Identification State Feedback Control for the Depth Control of the Studied Underwater Semi-Submersible Vehicle

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Abstract—This study focuses on the depth control of an unmanned semi-submersible vehicle (USV), the submersible depth of which should not exceed 3 meters to make the depth control performance robust to environmental disturbances. Depth control performance, including overshoot values and static state error of depth, should be limited within predetermined limits; otherwise, a venture issue may occur in the USV system. Therefore, achieving the desired performance even with unexpected sea wave disturbances to the USV system remains a challenge. Moreover, some model parameters are unknown. The control parameters of the improved identification state feedback control are presented for the USV diving plane control. Lake trials are performed to validate that the suggested controller has good control performances and strong immunity to couple state surge speed and the lake environments.

Keywords—unmanned semi-submersible vehicle; identification control; multi-model switching technology; depth control; sea trial

I. INTRODUCTION

Unmanned semi-submersible vehicles (USVs) have been developed for mine counter measures[1] and bathymetric surveys[2-3], as well as to support autonomous underwater vehicle (AUV) operations by serving as communication relays[4-5] since the last decade of the 20th century. USVs are suitable for use in data collection under adverse weather conditions[7]. USVs are subjected to external disturbances attributed to unforeseen complex sea states because of the allowed shallow submerging water area. A USV system can be considered as one semi-submersible autonomous underwater vehicle system, the depth control of which is difficult to perform because of strong external disturbances from the sea surface. Moreover, a USV system is a strong coupled system, which causes the design of a USV controller[6-7] to be complex.

Only a handful of papers address motion control systems for USVs. The depth controller of DOLPHIN Mk2 comprises proportional, integral, and derivative (PID), as well as feed forward controllers. The depth control of the studied USV system was originally a PID controller. However, such controller is subjected to unexpected disturbances from the sea environment. Moreover, surge speeds can worsen depth control performance because of the strong coupled relationship between surge speed and depth. From the above features of USV controllers, most control schemes consider the uncertainty of USV control models by resorting to some adaptive or fuzzy controllers[8] that do not completely rely on the precision of control models. Thus, many successful applications in engineering fuzzy logic controllers have been widely and successfully used for nonlinear system modeling and for controlling unknown systems for more than two decades[9-11]. State feedback control is a widely used algorithm for linear systems[13,14] because of its straightforward control process. This algorithm is also applied to nonlinear system fields in combination with other control algorithms, such as fuzzy control[15] and SMC[16], among others[17], because of its convenient setting of feedback parameters with pole placement. The depth demand of the studied USV resembles that of two types of USV systems, as described in Fig. 1 and Fig. 2. The bodies of these USVs should not be completely submerged in water. USVs have parts that are exposed to the sea surface and thus fail to avoid the influence of sea waves.

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The studied USV of this paper makes full use of a water-jet-propelled system for surge speed while two horizontal rudders to control submersible depth. Depths beyond 3.5 m are usually considered as the maximum limit, and most field trials are limited to less than 3 m. The maximum depth error should not be more than 0.5 m if the desired depth is 3 m. This issue indicates that depth control should be robust under different sea environments and that control performance, particularly in terms of the overshoot of depth control, should be confined within small limits.

II. VERTICAL PLANE MODEL OF USV

As described by Fosson[19], a USV system has six ordinary nonlinear differential equations that denote the effected forces and force moments on six degrees of freedom. However, these equations are characterized by strong nonlinearity and states that are coupled with one another. Designing the control algorithm is difficult if these equations are not simplified [17]. A submarine model generally shows different forms according to the classes of control drivers and research order [18–19]. This paper considers the USV described in Fig. 3. Two stern rudders and two bow rudders are jointly employed to realize the depth control of USV. The bow rudder angles are adjusted following the stern rudders angles.

This paper mainly focuses on the diving plane of the studied USV system because of the poor depth performance during sea trials. Depth control is realized by two lateral stern rubbers arranged on the system aft-body. The vertical plane model is described as in Eqs. (1) to (3) based on the controlled object and the decoupled model.

As regards the studied USV system, the pitch $\theta \in (-15^\circ, 15^\circ)$ and the heave velocity $w = 0$, such that $\sin \theta = \theta$. The depth motion equation of the USV under earth-fixed reference frame is given by

$$\dot{z} = -u \sin \theta + w \cos \theta = -u \theta$$

(1)

The variable $u$ is the forward speed or surge speed, $\theta$ is the pitch, and $w$ is the heave velocity.

The pitch kinematics can be described as

$$\dot{\theta} = q$$

(2)

The pitch rate equation could be described as

$$(I_{y} - M_{\delta_{y}}) \dot{q} = M_{y} \dot{u} - (z_{o} W - z_{b} B) \theta + M_{\delta_{y}} u^{2} \dot{\delta}_{y}$$

(3)

where $\delta_{y}$ is the stern plane angle.

