Motion control of Thruster-driven Underwater Vehicle based on Model predictive control

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***Abstract*—Underwater vehicles have been developed over the last six decades for potential uses in scientific, commercial, environmental, and military purposes, and always utilized to perform difficult tasks in cluttered environments such as deep-sea mining, underwater sampling and oceanic investigations. Since underwater vehicles have nonlinear and highly coupled dynamics, motion control can be difficult when completing complex tasks. This paper describes the implementation of a model predictive controller novel in a class of thruster-driven underwater vehicle. In this paper, a constrained discrete-time model predictive control method is employed for the motion control of thruster-driven underwater vehicles. A nonlinear model in six degree of freedom is established based on the dynamics of human occupied vehicle Jiao-long, and converted into a state space model after practical simplification. To ensure the performance of model predictive controller, a full feedback state observer is established to observe the state. In addition, Hildreth's quadratic programming algorithm is incorporated for solving the optimal control sequence, which greatly reduced the computation of the model predictive control algorithm. In order to show the effectiveness of the motion control method, simulations based on dynamics of human occupied vehicle Jiao-long are conducted. Performance on depth control, heading control and hovering control are evaluated. All the results demonstrate the effectiveness of the method.**

Keywords*—*Human occupied vehicles (HOVs); Hover positioning control; Model predictive control (MPC); Hildreth programming producer

I. INTRODUCTION

Unlike traditional underwater vehicles driven by propellers, jets or rudders, thruster-driven underwater vehicles only use thrusters as motion actuators. Traditional underwater vehicles which use propellers and rudders as motion actuators, autonomous underwater vehicles (AUVs), for example, are always utilized to perform underwater observation tasks which need long-range cruising and higher speeds. For tasks like deep-sea mining, underwater sampling and underwater salvage, thruster-driven underwater vehicles such as suspended underwater vehicles (SUVs), human occupied vehicles (HOVs) and remotely operated vehicles (ROVs) are widely used. The prototype depicted in figure 1 show a suspended thruster-driven underwater vehicle used in deep-sea mining application.

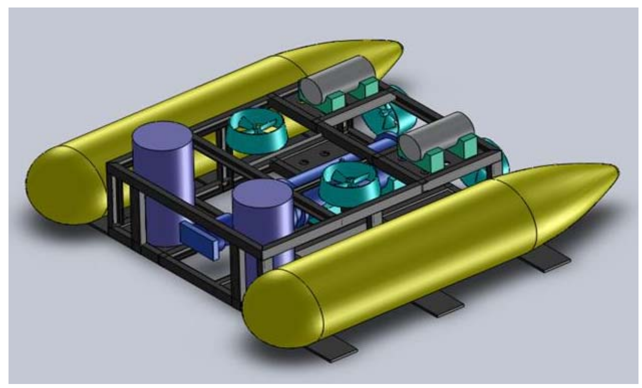

Fig. 1. Thruster-driven underwater vehicle used in deep-sea mining application

In order to accomplish tasks mentioned above, thruster-driven underwater vehicles usually need more complex motion control, such as precise hovering, precise target tracking, high accurate speed, height and heading control.

The design, implementation and testing of the control systems for underwater vehicles have been addressed by several researchers during the last decade[1, 2]. Several advanced motion control systems have been proposed, such as improved PID control[3], fuzzy control[4], neural network control[5], adaptive control[6], sliding control[7], and so on. Thruster-driven underwater vehicles, which work underwater, have big inertia. In order to achieve precise motion control, it's better to suppress the overshoot for the motion of the vehicle with the future motion information[8]. While none of the control strategies mentioned above take the future motion information of the vehicle into consideration.

Model Predictive Control (MPC)[9, 10] is a model based control algorithm that solves a finite horizon optimal control problem, using the current state of the system as the initial state. The optimization results in a sequence of optimal control actions where only the first control move is implemented[11]. MPC controllers for marine vehicles have been proposed in the

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past but mostly for the heading and the tracking control of ships[12-14]. A model predictive controller is presented in[15] for an autonomous underwater vehicle.

