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Design and Implementation of an Autonomous USV in Bathymetric Surveys

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Abstract: This paper describes the system configuration and control method of an autonomous Unmanned Surface Vehicle (USV) and its implementation in bathymetric surveys. The USV prototype, power unit, control unit, sensory system and communication system are designed and constructed. The control method for a path-following problem is designed and then embedded into the USV's control unit. The complete USV is then implemented in bathymetric surveys. During each survey, the ground control station (GCS) sends a survey request containing the survey path's parameters, which consist of the coordinates defining the area of interest and the map resolution. Upon receiving the survey request, the USV automatically calculate the set of waypoints from the parameters in the request. The USV move to each waypoint, collecting the depth data in the process. The USV's coordinates and the corresponding depth the is continuously sent to the GCS. The survey data is saved on the GCS and then used to build the depth map of the area of interest.

Keywords: *usv, unmanned surface vehicle, path-planning, path-following, bathymetric survey*

1. Introduction

In recent years, development on Unmanned Surface Vehicle (USV) has made significant progress [1,2], improving USVs' capabilities in a variety of missions including bathymetric survey, collecting water sample, relaying communication signals, lifeguard assistance and rescue. One of the key features of an autonomous USV deployed in these applications is path-planning and path-following. Motivated by our previous work [3], in this paper, we present a control method for the path-planning and path-following problem and demonstrates its effectiveness in experimental bathymetric surveys.

2. System configuration

The USV 's configuration considered is a twin-hull catamaran configuration with two stationary thrusters, each attached to one hull of the USV. The yawing motion of the USV is actuated by the differential thrust between the thrusters.
The control system consists of the control unit on the USV and the ground control station (GCS). The USV's control unit is an integrated circuit consisting of a microcontroller, Global Navigation Satellite System (GNSS) module, digital compass, Wi-Fi, and radio communication modules. The USV is equipped with a Single-beam Echo-sounder.
Bathymetric surveys requires that the USV move in closely spaced parallel paths covering the area of interest. The USV is required to follow the path and continuously collect depth data and send it, along with the USV coordinates to the GCS. To initialize the survey, the GCS send a survey request to the USV. This request contains the coordinates defining the area of interest and the distance between the parallel paths. From the parameters in the request, the USV's control unit calculate the set of numbered waypoints the USV needs to reach in order to complete the survey requested by the GCS.

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3. Control method

From the GNSS module and digital compass, the USV's coordinates $R_{USV}(x_{USV}, y_{USV})$ and heading (ψ) are determined.
From the survey request, 4 coordinates $R_1(x_1, y_1)$, $R_2(x_2, y_2)$, $R_3(x_3, y_3)$, $R_4(x_4, y_4)$, defining the quadrilateral area of interest and the distance between parallel paths (d) are determined.
The number of waypoints (n) and coordinates of waypoints $R_{w_k}(x_{w_k}, y_{w_k})$ are calculated as follows

$$n = \left\lfloor \frac{d(R_1, R_2)}{d} \right\rfloor \tag{1}$$

where $d(R_1, R_2) = (\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$.

$$R_{w_k} = \begin{cases} \left[R_1 + (R_2 - R_1).\frac{\lfloor k/4 \rfloor}{n} \right] & if\ (k\ mod\ 4) = 0 \\ \left[R_1 + (R_2 - R_1).\frac{\lfloor k/4 \rfloor + 1}{n} \right] & if\ (k\ mod\ 4) = 1 \\ \left[R_4 + (R_4 - R_3).\frac{\lfloor k/4 \rfloor}{n} \right] & if\ (k\ mod\ 4) = 2 \\ \left[R_4 + (R_4 - R_3).\frac{\lfloor k/4 \rfloor + 1}{n} \right] & if\ (k\ mod\ 4) = 3 \end{cases} \tag{2}$$

where $k \in [1, n]$ denotes the sequential number of the waypoint.

