

Efficient Path Planning Algorithms for Unmanned Surface Vehicle

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Abstract: The C-Enduro Unmanned Surface Vehicle (USV) is designed to operate at sea for extended periods of time (up to 3 months). To increase the endurance capability of the USV, an energy efficient path planning algorithm is developed. The proposed path planning algorithm integrates the Voronoi diagram, Visibility algorithm, Dijkstra search algorithm and takes also into account the sea current data. Ten USV simulated mission scenarios at different time of day and start/end points were analysed. The proposed approach shows that the amount of energy saved can be up to 21%. Moreover, the proposed algorithm can be used to calculate a collision free and energy efficient path to keep the USV safe and improve the USV capability. The safety distance between the USV and the coastline can also be configured by the user.

Keywords: unmanned surface vehicles; collision avoidance; Voronoi diagram; Visibility graph; path planning

1. ASV VEHICLE DESCRIPTION

The C-Enduro USV was developed under a UK Government-backed Small Business Research Initiative (SBRI) initiated by the National Oceanography Centres (NOC) requirement for long endurance USVs for environmental research. The team behind the C-Enduro, led by ASV, includes Hyperdrive Ltd who investigated motor options and power management systems and Cranfield University who have conducted research into various guidance algorithms for USVs (Savvaris et al. (2014); Niu et al. (2016); Lu et al. (2016)). In Figure 1, we show the developed C-Enduro unmanned marine surface vehicle at sea during sea trials.



Fig. 1. The C-Enduro Unmanned Surface Vehicle .

To improve long endurance capability, the C-Enduro vehicle has a "three pillar" energy system including solar panels, a wind generator and a diesel generator. Calculations and tests show that this "three pillar" energy system, combined with efficient power management and

Table 1. Technical specification of the C-Enduro USV.

Physical	Specification
length	4.2 m
beam	2.4m (road transportable)
height	2.8m (including antenna)
	1.5m (mast off)
draft	0.4m
weight	350kg (lightship)
primary propulsion	2 DC brushless motors

command and control systems packaged in a rugged self-righting vehicle, provides the greatest likelihood of meeting the performance requirement. In Table 1, we show the physical technical specification of the vessel, while in Table 2 the technical specifications of the wind generator, diesel generator and the solar panel are given.

In terms of the power system hardware, the C-Enduro USV meets the long endurance characteristics and requirements required to accomplish its mission. However, to further improve the endurance capacity an efficient path planning is also required. Since the C-Enduro is designed to travel long distances and operate in various sea and weather conditions, the efficient path planning plays an important role in accomplishing successful operations. This paper presents a new energy efficient path planning method that integrates Voronoi diagram, Visibility algorithm, Dijkstra search algorithm and energy consumption weight. The energy efficiency of the proposed algorithm has been validated in 10 USV missions.

2. PATH PLANNING LITERATURE REVIEW

Depending on the environment, four different path planning methods can be used: roadmap-based approaches,

Table 2. Power and Controls Technical Specification

Power and controls	Specification
endurance	Up to 3 months utilising solar/wind/diesel energy
solar panel system	Generating a peak electrical power of 1200W
diesel generator system	Providing a peak charging power of 2.5kW
wind turbine system	Lightweight three blade system generating a peak output power of 720W

cell decomposition, potential fields, and bug algorithms. The goal of *roadmap based* approaches is to reduce the N-dimensional configuration space to a set of one-dimensional paths, which are then searched. Two famous roadmap-based approaches are the visibility graph and the Voronoi diagram (Wein et al. (2007)). The efficiency of using visibility graphs for determining the shortest path was demonstrated by Kaluder et al. (2011), whereas the use of Voronoi diagrams for USV dynamic path planning was presented in the work of Wu et al. (2013). The advantage of Voronoi diagrams is the short computing time, although the disadvantages include the non-optimal nature of the Voronoi road map and the redundant waypoints. The advantage of the Visibility algorithm is that it can generate an optimal path, although a disadvantage is the increased computing time compared with that of the Voronoi diagram.

