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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 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.

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

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,

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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 Kaluđer 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 $O(nlog(n))$ 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 $O(nlog(n))$ 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