Development of a USV Testbed and Its System Check Experiments at Sea

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Abstract

The catamaran type USV is useful as an autonomous platform for various activities in the field of marine engineering, such as collection of marine waste in ports, ocean observation platforms, automated vessels for offshore wind farm maintenance, or installation of a subsea drilling machine and so on. The authors have been developing an experimental testbed of USV platform to conduct basic studies on control algorithms by simulation as well as hardware systems to conduct sea experiments. In this paper, we report on some simulation results of LQR based control algorithm and introduce the testbed system with its system check experiment results near our university pier.

Keywords: Offshore wind farm maintenance, USV, Sea experiment, Subsea mining.

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 is possible to apply it to the installation of the deep seafloor drilling equipment in the development 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]. In addition, we have conducted a basic study of the trajectory tracking control algorithm by computer simulation. Although each of these studies was useful as an initial study method, the following problems were recognized as the limitations of the study in tank experiments and computer simulations.

Tank experiment:

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

(2) The navigable range of USV is limited.

Computer simulation:

(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 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.

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 control 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.

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.

Fig.1 Configuration of USV Testbed.

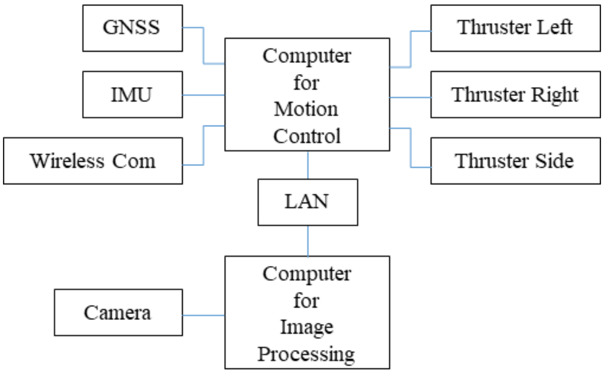

Fig.2 Control System Architecture

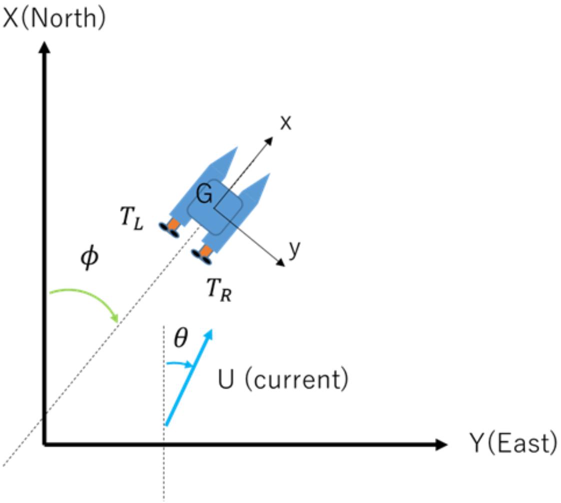

Fig.3 Coordinate System for Controller Modeling

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 testbed[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:

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

Sway:

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

Yaw:

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

Here, m is mass, m_a is added mass, u is surge velocity, v is sway velocity, ω is angular velocity of yaw, ρ is water density, C_d is drag coefficient, A_x, A_y are typical area of the hull in each direction, I is the moment of inertia of the hull, I_a is the added inertia by the surrounding fluid, u_C is x component of current velocity, v_C is y component of current velocity, L is the length of the hull, T_R, T_L, T_S are thruster forces. The suffixes are as R means right, L means left, S means side. l 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.

$$\phi=\phi_0+\int_0^t\omega\,dt \qquad (4)$$

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

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

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

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

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

Equation (7) is written as follows.

$$\boldsymbol{M}\ddot{\boldsymbol{\xi}}+\boldsymbol{C}\dot{\boldsymbol{\xi}}=\boldsymbol{L}\boldsymbol{f} \qquad (9)$$
$$\dot{\boldsymbol{\xi}}=\boldsymbol{R}\dot{\boldsymbol{x}} \qquad (10)$$

