Description

Pathfinding Control System And Method For Unmanned Boat Based On Digital Twin And Parallel Controller

TECHNICAL FIELD

The present disclosure relates to the field of pathfinding control for unmanned boats, and in particular, to a pathfinding control system and method for an unmanned boat based on Digital Twin and a parallel controller.

BACKGROUND

Pathfinding control, also known as pathfinding control, is a basic issue in unmanned boat motion control. The pathfinding control problem involves two control objectives, i.e., respectively a geometric control objective and a dynamic control objective. Wherein, the geometric control objective is used to meet the spatial requirements of the output space, while the dynamic control objective is used to meet the dynamic behavior requirements on the path. Compared with trajectory tracking control, time constraints and spatial constraints in pathfinding control are decoupled from each other, which makes the design of path parameter update laws more flexible, in order to obtain better control performance. Due to a wide application of pathfinding control problems in the field of unmanned boats, relevant scholars have studied it from different angles in recent years, including research on single unmanned boat systems and research on multiple unmanned boat systems.

There are the following problems in existing pathfinding control methods of Unmanned Boats:

Firstly, the existing pathfinding control methods for an Unmanned Boat only consider the physical unmanned boat system in the physical space, and do not consider an integration environment of the physical space and the information space. It is difficult to realize efficient collaboration and optimized control between the physical unmanned boat system in the physical space and the virtual unmanned boat systems in the information space.

Secondly, most of the current pathfinding control methods for Unmanned Boats are based on unidirectional updates motion model of the sensor data of the physical unmanned boat system. This approach lacks information flow from the motion model to the physical unmanned boat system, making it impossible to realize bidirectional data flow and synchronous mapping between the physical unmanned boat system and virtual unmanned boat system.

Thirdly, existing pathfinding control methods for an Unmanned Boat are mostly based on simulation or experiments to verify the performance of the designed controller. This process is usually independent of the actual execution system and lacks real-time feedback and control strategy optimization.

SUMMARY

In order to solve the existing technical problems for a pathfinding control method for an Unmanned Boat in the prior art, such as: not considering an integration environment of the physical space and the information space, lack of information flow from the motion model to the physical unmanned vehicle system, and the actual execution system lacking real-time feedback and control strategies optimization, the present disclosure proposes a pathfinding control system for an unmanned boat based on Digital Twin and a parallel controller.

The technical solution of the present disclosure is as follows:

a pathfinding control system for an unmanned boat based on Digital Twin and a parallel controller,

including: a physical unmanned boat system, an actual controller configured to generate a physical unmanned boat's control input to control the physical unmanned boat system, an unmanned boat motion Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate an unmanned boat guidance signal, a dynamic controller configured to generate a control input for the virtual unmanned boat to control an artificial system composed of the virtual unmanned boat motion Digital Twin model according to the guidance signal and speed information of the virtual unmanned boat at the current moment, a path parameter update law configured to provide a path parameter for the unmanned boat; where

the input of the physical unmanned boat system is connected to the output of the actual controller, while its output end is connected to the input end of the actual controller;

the input end of the actual controller is connected to an actual input end including position information and directional information for an unmanned boat actual reference path and the output end of the physical unmanned boat system, respectively; the output end of the actual controller is connected to the input end of the physical unmanned boat system;

the input end of the unmanned boat motion Digital Twin model is connected to the output end of the dynamic controller; the output end of the unmanned boat motion Digital Twin model is connected to the input end of the kinematic controller and the input end of the dynamic controller, respectively;

the input end of the kinematic controller is connected to an artificial input end including position information and directional information for an physical unmanned boat reference path, the output end of the path parameter update law and the output end of the unmanned boat motion Digital Twin model, respectively; the output end of the kinematic controller is connected to the input end of the dynamic controller and the input end of the path parameter update law, respectively;

the input end of the dynamic controller is connected to the output end of the kinematic controller and the output end of the unmanned boat motion Digital Twin model, respectively; the output end of the dynamic controller is connected to the input end of the unmanned boat motion Digital Twin model; and

the input end of the path parameter update law is connected to the output end of the kinematic controller; the output end of the path parameter update law is connected to the input end of the kinematic controller.