Another planning method is *cell decomposition* approach, such as A* algorithm, and the approach could be either exact or approximate. It is used by Li et al. (2011) for UAV path planning. The application of A* for an USV that must avoid underwater obstacles was tested experimentally by Phanthong et al. (2014). The *potential field* method is another widely used planning method because the computational load required to generate the trajectory is small. In general, the trajectory can be generated in real-time and planning and control are merged into one function. Planning the potential field path can be coupled directly to a control algorithm. However, the approach may become trapped in local minima in the potential field (Koren and Borenstein (1991)). Due to this limitation, it has been mainly used for local path planning. Finally, *bug algorithm* is a limited-knowledge path planning approach. It assume only local knowledge of the environment and a global goal. Its efficiency for robot path planning using a range sensor was presented by Buniyamin et al. (2011), while its use for obstacle avoidance was presented by Loe (2008).

Path planning under environmental disturbances and uncertainties are inevitable in USV path planning. Thus, ocean environmental effects should be properly considered in path planning on the ocean surface so as to achieve less energy consumption. Too little research has concerned this issue in their path planning approaches (Liu et al. (2016)). Generating energy-efficient paths presents new challenges for USV path planning, as it requires not only novel and realistic energy cost functions, but also powerful computational approaches due to the inherent problem complexity.

3. ENVIRONMENTAL DATASETS

The traditional path planning method for the marine vehicles is either heading to the destination directly or

taking the shortest route, without taking into account the current data. The proposed path planning algorithm improves the USV endurance capability by analysing the sea current data.

The development in ocean science and satellite remote sensing technology meant that ocean currents states can be predicted more accurately. The data used in this investigation is from TideTech Ltd. The sea current data is compiled in grib files. Grib file is a concise data format used to store historical and forecast weather data. The advantage of using the TideTech data is that we can get the forecast of the sea current and can therefore use this information to optimise the path before the C-Enduro USV starts its mission. The resolution of Singapore strait is 800 meters; The update time step is 1 hour. The forecast length is 48 hours. See TideTech Ltd. (2015).

The coastline data was obtained from NCAR Research Data Archive. The coastline data used in this paper is of high resolution that consists of points about 200m apart.

4. EFFICIENT PATH PLANNING ALGORITHM

The proposed efficient path planning algorithm consists of five parts: Voronoi diagram, USV energy consumption model implementation, Dijkstra search, Visibility algorithm and Dijkstra search.

The advantage of using the Voronoi diagram rather than other methods, among which the Visibility Graph prevails, is its computing efficiency. The Voronoi diagram can be calculated out in $O(n \log(n))$ time, whereas the Visibility graph can take up to $O(n^2)$ time. However, the Voronoi road map is far from optimal. Although Visibility algorithm computing time is longer, its path is optimal. Therefore, in this paper the Voronoi diagram and the Visibility algorithm are integrated to calculate the optimal path in $O(n \log(n))$ time.

The Voronoi diagram is first implemented to provide the USV collision free road map. USV energy consumption model provides the method to calculate the USV energy consumption weight under different sea current state. The Dijkstra search is implemented to generate the Voronoi energy efficient path. However, the path is not optimal and includes redundant waypoints. Therefore, the Visibility algorithm is applied to optimise the Voronoi energy efficient path. Finally, the Dijkstra search is used again to calculate out the Visibility-Voronoi energy efficient path.

4.1 Voronoi diagram implementation

The first step of Voronoi diagram generation is to expand the coastline of each island. The expanded coastlines will keep the shape of the original coastline and the distance r meters between the original coastline and the expanded

coastline can be configured by the users, which means the USV will be always kept r meters away from the islands coastlines. The reason to expand the island coastline is to keep the USV absolutely clear from the islands in the existing of uncertainty of the map data.