In this paper, a constrained discrete-time MPC method is employed for the motion control of thruster-driven underwater vehicles. A nonlinear model in six degree of freedom is established based on the dynamics of HOV Jiao-long, and converted into a state space model after practical simplification. To ensure the performance of MPC controller, a full feedback state observer is established to observe the state. In addition, Hildreth's quadratic programming algorithm is incorporated for solving the optimal control sequence, which greatly reduced the computation of the MPC algorithm. In order to show the effectiveness of the motion control method, simulation based on dynamics of HOV Jiao-long are conducted. Performance on depth control and heading control are contrasted with the PID and fuzzy PID algorithm, performance on hovering control are compared with the adaptive LQR algorithm.

II. MATHEMATICAL MODELLING OF THRUSTER-DRIVEN UNDERWATER VEHICLE

A. Coordinates and Notations

Coordinates widely used in the published literature of underwater vehicles [16] is illustrated in figure 2. Nomenclatures and notations associated with those coordinates are defined as follows.

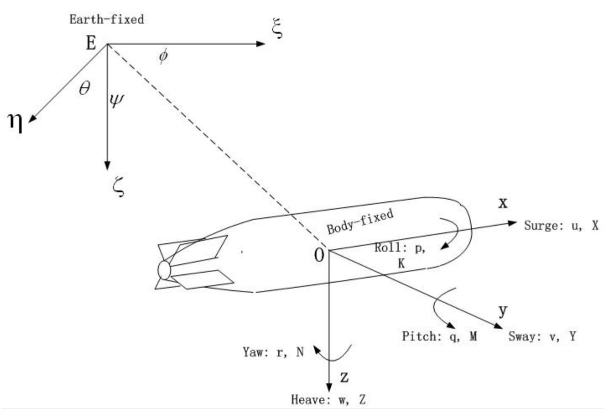

Fig. 2. Coordinates of underwater vehicles

- $E-\xi\eta\zeta$: are earth-fixed coordinates.
- $E-xyz$: are body-fixed coordinates.
- u,v,w : are surge, sway and heave speed of the vehicle.
- ξ,η,ζ : the positions of the vehicle with respect to the earth fixed coordinates.
- ϕ,θ,ψ : the orientations of the vehicle with respect to the earth fixed coordinates.
- p,q,r : the rotation velocities of the vehicle with respect to the body fixed coordinates.
- X,Y,Z : the total forces acting on the vehicle with respect to the body fixed coordinates.
- K,M,N : the moments acting on vehicles with respect to the body fixed coordinates.

The relationship between the earth-fixed coordinates and body-fixed coordinates can be described by transform matrix R:

$$R=\begin{bmatrix}\cos\psi\cos\theta & \cos\psi\sin\theta\sin\varphi-\sin\psi\cos\varphi & \cos\psi\sin\theta\cos\varphi+\sin\psi\sin\varphi\\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\varphi+\cos\psi\cos\varphi & \sin\psi\sin\theta\cos\varphi-\cos\psi\sin\varphi\\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi\end{bmatrix}$$

The relationship between vehicle position ξ,η,ζ and speed u,v,w can be described as:

$$\begin{bmatrix}\dot{\xi}\\ \dot{\eta}\\ \dot{\zeta}\end{bmatrix}=R\begin{bmatrix}u\\ v\\ w\end{bmatrix} \tag{1}$$

The relationship between vehicle orientations and rotational velocities can be described as:

$$\begin{bmatrix}\dot{\varphi}\\ \dot{\theta}\\ \dot{\Psi}\end{bmatrix}=T\begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{2}$$

where: $T=\begin{bmatrix}1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta\\ 0 & \cos\varphi & -\sin\varphi\\ 0 & \sin\varphi\sec\theta & \cos\varphi\sec\theta\end{bmatrix}$

B. Mathematical Model of HOV Jiao-long

Human occupied vehicle Jiao-long is a thruster-driven underwater vehicle that can work at 7000 meters depth underwater. HOV Jiao-long is equipped with seven thrusters[17], four vector thrusters mounted at the rear, two at middle and one bow horizontal thruster at forehead of the vehicle.

