A Model Estimation and Multi-variable Control of an Unmanned Surface Vehicle with Two Fixed Thrusters

Jeong-Hong Park, Hyung-Won Shim, Bong-Huan Jun, Sea-Moon Kim, Pan-Mook Lee and Yong-Kon Lim
Maritime and Ocean Engineering Research Institute, KORDI
Daejeon, Republic of Korea

Abstract- **This paper presents a dynamic model estimation using system identification (SI) technique and a multivariable controller design for an unmanned surface vehicle (USV) with two fixed thrusters. The catamaran shaped USV has been developed for marine research and surveying exploration in costal area. To validate the automatic control performance of USV, which is designed by classical PID controller, we carried out experiments to keep the USV's position at a fixed point and to track predefined positions. As a result, we have found that it needs time-consuming efforts to tuning the weight between heading and speed controller since the yawing and surge motions are tightly coupled to the two thrusters. In order to solve the problem, it is necessary to introduce the multivariable controller design method. And a numerical dynamic model is required for the model based design. This paper addresses the estimation of a dynamic model of the USV based on the experimental results and the design of Linear-Quadratic (LQ) controller based on a multivariable control method. To verify the efficiency of the designed controller using the estimated dynamic model, numerical simulations were carried out.**

I. INTRODUCTION

Over the past few decades, numerous autonomous marine vehicles have been developed in particular for marine research and ocean survey such as an Autonomous Underwater Vehicle (AUV) for underwater probes and an Unmanned Surface Vehicle (USV) for investigation in shallow water. In addition, several studies have been made on control algorithms to improve control performances on dynamic characters of these vehicles [1], [2].

Korea Ocean Research and Development Institute (KORDI) has developed an USV of which the missions are firstly to survey shallow costal area with on board camera, and secondly to support works of the underwater vehicles by aiding the communication and localization. The vehicle's basic functions required for performing the missions are to keep her position at a fixed point and to follow predefined way-points automatically.

We have designed a PD controller for position keeping and tracking, and then carried out experimental test to confirm the convergence of controller in the sea-trial. However, it was difficult to satisfy simultaneously the performances required for the forward speed and heading control in the surge and yaw motion, since the developed catamaran shaped USV is a non-holonomic and coupled system with two fixed thrusters. The USV maneuvering problem contains coupled dynamics of the surge and yaw motion. In order to handle this problem, a multiple-input multiple-output (MIMO) approach is required in the control problem [3]. However, the dynamic model of this vehicle is not known.

In order to solve the problem, we designed a multivariable controller for the USV using Linear Quadratic (LQ) method. The linearized numerical model of the USV, which is required for controller design, was estimated in least square sense from the experimental data. The model estimation and controller design of the USV are presented in this paper.

The paper is organized as follows. Section Ⅱ describes overall structures, specifications, and control system architecture of the developed USV. In Section Ⅲ, we analyze the experimental results of position keeping and tracking control carried out in the sea-trial with PD controller. And, Section Ⅳ describes the SI procedure and the estimated numerical model obtained by SI technique. And then, Section Ⅴ presents the multivariable optimal LQ controller design based on the estimated numerical model, and the simulation results to verify the performance of the designed controller. Finally, the conclusion is given in Section Ⅵ.

II. USV ARCHITECTURE

In this chapter, we present the overall structures, specifications and control system architecture of the developed catamaran shaped USV.

A. Overall structure and Specifications

The USV is equipped with two fixed thrusters in its stern, GPS, AHRS (Attitude Heading Reference System), RF communication and wireless LAN communication module for remote control, the control device for autonomous navigation, and a camera-light system for observation of the surrounding environment as shown in Fig.1.

The specifications of USV are shown in Table 1. The batteries, which are used to provide the power for the propulsion system and control system, are carried within the control devices box.

B. Control System Architecture

The control system can be classified into two main groups ; Remote system and USV system as shown in Fig. 2. The remote system consists of a RC transmitter for manual control,

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Figure 1. Appearance and components of USV