Here, $\dot{\boldsymbol{\xi}}$ is the velocity vector in USV fixed coordinate, $\dot{\boldsymbol{x}}$ is the velocity vector in the global coordinate. $\boldsymbol{R}$ 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.

$$\boldsymbol{M}\boldsymbol{R}\ddot{\boldsymbol{x}}+\boldsymbol{M}\dot{\boldsymbol{R}}\dot{\boldsymbol{x}}+\boldsymbol{C}\boldsymbol{R}\dot{\boldsymbol{x}}=\boldsymbol{L}\boldsymbol{f} \qquad (11)$$

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

$$\boldsymbol{e}=\boldsymbol{x}-\boldsymbol{x_t} \qquad (12)$$

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

$$\dot{\boldsymbol{z}}=\boldsymbol{e} \qquad (13)$$

Then, let the control state vector as $\dot{\boldsymbol{X}}=[\boldsymbol{z}\quad \boldsymbol{e}\quad \dot{\boldsymbol{e}}]^{\boldsymbol{T}}$ and the state equation as follows.

$$\dot{\boldsymbol{X}}=\boldsymbol{A}\boldsymbol{X}+\boldsymbol{B}\boldsymbol{f} \qquad (14)$$

Setting the optimization function J as,

$$J=\int_0^\infty(\boldsymbol{X^T}\boldsymbol{Q}\boldsymbol{X}+\boldsymbol{f^T}\boldsymbol{R}\boldsymbol{f})\,dt \qquad (15)$$

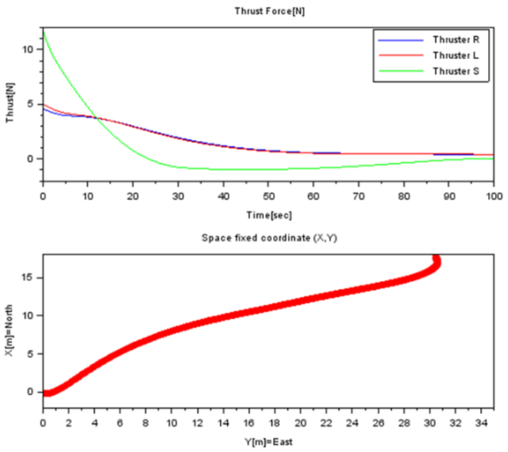

Fig.4 Simulation Result from (0,0) to (30,20) current direction was 180 deg.

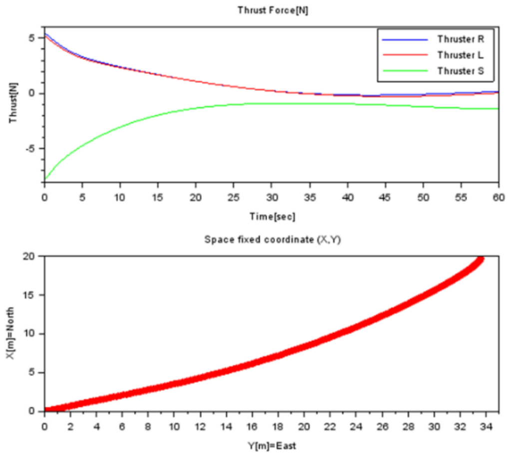

Fig.5 Simulation Result from (0,0) to (30,20) current direction was 90 deg.

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

$$\boldsymbol{f} = -\boldsymbol{G}\boldsymbol{X} \qquad (16)$$

4. Simulation Results

To verify the control algorithm above, we made a simulation program and carried out simulations in several different conditions Figure 4 and 5 show the trajectory and control forces in the case of the target way point was set to (30m, 20m). The current speed was 0.3m/s and its direction was 180 deg (against to the direction of the USV) in Fig.4, and 90 deg (from the side of the USV) in Fig.5. Nonlinear drag force is considered in this simulation. The USV successfully reached the target point and the control algorithm worked as expected.

5. Conclusion and Future Work

The 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.

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