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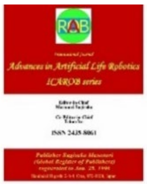

Research Article

Development of a USV Testbed and Its Basic Trajectory Tracking Control

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ABSTRACT

In recent years, autonomous platforms have been developed to reduce the cost of various activities in the field of marine engineering, such as ocean observation platforms, autopilot vessels for maintenance of offshore wind farms, and the installation of submarine drilling rigs. Catamaran-type USVs are one of the useful platforms in these activities. The authors have been developing an experimental testbed of USV platform to conduct basic studies on control algorithms through sea experiments. The USV must be capable of following a given trajectory and accomplishing its mission in the face of wind, currents, and other unknown disturbances while avoiding other vessels and obstacles at sea. This paper presents our testbed design and LQR based control algorithm to implement the basic ability of trajectory tracking, which is intended to be used to collect data for designing AI based control algorithm in the near future.

1. Introduction

Catamaran-type USVs are useful in various marine projects that have been increasing in recent years, such as the collection of marine plastic waste, wide area observation networks of ocean environment, offshore wind power platform maintenance, or installation of a subsea machinery and so on. If the size of the ship is increased, it will be even possible to apply it to installation of deep seafloor drilling equipment in the project of subsea mining. These USVs are required to have the ability to follow a given trajectory and carry out missions in unknown disturbances such as wind and tidal currents while avoiding other ships and obstacles at sea. Autonomous navigation algorithms such as following a given trajectory, reaching a target point, avoiding obstacles, etc. are essential functions of a USV, although there are differences in actual individual operations depending on a given mission.

So far, the authors have constructed a water tank experimental system consisting of a catamaran and its position detection system, and verified the obstacle avoidance algorithm [1]. The tank experiment is useful to check the basic idea in the laboratory, however, the following problems were recognized as the limitations of the study in tank experiments.

(1) It is difficult to introduce unknown disturbances such as waves and wind.

(2) The navigable range of USV is limited.

(3) It is not easy to simulate communication problems between a USV and a land base.

In order to clear these issues, it is necessary to repeat the experiment in the actual sea area. For this purpose, the authors are constructing an actual sea area experiment

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system assuming that the experiment will be conducted in a relatively quiet harbor as the first step. In this paper, we will introduce the outline of the experimental system design and the simulation results on the effectiveness of the optimal control algorithm for trajectory tracking under disturbances. As a trajectory control algorithm for autonomous vessels, an AI-based method, which has recently entered the stage of practical application, is also considered to be effective. In this study, we conducted simulations to verify the implementation of a basic trajectory tracking control algorithm based on LQR control on this experimental system in order to obtain teacher data for the trajectory tracking to be learned by the AI program.

2. Testbed System Configuration

Figure 1 shows the configuration of the USV testbed. The length is around 1.3m and the width is around 0.8m. Its draft varies depending on its weight. Figure 2 shows the hardware system architecture placed inside the watertight compartment. We implemented two board computers. The one is for motion control and the other is for image processing. They communicate through a LAN cable. Usually, a ship testbed has one thruster and one rudder and the control problem becomes under-actuated [2]. However, considering some simulation results, we implemented three thrusters to precisely control 3 DOF of (x,y,yaw).

The global position of the USV is measured by a GNSS, whose position detection accuracy has been greatly improved recently, as within 0.1m radius without RTK. Yaw angle can be estimated by the GNSS once the USV started cruising, however, when it stops the estimation becomes degrading. So we implemented 9DOF IMU module mainly to detect its yaw angle when the USV isn't cruising. We use wireless LAN of the board computer to monitor its inner status if the testbed is near our land computer base. But the distance we can communicate is limited. As the testbed is supposed to cruise around 1~2km off the shore, we implemented a wireless communication device which can transmit RS232 signals for long distance communication. Through this, we can not only monitor its inner control situation but also control it manually from land PC in case the automatic control system doesn't work well or when we want it to obey our order during experiments.

Fig.1 Configuration of USV Testbed.