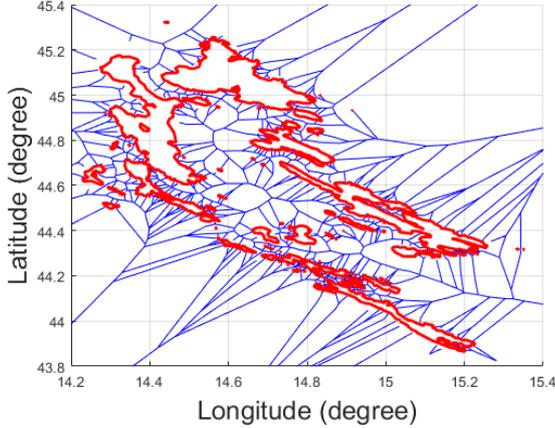


Fig. 2. Croatia islands Voronoi road map.

Then the Voronoi diagram can be calculated by processing the expanded islands coastline data using the voronin function in Matlab. The Voronoi road map of the processed islands of the coast of Croatia are shown in Fig. 2.

The generated road paths that have intersections with the island coastlines were moved away. Furthermore, the roads path generated inside the island coastlines were also removed. All the road paths that were kept are collision free paths. In Fig. 2, the red districts represent the expanded islands coastlines and the blue lines represent all the potential road paths. The Voronoi vertices and path information are stored into a waypoint sparse matrix M .

4.2 USV energy consumption model

For an USV that is commanded to travel from waypoint N_i to waypoint N_{i+1} , the ground speed of the USV is denoted by \vec{v}_g , the sea current speed is denoted by \vec{v}_c , and the relative USV speed is denoted by \vec{v}_u . The parameters satisfy the following equation:

$$\vec{v}_g = \vec{v}_c + \vec{v}_u \quad (1)$$

The hydrodynamic drag \mathbf{F}_d can be calculated by the following equation: equation:

$$\mathbf{F}_d = \alpha |v_u|^2 \quad (2)$$

where α represents a USV constant drag parameters. The USV energy consumption weight \mathbf{E} can be calculated by the following equation:

$$\mathbf{E} = |v_u| \cdot \alpha |v_u|^2 \cdot \frac{|N_i N_{i+1}|}{|v_g|} = \alpha |v_u|^3 \cdot \frac{|N_i N_{i+1}|}{|v_g|} \quad (3)$$

Therefore, when the USV path and the sea current data are given and the ground velocity of the USV is constant, the energy consumption weight of the path can be calculated.

4.3 Dijkstra search

Dijkstra's algorithm is an algorithm for finding paths that have the minimum weight between nodes in a graph. Its

efficiency has been proven in many work about path planning published by other researchers. To find out the path that requires the minimum energy, the cost weight between the adjacent waypoints in needs to be calculated and filled into the waypoint sparse matrix M . By implementing Dijkstra's algorithm, the energy efficient path is generated in Fig. 3.

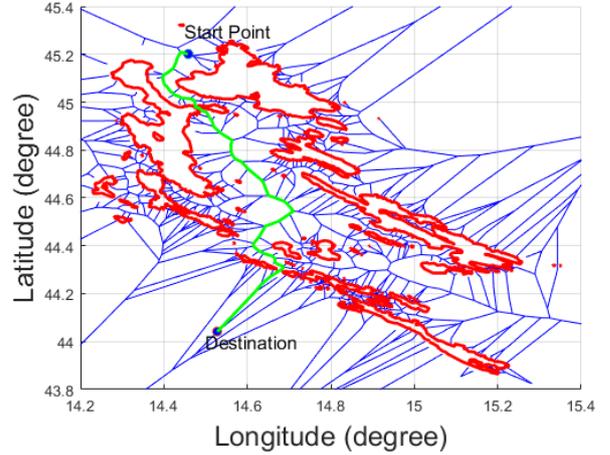


Fig. 3. Voronoi energy efficient path.

The USV is commanded to travel from location (14.45, 45.20) to location (14.50, 44.10). The map data is generated from high resolution coastline data made up of 115 islands off the coast of Croatia. The nearest nodes to the start point and the destination are calculated first. By processing the waypoint sparse matrix M , Dijkstra search generates the path that needs the minimum energy weight between the start point and the destination in the Voronoi road map. The green path in Fig. 3 represents the Voronoi energy efficient path from start point to the destination.