Preferably, a mathematical model for the physical unmanned boat system is expressed by the following formula:

$$\begin{cases} \dot{\eta} = R(\psi)\nu \\ \dot{\nu} = \sigma + (M^*)^{-1}\tau \end{cases} \tag{1}$$

wherein $\eta = [x, y, \psi]^T \in \mathrm{R}^3$ is position information and yaw angle information for an unmanned boat ; $[\cdot]^T$ represents transpose of a matrix or a vector; $\nu = [u, v, r]^T \in \mathrm{R}^3$ are the longitudinal speed, lateral speed and yaw rate for the unmanned boat; $M \in \mathrm{R}^{3\times3}$ is an inertia matrix of the unmanned boat, $M^* \in \mathrm{R}^{3\times3}$ is a calibration value of M; $\tau = [\tau_u, \tau_v, \tau_r]^T \in \mathrm{R}^3$ is a control input for the physical unmanned boat; $R(\psi) \in \mathrm{R}^{3\times3}$ is a rotation matrix, expressed as follows:

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$\sigma \in \mathrm{R}^3$ is a system total disturbance, expressed as follows:

$$\sigma = M^{-1}(-C(\nu)\nu - D(\nu)\nu + \tau_w) + (M^{-1} - (M^*)^{-1})\tau$$

wherein $C(\nu) \in \mathrm{R}^{3\times3}$ is a centripetal force and a Coriolis force coefficient matrix; $D(\nu) \in \mathrm{R}^{3\times3}$ is a hydrodynamic damping matrix; $\tau_w = [\tau_{u\mathrm{w}}, \tau_{vw}, \tau_{rw}]^T \in \mathrm{R}^3$ is a disturbance caused by time-varying wind and wave current.

Preferably, the unmanned boat motion Digital Twin model includes:

the input signals of the unmanned boat motion Digital Twin model are position information η, speed information ν for a physical unmanned boat system, the control input for the virtual unmanned boat τ; the output signals of the unmanned boat motion Digital Twin model are position information $\hat{\eta}$, speed information $\hat{\nu}$, the system total disturbance's estimation value $\hat{\sigma}$ for the virtual unmanned boat in the Digital Twin model in the artificial system,

the unmanned boat motion Digital Twin model is designed as follows:

$$\begin{cases} \dot{\hat{\eta}} = R(\psi)\hat{\nu} - k_1(\hat{\eta} - \eta) \\ \dot{\hat{\nu}} = \hat{\sigma} - k_2(\hat{\nu} - \nu) + (M^*)^{-1}\tau \\ \dot{\hat{\sigma}} = -k_3(\hat{\nu} - \nu) \end{cases} \tag{3}$$

, and

wherein $k_1 \in \mathrm{R}$, $k_2 \in \mathrm{R}$, $k_3 \in \mathrm{R}$ are control gains.

Preferably, the kinematic controller includes:

the input signals of the kinematic controller are the artificial input end $\eta_d(w)$ comprising position information and directional information for an unmanned boat actual reference path, a path parameter *w*, position information $\hat{\eta} = [\hat{x}, \hat{y}, \hat{\psi}]^T \in \mathrm{R}^3$ for a virtual unmanned boat in the Digital Twin model in the artificial system; the output signals of the kinematic controller are the pathfinding error η_e and the guidance signal ν_c in the Digital Twin model in the artificial system,

the kinematic controller is designed as follows:

$$\begin{cases} \eta_e = \hat{\eta} - \eta_d(w) \\ \nu_c = -\dfrac{K_{c1}R^T(\psi)\eta_e}{\sqrt{\| \eta_e\|^2 + \Delta_1^2}} + R^T(\psi)\eta_d^w(w)w_s \end{cases} \tag{4}$$

wherein $K_{c1} \in \mathrm{R}^{3\times 3}$ is a gain coefficient matrix, $\sqrt{\| \eta_e\|^2 + \Delta_1^2}$ is a saturation term, $\Delta_1 \in \mathrm{R}_+$ is a design parameter.

Preferably, the path parameter update law includes:

the input signals of the path parameter update law are a pathfinding error η_e in the Digital Twin model in the artificial system; the output signals of the path parameter update law are a path parameter w,

the path parameter update law is designed as follows:

$$\begin{cases} \dot{w} = w_s - \rho \\ \dot{\rho} = -\alpha(\rho + \beta(\eta_d^w(w))^T\eta_e) \end{cases} \tag{5}$$

wherein w_s is a desired path update rate, $\alpha, \beta \in \mathrm{R}_+$ is a given design parameter, ρ is a variable design parameter.