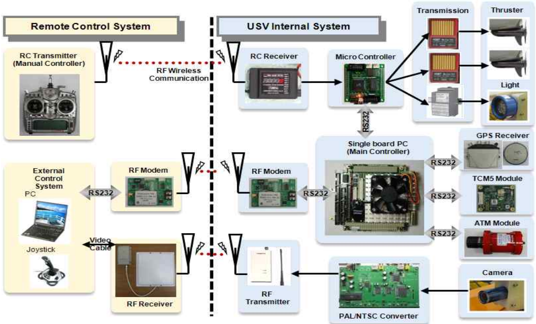


Figure 2. Control system architecture

TABLE I
SPECIFICATION OF THE USV

Item	Description
Dimension (L X W X H)	1.5 m X 0.8 m X 0.4 m
Weight in air	60 kg
Payload	20 kg
Thrust	Thruster Transom 2ea 60 lbs. (30 lbs./ea)
Maximum speed	1 m/s
Material	Fiber Reinforced Plastic (FRP)
Battery	Lithium polymer Battery -. Propulsion system (22.2Vdc/6,000mAh) : 1ea -. Control System (11.1Vdc/12,000mAh) : 1ea
Equipment & Sensor	Camera-Light, GPS & Antenna, RF Antenna, Wireless LAN, Electronic Box of Control system, AHRS

a RF modem data communication, a RF receiver for image data reception, and a general PC for remote control. The USV system consists of a GPS for position estimation, an AHRS for attitude estimation, an embedded computer for autonomous navigation and control of this vehicle, a microcontroller for thruster control, a RF modem for communication between remote control computer and embedded computer, a RF transmitter for image data transmission, a RC receiver for manual control, and camera-light system.

III. EXPERIMENTS

This section presents the results of a dynamic positioning (DP) and a way-point tracking control experiment. The aims of this experiment are to confirm the control performance of classical PID controller for the underactuated system and to acquire the input/output data of the USV, which is used for estimation of numerical model.

A. Dynamic Positioning (DP) experiment results

Fig. 3 and Fig. 4 illustrate the result of the DP experiment in which the USV moved to a target at (470373, 3872279) in UTM coordinate system and kept the target position. The position of the USV tended to stay at near the target as shown in Fig. 3 and Fig. 4, considering a tolerance range of GPS which is ±1.5m.

B. Way-point experiments results

Fig. 5 and Fig. 6 show the results from way-point tracking test where the USV is programmed to follow the predefined six way-points. When the distance between this vehicle and the first way-point is reduced to less than ±2.5m, it is considered that the way-point has been reached as shown in Fig.6. And then, the USV turns to the next way-point.

C. Conclusions of Experiments in the sea-trial

As mentioned above, the result of experiment was performed in regard to the DP and way-points tracking control test. However, it was difficult to obtain the optimal control performance for the speed and heading control using PD controller, since surge and yaw motion are tightly coupled with the two thruster inputs.

Moreover, it was bothersome and time-consuming to find the optimal gains of the heading and speed controller at the same time since we had to rely on trial and error method based on rough numerical model or real model.

In order to solve the problem, we adopt an estimation technique for the numerical dynamic model and present a multivariable optimal LQ controller based on the estimated model. The details of estimation and controller design methods were described further in the next section.

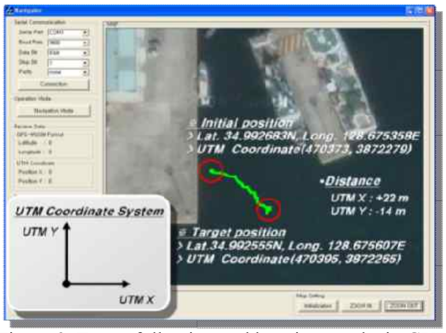


Figure 3. Target following and keeping results in GUI

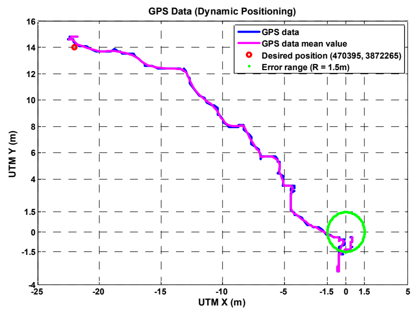


Figure 4. Target following and keeping results in UTM coordination

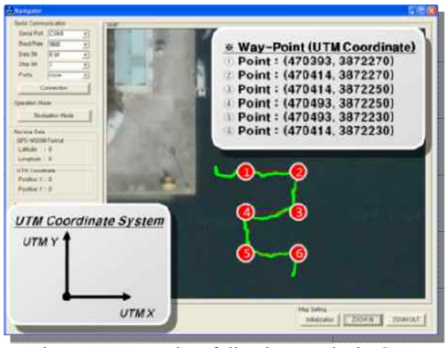


Figure 5. Way-points following results in GUI

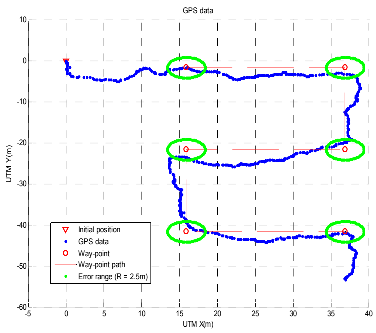


Figure 6. Way-points following results in UTM coordination

IV. Model Estimation

In this section, we describe an estimation method for the dynamic model of USV in order to improve the accuracy of numerical model using experimental data. In this paper, an SI technique based on the least-squares (LS) method is used using the previous experimental results [4]. To verify the estimated numerical model, we present a comparison of simulation and experimental results in this section.