The state-space expression of the diving plane can be described as

$$\begin{cases}
\dot{z} = -u \theta \\
\dot{\theta} = q \\
\dot{q} = a_1 \theta + a_2 u \theta + b_1 u^{2} \delta_{y}
\end{cases}$$

(4)

where variables $a_1$, $a_2$, and $b_1$ coincide with $a_1 = \frac{(z_{o} W - z_{b} B)}{(I_{y} - M_{\delta_{y}})}$, $a_2 = \frac{M_{y}}{(I_{y} - M_{\delta_{y}})}$, and $b_1 = \frac{M_{\delta_{y}}}{(I_{y} - M_{\delta_{y}})}$, respectively; and $\dot{\theta} - d_{1} \dot{u} \theta - d_{2} \dot{q} = b_{1} u^{2} \delta_{y}$.

The parameters of the diving plane model will be simply introduced, and the detailed denotation can be found in a previous work [18]. The states of the diving plane model are depth $z$ (meter), pitch $\theta$ (radian), and pitch rate $q$ (radian/second). The parameters $Z$, and $M$, denote the hydrodynamic coefficients of the diving plane model. $I_{y}$ is the inertia moment; $W$ and $B$ are the weight and submerged buoyancy force of USV, respectively; and $h$ is the distance between the gravity and buoyancy centers of the $z$ axis of the USV body-fixed frame. $\delta_{y}$ (radian) is the angle value of the hydroplane of the studied USV and is also the control input.

**Remark**

The variables $d_{1}$, $d_{2}$ and $b_{1}$ denoted in Eq.(4) are unknown. Therefore, the USV system under consideration will be the control algorithm, called feedback control algorithm, which is formed with these unknown model parameters. The parameters ($d_{1}$, $d_{2}$ and $b_{1}$) are identified by data come from some lake trials.

III. IDENTIFICATION METHOD BASED ON SWITCHING MODEL CONTROL FOR USV DEPTH CONTROL

The limited submersible depth causes the motions of a USV system to be directly influenced by wave forces coming from the water surface. The description of wave forces is a
controversial issue, making the external disturbances on USV motions difficult to describe by using mathematical expressions. Moreover, the model parameters of the USV system are unknown, thus making the establishment of the controller more difficult. The depth control parameters of state feedback control are decided by some identification model of the USV system. Fig. 4 shows a block diagram of the depth control of the studied USV system.

![Block diagram of the proposed control system for USV vertical plane motions](image)

Fig. 4. Block diagram of the proposed control system for USV vertical plane motions

A. State feedback control parameters for the identification model

State feedback control algorithm depends on system models, whereas system performance is determined by the preset pole placements of a closed-loop system. The control parameters of a feedback controller are dependent on the system model, such that a fuzzy controller is introduced to deal with the unknown model parameters of the considered USV system.

We rearrange Eq. (4) and describe it as state-space expression given by

\[
\begin{bmatrix}
\dot{z} \\
\dot{\theta} \\
\dot{q}
\end{bmatrix} =
\begin{bmatrix}
0 & -u & 0 \\
0 & 0 & 1 \\
0 & a_1 & a_2 u
\end{bmatrix}
\begin{bmatrix}
z \\
\theta \\
q
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
a_2 u
\end{bmatrix}
\delta_i
\]  

(5)

The error state-space of a USV system is generally introduced to facilitate research on system stability. State errors of the depth control model (5) are defined as

\[
\begin{bmatrix}
e_z \\
e_\theta \\
e_q
\end{bmatrix} =
\begin{bmatrix}
z \\
\theta - \theta_i \\
q
\end{bmatrix}
\]  

(6)

Therefore, the error of state-space expression can be presented as

\[
\begin{bmatrix}
\dot{e}_z \\
\dot{e}_\theta \\
\dot{e}_q
\end{bmatrix} =
\begin{bmatrix}
0 & -u & 0 \\
0 & 0 & 1 \\
0 & a_1 & a_2 u
\end{bmatrix}
\begin{bmatrix}
e_z \\
e_\theta \\
e_q
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
da_2 u
\end{bmatrix}
\delta_i
\]  

(7)

The key idea of feedback control is to assign the predesigned eigenvalues according to the desired system performance. The eigenvalues are equal to the roots of the character equation of the considered system if no pole-zero cancellation occurs.