Preferably, the dynamic controller includes:

the input signals of the dynamic controller are the speed information $\hat{\nu}=[\hat{u},\hat{v},\hat{r}]^T\in \mathrm{R}^3$, the guidance signal v_c, the system total disturbance's estimation value $\hat{\sigma}=[\hat{\sigma}_u,\hat{\sigma}_v,\hat{\sigma}_r]^T\in \mathrm{R}^3$ for the virtual unmanned boat in the Digital Twin model in the artificial system; the output signal of the dynamic controller is a control input for the virtual unmanned boat τ ,

the dynamic controller is designed as follows:

$$\begin{cases} \nu_e=\hat{\nu}-\nu_c \\ \tau=M^*\left(-\dfrac{K_{c2}\nu_e}{\sqrt{\|\ \nu_e\|^2+\Delta_2^2}}-R^T(\psi)\eta_e-\hat{\sigma}+\dot{\nu}_c\right) \end{cases} \tag{6}$$

wherein $K_{c2}\in \mathrm{R}^{3\times 3}$ is a gain coefficient matrix, $\sqrt{\|\ \nu_e\|^2+\Delta_2^2}$ is a saturation term, $\Delta_2\in \mathrm{R}_+$ is a design parameter.

Preferably, the actual controller is obtained from the Parallel Controller, the two are mirror images of each other. And the input signal and the output signal of the actual controller are both consistent with the Parallel Controller; the parallel controller including: a kinematic controller, a dynamic controller, and a path parameter update law.

A pathfinding control method for an unmanned boat based on Digital Twin and a parallel controller:

S1: constructing an unmanned boat pathfinding control system: wherein, the system includes: a physical unmanned boat system, an actual controller configured to generate a control input for a physical unmanned boat to control the physical unmanned boat system, an unmanned boat motion Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate an unmanned boat guidance signal, a dynamic controller configured to generate a control input for the virtual unmanned boat to control an artificial system composed of the unmanned boat motion Digital Twin model according to the guidance signal and speed information of the virtual unmanned boat at the current moment, a path parameter update law configured to provide a path parameter for the unmanned boat;

S2: transmitting signals for the virtual unmanned boat: transmitting position information$\hat{\eta}$ for a virtual unmanned boat given by the artificial input and the unmanned boat motion Digital Twin model at the current moment to the kinematic controller; the path parameter update law simultaneously providing a path parameter *w*; the kinematic controller generating the guidance signal v_c and transmitting them to the dynamic controller; the dynamic controller generating the virtual unmanned

boat's control input τ to control the artificial system composed of an unmanned boat motion Digital Twin model according to the guidance signal v_c and speed information $\hat{v}$ for the virtual unmanned boat at a current moment; and

S3: transmitting signals for the physical unmanned boat system: inputting the actual input and status information of the physical unmanned boat $\hat{\eta}$, $\hat{v}$ into the actual controller together; the actual controller generating the physical unmanned boat's control input τ to control a physical unmanned boat system.

Compared with the prior art, the present disclosure has the following beneficial effects:

The present disclosure provides a pathfinding control system and method for an unmanned boat based on Digital Twin and a parallel controller, where the system includes: a physical unmanned boat system, an actual controller configured to generate a control input to control the physical unmanned boat system, an unmanned boat motion Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate an unmanned boat guidance signal, a dynamic controller configured to generate a control input to control an artificial system composed of the unmanned boat motion Digital Twin model according to the guidance signal and speed information of the virtual unmanned boat at the current moment, a path parameter update law configured to provide a path parameter for the unmanned boat.

The parallel controllers designed by present disclosure integrate the virtual unmanned boat system from the constructed information space into the environment, and drives the virtual unmanned boat system and the physical unmanned boat system simultaneously, so as to realize a mutual mapping and a virtual-actual interaction between the both systems.

The Digital Twin model in the artificial system in the present disclosure updates the status information based on the physical unmanned boat, and realizes the pathfinding control of the physical unmanned boat system according to the designed parallel controller, realizing bidirectional data flow and synchronous mapping between the physical unmanned boat system and the virtual unmanned boat system.

Thirdly, the parallel controllers designed by the present disclosure can perform calculation experiments based on the constructed Digital Twin model in the artificial system. By performing a deduction simulation on the Digital Twin model in the artificial system, a dynamic evaluation and a dynamic optimization of the performance of the designed parallel controllers is achieved.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic structural diagram of an unmanned boat based on Digital Twin and parallel controllers.

Figure 2 is a schematic diagram of parallel pathfinding control performance.

Figure 3 is a pathfinding error diagram of the unmanned boat in the Digital Twin model of the artificial system and in the actual system.

Figure 4 is a curve graph of the position and the directional of the unmanned boat in the Digital Twin model of the artificial system and in the actual system.