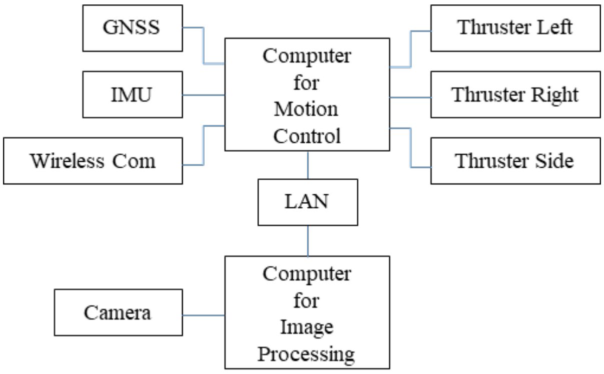

Fig.2 USV Hardware System Architecture

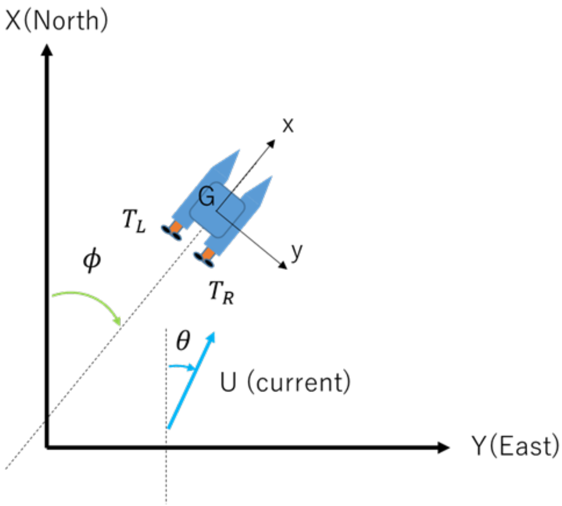

Fig.3 Coordinate System for Controller Modeling

A forward camera is mounted on the deck to detect obstacles on its trajectory during navigation. The camera is also supposed to be used for AI image processing experiments for inspection of port structures.

3. Control Algorithm

Though the real dynamics of the USV is complicated due to its coupled motions of 6 DOF and environmental forces as wave, wind and current, we need to abstract the essential components of the dynamics. The main control purpose in this paper is the trajectory tracking or position keeping on the surface, so only 3 DOF of surge, sway and yaw are hired for the dynamics modeling of the USV [3]. Figure 3 shows the coordinate system for the modeling of equation of motion. The USV position determined by GNSS is based on the fixed global coordinate whose origin is set from the start point. The X axis is parallel to the longitude, and the Y axis is parallel to the latitude. On the other hand, its thruster forces work based on the local coordinate whose origin is USV's COG. The nonlinear equations of motion are as follows.

Surge:

$$(m+m_a)(\dot{u}-v\omega)+\rho C_d A_x|u-u_C|(u-u_C) = T_R+T_L \tag{1}$$

Sway:

$$(m+m_a)(\dot{v}+u\omega)+\rho C_d A_y|v-v_C|(v-v_C) = T_S \tag{2}$$

Yaw:

$$(I+I_a)\dot{\omega}+\frac{1}{2}\rho C_d\frac{A_y}{2}\left|\omega\frac{L}{4}\right|\left(\omega\frac{L}{4}\right)\cdot L = -l\cdot T_R+l\cdot T_L \tag{3}$$

Here, m is mass, is added mass, u is surge velocity, v is sway velocity, is angular velocity of yaw, is water density, is drag coefficient, , are typical area of the hull in each direction, is the moment of inertia of the hull, is the added inertia by the surrounding fluid, is x component of current velocity, is y component of current velocity, L is the length of the hull, , , are thruster forces. The suffixes are as R means right, L means left, S means side. means the length from the centerline of the hull to the thruster attached point. The drag force by the fluid is based on the modified Morrison's equation which includes the current effects. The relation between the USV fixed coordinate and the global coordinate is as follows.

$$\phi = \phi_0 + \int_0^t \omega\, dt \tag{4}$$

$$X = X_0 + \int_0^t (u\cos\phi - v\sin\phi)\, dt \tag{5}$$

$$Y = Y_0 + \int_0^t (u\sin\phi + v\cos\phi)\, dt \tag{6}$$

The following nominal model can be obtained by linearly approximating the nonlinear term of the fluid force using typical cruising velocity.

$$\begin{bmatrix} m+m_a & 0 & 0 \\ 0 & m+m_a & 0 \\ 0 & 0 & I+I_a \end{bmatrix}\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{\omega}\end{bmatrix} + \begin{bmatrix} \rho C_d A_x\bar{u} & 0 & 0 \\ 0 & \rho C_d A_y\bar{v} & 0 \\ 0 & 0 & \frac{1}{64}\rho C_{dI} A_y L^3\bar{\omega} \end{bmatrix}\begin{bmatrix}u\\ v\\ \omega\end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \\ -l & l & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix}T_R\\ T_L\\ T_S\end{bmatrix} \tag{7}$$

$$\begin{bmatrix}u\\ v\\ \omega\end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \omega\end{bmatrix} \tag{8}$$