Theory 1: If the system is controllable, a state gain \( \mathbf{K} \) can always be found to set the eigenvalues of the closed-loop system at arbitrary values. □

The equation below will consider the question of whether the diving plane model is controllable or the eigenvalue can be predesigned. We propose \( \dot{z} = \frac{e}{u} \) to design system (7) as the canonical equation of the state space control model (8).

\[
\begin{bmatrix}
\dot{z} \\
\dot{e}_\theta \\
\dot{q}
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
0 & a_1 & a_2 u
\end{bmatrix}
\begin{bmatrix}
z \\
e_\theta \\
q
\end{bmatrix} +
\begin{bmatrix}
0 \\
e_\theta \\
b_2 u^2
\end{bmatrix}
\]  

(8)

Based on theory 1, we consider the controllable matrix

\[
\mathbf{M}_c = \begin{bmatrix} 0 & 0 & -b_1 u^3 \\
0 & b_2 u^2 & * \\
b_3 u^2 & * & *
\end{bmatrix},
\]

which is full rank unless the surge velocity is zero. Therefore, the poles of the closed loop can be placed at any desired location, and model (8) is completely controllable. If eigenvalues \( \lambda_{\theta_1}, \lambda_{\theta_2}, \lambda_\theta \), are preset, the desired characteristic polynomial of the closed-loop system becomes

\[
p(s) = (s - \lambda_{\theta_1})(s - \lambda_{\theta_2})(s - \lambda_\theta)
\]  

(9)

We preset the form of the feedback control law as

\[
\delta_i = \kappa_{\theta_1} z + \kappa_{\theta_2} e_\theta + \kappa_\theta q
\]  

(10)

If all eigenvalues are less than zero, the state feedback control is asymptotically stable. The feedback control parameters \( \kappa_{\theta_1}, \kappa_{\theta_2}, \kappa_\theta \) can be confirmed by the character polynomial (9).

According to the definition of the canonical equation of feedback control, the characteristic polynomial can be directly determined based on the last line of the input matrix of the state-space control model (8). Substituting the control law (10) into (8) yields the character polynomial with feedback control law

\[
Q(s) = s^3 - (a_3 u + b_2 u^2 \kappa_\theta) s^2 - (a_4 + b_3 u^2 \kappa_\theta) s + b_4 u^2 \kappa_{\theta_1}
\]  

(11)

The right-hand side of Eq. (9) is expanded as

\[
p(s) = s^3 - (\lambda_{\theta_1} + \lambda_{\theta_2} + \lambda_\theta) s^2 + (\lambda_{\theta_1} \lambda_{\theta_2} + \lambda_{\theta_1} \lambda_\theta + \lambda_{\theta_2} \lambda_\theta) s - \lambda_{\theta_1} \lambda_{\theta_2} \lambda_\theta
\]  

(12)

We hope aim for the state feedback control law to make the poles of the closed-loop system locate at the desired placements in the s-domain. Therefore, Eq. (11) is equivalent to Eq. (12), viz. \( p(s) = Q(s) \).

Finally, the control parameters of control law are deduced

\[
\begin{bmatrix}
\kappa_{\theta_1} \\
\kappa_{\theta_2} \\
\kappa_\theta
\end{bmatrix} =
\begin{bmatrix}
\lambda_{\theta_1} + \lambda_{\theta_2} + \lambda_\theta - a_3 u \\
\lambda_{\theta_1} \lambda_{\theta_2} + \lambda_{\theta_1} \lambda_\theta + \lambda_{\theta_2} \lambda_\theta + a_4 \\
\lambda_{\theta_1} \lambda_{\theta_2} \lambda_\theta + a_1
\end{bmatrix}
\]  

(13)

The surge speed \( u \) should satisfy the following conditions, as confirmed by some trials:
According to these control parameters, the controller can be designed as
\[
\delta_s = \kappa_s e_s + \kappa_\phi e_\phi + \kappa_q q
\]  
(15)

Although the preset poles of the closed-loop system (7) are known, the control parameters can be certain according to the identification parameters \(a_1, a_2\) and \(b_1\) from the TABLE I.

B. Identification models for the depth control models of the studied USV

The following symbol described in the equations, the symbol \(k\) is the \(k\) th data of lake trial and the subscript \(N\) describes the number of the sampled data.

According to the depth model control of USV system (Eq.(4)), the identification model is the following:
\[
\dot{q} = a_1 \theta + a_2 uq + b_1 u^2 \delta_s
\]  
(16)

Therefore, the needed identification parameters are \(a_1, a_2, b_1\) and \(h_1\), the input variables are \(\theta, uq\) and \(u^2 \delta_s\), as well as the output variable is the acceleration \(q\) viz. \(q\). According to the least squares method, the desired identification model is followed as
\[
\vartheta = \left[ a_1, a_2, b_1 \right]^T
\]  
(17)

Where \(\vartheta\) is the estimated parameter set, therefore the identification model can also be described as
\[
q(k+1) = \Phi^\top(k) \vartheta(k) + e(k)
\]  
(18)

