

SMALL UNMANNED SURFACE VEHICLE IN AUTONOMOUS WAY-POINT EXPERIMENT AND SIMULATIONS FOR STRAIGHT PATH TRACKER

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Abstract

The small unmanned surface vehicle (USV) in autonomous motion can be implemented in surveying applications and water management systems. In process of autonomous navigation, the precision of position and path-way are necessary for the operation. This research was aimed to investigate and track the path-way by using a perpendicular straight line error between way-point for small USV system. The kinematic and dynamical models are formulated and implemented in MATLAB® and Simulink programs. The investigations for autonomous way-point tests are divided into two main parts; experimental results used an ArduPilotMega(APM2.8) flight control board, and simulation results by using mathematical dynamic model. Both experiments are analyzed by using a tracking-error for the straight path, which can be described the mean and standard deviation values. The results will help to predict the tendency of error, while operating on the field tests. Moreover, this model can be applied to improve system identification as well as to enhance a controller design of a real unmanned surface vehicle.

Keywords: Unmanned surface veicle (USV), perpendicular straight line, ArduPilotMega(APM2.8), tracking-error, mean and standard deviation

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Introduction

The development of automatic survey vehicle was investigated for several aspect; especially installation of measurement devices and fused sensors for analysis. The ability to track the planned route is the main purpose for many investigation and commercial applications as well. In general, the official personals collected survey data and manage the acceptable level of control in order to maintain a high accurate on mobile robots. This is an important part that will make the unmanned surface vehicle work successfully and efficiently.

Modeling and control of a small autonomous boat (SAB) from Qatar University implemented a cascade PID controller with NI myRIO program for the course-keeping simulation and experimental validation (Noorizadeh and Meskin, 2017). Moreover, the Lanxin Unmanned Surface Vehicle of Dalian Maritime University (DMU) develop a trajectory-tracking controller based on backstepping algorithm (Yunsheng *et al.*, 2017). Maritime Tactical System, Inc, (MARTAC) developed the MANTAS USVs with a 12 ft catamaran hull and a payload more than 145 lbs. The system focuses for an applications of detection monitoring driver or swimmer (harbor security) by using a high resolution multibeam echosounder and a bathmetric imaging (Rowley, 2018).

From the problem and introduction, this paper presents small USV developments for straight path tracker and autonomous waypoint. In section II the component and specific of small USV is described. The kinematic and dynamic analysis for small USV

is explained in section III. Section IV shows experimental result using ArduPilot, compared to a simulation model for perpendicular of straight path between waypoint. Lastly, evaluations of tracking-error for the straight path are compared and summarized Section V.

Materials and Methods

Equipment and Schematic Diagram

In this design, small unmanned surface vehicle (Model: G-75, Manufacturer: Giant Racer) with a maximum dimension of $114.3 \times 38.1 \times 22.86$ cm is implemented. A 12V_{DC} 9Ah battery is used as a power source for dual motor drive boat with two propellers (Model: Dual VNH2SP30, Manufacturer: Pololu), and ArduPilot(APM2.8) is used for GPS navigation path planning. The configuration mission data logs, and tuning feed-back control on ground station is implemented and recorded by Software Mission Planner. The pulse-width is used to command a propeller-left/right (port/star) simultaneously. A schematic wiring diagram for the command parameters (throttle and steering) of autopilot are transferred to microcontroller Arduino board. The propeller design with 2-blade has a diameter 4.7 cm. All electronics components for small unmanned surface vehicle are shown in (Figure 1).

Mathematical Models Small USV

The Mathematical models for this USV are investigated based on kinematics and dynamics models (Thor, 1994). The motion of small USV with 6 Degree of Freedom (6-DOF) are analyzed and formulated. The notations for the analysis are summarized in Table1.

To analyze the position and orientation of a USV, the time derivative of position and orientation are used to formulate a linear and angular velocity. The coordinate of the simulation system shows the behavior and achieve target of the automatic vessel movement. Thus, design control system of

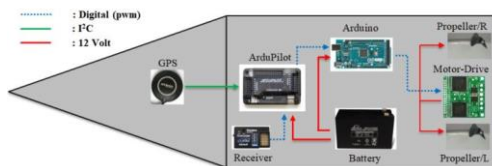
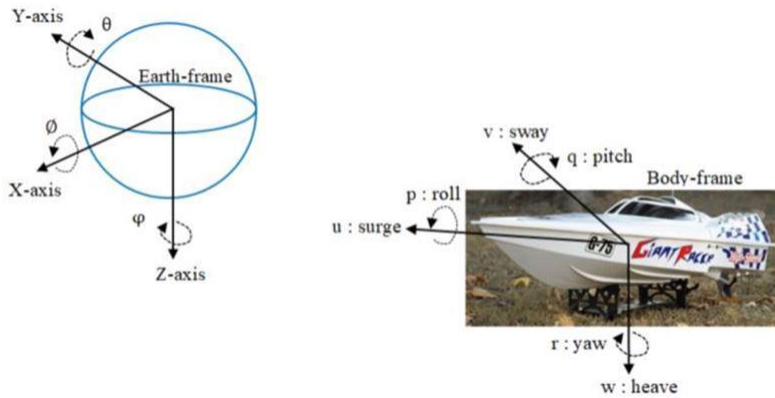