Equation (7) is written as follows.

$$\boldsymbol{M\ddot{\xi}} + \boldsymbol{C\dot{\xi}} = \boldsymbol{Lf} \tag{9}$$

$$\boldsymbol{\dot{\xi}} = \boldsymbol{R\dot{x}} \tag{10}$$

Here, is the velocity vector in USV fixed coordinate, is the velocity vector in the global coordinate. is the transformation matrix depending on the yaw angle.

Since the control target is set at a point on the global coordinates, the control system is designed with the global coordinate system.

$$\boldsymbol{MR\ddot{x}} + \boldsymbol{M\dot{R}\dot{x}} + \boldsymbol{CR\dot{x}} = \boldsymbol{Lf} \tag{11}$$

Let $\boldsymbol{e}$ be the error vector between the current position and the target point.

$$\boldsymbol{e} = \boldsymbol{x} - \boldsymbol{x_t} \tag{12}$$

To implement 1-type servo system, introducing variable z as follow,

$$\boldsymbol{\dot{z}} = \boldsymbol{e} \tag{13}$$

Then, let the control state vector as and the state equation as follows.

$$\boldsymbol{\dot{X}} = \boldsymbol{AX} + \boldsymbol{Bf} \tag{14}$$

Setting the optimization function J as,

$$J = \int_0^\infty (\boldsymbol{X^T QX} + \boldsymbol{f^T Rf})\, dt \tag{15}$$

The control force vector is obtained as follows by solving the LQR gain in each control ste

$$\boldsymbol{f} = -\boldsymbol{GX} \tag{16}$$

4. Simulation

To verify the control algorithm above, we made a simulation program and carried out simulations in several different conditions. Table 1 shows the control modes for trajectory tracking. In the simulations, the USV starts at [0,0] point with initial azimuth angle 90 degree. The first mode is "Cruise" mode, which means the path was set from [0,0] to [0,20m]. As the target waypoint was set to [0,20m], the target azimuth of the USV was set to 90 degrees. If the USV reaches within an allowable range of the target waypoint, the control mode shifts to "Turning Around" mode, which means the USV turns its head toward the given target azimuth angle with keeping its position around the target waypoint. As for the allowable range, it depends on the strength of the current or other disturbances. In this simulation, we set the allowable range was within 5m radius. If the USV strictly tracks the trajectory given in the Table 1, the shape of the trajectory becomes a square whose side is 20m.

Figure 4 shows the trajectory tracking simulation result example of using LQR controller without servo algorithm, which means there is no integrator and PD feedback only. The current speed is set to 0.2m/s and the current direction is set to 0 degree (from South to North). As shown in the Figure 4, if the controller was PD feedback only, the USV cannot keep the given trajectory.

Figure 5 shows the trajectory tracking simulation result example of using LQR controller with servo algorithm described in the former section. The current condition is the same as the simulation in Figure 4. As shown in Figure 5, the USV can track the given trajectory better than Figure 4 case.

Figure 6 shows when the current speed is 0.3m/s and the current direction is 180 degrees (from North to South). In this case, despite the servo system, there is an error in trajectory tracking. This is because there is only one thruster in the lateral direction and the optimal gain weights were set so that the thrust of the thruster to be implemented does not exceed the maximum value. However, it was confirmed that this control algorithm was able to track the trajectory within the set tolerance.

Figure 7 shows the control forces in this simulation. The time series of Thruster S output shown in Figure 7 indicates that the servo system works against the current from the north, gradually increasing the control force.

From these simulations, the proposed control algorithm is expected to work effectively in acquiring experimental data in real sea areas for generating AI teacher data.