According to the least squares criterion function:
\[
J = \sum_{i=1}^{N} \left( q(k+i+1) - \Phi^\top(k+i) \vartheta \right)^2
\]  
(19)

Obtain the minimum value of the function (19) by the maximum principle:
\[
\frac{\partial J}{\partial \theta} = -\Phi^\top_N (Y_N - \Phi_N \vartheta) - \Phi^\top_N (Y_N - \Phi_N \vartheta)
\]  
(20)

Under the condition \(\Phi^\top_N \Phi^\top_N\), the evaluation value of least squares method can be get according to the Eq.(20):
\[
\tilde{\theta}_N = (\Phi^\top_N \Phi_N)^{-1} \Phi^\top_N Y_N
\]  
(21)

TABLE I. THE DIFFERENT IDENTIFICATION PARAMETERS UNDER VARY LAKE TRIALS

| trial parameter | 1   | 2   | 3   | 4   | 5   |
|-----------------|-----|-----|-----|-----|-----|
| \(a_1\)         | 0.295 | 0.3283 | 0.3366 | 0.2912 | 0.3261 |

Using five sets data from the lake trials which are executed by open-loop control, five sets model parameters \(\tilde{\theta}_N\) are obtained listed in the TABLE I.

To achieve some accurate model parameters, we introduce one function to fusion these model parameters from TABLE I.

\[
\bar{\theta} = \frac{\sum_{i=1}^{r} \tilde{\theta}}{r}
\]  
(22)

Here \(r=5\) which is number of the lake trials for identification parameters.

According to Eq.(22) and the data of TAB. I, the model control parameters fusion are obtained the rearranged parameter row vector
\[
\tilde{\theta} = [a_1; a_2; b_1] = [0.3154; -0.0037; 0.0015].
\]

To valuate the vector, the curves of state variable pitch rate fitting is executed and the result is described as the Fig.5 which shows the well fitting. And the fitting error is less than 0.5 which is computed by the following equation:
\[
\bar{e} = \sum_{i=1}^{N} \left| Y_i - \vartheta^\top(i,k) \vartheta(1,k) \right| / N
\]  
(23)

Where \(N\) is the number of the sampled data from the five sets any one lake trial result.

The fitting curve shows that the parameters \(\tilde{\theta}\) is accepted therefore it is considered as the identification parameter of the Eq.(17).

Fig. 5. Fitting curves by the fitting error less than 0.5

Remark 2: The identification state feedback control parameters are obtained by submitting the model parameters \(\tilde{\theta}\) into equation
set(13) and presetting the eigen values $\lambda_e = -0.5$, $\lambda_g = -1.2$ and $\lambda_s = 0.3$.

IV. LAKE TRIALS FOR THE DEPTH CONTROL OF THE USV UNDER CONSIDERATION

To assess the performance of the depth control of the USV system with the approving control algorithm viz. identification feedback control based on the switching laws, some lake trials have been performed. This study is mainly concerned with the stability, dynamic performance. Fig. 6 shows the submerged USV system at a 3 m depth.

A. Performance of the USV system with PID in lake trials

Fig. 7 describes the results of the change in depth control when the USV is investigated with a PID controller at sea. The sequence of the desired depth values is described as the vector m. The results of Fig. 7 denote that some performance aspects, such as the steady-state error, stability, and transient response should be improved. The desired depth is 2 meters underwater, whereas the system can not be stable and it is oscillation. Moreover, Fig. 7 shows that some buffeting appears as the USV is running through the sea, which indicates that the state depth of the USV system is susceptible to the disturbance from the sea environment. Another issue that should be considered is that the surge speed and the state depth are coupled with each other because of their instability synchronously.

B. Performance of the USV system with FDFC under different sea states

To improve the depth control performance of the USV system controlled by PID, the advised algorithm identification state feedback control detailed in Remark2 was introduced during lake trials.

The Control performance is assessed during lake trials, and the experiment results are exhibited in Fig.8. The curves in Fig. 8 show that the overshoot is less than 5% with the desired depth of 2 m, and the settling time is less than 100 seconds. The static error curve is smooth and does not exhibit a steady state error. Compared with PID control, the advised identification state feedback control improved the control performances of the USV. Moreover, the results denote that the USV is robust to the strong disturbances in the lake.

V. CONCLUSIONS

To improve the depth control performances of the USV in lake trials, a robust controller identification state feedback control is introduced. The common form of the dynamic feedback control law whose control parameters are adjusted by the surge speeds is described according to the general standard of the USV control model. The model parameters are identified by the open loop depth control of the USV system. Compared with the PID controller, the advised control improved the performances of depth, made the USV system strong and robust to coupled state surge speed and disturbances from the lake.

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