Figure 5 is a curve graph of a longitudinal speed, a transverse speed and a yaw angular velocity of the unmanned boat in the Digital Twin model of the artificial system and in the actual system.

Figure 6 is an observation effect diagram of the system total disturbance.

Figure 7 is a curve diagram of control inputs for the unmanned boat in the Digital Twin model of the artificial system and in the actual system.

DETAILED DESCRIPTION

The present disclosure will be further described hereinafter in conjunction with the accompanying drawings and embodiments.

A structure of a pathfinding control system for an unmanned boat based on Digital Twin and a parallel controller designed by the present disclosure is shown in Figure 1.,

including: a physical unmanned boat system, an actual controller configured to generate a physical unmanned boat's control input to control the physical unmanned boat system, an unmanned boat motion Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate an unmanned boat guidance signal, a dynamic controller configured to generate a control input for the virtual unmanned boat to control an artificial system composed of the unmanned boat motion Digital Twin model according to the guidance signal and speed information of the virtual unmanned boat at the current moment, a path parameter update law configured to provide a path parameter for the unmanned boat; where

the input of the physical unmanned boat system is connected to the output of the actual controller, while its output end is connected to the input end of the actual controller;

the input end of the actual controller is connected to an actual input end including position information and directional information for an unmanned boat actual reference path and the output end of the physical unmanned boat system, respectively; the output end of the actual controller is connected to the input end of the physical unmanned boat system;

the input end of the unmanned boat motion Digital Twin model is connected to the output end of the dynamic controller; the output end of the unmanned boat motion Digital Twin model is connected to the input end of the kinematic controller and the input end of the dynamic controller, respectively;

the input end of the kinematic controller is connected to an artificial input end including position information and directional information for an physical unmanned boat virtual reference path, the output end of the path parameter update law and the output end of the unmanned boat motion Digital Twin model, respectively; the output end of the kinematic controller is connected to the input end of the dynamic controller

and the input end of the path parameter update law, respectively;

the input end of the dynamic controller is connected to the output end of the kinematic controller and the output end of the unmanned boat motion Digital Twin model, respectively; the output end of the dynamic controller is connected to the input end of the unmanned boat motion Digital Twin model; and

the input end of the path parameter update law is connected to the output end of the kinematic controller; the output end of the path parameter update law is connected to the input end of the kinematic controller.

Preferably, a mathematical model for the physical unmanned boat system is expressed by the following formula:

$$\begin{cases} \dot{\eta} = R(\psi)\nu \\ \dot{\nu} = \sigma + (M^*)^{-1}\tau \end{cases} \tag{1}$$

wherein $\eta = [x, y, \psi]^T \in \mathrm{R}^3$ is position information and yaw angle information for an unmanned boat ; $[\cdot]^T$ represents a transpose of a matrix or a vector; $\nu = [u, v, r]^T \in \mathrm{R}^3$ are the longitudinal speed, lateral speed and yaw rate for the unmanned boat; $M \in \mathrm{R}^{3\times3}$ is an inertia matrix of the unmanned boat, $M^* \in \mathrm{R}^{3\times3}$ is a calibration value of M; $\tau = [\tau_u, \tau_v, \tau_r]^T \in \mathrm{R}^3$ is a control input for the physical unmanned boat; $R(\psi) \in \mathrm{R}^{3\times3}$ is a rotation matrix, expressed as follows:

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$\sigma \in \mathrm{R}^3$ is a system total disturbance, expressed as follows:

$$\sigma = M^{-1}(-C(\nu)\nu - D(\nu)\nu + \tau_w) + (M^{-1} - (M^*)^{-1})\tau$$

wherein $C(\nu) \in \mathrm{R}^{3\times3}$ is a centripetal force and a Coriolis force coefficient matrix; $D(\nu) \in \mathrm{R}^{3\times3}$ is a hydrodynamic damping matrix; $\tau_w = [\tau_{uw}, \tau_{vw}, \tau_{rw}]^T \in \mathrm{R}^3$ is a disturbance caused by time-varying wind and wave current.

Preferably, the unmanned boat motion Digital Twin model includes:

the input signals of the unmanned boat motion Digital Twin model are position information η, speed information v for a physical unmanned boat system, the control input for virtual unmanned boat τ; the output signals of the unmanned boat motion Digital Twin model are position information $\hat{\eta}$, speed information $\hat{v}$, the

system total disturbance's estimation value $\hat{\sigma}$ for the virtual unmanned boat in the Digital Twin model in the artificial system,

the unmanned boat motion Digital Twin model is designed as follows:

$$\begin{cases} \dot{\hat{\eta}} = R(\psi)\hat{\nu} - k_1(\hat{\eta} - \eta) \\ \dot{\hat{\nu}} = \hat{\sigma} - k_2(\hat{\nu} - \nu) + (M^*)^{-1}\tau \\ \dot{\hat{\sigma}} = -k_3(\hat{\nu} - \nu) \end{cases} \tag{3}$$

wherein $k_1 \in \mathrm{R}$, $k_2 \in \mathrm{R}$, $k_3 \in \mathrm{R}$ are control gains.

