm 1 MRRT*-Connect

$V_a \leftarrow \{x_{init}\}$; $E_a \leftarrow \emptyset$; $V_b \leftarrow \{x_{goal}\}$; $E_b \leftarrow \emptyset$;
$P_a \leftarrow \emptyset$;$P_b \leftarrow \emptyset$;
$x_{bnew} \leftarrow x_{goal}$;
for $i = 1, ..., n$ **do**
  x_{new}, V, E= CONNECT* $(G_a = (V_a, E_a), x_{bnew})$
  $x_{anew} \leftarrow x_{new}$;
  $V_a \leftarrow V$;
  $E_a \leftarrow E$;
  x_{new}, V, E= CONNECT* $(G_b = (V_b, E_b), x_{anew})$
  $x_{bnew} \leftarrow x_{new}$;
  $V_b \leftarrow V$;
  $E_b \leftarrow E$;
  for $j = 1, ..., Length(V_a)$ **do**
    for $k = 1, ..., Length(V_b)$ **do**
      if $V_a(j) = V_b(k)$ **then**
        $G = (V_a \cup V_b, E_a \cup E_b)$;
      end if
    end for
  end for
  return V_a V_b
end for

Algorithm 2 Connect*

function CONNECT*$(G = (V, E), x)$
  $x_{rand} \leftarrow x$;
  $x_{nearest} \leftarrow Nearest(G = (V, E), x_{rand})$;
  $x_{new} \leftarrow Steer(x_{nearest}, x_{rand})$;
  if $ObtacleFree(x_{nearest}, x_{new})$ **then**
    RRT*$(G = (V, E), x_{nearest}, x_{new})$
  else
    $x_{rand} \leftarrow RandomSmple(i)$;
    $x_{nearest} \leftarrow Nearest(G = (V, E), x_{rand})$;
    $x_{new} \leftarrow Steer(x_{nearest}, x_{rand})$;
    if $ObtacleFree(x_{nearest}, x_{new})$ **then**
      RRT*$(G = (V, E), x_{nearest}, x_{new})$
    end if
  end if
  return x_{new}, V, E;
end function

Nearest: It is used to calculate the closest vertex in V from x based on the Euclidean distance

Steer: A fixed incremental distance parameter η of the steering procedure is used as a step to extend the distance η with the direction from the point $x_{nearest}$ to x

ObtacleFree: The Boolean function ObtacleFree ($x_{nearest}$, x_{new}) returns “True” if the line segment between $x_{nearest}$ and x_{new} does not intersect with the obstacles and “False” otherwise.

Path Planning

MRRT*-Connect

Algorithm 3 RRT*

function RRT*$(G = (V, E), x_{nearest}, x_{new})$
  $V \leftarrow V \cup x_{new}$;
  $x_{min} \leftarrow x_{nearest}$;;
  $c_{min} \leftarrow Cost(x_{nearest}) + c(Line(x_{nearest}, x_{new}))$;
  $X_{near} \leftarrow Near(G = (V, E), x_{new}, min(\gamma_{RRT*}(log(card(V))/card(V))^{1/d}, \eta))$;
  for all $x_{near} \in X_{near}$ **do**
    if $CollisionFree(x_{near}, x_{new}) \wedge Cost(x_{near}) + c(Line(x_{near}, x_{new})) < c_{min}$ **then**
      $x_{min} \leftarrow x_{near}$;
      $c_{min} \leftarrow Cost(x_{near}) + c(Line(x_{new}, x_{near}))$;
    end if
    $E \leftarrow E \cup (x_{min}, x_{new})$;
  end for
  for all $x_{near} \in X_{near}$ **do**
    if $CollisionFree(x_{near}, x_{new}) \wedge Cost(x_{near}) + c(Line(x_{near}, x_{new})) < Cost(x_{near})$ **then**
      $x_{parent} \leftarrow Parent(x_{near})$;
      $E \leftarrow (E \setminus (x_{parent}, x_{near})) \cup (x_{new}, x_{near})$;
    end if
  end for
end function

Cost: *Cost* (*x*) means a function that maps the vertex *x* to the cost from the root of the tree to *x*.

Near: It is an evolutionary structure optimization function, which considers Connections from the new vertex x_{new} to vertices in X_{near} within a distance. The obtained new vertexes are used to compete the minimum "*Cost*", and the minimum-cost path will asymptotically converge to an optimal solution.

Swap: The function is used to reverse the roles of two trees.

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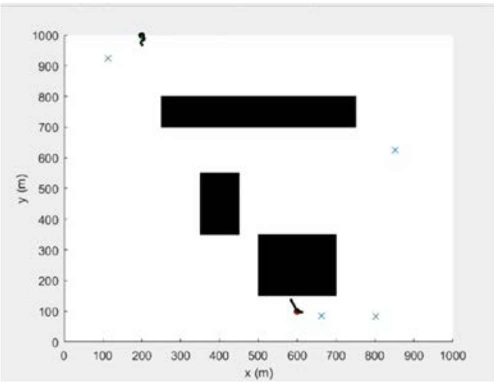
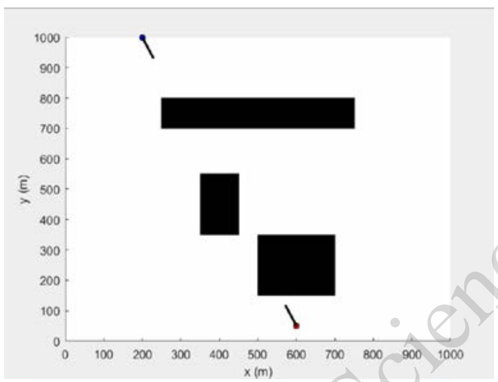
Simulation and Field Tests

