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Research Article

A Hybrid Approach for Coordinated Formation Control of Multiple Surface Vessels

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This paper investigates the coordination control of multiple marine vessels in different operational modes. Based on hybrid control theory, a novel coordinated formation control approach is proposed. The proposed method comprises several continuous state controllers and discrete event logics. Continuous controllers for coordinated formation, coordinated dynamic positioning and coordinated path following are designed, and an appropriate weighting function is given to switch between these controllers according to initiated commands. In order to ensure the security of coordination operations of vessels in arbitrary initial locations, the supervisory switching control method is employed in the integrated coordination control system where all the controllers are governed by a supervisor. The effectiveness of the proposed coordinated formation control approach is finally illustrated by simulations.

1. Introduction

Coordination control of multiple marine vessels has been receiving more and more attention in recent decades due to its widespread applications, for example, the oil and gas exploration, seismic monitoring of the seabed, underway replenishment at sea, and some other complicated marine tasks. All of these applications need coordination operations which require multiple vessels to perform the complicated task together while maintaining the desired formation pattern. Generally speaking, coordination control of multiple vessels includes formation, coordinated dynamic positioning, coordinated path following, and other typical tasks [1], each of which can be seen as a mode.

In recent years, many studies on coordination control issues of multiple marine vessels have been widely reported in the existing literatures which are mainly focused on formation control, coordinated dynamic positioning, and coordinated path following. For every issue, several advanced methods are employed to design the controllers, such as leader-following, virtual-structure, and behavioral coordination strategies for formation control [2–4]; and Lagrangian constraint functions [5], nonlinear model predictive control [6], and graph theory [7] for coordination control; some other methods for coordinated path following are introduced in [8–12]. Besides, communication issues between marine vessels like link failures and time-delay are also discussed deeply; related researches can be seen in [13, 14]. A common trait for all the above work is that the controller design of coordination control is usually completed under a specific coordination operation mode, for example, controller design for dynamic positioning or path following. However, in some applications the marine vessels are required to perform coordination operations from one mode to another; for instance, the vessels first execute formation control and then execute path following.

This need motivates the research on controller structure design of multioperational modes for marine vessels. In this structure, the vessels should be able to switch from one mode to another according to different requirements. A switching system including continuous state controllers and discrete logics is feasible. The logics can switch smoothly between continuous controllers following different operations [15]. Such a system is also called hybrid system [16–19], which is a hot topic in last few years. Reference [20] had realized coordinated dynamic positioning using hybrid control system. However, a critical issue worth noting is the switching stability of the whole system. To address this potential problem, supervisory switching control [21] approach could be

employed to guarantee the stability of the whole hybrid system, because this method can accomplish the coordination tasks which include various operational modes in one control system. The maneuver of a single vessel in different operational modes has been investigated in [22] with the application of supervisory switching control. Another similar application can be found in [23].

In this paper, we concern the maneuver of multiple vessels in different operational modes. Based on hybrid control theory, a novel coordination control approach is proposed, which integrates coordinated formation, coordinated dynamic positioning, and coordinated path following controllers in one system. These controllers can switch mutually according to switching logics determined by various operational modes. Moreover, the supervisory switching control method is employed in the design of the controllers for coordinated path following. Therefore, more complicated tasks can be accomplished with acceptable performance. The rest of this paper is organized as follows. Section 2 introduces the vessel model. Section 3 describes the proposed coordination control method in detail, including coordinated dynamic positioning controller, coordinated path following controller, switching logics, and supervisory switching control method. The simulation of coordination tasks of three vessels is carried out to demonstrate the validity of the proposed control approach in Section 4. At last, we draw conclusion in Section 5.