The Voronoi road map is constructed in around 7 seconds using the Matlab simulation software. By contrast, when implementing the Visibility algorithm to generate the road map, more than 10 minutes is needed. As can be seen, the Voronoi diagram is computing efficiently. However, the green path is far from optimal due to the existing redundant nodes. Therefore, the Visibility algorithm will be implemented later to optimise the path.

4.4 Visibility algorithm

As the energy efficient path generated from Voronoi diagram is not optimal, Visibility algorithm is implemented.

Assuming the generated energy efficient path allows the USV to travel from waypoint N_i to waypoint N_{i+2} via waypoint N_{i+1} . The implementation of Visibility algorithm is to provide more possible paths. If the path from waypoint N_i to waypoint N_{i+2} does not cross any islands, the path $N_i - N_{i+2}$ will be added. By processing the generated Voronoi efficient path using Visibility algorithm, more available paths will be generated and Dijkstra search algorithm will be used again to calculate the most efficient path among these possible paths.

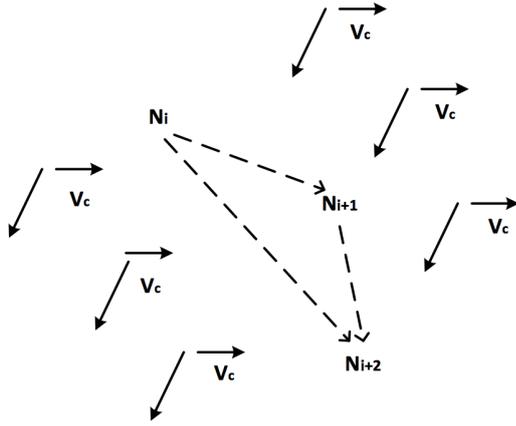


Fig. 4. Visibility algorithm demonstration.

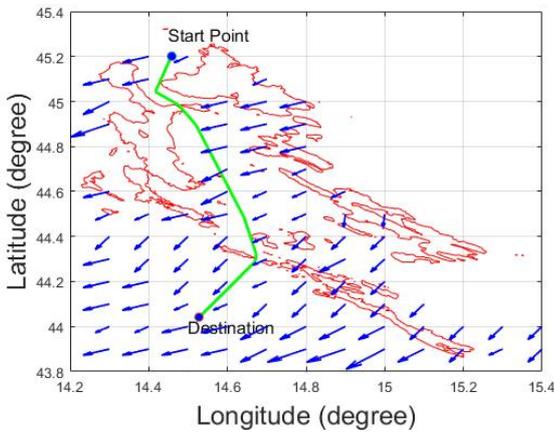


Fig. 5. Energy efficient path based on the simulated conditions at 12:00 hours on 14th June 2014.

4.5 Dijkstra search

By implementing Dijkstra's algorithm, the Visibility-Voronoi energy efficient path is calculated out, as shown in Fig. 5. The green path is the generated energy efficient path. The sea current state is also denoted by blue arrow in the figure. The simulated time was at 12:00am on 14/06/2014.

5. SIMULATION RESULT

In the simulation, the USV was commanded to travel from location (103.68, 1.30) to location (103.90, 1.08). The simulation area used this time was the Singapore strait. The simulation time was at 2:00am on 11/06/2014. It was assumed that the sea current was time-invariant when the USV was travelling. The reference sea current data was measured at 2:00am on 11/06/2014. The USV commanded ground speed was 1 m/s.

In Fig. 6, the green path represents the Voronoi energy efficient path. By changing the Voronoi path weight from the energy consumption weight to the distance weight and implementing Dijkstra's algorithm, the new Voronoi shortest path is generated as shown in Fig. 7. It can be seen that the efficient path and the shortest path are obviously different.