A. Numerical dynamic model

A general dynamic equation for the USV is given with (1).

$$M_{\dot{v}}+C(v)v + D(v) = \tau \qquad (1)$$

where matrix M is the system inertia matrix, $C(v)$ is a coriolis-centripetal matrix, $D(v)$ is a damping matrix, and vector τ consists of external forces and moments acting on the vehicle. Linear and angular velocities vector $v = [u, v, w, p, q, r]^{\mathrm{T}}$, and linear and angular accelerations vector $\dot{v} = [\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}]^T$ are defined in the body-fixed coordinate system.

The kinematic equations can be expressed in vector form as

$$\dot{\eta} = J(\eta)v \qquad (2)$$

where positions vector and attitude $\eta = [x, y, z, \varphi, \theta, \psi]^{\mathrm{T}}$, and its time differential vector $\dot{\eta} = [\dot{x}, \dot{y}, \dot{z}, \dot{\varphi}, \dot{\theta}, \dot{\psi}]^T$ is defined in the earth-fixed coordinate system.

Neglecting vertical motion and high order damping term, and selecting surging and yawing motion for simplicity, we can abbreviate the 6-DOF equations as following simplified form [5], [6].

$$\dot{u} = \left(\frac{X_u}{m-X_{\dot{u}}}\right)u + \left(\frac{1}{m-X_{\dot{u}}}\right)U_{T1} + \left(\frac{1}{m-X_{\dot{u}}}\right)U_{T2} \qquad (3)$$

$$\dot{r} = \left(\frac{N_r}{I_z-N_{\dot{r}}}\right)r + \left(\frac{1}{I_z-N_{\dot{r}}}\right)U_{T1} - \left(\frac{1}{I_z-N_{\dot{r}}}\right)U_{T2} \qquad (4)$$

where U_{T1} and U_{T2} are control inputs of two thrusters, m is the mass of the USV, X_u and N_r are linear damping in surge and yaw, $X_{\dot{u}}$ and $N_{\dot{r}}$ are added mass in surge and yaw, and I_z is moment of inertia about the Z-axis in the earth-fixed coordinate system [5].

B. System identification

The numerical model of the USV is estimated using SI technique. In the field of SI technique, the LS method is commonly used to minimize the sum of the matching error between the experimental results and the model outputs [6], [7].

The unknown parameters can be defined as lumped parameters in the numerical model, and the dynamic model is expressed using the defined lumped parameters as

$$\dot{u} = \alpha_1 u + \alpha_2 U_{T1} + \alpha_3 U_{T2} \qquad (5)$$

$$\dot{r} = \beta_1 r + \beta_2 U_{T1} + \beta_3 U_{T2} \qquad (6)$$

and then, the vector forms can be expressed as

$$\dot{R_u}(t) = {\Phi_u}^T F_u(t) \qquad (7)$$

$$\dot{R_r}(t) = {\Phi_r}^T F_r(t) \qquad (8)$$

where $\Phi_u = [\alpha_1, \alpha_2\ \alpha_3]^T$ and $\Phi_r = [\beta_1, \beta_2\ \beta_3]^T$ vectors are the lumped parameters of the model, $F_u = [u, U_{T1},\ U_{T2}]^T$ and $F_r = [r, U_{T1},\ U_{T2}]^T$ vectors are measured data from experimental results, and $\dot{R_u} = [\dot{u}]$ and $\dot{R_r} = [\dot{r}]$ vectors are the model output for accelerations in surge and yaw motion respectively. Since the equations (7) and (8) are linear, we can apply LS method to fine the best estimations of the unknown parameters in the numerical model (5) and (6). The solution of the lumped parameter vector is obtained by the Moore-Penrose pseudo-inverse as follows [4].

$$\Phi_u = (\dot{R_u}{F_u}^T(F_u{F_u}^T)^{-1})^T \qquad (9)$$

$$\Phi_r = (\dot{R_r}{F_r}^T(F_r{F_r}^T)^{-1})^T \qquad (10)$$

C. Simulation Results

We validated the estimated model using the cross simulation, which uses another set of experimental data no used for estimation [8]. The lumped parameters acquired from the model estimation are shown in Table Ⅱ.