Figure 1. Instrument diagram for small unmanned surface vehicle

Table 1. Notations used for kinematic model of unmanned surface vehicle

6 DOF	Motion Description	Position and Euler angles	Linear and Angular Velocity
1	Motion in x-direction (surge)	x	u
2	Motion in y-direction (sway)	y	v
3	Motion in z-direction (heave)	z	w
4	Rotation about x-axis (roll)	ϕ	p
5	Rotation about y-axis (pitch)	θ	q
6	Rotation about z-axis (yaw)	ψ	r

**Figure 2. Vehicle model reference with earth-frame and body-frame coordinate**

model can reduce complexity by choose to have the minimum degree of freedom as be required.

Kinematic Model

The vessel mechanism motion regardless force and torque was used in this kinematic model. The variables of kinematic was described with respect to the previous notations. The relationship between earth-frame and body-frame reference have been established as shown in (Figure 2).

The motion of vessel is transformed to reference-frame represented by a transformation matrix in Jacobian matrices $J_1(\eta_2)$ and $J_2(\eta_2)$ of position and orientation as shown in Equation (1).

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3 \times 3} \\ 0_{3 \times 3} & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \quad (1)$$

The mathematical model can be simplified by using a 2-DOF (surge and yaw) to represent a small USV based on an

assumption that sway, heave, roll and pitch are negligible for the motion of USV. The transformation matrix of earth-frame reference ($\dot{\eta}_1 = [\dot{x} \ \dot{y}]^T$, $\dot{\eta}_2 = [\dot{\phi}]$) are formulated from time-derivative of position and Euler angle in body-frame ($V_1 = u$, $V_2 = r$). They are both represented as a vector of linear and angular velocity respectively.

Dynamic Model

In the equation of motion of small USV based on Newton's second law, the dynamic model can be evaluated, apply to forward force (X) and yaw moment (N) in body-frame, which are (τ) external forces two thrusters configuration matrix (B) and vector control input force ($u = [T_L \ T_R]^T$) has direct thrust a forward force ($X = T_L + T_R$) and moment force ($N = -T_L X_L + T_R X_R$), shown in Equation (2).

$$M\dot{v} + C(v) + D(v)v + g(\eta) = \tau = Bu \quad (2)$$

where $C(v) = C_A(v) + C_{RB}(v)$ is a Coriolis matrix, (D) is a hydrodynamic damping force matrix as describe in (Prempraneerach, 2016), and $g(\eta)$ is the term gravitation that can be

neglected for simplified expression. In this design, the hydrodynamics forces and moment is then derived from the rigid-body mass and inertia: $M = (M_A + M_{RB})$. The input force is then formulated in the following equation.

$$\begin{aligned}\dot{u} &= \left(\frac{X_u}{m - X_{\dot{u}}} \right) u + \left(\frac{1}{m - X_{\dot{u}}} \right) T_L + \left(\frac{1}{m - X_{\dot{u}}} \right) T_R \\ \dot{r} &= \left(\frac{N_r}{I_{zz} - N_{\dot{r}}} \right) r + \left(\frac{X_L}{I_{zz} - N_{\dot{r}}} \right) T_L - \left(\frac{X_R}{I_{zz} - N_{\dot{r}}} \right) T_R\end{aligned}\quad (3)$$

where m represents the total mass of the small USV, I_z is a moment of inertia about z-axis, a length CM to propeller motor along y-axis (X_L , X_R) and (T_L , T_R) acting on input thrust forces.

Results and Discussion

In this experiment, we conducted a real test for tracking the coordinates with automatic control of the vehicle in the RMUTT pond as shown in (Figure 3). The data is collected for the values of latitude, longitude, and heading angle of the autonomous movement without disturbance in order to evaluate the straight path tracker in next session.

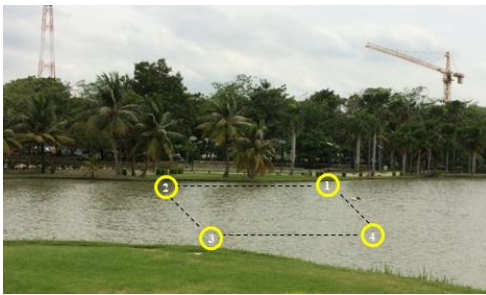


Figure 3. A waypoint in RMUTT pond used for the autonomous motion of USV

Simulation Results with 4 Waypoints

The performance of small USV is simulated for dynamic and kinematic models by using MATLAB® and Simulink program. The radius of coverage is 0.5 m. The distance and heading error is approximated by using

PID controller feedback. The heading angle error from each pathway is shown in Figure 4.