Preferably, the kinematic controller includes:

the input signals of the kinematic controller are the artificial input end $\eta_d(w)$ comprising position information and directional information for an unmanned boat actual reference path, a path parameter *w*, position information $\hat{\eta} = [\hat{x}, \hat{y}, \hat{\psi}]^T \in \mathrm{R}^3$ for a virtual unmanned boat in the Digital Twin model in the artificial system; the output signals of the kinematic controller are the pathfinding error η_e and the guidance signal ν_c in the Digital Twin model in the artificial system,

the kinematic controller is designed as follows:

$$\begin{cases} \eta_e = \hat{\eta} - \eta_d(w) \\ \nu_c = -\dfrac{K_{c1}R^T(\psi)\eta_e}{\sqrt{\| \eta_e\|^2 + \Delta_1^2}} + R^T(\psi)\eta_d^w(w)w_s \end{cases} \tag{4}$$

wherein $K_{c1} \in \mathrm{R}^{3\times 3}$ is a gain coefficient matrix, $\sqrt{\| \eta_e\|^2 + \Delta_1^2}$ is a saturation term, $\Delta_1 \in \mathrm{R}_+$ is a design parameter.

Preferably, the path parameter update law includes:

the input signals of the path parameter update law are a pathfinding error η_e in the Digital Twin model in the artificial system; the output signals of the path parameter update law are a path parameter w,

the path parameter update law is designed as follows:

$$\begin{cases} \dot{w} = w_s - \rho \\ \dot{\rho} = -\alpha(\rho + \beta(\eta_d^w(w))^T\eta_e) \end{cases} \tag{5}$$

wherein w_s is a desired path update rate, $\alpha, \beta \in \mathrm{R}_+$ is a given design

parameter, ρ is a variable design parameter.

Preferably, the dynamic controller includes:

the input signals of the dynamic controller are the speed information $\hat{\nu}=[\hat{u},\hat{v},\hat{r}]^T\in \mathrm{R}^3$, the guidance signal v_c, the system total disturbance's estimation value $\hat{\sigma}=[\hat{\sigma}_u,\hat{\sigma}_v,\hat{\sigma}_r]^T\in \mathrm{R}^3$ for the virtual unmanned boat in the Digital Twin model in the artificial system; the output signal of the dynamic controller is a control input for the virtual unmanned boat τ ,

the dynamic controller is designed as follows:

$$\begin{cases} \nu_e=\hat{\nu}-\nu_c \\ \tau=M^*\left(-\dfrac{K_{c2}\nu_e}{\sqrt{\|\ \nu_e\|^2+\Delta_2^2}}-R^T(\psi)\eta_e-\hat{\sigma}+\dot{\nu}_c\right) \end{cases} \tag{6}$$

wherein $K_{c2}\in \mathrm{R}^{3\times 3}$ is a gain coefficient matrix, $\sqrt{\|\ \nu_e\|^2+\Delta_2^2}$ is a saturation term, $\Delta_2\in \mathrm{R}_+$ is a design parameter.

Preferably, the actual controller is obtained by copying the Parallel Controller, the two are mirror images of each other. And the input signal and the output signal of the actual controller are both consistent with the Parallel Controller; the parallel controller including: a kinematic controller, a dynamic controller, and a path parameter update law.

A pathfinding control method for an unmanned boat based on Digital Twin and a parallel controller:

S1: constructing an unmanned boat pathfinding control system: wherein, the system includes: a physical unmanned boat system, an actual controller configured to generate a control input for a physical unmanned boat to control the physical unmanned boat system, an unmanned boat motion Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate an unmanned boat guidance signal, a dynamic controller configured to generate a control input for the virtual unmanned boat to control an artificial system composed of the unmanned boat motion Digital Twin model according to the guidance signal and speed information of the virtual unmanned boat at the current moment, a path parameter update law configured to provide a path parameter for the unmanned boat;