For HOV Jiao-long, the motion control mainly focused on surge, sway, heave and yaw movement. The gravity and buoyancy of the vehicle are nearly equal, the left part and the right pate of the vehicle are symmetrical. Take all the aspects mentioned above into consideration, the transform formula between the earth-fixed coordinates and body-fixed coordinates can be simplified as:

$$\begin{bmatrix}\dot{\xi}\\ \dot{\eta}\\ \dot{\zeta}\\ \dot{\psi}\end{bmatrix}=\begin{bmatrix}\cos\psi & -\sin\psi & 0 & 0\\ \sin\psi & \cos\psi & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}u\\ v\\ w\\ r\end{bmatrix} \tag{3}$$

Choose the origin of the body-fixed coordinate match the center of buoyancy of the vehicle, the dynamics of HOV Jiao-long can be simplified as:

$$
\begin{cases}
m[\dot{u}-ru]=\frac{\rho L^4}{2}X_n r^2+\frac{\rho L^3}{2}[X_{\dot{u}}\dot{u}+X_{vr}vr]+\frac{\rho L^2}{2}[X_{uu}u^2+X_{vv}v^2+X_{ww}w^2] \\
\qquad +T_X+T_X \\
m[\dot{v}+ru]=\frac{\rho L^4}{2}Y_r\dot{r}+\frac{\rho L^3}{2}[Y_{\dot{v}}\dot{v}+Y_{wr}wr]+\frac{\rho L^3}{2}[Y_r ur+Y_{v|r|}\frac{v}{|v|}(v^2+w^2)^{1/2}\,|r|] \\
\qquad +\frac{\rho L^2}{2}[Y_0u^2+Y_v uv+Y_{v|v|}v(v^2+w^2)^{1/2}]+\frac{\rho L^2}{2}Y_{vw}vw+T_Y \\
m\dot{w}=\frac{\rho L^4}{2}Z_{rr}r^2+\frac{\rho L^3}{2}[Z_{\dot{w}}\dot{w}+Z_{vr}vr]+\frac{\rho L^2}{2}[Z_0u^2+Z_v uw+Z_{|w|}u\,|w| \\
\qquad +Z_{w|w|}w(v^2+w^2)^{1/2}+Z_{w|w|}\,|w(v^2+w^2)^{1/2}\,|]+\frac{\rho L^2}{2}Z_{vv}vv+T_Z \\
I_z\dot{r}=\frac{\rho L^5}{2}[N_{\dot{r}}\dot{r}+N_{r|r|}r\,|r\,|]+\frac{\rho L^4}{2}[N_{\dot{v}}\dot{v}+N_{wr}wr+N_r ur+N_{|v|r}(v^2+w^2)^{1/2}r] \\
\qquad +\frac{\rho L^3}{2}[N_0u^2+N_v uv+N_{v|v|}v(v^2+w^2)^{1/2}+N_{vw}vw]+T_N
\end{cases}
\tag{4}
$$