The USV is controlled to consecutively approach the waypoints starting from waypoint R_{w_1}. As the USV's coordinates is within the approach radius $r_{approach}$ from the curent waypoint R_{w_k} for a given interval $t_{approach}$, k is incremented by 1. The survey ends when the USV approaches waypoint R_{w_n}.
The desired heading $\psi_{control}$ of the USV is designed as follows

$$\psi_{control} = atan2(y_{w_k} - y, x_{w_k} - x) \tag{3}$$

The control thrust $T_{control}$ and control yaw moment $N_{control}$ are designed as follows

$$\begin{cases} T_{control} = k_{e_\psi} k_\Delta u_{cruise} \\ N_{control} = k_\psi e_\psi \end{cases} \tag{4}$$

where $k_{e_\psi} = \frac{1}{1+a.e_\psi{}^2}$, $k_\Delta = \frac{d\left(R_{USV},R_{w_k}\right)^2}{d\left(R_{USV},R_{w_k}\right)^2+b}$, $a > 0$, $b > 0$, $u_{cruise} > 0$ is the cruise speed, $k_\psi > 0$, $e_\psi = \psi_{control} - \psi$ is the heading error.

The k_{e_ψ} factor in the thrust control term is designed to constrain the surge velocity when the heading error is large. This enable the USV to maintain stability during correction of the heading angle before accelerating to the waypoints.

The k_Δ factor in the thrust control term is designed to decelerate the USV as it approaches the waypoints, which reduces overshooting when the USV switch from one waypoint to another. The thrust on each motor is allocated as follows

$$\begin{bmatrix} f_{stbd} \\ f_{port} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{4B_{CL}} \\ \frac{1}{2} & -\frac{1}{4B_{CL}} \end{bmatrix} \cdot \begin{bmatrix} T_{control} \\ N_{control} \end{bmatrix} \tag{5}$$

where f_{stbd} and f_{port} denote the thrust on the starboard-side motor and the port-side motor, respectively, B_{CL} is the lateral spacing between the two hulls' centerlines.

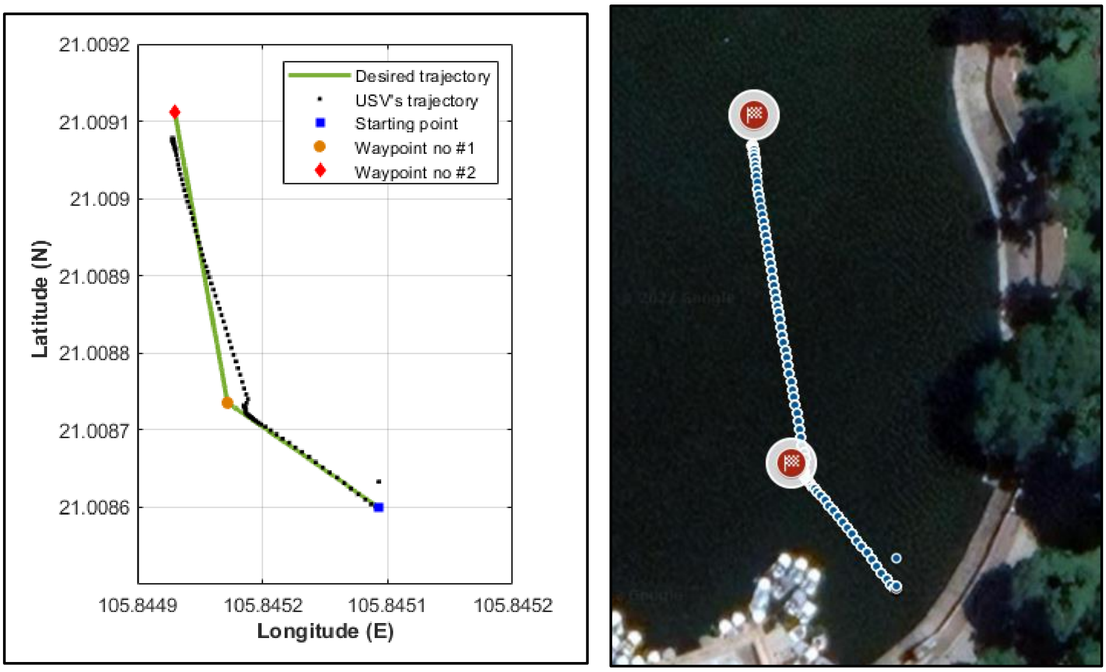

Figure 1. Desired trajectory and USV's trajectory (experimental test #1)