S2: transmitting signals for the virtual unmanned boat: transmitting position information$\hat{\eta}$ for a virtual unmanned boat given by the artificial input and the unmanned boat motion Digital Twin model at the current moment to the kinematic controller; the path parameter update law simultaneously providing a path parameter

w; the kinematic controller generating the guidance signal v_c and transmitting them to the dynamic controller; the dynamic controller generating the virtual unmanned boat's control input τ to control the artificial system composed of an unmanned boat motion Digital Twin model according to the guidance signal v_c and speed information $\hat{v}$ for the virtual unmanned boat at a current moment; and

S3: transmitting signals for the physical unmanned boat system: inputting the actual input and status information of the physical unmanned boat $\hat{\eta}$, $\hat{v}$ into the actual controller together; the actual controller generating the physical unmanned boat's a control input τ to control a physical unmanned boat system.

The virtual unmanned boat and the physical unmanned boat achieve virtual-physical interaction and parallel interaction between both of them according to the real-time status information interaction between the controller part and the controlled object part.

The control parameters are selected for equations (3)-(6) as follows:

$K_{c1} = diag\{0.1, 0.1, 0.1\}$, $\Delta_1 = 1$, $K_{c2} = diag\{5,5,2\}$, $\Delta_2 = 1$, $\mathrm{w_s} = 1$, $\alpha = 10$, $\beta = 10$, $k_1 = 20$, $k_2 = 20$, $k_3 = 100$, wherein, $diag$ represents a diagonal matrix.

The simulation results are shown in Figures 2-7. Figure 2 shows the motion trajectory of pathfinding control for the unmanned boat. In the Figure 2, the dotted line is a desired path, the solid line is an actual path of the unmanned boat, and the horizontal and vertical coordinates are the size of the map. It can be seen from the Figure 2 that in a short period of time, the actual path of the unmanned boat will coincide with the desired path, indicating that the unmanned boat can track the desired path well. Figure 3 shows pathfinding errors between the artificial system and the actual system. The horizontal coordinate is time, and the vertical coordinates are a longitudinal tracking error, a transverse tracking error and a directional tracking error. From the Figure 3, we can see the tracking errors between the artificial system and the actual system all converge to near zero in the steady state. In Figure 4, the vertical coordinates are position information and directional information of the unmanned boat, and the horizontal coordinate is time. It can be seen from the Figure 4 that both the artificial system and the actual system can track the reference signal well. In Figure 5, the vertical coordinate is speed information of the unmanned boat, and the horizontal coordinate is time. It can be seen from the Figure 5 that the speed signals of the artificial system and the actual system can accurately track the guidance signal after a short transient process. In Figure 6, the vertical coordinates are the disturbances in the longitudinal, transverse and yaw directions, and the horizontal coordinate is time. The estimation value represented by the solid line and the actual value represented by the dotted line coincide with the curves in the Figure 6, which can indicate the designed unmanned boat motion Digital Twin model can accurately estimate the system total disturbance. In Figure 7, the vertical coordinates are thrust forces in the longitudinal and transverse directions of the unmanned boat, and a moment of force in the yaw direction; the horizontal coordinate is time. Where, the solid line is the artificial system, and the dotted line is the actual system. Both of the

above two curves tend to be consistent.

The present disclosure is not limited to the present embodiment, and any equivalent concepts or changes within the technical scope disclosed in the present disclosure are included in the protection scope of the present disclosure.

Claims

1. A pathfinding control system for an unmanned boat based on digital twin and a parallel controller, comprising:

a physical unmanned boat system, an actual controller configured to generate a physical unmanned boat's control input for controlling the physical unmanned boat system, an unmanned boat movement Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate guidance signals for unmanned boats, a dynamic controller configured to generate control inputs for the virtual unmanned boat based on said guidance signals in addition to present speed information of the virtual unmanned boat, wherein said control inputs control the manual system composed of the unmanned boat movement Digital Twin model, and a path parameter update law configured to provide a path parameter for the unmanned boat, wherein

the input end of the physical unmanned boat system is connected to the output end of the actual controller, while the physical unmanned boat system output end is connected to the input end of the actual controller;

the input end of the actual controller is connected to an actual input end comprising positional and directional information for an unmanned boat actual reference path and the output end of the physical unmanned boat system, respectively, and the output end of the actual controller is connected to the input end of the physical unmanned boat system;

the input end of the unmanned boat motion Digital Twin model is connected to the output end of the dynamic controller, and the output end of the unmanned boat motion Digital Twin model is connected to the input end of the kinematic controller and the input end of the dynamic controller, respectively;

the input end of the kinematic controller is connected to an artificial input end comprising position information and directional information for a physical unmanned boat reference path, the output end of the path parameter update law and the output end of the unmanned boat motion Digital Twin model, respectively, and the output end of the kinematic controller is connected to the input end of the dynamic controller and the input end of the path parameter update law, respectively;

the input end of the dynamic controller is connected to the output end of the kinematic controller and the output end of the unmanned boat motion Digital Twin model, respectively, and the output end of the dynamic controller is connected to the input end of the unmanned boat motion Digital Twin model; and

the input end of the path parameter update law is connected to the output end of the kinematic controller, and the output end of the path parameter update law is connected to the input end of the kinematic controller.