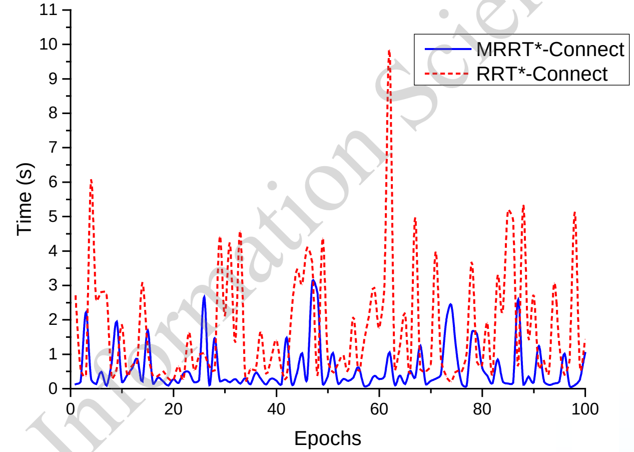
Simulation comparison



RRT*-Connect



MRRT*-Connect



Simulation results for two planners.

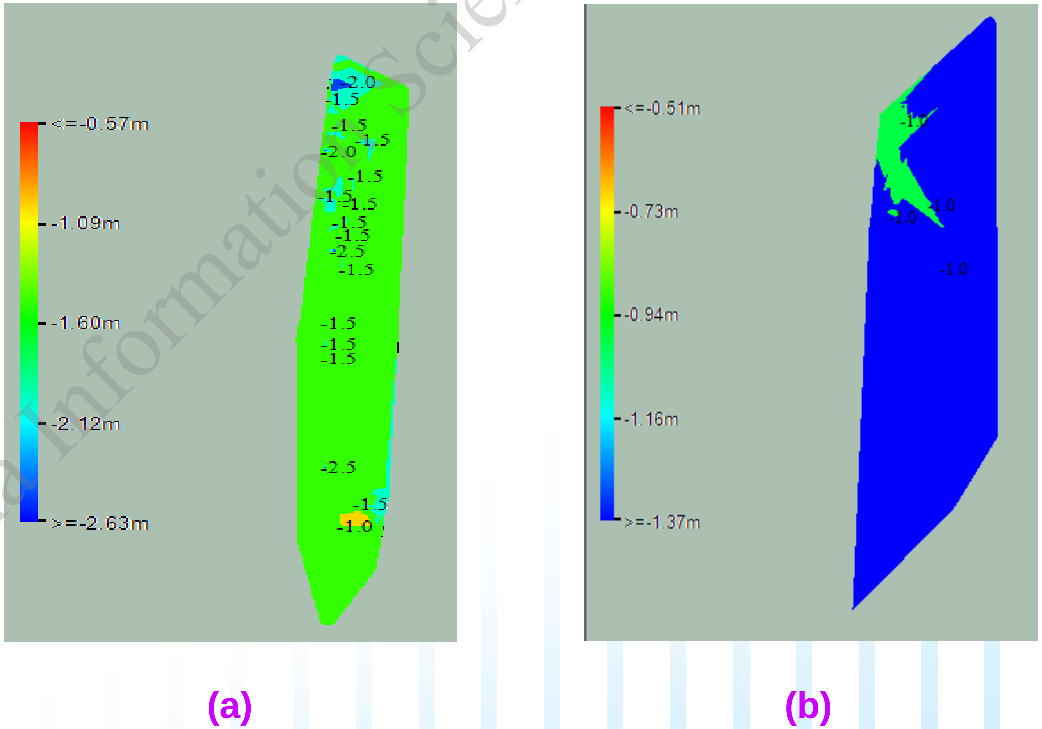
- Average computation time:
  - RRT*-Connect: 1.732 s
  - MRRT*-Connect: 0.57 s, faster convergence rate
- The standard deviation:
  - RRT*-Connect: 1.69
  - MRRT*-Connect: 0.67, better stability and convergence property

Simulation and Field Tests

Underwater topographical mapping

The process of topographical mapping.

- The thickness of carnallite layer could be estimated through the relative benchmark of topography
- Intuitively display the change of the carnallite layer



Underwater topographical mapping of the Salt Pond.

Simulation and Field Tests

Automatic carnallite sampling

The process of carnallite sampling.

The collected carnallite sample.

- As could be observed, the stratification of the carnallite layer was clearly identified.
- It proved that the device was feasible.

Simulation and Field Tests

Online brine ion concentration detection

Brine suction and extrusion.

Testing result of ion concentration

Ion	Concentration (%)
K^+	0.56
Na^+	0.40
Ca^{2+}	0.02
Mg^{2+}	10.22
Cl^-	28.55
NO^{3-}	0.01

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Conclusion and Future Work

Conclusion

- A modularized and multifunctional USV system is investigated, different devices of the USV are customized to meet the various needs of different applications.
- A modified RRT algorithm is employed to generate paths with faster convergence rate and better stability.
- Both simulation and field experiments are carried out to verify the effectiveness of the proposed planner and the developed platform.

Conclusion and Future Work

Future work

- Accurate modeling bathymetric models are crucial to interpolate the depths and fill the gaps between the survey lines.
- How to improve the estimation of the thickness of carnallite layer from both theoretical and practical points of view is also a valuable research issue.

Multi-beam sounding system

Thank you for your attention