Table 1 Control modes for trajectory tracking

	Mode	Start Point	Initial Azimuth [deg]	Target Azimuth [deg]	Target Waypoint
1	Cruise	[0, 0]	90	90	[0, 20]
2	Turning Around	Around [0,20]	From 90 to 0	0	[0, 20]
3	Cruise	From [0, 20]	Around 0	0	[20, 20]
4	Turning Around	Around [20,20]	From 0 to -90	-90	[20, 20]
5	Cruise	From [20, 20]	Around -90	-90	[20, 0]

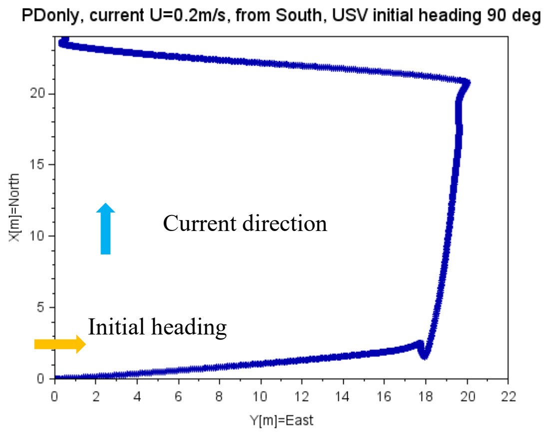

Fig.4 Simulation result when the controller is PD only.

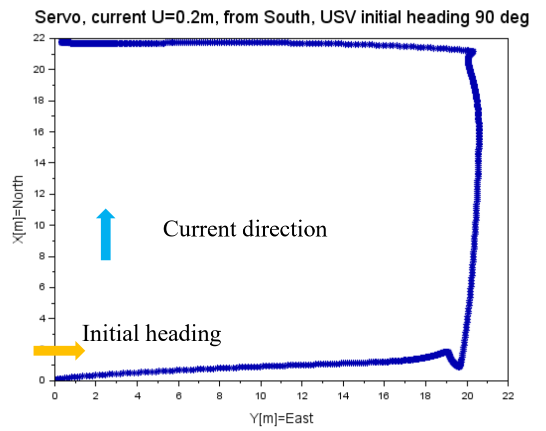

Fig.5 Simulation result with servo algorithm controller.

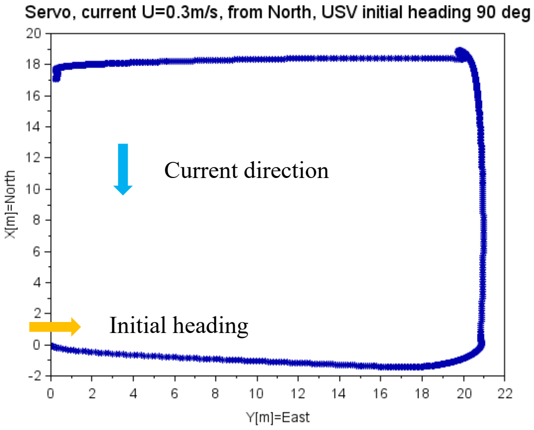

Fig.6 Simulation result at different current condition.

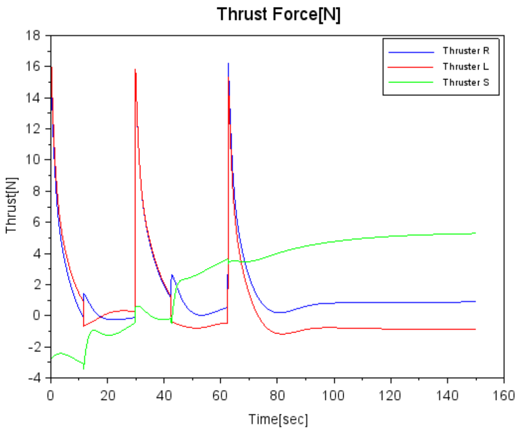

Fig.7 An example of control force time series.

5. Conclusion and Future Work

In this study, in order to implement trajectory following control for the USV experimental system currently being built and used in the real sea, we designed a servo system optimal control algorithm that solves the Riccati equation in real time at each control step, and performed simulations considering nonlinear hydrodynamic forces for different directions and strengths of tidal currents. As a result, it was confirmed that the optimal control gain based on a linearized nominal model can be used to construct a control system that follows a given trajectory and reaches the target waypoint within an acceptable error range. optimum control algorithm of the USV experimental system was designed, and some simulations were carried out by changing the direction and strength of the current. As a result, it was confirmed that a control system to reach the target way point can be constructed by using the optimum control gain based on the linearized nominal model. The verification in the sea experiment is our next step of this research. In the future, we will conduct trajectory following experiments using the proposed control system and accumulate the data as teacher data. While conducting at-sea experiments using this USV model, we will continue to study AI control algorithms that adapt to unknown disturbances that have not been modeled.

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