2. The pathfinding control system of claim 1 for the unmanned boat based on Digital Twin and the parallel controller, wherein a mathematical model for the physical unmanned boat system is expressed by the following formula:

$$\begin{cases} \dot{\eta} = R(\psi)\nu \\ \dot{\nu} = \sigma + (M^*)^{-1}\tau \end{cases} \quad (1)$$

Wherein $\eta=[x,y,\psi]^T\in\mathrm{R}^3$ is position information and yaw angle information for an unmanned boat ; $[\cdot]^T$ represents transpose of a matrix or a vector; $\nu=[u,v,r]^T\in\mathrm{R}^3$ are the longitudinal speed, lateral speed and yaw rate for the unmanned boat; $M\in\mathrm{R}^{3\times3}$ is an inertia matrix of the unmanned boat, $M^*\in\mathrm{R}^{3\times3}$ is a calibration value of M; $\tau=[\tau_u,\tau_v,\tau_r]^T\in\mathrm{R}^3$ is a control input for the physical unmanned boat; $R(\psi)\in\mathrm{R}^{3\times3}$ is a rotation matrix, expressed as follows:

$$R(\psi)=\begin{bmatrix}\cos(\psi) & -\sin(\psi) & 0\\ \sin(\psi) & \cos(\psi) & 0\\ 0 & 0 & 1\end{bmatrix} \tag{2}$$

$\sigma\in\mathrm{R}^3$ is a system total disturbance, expressed as follows:

$$\sigma=M^{-1}(-C(\nu)\nu-D(\nu)\nu+\tau_w)+(M^{-1}-(M^*)^{-1})\tau$$

wherein $C(\nu)\in\mathrm{R}^{3\times3}$ is a centripetal force and a Coriolis force coefficient matrix; $D(\nu)\in\mathrm{R}^{3\times3}$ is a hydrodynamic damping matrix; $\tau_w=[\tau_{uw},\tau_{vw},\tau_{rw}]^T\in\mathrm{R}^3$ is a disturbance caused by time-varying wind and wave current.

3. The pathfinding control system of claim 2 for the unmanned boat based on Digital Twin and the parallel controller, wherein the unmanned boat motion Digital Twin model comprises:

the input signals of the unmanned boat motion Digital Twin model are position information η, speed information v for a physical unmanned boat system, the control input of the virtual unmanned boat τ; the output signals of the unmanned boat motion Digital Twin model are position information $\hat{\eta}$, speed information $\hat{v}$, the system total disturbance's estimation value $\hat{\sigma}$ for the virtual unmanned boat in the Digital Twin model in the artificial system,

the unmanned boat motion Digital Twin model designed as follows:

$$\begin{cases}\dot{\hat{\eta}}=R(\psi)\hat{\nu}-k_1(\hat{\eta}-\eta)\\ \dot{\hat{\nu}}=\hat{\sigma}-k_2(\hat{\nu}-\nu)+(M^*)^{-1}\tau\\ \dot{\hat{\sigma}}=-k_3(\hat{\nu}-\nu)\end{cases} \tag{3}$$

wherein $k_1\in\mathrm{R}$, $k_2\in\mathrm{R}$, $k_3\in\mathrm{R}$ are control gains.

4. The pathfinding control system of claim 3 for the unmanned boat based on Digital Twin and the parallel controller, wherein the kinematic controller comprises:

the input signals of the kinematic controller are the artificial input end $\eta_d(w)$ comprising position information and directional information for an unmanned boat actual reference path, a path parameter w, position information $\hat{\eta}=[\hat{x},\hat{y},\hat{\psi}]^T\in \mathrm{R}^3$ for a virtual unmanned boat in the Digital Twin model in the artificial system; the output signals of the kinematic controller are the pathfinding error η_e and the guidance signal ν_c in the Digital Twin model in the artificial system,

the kinematic controller is designed as follows:

$$\begin{cases} \eta_e=\hat{\eta}-\eta_d(w) \\ \nu_c=-\dfrac{K_{c1}R^T(\psi)\eta_e}{\sqrt{\|\ \eta_e\|^2+\Delta_1^2}}+R^T(\psi)\eta_d^w(w)w_s \end{cases} \tag{4}$$

, and

Wherein w_s is a desired path update rate, $K_{c1}\in \mathrm{R}^{3\times 3}$ is a gain coefficient matrix, $\sqrt{\|\ \eta_e\|^2+\Delta_1^2}$ is a saturation term, $\Delta_1\in \mathrm{R}_+$ is a design parameter.