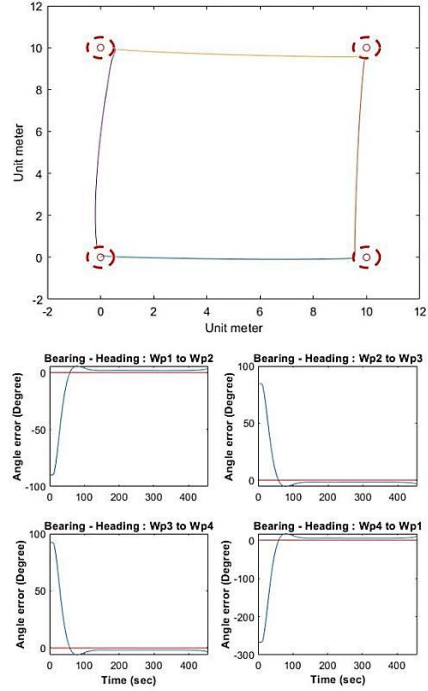


Figure 4. Simulation results for autonomous 4-waypoints tracking (Left), and heading error response for each pathway (Right)

Experiment Results with 4 Waypoints

To examine the tracking error for an autonomous USV, 4-waypoint movement is defined as target waypoints with a radius coverage of 2 m. The two variables that are investigated is the distance between waypoint and angle of the vessel (Heading : ψ), when comparing to the angle of target (Bearing : β) as shown in Figure 5.

Analytical Result for Perpendicular Straight Path Tracking Error of small USV

This research implements a Pythagoras theorem to calculate a straight path for a tracking error based on the previous model (Sherman and Anthony, 1993). The survey data is calculate for the mean and standard

deviation values, compared to the straight line as shown in (Figure 6).

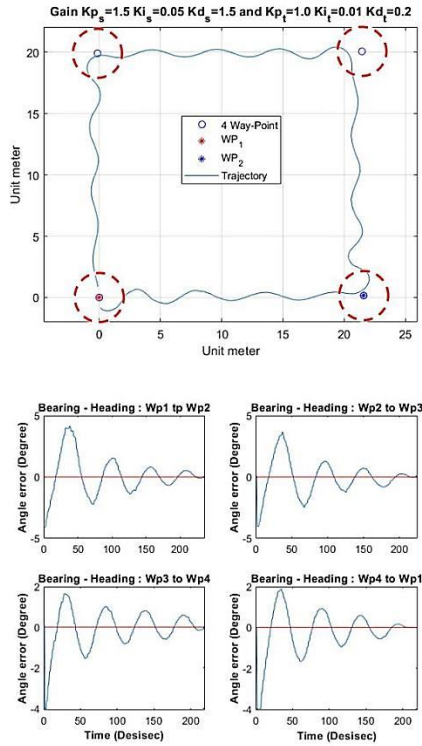


Figure 5. Experimental results for autonomous 4-waypoints tracking (Left) and heading error response for each pathway (Right)

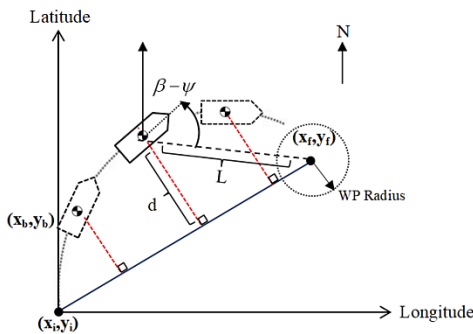


Figure 6. Tracking-error (d) definition for straight line between waypoint

Perpendicular straight line between waypoint

The vessel trajectory line between waypoint initial (x_i, y_i) and waypoint final (x_f, y_f) can be described as an equation of $a \cdot x_b + b \cdot y_b + c = 0$, where $-(a/b)$ is slope of straight line, and (x_b, y_b) is the point that is differ from required path in the perpendicular distance (d). The tracking-error (d) can be calculated from the trajectory line as shown in Equation (4).

$$\text{Tracking_error}(d) = \frac{a \cdot x_b + b \cdot y_b + c}{\sqrt{a^2 + b^2}} \quad (4)$$

Comparison Between Experimental Navigation and Simulation Results

Tracking errors based on a straight line is compared for small USV for each pathway. This result can be used to check the position of