From equation (4), Six DOF time variant state space model of HOV Jiao-long can be depicted as:

$$
\dot{X}=\begin{bmatrix} A & 0 \\ R_1 & 0 \end{bmatrix}X+BU \tag{5}
$$

where

$$
X=\begin{bmatrix} u & v & w & r & \xi & \eta & \zeta & \psi \end{bmatrix}^T
$$

$$
U=\begin{bmatrix} T_x & T_y & T_z & M_z \end{bmatrix}^T
$$

$$
A=\begin{bmatrix}
\frac{\frac{1}{2}\rho L^2X_{uu}u}{m-\frac{1}{2}\rho L^3X_{\dot{u}}} & \frac{\frac{1}{2}\rho L^2X_{vv}v}{m-\frac{1}{2}\rho L^3X_{\dot{u}}} & \frac{\frac{1}{2}\rho L^2X_{ww}w}{m-\frac{1}{2}\rho L^3X_{\dot{u}}} & \frac{\frac{1}{2}\rho L^4X_{rr}r+\frac{1}{2}\rho L^3X_{vr}v+mv}{m-\frac{1}{2}\rho L^3X_{\dot{u}}} \\
\frac{\frac{1}{2}\rho L^3Y_r r+\frac{1}{2}\rho L^2(Y_0u+Y_{\dot{v}}v)}{m-\frac{1}{2}\rho L^3Y_{\dot{v}}} & \frac{\frac{1}{2}\rho L^2(v^2+w^2)^{\frac{1}{2}}}{m-\frac{1}{2}\rho L^3Y_{\dot{v}}} & \frac{\frac{1}{2}\rho L^2Y_{vw}v}{m-\frac{1}{2}\rho L^3Y_{\dot{v}}} & \frac{\frac{1}{2}\rho L^3(Y_{vr}w+Y_{v|r|}\frac{v}{|v|}\frac{|v|}{r}(v^2+w^2)^{\frac{1}{2}})+mu}{m-\frac{1}{2}\rho L^3Y_{\dot{v}}} \\
\frac{\frac{1}{2}\rho L^2(Z_0u+Z_w w+Z_{|w|}|w|)}{m-\frac{1}{2}\rho L^3Z_{\dot{w}}} & \frac{\frac{1}{2}\rho L^2Z_{rv}v}{m-\frac{1}{2}\rho L^3Z_{\dot{w}}} & \frac{\frac{1}{2}\rho L^2(Z_{w|w|}(v^2+w^2)^{\frac{1}{2}}+Z_{ww}\frac{(v^2+w^2)^{\frac{1}{2}}|w|}{w})}{m-\frac{1}{2}\rho L^3Z_{\dot{w}}} & \frac{\frac{1}{2}\rho L^4Z_{rr}r+\frac{1}{2}\rho L^3Z_{vr}v}{m-\frac{1}{2}\rho L^3Z_{\dot{w}}} \\
\frac{\frac{1}{2}\rho L^3(N_0u+N_v v)+\frac{1}{2}\rho L^4N_r r}{I_z-\frac{1}{2}\rho L^5N_{\dot{r}}} & \frac{\frac{1}{2}\rho L^3(N_{vw}w+N_{v|v|}(v^2+w^2)^{\frac{1}{2}})}{I_z-\frac{1}{2}\rho L^5N_{\dot{r}}} & \frac{\frac{1}{2}\rho L^4N_{wr}w}{I_z-\frac{1}{2}\rho L^5N_{\dot{r}}} & \frac{\frac{1}{2}\rho L^5N_{r|r|}|r|+\frac{1}{2}\rho L^4N_{|v|r}(v^2+w^2)^{\frac{1}{2}}}{I_z-\frac{1}{2}\rho L^5N_{\dot{r}}}
\end{bmatrix}
$$

$$
B=\begin{bmatrix}
\frac{1}{m-\frac{1}{2}\rho L^3X_{\dot{u}}} & 0 & 0 & 0 \\
0 & \frac{1}{m-\frac{1}{2}\rho L^3Y_{\dot{v}}} & 0 & 0 \\
0 & 0 & \frac{1}{m-\frac{1}{2}\rho L^3Z_{\dot{w}}} & 0 \\
0 & 0 & 0 & \frac{1}{I_z-\frac{1}{2}\rho L^5N_{\dot{r}}}
\end{bmatrix}
$$

$$
R_1=\begin{bmatrix}
\cos\psi & -\sin\psi & 0 & 0 \\
\sin\psi & \cos\psi & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