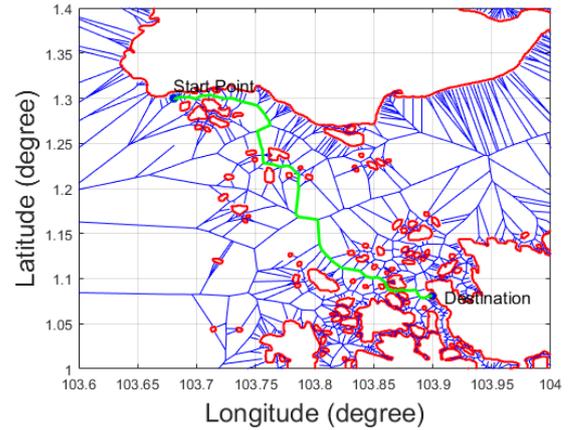


Fig. 6. Voronoi energy efficient path based on the sea current data at 2:00 hours on the 11th June 2014.

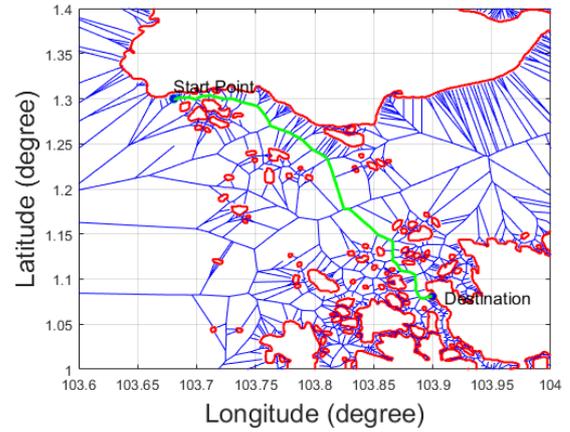


Fig. 7. Voronoi shortest path generated based on the distance weight.

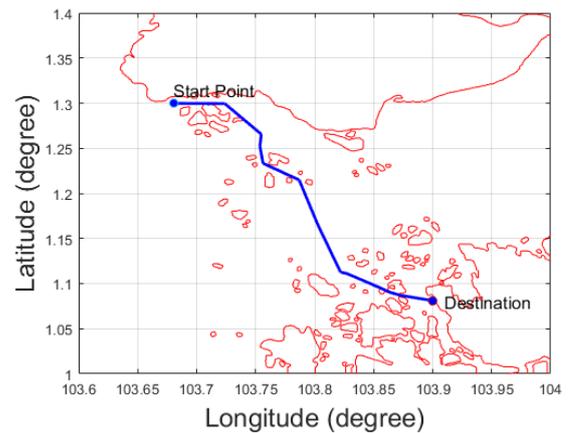


Fig. 8. The Visibility-Voronoi energy efficient path.

By implementing Visibility algorithm and Dijkstra's search algorithm, the Visibility-Voronoi efficient path is shown in Fig. 8. The Visibility-Voronoi shortest path is shown in Fig. 9. It can be inferred that Visibility algorithm has optimised both the Voronoi energy efficient path and the Voronoi shortest path. Moreover, the paths are free

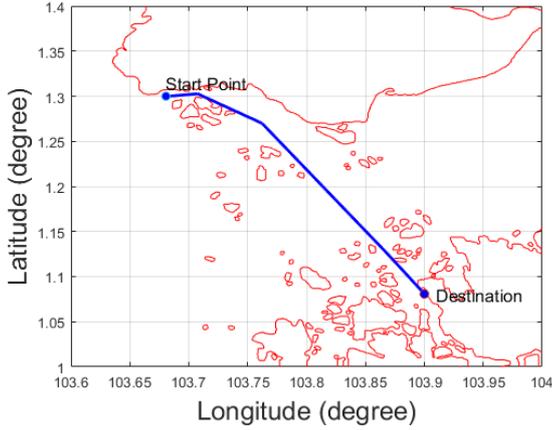


Fig. 9. The Visibility-Voronoi shortest path.

from obstacles, which confirms the validity of the Voronoi diagram approach.