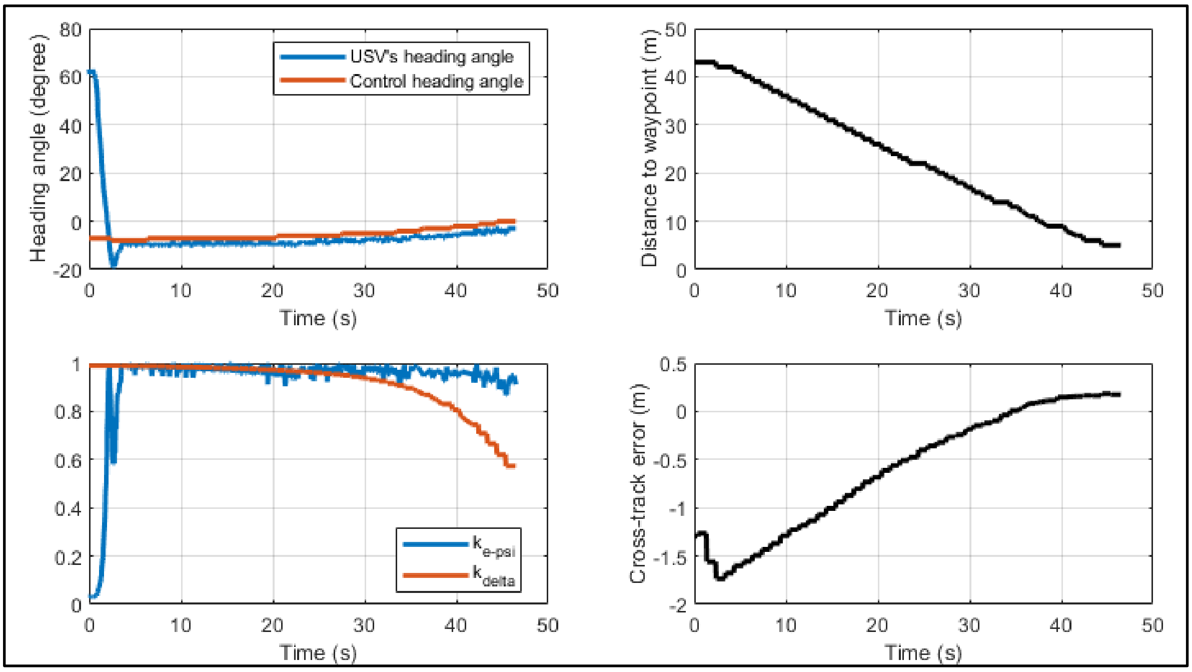

Figure 2. USV's tracking performance (experimental test #1)

4. Experimental results

In experimental test #1, in order to first assess the tracking performance to each waypoint, the USV is controlled to approach two waypoints. The desired trajectory and the USV's trajectory are shown in **Fig. 1**. The tracking performance of the proposed control method is assessed by the heading angle, k_{e_ψ}, k_Δ and the cross-track error.

Experimental results in **Fig. 2** show that at $t = 0s$, initial error in the heading error is $e_\psi \approx 65°$. At $t = 5s$, the heading error stabilises about 0°. After $t > 5s$, the heading error e_ψ fluctuates about 0° with amplitude under 5°.

Fig. 2 also show that k_{e_ψ} effectively constrain the surge velocity, maintain the USV's stability during correction of the heading. k_Δ is shown to effectively decelerate the USV when it approaches the waypoint.

In experimental test #2, from the survey request, four bounding coordinates that define the area of interest are determined. The USV calculates the coordinates of the waypoints and then approaches each waypoint, hence, following the desired trajectory. During this process, the USV constantly collected and send depth data to the GCS. The collected depth is then used to construct the depth map of the surveyed area.