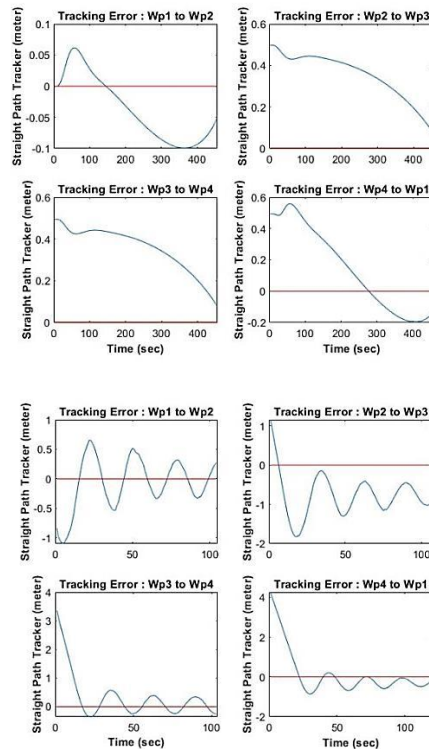


Figure 7. Small USV tracking-error from the simulate (Left) and experimental result (Right) (Unit: meter)

Table 2. A maximum and minimum error from experiments

Waypoint Descriptions	Simulate USV tracking : (m)		Experimental USV tracking : (m)	
	Minimum	Maximum	Minimum	Maximum
Waypoint1 to Waypoint2	-0.0993	0.0616	-1.0954	0.6528
Waypoint2 to Waypoint3	0.0739	0.4972	-1.8281	1.1533
Waypoint3 to Waypoint4	0.0783	0.4945	-0.3535	3.3641
Waypoint4 to Waypoint1	-0.1959	0.5589	-0.8642	4.2560

Table 3. A mean and standard deviation for error values from experiments

Waypoint Descriptions	Simulate USV tracking : (m)		Reality USV tracking : (m)	
	Mean	STD	Mean	STD
Waypoint1 to Waypoint2	-0.0364	0.0522	-0.0680	0.4333
Waypoint2 to Waypoint3	0.3541	0.1095	-0.7775	0.5374
Waypoint3 to Waypoint4	0.3566	0.1056	0.3170	0.7664
Waypoint4 to Waypoint1	0.1445	0.2680	0.1240	1.1226

boat as shown in (Figure 7). The positive result represents the point (x_b, y_b) is on the side original and a negative value represents a point that is opposite to the origin.

Tracking-Error value of real and simulation from small USV

In these experiments, we demonstrated a perpendicular straight line minimum and maximum error from a simulation and experimental tracking of small USV as shown in Table 2. However, these can analyze this information to increase the reliability of the calculations in the next section.

However, the autonomous result for small USV in straight path tracker is recorded and compared. The tracking error indicated the error values for a group out of error in term of average and standard deviations as shown in the following Table 3.

Conclusions

This article presents the design of straight path tracker. For the automatic control without disturbance of the small USV according to the specified target coordinates, divide the control loop into two loops position control and angle control of the vessel. In this research, experiment 1) Simulation using the kinematics and dynamic model using the MATLAB® and Simulink program that inputs the linear speed and angular velocity for the vessel to control

movement and 2) Experiment using ArduPilot(APM2.8) collect GPS position and feedback PID controller. From the test results, controller can control the vessel movement to the desired target position, with the tracking error of the vessel mean maximum at 0.77 m and mean minimum at 0.03 m. As the results of standard deviation measurement for a group spread out from average data of vessel maximum at 1.12 and minimum at 0.05, then analysing can be described the results will help to predict the tendency of error and based on alternative of survey data to manage acceptable.

References

- Noorizadeh, M. and Meskin, N. (2017). Design of small autonomous boat for course-keeping maneuvers. Proceedings of the 4th International Conference on Control: Decision and Information Technologies (CoDIT); April 5-7, 2017; Barcelona, Spain, p. 0908-0912.
- Prempraneerach, P. (2016). Teajjectory tracking using sliding mode control for autonomous surface vessel. Proceeding of the International Computer Science and Engineering Conference (ICSEC); December 14-17, 2016, Chiang Mai, Thailand, p. 1-6.
- Rowley, J. (2018). Autonomous unmanned surface vehicles (USV): A paradigm shift for harbor security and underwater bathymetric imaging. Proceeding of the OCEANS 2018 MTS/IEEE Charleston; October 22-25, 2018, Charleston, South Carolina, p. 1-6.
- Sherman, K.S. and Anthony, B. (1993). Calculas and Analytic Geometry. 5th ed. McGraw-Hill, p. 1,232.

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- Thor, I.F. (1994). Guidance and Control of Ocean Vehicle. 1st ed. John Wiley & Sons, NY, 475p.
- Yunsheng, F., Yutong, S., and Guofeng, W. (2017). On model parameter identification and trajectory tracking control for USV based on backstepping. Proceeding of the 36th Chinese Control Conference (CCC); July 26-28, 2017, Dalian, China, p. 4,757-4,761.