Fig. 7 and Fig. 8 illustrate the comparison of measured data with those of roughly estimated previous model and newly identified model in surge and yaw motion. From these figures, it was obvious that the estimated numerical model is closer to the actual USV model than the previous model as shown in Fig. 7 and Fig. 8.

TABLE Ⅱ
DEFINITION OF LUMPED PARAMETERS

Item	Lumped Parameters	Physical Definition	Identification Results
Surge Model	α_1	$\left(\frac{X_u}{m-X_{\dot{u}}}\right)$	-0.01155
	α_2	$\left(\frac{1}{m-X_{\dot{u}}}\right)$	-0.0060
	α_3	$\left(\frac{1}{m-X_{\dot{u}}}\right)$	-0.0071
Yaw Model	β_1	$\left(\frac{N_r}{I_z-N_{\dot{r}}}\right)$	-1.1049
	β_2	$\left(\frac{1}{I_z-N_{\dot{r}}}\right)$	-0.7104
	β_3	$\left(\frac{-1}{I_z-N_{\dot{r}}}\right)$	-0.5985

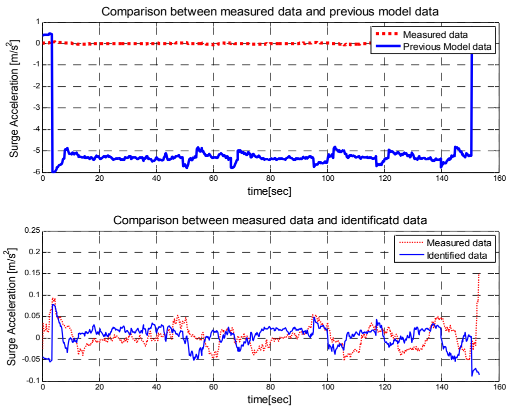


Figure 7. Results for surge motion

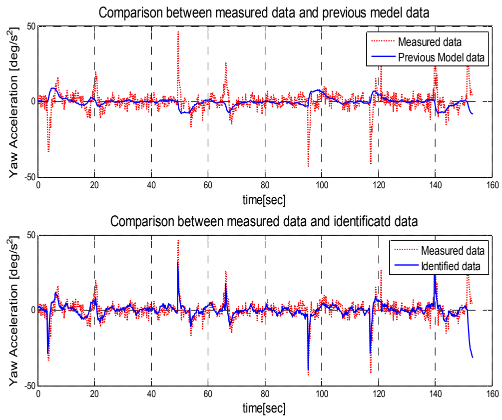


Figure 8. Results for yaw motion

V. CONTROL DESIGN AND SIMULATION

As stated above, the USV maneuvering problem contains coupled dynamics of the USV surge and yaw motion. Therefore, this section presents the optimal LQ controller design based on the estimated dynamic model of the USV system. The simulations were carried out to verify the performance of the designed controller.

A. Control Design

The system dynamics are contained in the state equation as follows

$$\dot{X} = AX + BU \quad (11)$$

$$Y = CX \quad (12)$$

, where $X = [u, r, \psi]^T$ and $\dot{X} = [\dot{u}, \dot{r}, \dot{\psi}]^T$ are the state vector, and its time-differential U is the control input, A is the plant matrix, B is an input matrix, Y is output vector, and C is an output matrix. The plant matrix and the input matrix are obtained from the estimated model parameters shown in Table Ⅱ as follow

$$A = \begin{bmatrix} -0.01155 & 0 & 0 \\ 0 & -1.1049 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$
$$B = \begin{bmatrix} -0.006 & -0.0071 \\ -0.7104 & -0.5985 \\ 0 & 0 \end{bmatrix} \quad (13)$$
$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

We consider the performance index function for output error and control input to design a LQ controller as follows

$$J_o = \frac{1}{2}\int_0^T \left(\tilde{Y}^T Q \tilde{Y} + U^T R U\right) d\tau = \frac{1}{2}\int_0^T \left(\tilde{X}^T \tilde{Q} \tilde{X} + U^T R U\right) d\tau \quad (14)$$

where $\tilde{Y} = Y - Y_d = C(X - X_d) = C\tilde{X}$, $\tilde{Q} = C^T Q C$, X_d and Y_d are desired values of states and outputs respectively, Q and $\tilde{Q}$ are semi-positive definite matrix, and R is positive definite matrix. Then, for minimizing (10), optimal control input u^{opt} is obtained from follows (15)~(17).