5. The pathfinding control system of claim 4 for the unmanned boat based on Digital Twin and the parallel controller, wherein the path parameter update law comprises:

a pathfinding error η_e from the input signals of the path parameter update law in the Digital Twin model in the artificial system; a path parameter w given the output signals of the path parameter update law wherein the path parameter update law is designed as follows:

$$\begin{cases} \dot{w}=w_s-\rho \\ \dot{\rho}=-\alpha(\rho+\beta(\eta_d^w(w))^T\eta_e) \end{cases} \tag{5}$$

wherein $\alpha,\beta\in \mathrm{R}_+$ is a given design parameter, and ρ is a variable design parameter.

6. The pathfinding control system of claim 5 for the unmanned boat based on Digital Twin and the parallel controller, wherein the dynamic controller comprises:

the input signals of the dynamic controller are the speed information $\hat{\nu}=[\hat{u},\hat{v},\hat{r}]^T\in \mathrm{R}^3$, the guidance signal v_c, the system total disturbance's estimation

value $\hat{\sigma}=[\hat{\sigma}_u,\hat{\sigma}_v,\hat{\sigma}_r]^T\in \mathrm{R}^3$ for the virtual unmanned boat in the Digital Twin model in the artificial system; the output signal of the dynamic controller is a control input for the virtual unmanned boat τ ,

the dynamic controller is designed as follows:

$$\begin{cases} \nu_e=\hat{\nu}-\nu_c \\ \tau=M^*\left(-\dfrac{K_{c2}\nu_e}{\sqrt{\|\ \nu_e\|^2+\Delta_2^2}}-R^T(\psi)\eta_e-\hat{\sigma}+\dot{\nu}_c\right) \end{cases} \tag{6}$$

wherein $K_{c2}\in \mathrm{R}^{3\times 3}$ is a gain coefficient matrix, $\sqrt{\|\ \nu_e\|^2+\Delta_2^2}$ is a saturation term, and $\Delta_2\in \mathrm{R}_+$ is a design parameter.

7. The pathfinding control system of claim 1 for the unmanned boat based on Digital Twin and the parallel controller, wherein the actual controller is obtained from the parallel controller, the two controllers are mirror images of each other; and the input signals and output signals of the actual controller are consistent with the Parallel Controller; the parallel controller including: a kinematic controller, a dynamic controller, and a path parameter update law.

8. A pathfinding control method for an unmanned boat based on Digital Twin and a parallel controller, wherein the method is based on the system according to any of claims 1-7, wherein the method including steps:

S1: constructing an unmanned boat pathfinding control system; wherein, the system comprises: a physical unmanned boat system, an actual controller configured to generate a control input for a physical unmanned boat to control the physical unmanned boat system, an unmanned boat motion Digital Twin model configured to generate position information for a virtual unmanned boat, a kinematic controller configured to generate an unmanned boat guidance signal, a dynamic controller configured to generate a control input for the virtual unmanned boat to control an artificial system composed of the unmanned boat motion Digital Twin model according to the guidance signal and speed information of the virtual unmanned boat at the current moment, a path parameter update law configured to provide a path parameter for the unmanned boat;

S2: transmitting signals for the virtual unmanned boat: transmitting position information$\hat{\eta}$ for a virtual unmanned boat given by the artificial input and the unmanned boat motion Digital Twin model at the current moment to the kinematic controller; the path parameter update law simultaneously providing a path parameter *w*; the kinematic controller generating the guidance signal v_c and transmitting them to the dynamic controller; the dynamic controller generating the virtual unmanned boat's control input τ to control the artificial system composed of an unmanned boat motion Digital Twin model according to the guidance signal v_c and speed information $\hat{v}$ for the virtual unmanned boat at a current moment; and

S3: transmitting signals for the physical unmanned boat system: inputting the actual input and status information of the physical unmanned boat $\hat{\eta}$, $\hat{v}$ into the actual controller together; the actual controller generating the physical unmanned boat's control input τ to control a physical unmanned boat system.