III. IMPLEMENTATION OF MPC CONTROLLER

A. Augmented Model

The augmented model of HOV Jiao-long is described by the following state space equations:

$$
\begin{bmatrix} \Delta x_m(k+1) \\ y(k+1) \end{bmatrix}=\overbrace{\begin{bmatrix} A_m & O_m{}^T \\ C_mA_m & I_{q\times q} \end{bmatrix}}^{A}\begin{bmatrix} \Delta x_m(k) \\ y(k) \end{bmatrix}+\overbrace{\begin{bmatrix} B_m \\ C_mB_m \end{bmatrix}}^{B}\Delta u(k) \tag{6}
$$

$$
y(k)=\begin{bmatrix} 0 & I \end{bmatrix}\begin{bmatrix} \Delta x_m(k) \\ y(k) \end{bmatrix} \tag{7}
$$

Where m denotes the number of input variables, q denotes the number of output variables. The matrices I and O denote the identity, and zero matrix of proper dimension respectively.

B. Predicted Output

Define N_p ($N_p \geq 1$) represents the prediction horizon, N_c represents the control horizon(0< $N_c \leq N_p$), k_i （ $k_i > 0$ ） represents the time instant when prediction starts. Then, the output sequence from k_i to k_i+N_p is given by:

$$
Y=\left[y(k_i+1\,|\,k_i),y(k_i+2\,|\,k_i),y(k_i+3\,|\,k_i),\cdots,y(k_i+N_p\,|\,k_i)\right]^T \tag{8}
$$

The control increment sequence from k_i to k_i+N_c is given by:

$$
\Delta U=\left[\Delta u(k_i),\Delta u(k_i+1),\Delta u(k_i+2),\cdots,\Delta u(k_i+N_c-1)\right]^T \tag{9}
$$

The predicted output is then expressed in the following form:

$$
Y=Fx(k_i)+\Phi\Delta U \tag{10}
$$

where

$$F=\begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ \vdots \\ CA^{N_p} \end{bmatrix};\Phi=\begin{bmatrix} CB & 0 & 0 & \cdots & 0 \\ CAB & CB & 0 & \cdots & 0 \\ CA^2B & CAB & CB & \cdots & 0 \\ \vdots & & & & \\ CA^{N_p-1}B & CA^{N_p-2}B & CA^{N_p-3}B & \cdots & CA^{N_p-N_c}B \end{bmatrix}.$$

In order to implement the MPC algorithm, all the current states of the system is needed. While in physical systems, there are always some states can't be measured, then state observers is needed to estimate these states. In this paper, the Luenberger observer is used to estimate the states of HOV Jiao-long. The observations given by:

$$\hat{x}(k+1)=\overbrace{A\hat{x}(k)+Bu(k)}^{\text{mod}\,el}+\overbrace{K_{ob}(y(k)-\hat{y}(k))}^{correction\quad term} \tag{11}$$

where K_{ob} is the gain matrix of the Luenberger observer.

C. Optimal Control Sequence

Assume the reference output sequence is given by:

$$R_s^{\,T}=\begin{bmatrix}1 & 1 & \cdots & 1\end{bmatrix}r(k_i) \tag{12}$$

$r(k_i)$ denotes the reference output at time instant k_i.

MPC is an iterative optimization technique: at each sampling time *k*, measure or estimate the current state, then obtain the optimal control sequence by solving a real-time optimization problem. For the MPC controller of HOV Jiao-long, the cost function in the real-time optimization problem is:

$$\begin{aligned} J=&(R_s-Fx(k_i))^T(R_s-Fx(k_i))-2\Delta U^T\Phi^T(R_s-Fx(k_i)) \\ &+\Delta U^T(\Phi^T\Phi+\overline{R})\Delta U \end{aligned} \tag{13}$$

where $\overline{R}=r_w\,\mathrm{I}_{\mathrm{m}N_c\times\mathrm{m}N_c}$, r_w is a design parameter.