$$U^{opt} = G_1 X + G_2 Y_d \quad (15)$$

$$G_1 = -R^{-1} B^T P \quad (16)$$

$$G_2 = -R^{-1} B^T (A + BG_1)^{-T} C^T Q \quad (17)$$

where P is the solution of the matrix Riccati equation defined as follows

$$PA + A^T P - PBR^{-1}B^T P + \tilde{Q} = 0 \quad (18)$$

The desired values of outputs are directly related with the tracking error. And we adopted the position and heading controller as

$$Y_d = \begin{bmatrix} k_{pu}\left(\sqrt{{x_e}^2 + {y_e}^2}\right) \\ k_{p\psi}\left(\tan^{-1}\left(\frac{y_e}{x_e}\right)\right) \end{bmatrix} \quad (19)$$

where k_{pu} and $k_{p\psi}$ are proportional control gains for the speed and heading respectively, and $x_e = x_d - x$ and $y_e = y_d - y$ are the tracking error in the earth-fixed coordinate system, the x_d and y_d are the desired position.

B. *Simulation Results*

To verify the performance of the designed controller, the simulations were carried out. The LQ controller gains are defined by (15)~(17) by selecting the weight matrices Q and R as follows

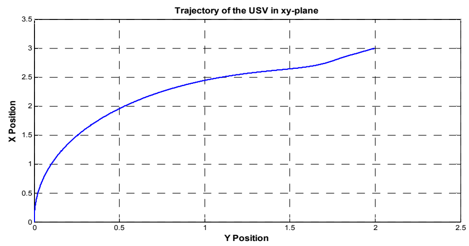
$$Q = \begin{bmatrix} 5 & 0 \\ 0 & 500 \end{bmatrix}, R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{20}$$

and k_{pu} and $k_{p\psi}$ are selected as follows

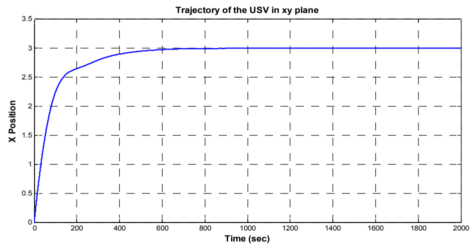
$$k_{pu} = 0.01, k_{p\psi} = 1 \tag{21}$$

The USV control simulation was carried out in Matlab/Simulink with designed controller using the estimated numerical model of the USV. In the simulation, a desired position was chosen as (2m, 1m) in xy-plane, and initial condition was selected as $x_0 = [0, 0, 0]^T$. During the simulation procedure, the control response characteristic of the system can be adjusted by changing the weighting matrices.

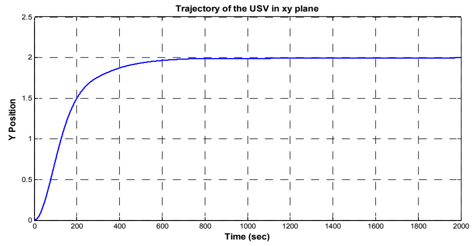
Fig. 9 displays the simulated trajectory of the USV. The results clearly show that the USV moves to the desired position and successfully keeps her position. The control responses of heading and speed are easily adjusted by the weight matrix Q in the objective function.



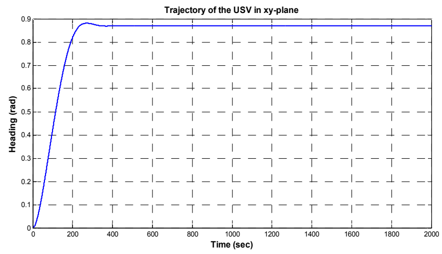
(a) USV trajectory in xy plane



(b) x position response



(c) y position response



(d) heading angle response

Figure 9. Simulation results of position controller

VI. CONCLUSIONS

In this paper, we presented the results of a dynamic positioning and a way-point tracking control experiment to confirm the control performance of designed PD controller in the sea-trial. However, we found that it was hard to obtain the optimal control performance for the speed and heading control using PD controller, since the developed USV is a non-holonomic with two fixed thrusters and is coupled dynamics of the surge and yaw motion. In order to solve this problem, we proposed the dynamic model estimation of the USV and design of the optimal LQ controller based on the estimated model. And then, the simulations were carried out to validate the estimated model and the designed controller. Simulation results show that the control objective was achieved successfully. The designed controller will be tested in sea-trial of the USV in near future.

ACKNOWLEDGMENT

This work was supported by Korea Ocean Research and Development Institute (KORDI) for the development of core technologies for autonomous mapping of the ocean bottom.

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