2. Vessel Model

The three-degree-of-freedom mathematic vessel model introduced in [24] is considered here. The model is described as follows:

$$\begin{gathered}\dot{\eta} = \mathbf{R}(\psi)\mathbf{v},\\ \mathbf{M}_v\dot{\mathbf{v}} + \mathbf{C}_v(\mathbf{v})\mathbf{v} + \mathbf{D}_v(\mathbf{v})\mathbf{v} = \tau_v,\end{gathered} \tag{1}$$

where $\eta = [n, e, \psi]^T$ is the generalized position and heading of the vessel in the earth-fixed reference frame, and $\mathbf{v} = [u, v, r]^T$ is the vector of generalized velocities with respect to the body-fixed reference frame. $\mathbf{R}(\psi)$ is a transformation matrix from the body-fixed to the earth-fixed reference frame, the form of which is as follows:

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

$\mathbf{M}_v$ represents a positive definite inertia mass matrix which includes added mass. $\mathbf{C}_v(\mathbf{v})$ and $\mathbf{D}_v(\mathbf{v})$ denote the Coriolis-centripetal matrix and damping matrix, respectively. τ_v is the vector of external forces and torques input.

The expression of vessel model in the earth-fixed reference frame is

$$\mathbf{M}(\eta)\ddot{\eta} + \mathbf{C}(\eta,\dot{\eta})\dot{\eta} + \mathbf{D}(\eta,\dot{\eta})\dot{\eta} = \tau. \tag{3}$$

It is obtained by applying the following kinematic transformations:

$$\begin{gathered}\mathbf{M}(\eta) = \mathbf{R}^{-T}(\psi)\mathbf{M}_v\mathbf{R}^{-1}(\psi),\\ \mathbf{C}(\eta,\dot{\eta}) = \mathbf{R}^{-T}(\psi)\left[\mathbf{C}_v(\mathbf{v}) - \mathbf{M}_v\mathbf{R}^{-1}(\psi)\dot{\mathbf{R}}(\psi)\right]\mathbf{R}^{-1}(\psi),\\ \mathbf{D}(\eta,\dot{\eta}) = \mathbf{R}^{-T}(\psi)\mathbf{D}_v(\mathbf{v})\mathbf{R}^{-1}(\psi),\\ \tau = \mathbf{R}^{-T}(\psi)\tau_v.\end{gathered} \tag{4}$$

The vessel model in the earth-fixed reference frame holds the following properties:

(1) $\mathbf{M}(\eta)$ is the symmetric positive definite inertia matrix, and satisfies

$$\lambda_{\min}(\mathbf{M}_i)\mathbf{I} \le \mathbf{M}(\eta) \le \lambda_{\max}(\mathbf{M}_i)\mathbf{I}, \tag{5}$$

(2) $\dot{\mathbf{M}}(\eta) - 2\mathbf{C}(\eta,\dot{\eta})$ is skew symmetric, which means

$$\eta^T\left(\dot{\mathbf{M}}(\eta) - 2\mathbf{C}(\eta,\dot{\eta})\right)\eta = 0, \quad \forall\eta \in \mathbb{R}^3, \tag{6}$$

(3) $\mathbf{D}(\eta,\dot{\eta})$ is positive definite and satisfies:

$$\eta^T\mathbf{D}(\eta,\dot{\eta})\eta > 0, \quad \forall\eta \ne \mathbf{0}. \tag{7}$$

3. Coordinated Controller Design

In practical marine tasks, if coordinated path following executes first in the operational process, the maneuver then has to be performed with two steps to avoid the inherent risk of collision between adjacent vessels. At the beginning, all vessels form the desired formation maintaining a sufficient relative distance between each other. Afterwards, a fleet of vessels implement the path following task. However, if coordinated dynamic positioning is the first task, then the coordinated path following can be performed directly. This section will show the core content of the proposed approach. Several controllers for various operational tasks/modes are designed and an appropriate algorithm is given as the switching logic. Suppose that a group of n vessels will be controlled to perform the coordination tasks. Detailed descriptions are as follows.

3.1. Coordinated Path following Controller. Two controllers are designed here to realize the coordinated path following task, which are coordinated formation controller and coordinated path following controller. A switching logic is given to transform from formation to path following.