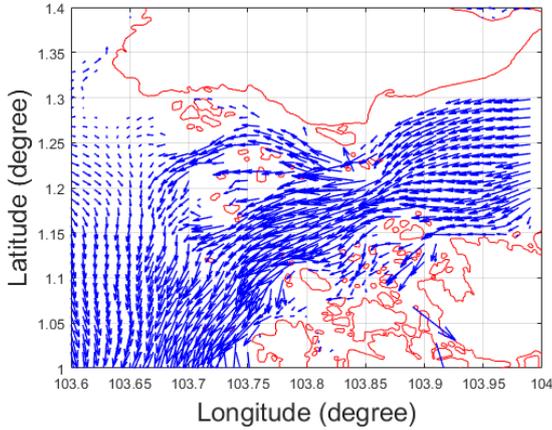


Fig. 10. Sea current state.

By analysing the sea current state as shown in Fig. 10, it can be seen that the path generated in Fig. 8 is keeping the USV away from going into the opposite direction to the sea current, which is the aim in that case to avoid the increase in energy consumption. However, the path in Fig. 9 just takes the distance into account instead of the energy and the aim in this case is just to find the shortest path. The simulation's power consumption records reveal that the VV efficient path has an energy cost of 0.3514α , whereas the VV shortest path has an energy cost of 0.4133α . Thus, the efficient path uses up to 14.98% less energy.

Then, the proposed algorithm was also simulated in a different time of day to see the impact of time on planning the efficient path. The previous simulation time is at 2:00 am on 11/06/2014. This time, the simulation time is at 5:00 am on 11/06/2014. The total energy consumption of the efficient path is 0.3549α , whereas that of the shortest path is 0.4256α . Therefore, the VV efficient path conserves approximately 16.61% energy.

The data in Figure 8, Figure 9 and Figure 11 are combined in Figure 12 to show the results of the proposed efficient path planning algorithm and the shortest paths at different times on the same day.

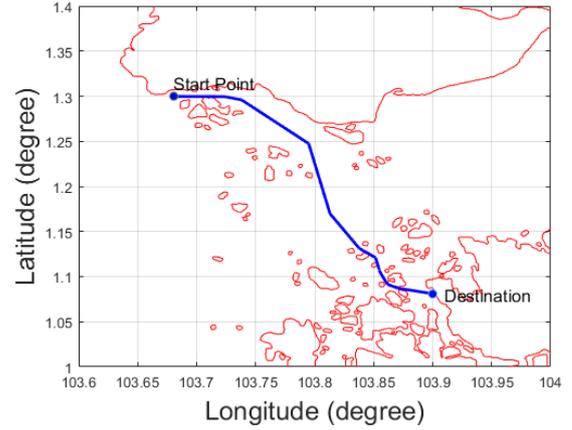


Fig. 11. The Visibility-Voronoi energy efficient path.

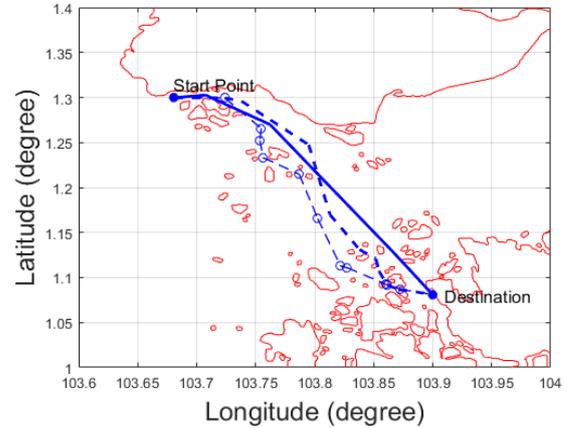


Fig. 12. Efficient paths at two different times w.r.t. shortest path.

In Figure 12, the solid blue path represents the shortest path, the dashed line represents the efficient path at 5:00 am on 11/06/2014, and the path with dashes and circles represents the efficient path generated at 2:00 am on 11/06/2014.