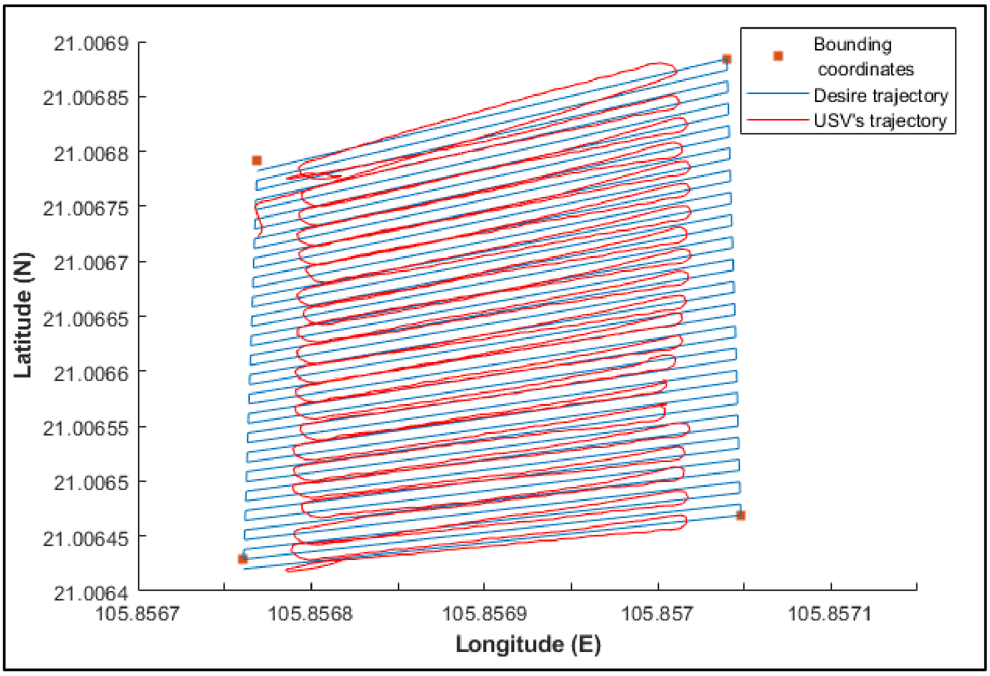

Figure 3. Desired trajectory and USV's trajectory (experimental test #2)

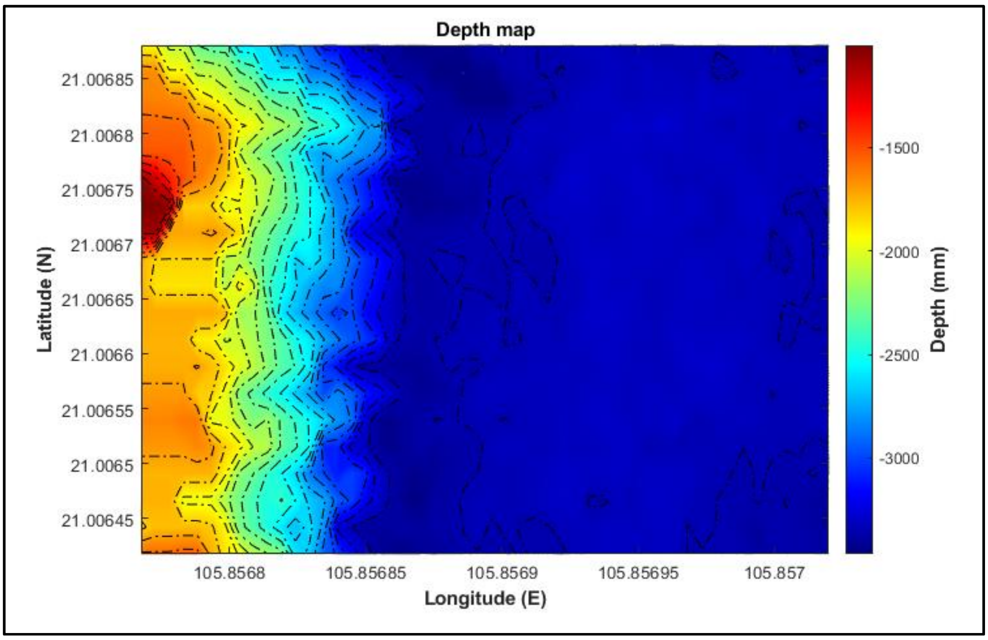

Figure 4. Constructed depth map (experimental test #2)

5. Conclusions

This paper introduces the design and configuration of an under-actuated USV, proposes a control method for the trajectory tracking problem and presents the implementation of the USV and the control method in bathymetric surveys. Experimental results show that the control method has good stability performance. The tracking error is shown to be within limits of acceptance. The depth map constructed from the collected data shows the feasibility of applying the control method in bathymetric surveys.

Acknowledgements

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