3.1.1. Formation Controller. Suppose that label $i = 1, 2, \ldots, n$ represents the ith vessel in the group and $\mathbf{l}_{0\mathbf{i}} = [x_{0i}, y_{0i}, \psi_{0i}]^T$ is the formation reference vector of each vessel. Establish the formation pattern for the vessels as that in [25]. Then the formation reference position of each vessel is defined as

$$\mathbf{x}_i = \eta_i(t) + \mathbf{R}(\psi_i(t))\mathbf{l}_{0i}. \tag{8}$$

The formation is achieved if and only if the formation reference positions arrive consensus, that is, $\mathbf{x}_1 = \mathbf{x}_2 = \cdots = \mathbf{x}_n$.

Based on the passivity-based consensus strategy [26], we can assume the dynamics of vessels to be the feedback path of the closed-loop system and define the auxiliary control input for each vessel as

$$\alpha_i = -\sum_{k=1}^{p} b_{ik}\phi_k(\mathbf{z}_k), \tag{9}$$

where $\mathbf{B} = \{b_{ik}\} \in \mathbb{R}^{n\times p}$ is the incidence matrix of the communication topology graph among the vessels one has

$$\mathbf{z}_k \triangleq \sum_{i=1}^{n} b_{ik}\mathbf{x}_i = \begin{cases} \mathbf{x}_i - \mathbf{x}_j, & \text{head of the link } k, \\ \mathbf{x}_j - \mathbf{x}_i, & \text{tail of the link } k, \end{cases} \tag{10}$$

is the synchronization error between vessel i and j which are connected by the kth communication link. $\phi_k(\mathbf{z}_k)$ is $\phi_k(\mathbf{z}_k) = [a_k z_{k1}, a_k z_{k2}, b_k z_{k3}]^T (\mathbf{z}_k = [z_{k1}, z_{k2}, z_{k3}]^T)$.

Suppose $\mathbf{v}_d$ is the desired constant velocity of the formation in the earth-fixed reference frame. If we define the velocity error vector in the earth-fixed reference frame as $\xi_i = \dot{\mathbf{x}}_i - \mathbf{v}_d$ and $\mathbf{f}_i$ as $\mathbf{f}_i = \mathbf{R}(\psi_i(t))\mathbf{l}_{0i}$. Then the formation control algorithm for each vessel is designed as

$$\tau_i = (\mathbf{C}_i + \mathbf{D}_i)(\mathbf{v}_d - \dot{\mathbf{f}}_i) - \mathbf{M}_i\ddot{\mathbf{f}}_i - \mathbf{K}_{di}\xi_i + \alpha_i, \tag{11}$$

where $\mathbf{K}_{di} = \mathbf{K}_{di}^T > 0$ is a positive constant matrix.

Taking the control law (11) into the vessel model (3) can obtain that

$$\mathbf{M}_i\dot{\xi}_i = -\mathbf{C}_i\xi_i + (\mathbf{D}_i + \mathbf{K}_{di})\xi_i + \alpha_i. \tag{12}$$

Define the storage function as

$$V_b(\xi) = \sum_{i=1}^{n} \frac{1}{2}\xi_i^T\mathbf{M}_i\xi_i. \tag{13}$$

then we can obtain

$$\begin{aligned} \dot{V}_b(\xi) &= \sum_{i=1}^{n} \frac{1}{2}\xi_i^T\dot{\mathbf{M}}_i\xi_i + \xi_i^T\mathbf{M}_i\dot{\xi}_i \\ &= \sum_{i=1}^{n} \xi_i^T\left(\frac{1}{2}\dot{\mathbf{M}}_i - \mathbf{C}_i\right)\xi_i - \xi_i^T(\mathbf{D}_i + \mathbf{K}_{di})\xi_i + \xi_i^T\alpha_i \\ &\le -\sum_{i=1}^{n}\left(\xi_i^T\mathbf{K}_{di}\xi_i + \xi_i^T\alpha_i\right). \end{aligned} \tag{14}$$

From the above inequality, we can conclude that the feedback path of the closed-loop system is passive. According to Theorem 1 in literature [26], the feedforward path of the closed-loop system is passive; then we can prove that the closed-loop system is uniformly globally asymptotically stable.