To increase the confidence level in the results and demonstrate the efficiency of the proposed efficient path planning algorithm, ten USV missions were simulated on 11/06/2014, and the results are shown in Table 3. The USV speed is set to 1 m/s. The variables of the missions include the starting point, destination and mission time; therefore, the sea current conditions are guaranteed to vary. The total energy consumption of the proposed efficient path planning algorithm was compared with the VV shortest path, and the energy savings were calculated and tabulated in the last column of Table 3.

Table 3 shows that using the VV energy-efficient path can save 5.22% to 21.43% in energy compared with the Voronoi shortest path. The segment showing the highest amount of saved energy at approximately 21.4% had a start point at location (103.95, 1.20) and an endpoint at location (103.75, 1.08) at 0:00 am on 11/06/2014. The segment showing the lowest amount of saved energy at approximately 5.22% had a start point at location (103.74, 1.30) and an endpoint at location (103.8, 1.08) at 0:00 am on 11/06/2014.

Table 3. Result of 10 USV missions.

No	Start point	Destination	Mission time	Efficient path length (km)	Shortest path length (km)	Efficient path energy	Shortest path energy	Energy saved
1	(103.68, 1.30)	(103.90, 1.08)	00:00 a.m.	38.132	36.043	0.3415 α	0.3856 α	11.44%
2	(103.68, 1.30)	(103.90, 1.08)	01:00 a.m.	38.631	36.043	0.3494 α	0.4080 α	14.37%
3	(103.68, 1.30)	(103.90, 1.08)	02:00 a.m.	38.926	36.043	0.3514 α	0.4133 α	14.98%
4	(103.68, 1.30)	(103.90, 1.08)	03:00 a.m.	37.713	36.043	0.3324 α	0.4064 α	18.22%
5	(103.68, 1.30)	(103.90, 1.08)	04:00 a.m.	37.785	36.043	0.3394 α	0.4086 α	16.94%
6	(103.74, 1.30)	(103.80, 1.08)	00:00 a.m.	26.990	24.566	0.2195 α	0.2316 α	5.22%
7	(103.95, 1.20)	(103.75, 1.08)	00:00 a.m.	28.607	27.922	0.1362 α	0.1734 α	21.43%
8	(103.95, 1.15)	(103.65, 1.25)	00:00 a.m.	43.225	39.037	0.2678 α	0.3249 α	17.57%
9	(103.68, 1.30)	(103.90, 1.08)	00:00 a.m.	38.132	36.043	0.3415 α	0.3856 α	11.44%
10	(103.68, 1.30)	(103.90, 1.08)	02:00 a.m.	38.926	36.043	0.3514 α	0.4133 α	14.99%

The reason for the energy saving amount difference of these 10 missions is that when the sea current direction changes a lot with the locations change, the energy efficient path will be very different with the shortest path and the energy efficient path will save a lot amount of energy comparing to the shortest path. By contrast, if the sea current is uncorrelated with the locations, the energy current path will be the same with the shortest path.

6. CONCLUSION AND FUTURE WORK

In this paper, the Voronoi diagram, Visibility algorithm and Dijkstra's search algorithms were integrated to calculate the energy efficient path. The proposed efficient path planning algorithm not only provide collision free path, but also takes into account the sea current influence on the USV energy consumption. Ten USV missions were simulated. The results show that the amount of energy saved depends on the locations and the mission time.

When the sea current state is uncorrelated with the locations, the difference in the energy consumption will be small. When the sea current state changes a lot with the location changing, the difference in energy consumption between the efficient path planning algorithm and the Visibility-Voronoi shortest algorithm will be high. In general, the proposed algorithm can be used to calculate a collision free and energy efficient path to keep the USV safe and improve the USV endurance capability. The safety distance r between the USV and the coastline can also be configured by the users, and the generated path always keeps the USV distance r away from the coastlines.

For the future work, the efficient path planning algorithm will also take into account the solar energy and the wind energy generation to maximise the endurance and energy production of the USV. This is important, since the energy consumption is not only linked to the thrusters but also depend on the payload. Some equipment for example, the winch when operated will result in an increase in the amount of power consumed and will have to be taken into account.

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