By solving the real-time optimization problem, the optimal control increment sequence is then expressed in the following form:

$$\Delta U=(\Phi^T\Phi+\overline{R})^{-1}(\Phi^TR_s-\Phi^TFx(k_i)) \tag{14}$$

In an actual physical system, the control outputs are limited by the capability of the system, namely constraints. The constraints of the real-time optimization problem in MPC controller design is given by:

$$\overbrace{\begin{bmatrix} M_1 \\ M_2 \end{bmatrix}}^{M}\Delta U\le\overbrace{\begin{bmatrix} N_1 \\ N_2 \end{bmatrix}}^{\gamma} \tag{15}$$

where

$$M_1=\begin{bmatrix}-C_2 \\ C_2\end{bmatrix};N_1=\begin{bmatrix}-U^{\min}+C_1u(k_i-1) \\ U^{\max}-C_1u(k_i-1)\end{bmatrix};M_2=\begin{bmatrix}-I \\ I\end{bmatrix};N_2=\begin{bmatrix}-\Delta U^{\min} \\ \Delta U^{\max}\end{bmatrix}.$$

Problem described above to solve the optimal control increment sequence can be rewritten as a quadratic programming (QP) problem:

$$\min \quad \mathrm{J}$$

$$\text{s.t.} \quad \overbrace{\begin{bmatrix} M_1 \\ M_2 \end{bmatrix}}^{M}\Delta U\le\overbrace{\begin{bmatrix} N_1 \\ N_2 \end{bmatrix}}^{\gamma}$$

To solve the QP problem, the Hildrerh programming procedure is utilized. the solution of the QP problem under the Hildrerh programming procedure is:

$$x=-E_{pq}^{\;-1}(M^T\lambda^*+F_{pq}) \tag{16}$$

where $\lambda_{act}^*=-(M_{act}E_{pq}^{-1}M_{act}^T)^{-1}(\gamma_{act}+M_{act}E_{pq}^{-1}F_{pq})$.

IV. SIMULATION RESULTS

In this section, simulation results are discussed to demonstrate the effectiveness of the proposed MPC scheme for the control of HOV Jiao-long.

A. Simulation Parameters

The MPC parameters used in the simulation are provided as follows:

Prediction Horizon: $\mathrm{N}_p=180$

Control Horizon: $N_c=20$

Weighting Matrix: $\overline{R}=\begin{bmatrix} 3e^{-5} & 0 & 0 & 0 \\ 0 & 1e^{-5} & 0 & 0 \\ 0 & 0 & 5e^{-6} & 0 \\ 0 & 0 & 0 & 3e^{-5} \end{bmatrix}$

Weighting matrices of the Luenberger observer:

$$R=\begin{bmatrix} 1e^{-4} & 0 & 0 & 0 \\ 0 & 1e^{-5} & 0 & 0 \\ 0 & 0 & 1e^{-4} & 0 \\ 0 & 0 & 0 & 1e^{-6} \end{bmatrix}$$

$$Q=\begin{bmatrix} 2e^{+5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1e^{+4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3e^{+4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4e^{+6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3e^{+4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & 0 & 0 & 0 & 0 & 1e^{+4} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 3e^{+4} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8e^{+4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

B. *Depth Control*

In depth control simulation, the vehicle is supposed to dive to a depth of 1 meter; the initial depth is 0 meter. In this case, the performance of MPC controller is depicted in figure 3:

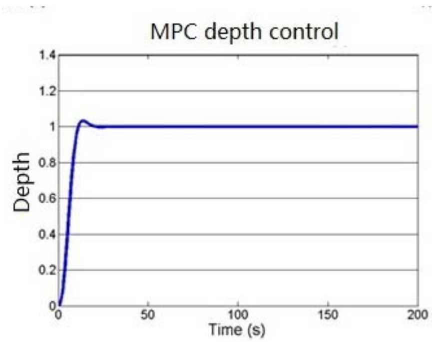

Fig. 3. Results of MPC depth control

The overshoot, rising time, setting time and steady state error of MPC controller in depth control simulation are given by table 1:

TABLE 1. DEPTH CONTROL PERFORMANCE

	Overshoot	Rising Time	Setting Time	Steady State Error
MPC	3.2%	11s	22s	0

C. *Heading Control*

In heading control simulation, suppose the initial heading of the vehicle is 0 degree, the set heading is 20 degree, the heading control performance of MPC controller is depicted in figure 4:

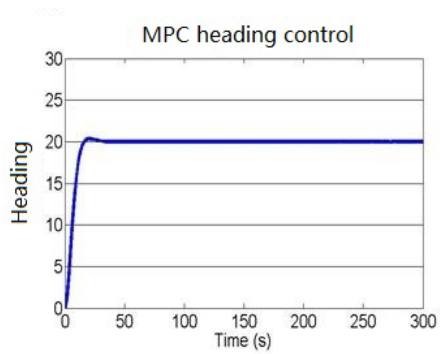

Fig. 4. Results of PID, fuzzy PID and MPC heading control

The overshoot, rising time, setting time and steady state error of MPC controller in heading control simulation are given by table 2:

TABLE 2. HEADING CONTROL PERFORMANCE

	Overshoot	Rising Time	Setting Time	Steady State Error
MPC	2.8%	39s	60s	0.7%

D. *Hovering Control*

For HOV Jiao-long, the hovering control includes the control of surge, sway, heave and yaw movement of the vehicle. In hovering control simulation, the performance of MPC controller is depicted in figure 5.

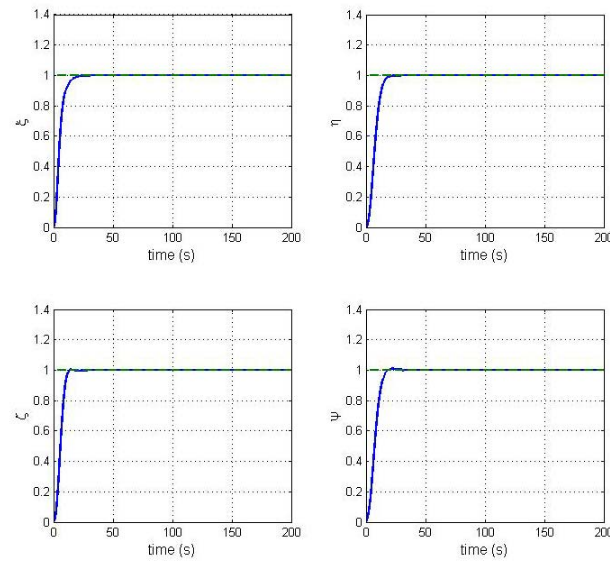

Fig. 5. Results of MPC hovering control

The overshoot, rising time, setting time and steady state error of MPC controller in hovering control simulation are given by table 3.

TABLE 3. HOVERING CONTROL PERFORMANCE OF MPC

	Overshoot	Rising Time	Setting Time	Steady State Error
ξ	0	9s	15s	0
η	0	11s	14s	0
ζ	0.31%	13s	13s	0
ψ	0.89%	18s	18s	0

V. CONCLUSION

This paper presents the design of a constrained discrete-time model predictive controller aiming at the motion control of a class of thruster-driven underwater vehicles. A nonlinear model in six degree of freedom is established based on the dynamics of HOV Jiao-long, and converted into a state space model after practical simplification. To ensure the performance of MPC controller, a full feedback state observer is established to observe the state. In addition, Hildreth's quadratic programming algorithm is incorporated for solving the optimal control sequence. The performance of the MPC controller is evaluated in simulations of depth control, heading control and hovering control. Simulation results clearly show the superiority of the proposed MPC controller.

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