3.1.2. Coordinated Path following Controller. When designing the coordinated path following controller, a virtual vessel labeled 0 is introduced as a leader to obtain a command velocity that drives the vessels move along the path. The coordination controller is designed using the above passivity-based strategy.

Define the formation reference vector of the leader vessel as $\mathbf{l}_{00} = 0$. The same as before, the auxiliary control inputs should achieve $\mathbf{x}_0 = \mathbf{x}_1 = \cdots = \mathbf{x}_n$. The desired command velocity $\mathbf{v}_d$ will be achieved by designing the path following controller for the leader vessel. Suppose the desired path of leader vessel is chosen as $\eta_d(\theta) = [n_d(\theta) \quad e_d(\theta) \quad \psi_d(\theta)]^T$. Then the desired velocity command is

$$\mathbf{v}_d = \mathbf{R}^{-1}(\psi_0)(\dot{\eta}_d(\theta)v_s - \mathbf{\Lambda}\mathbf{p}), \tag{15}$$

where $\mathbf{p} = \eta_0 - \eta_d(\theta(t))$ is the position tracking error vector of the virtual leader, and $\mathbf{\Lambda} = \mathbf{\Lambda}^T > 0$ is the positive constant matrix. v_s is the desired velocity along the path. $\theta(t)$ is the parameter of the appointed path.

Differentiating $\mathbf{v}_d$ gives

$$\begin{aligned} \dot{\mathbf{v}}_d &= \sigma + \dot{\mathbf{v}}_d^\theta\dot{\theta}, \\ \sigma &= -r_0\mathbf{S}\mathbf{v}_d - \mathbf{R}^{-1}(\psi_0)\mathbf{\Lambda}\mathbf{R}\mathbf{v}_0 + \mathbf{R}^{-1}(\psi_0)\dot{\eta}_d(\theta)\dot{v}_s^t, \\ \dot{\mathbf{v}}_d^\theta &= \mathbf{R}^{-1}(\psi_0)\left(-\mathbf{\Lambda}\dot{\eta}_d(\theta) + \ddot{\eta}_d(\theta)v_s + \dot{\eta}_d(\theta)\dot{v}_s^\theta\right), \end{aligned} \tag{16}$$

where

$$\mathbf{S} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{17}$$

and $\dot{\mathbf{v}}_d^\theta = \mathrm{d}\mathbf{v}_d/\mathrm{d}\theta$, $\dot{v}_s^\theta = \mathrm{d}v_s/\mathrm{d}\theta$, $\dot{v}_s^t = \mathrm{d}v_s/\mathrm{d}t$.

And the path parameter is updated through

$$\begin{aligned} \dot{\theta} &= v_s - w, \\ \dot{w} &= -\lambda w - \lambda\mu\left(\mathbf{p}^T\dot{\eta}_d(\theta)\right), \end{aligned} \tag{18}$$

where $\dot{\theta} = u_d/\sqrt{\dot{n}_d(\theta)^2 + \dot{e}_d(\theta)^2}$ and u_d are the desired velocity of the vessel. $w = v_s - \dot{\theta}$ is the velocity error along the path. λ and μ are positive constants.

Then we choose the coordinated path following control law for each vessel as

$$\tau_i = (\mathbf{C}_i + \mathbf{D}_i)(\mathbf{v}_d - \dot{\mathbf{f}}_i) + \mathbf{M}_i(\dot{\mathbf{v}}_d - \ddot{\mathbf{f}}_i) - \mathbf{K}_{di}(\dot{\mathbf{x}}_i - \mathbf{v}_d) + \alpha_i, \tag{19}$$

where $\mathbf{K}_{di} = \mathbf{K}_{di}^T > 0$ is a positive constant matrix.

Similarly to the stability analysis of the formation controller, we can prove the closed-loop system is uniformly globally asymptotically stable.

3.1.3. Transformation from the Formation Controller to the Coordinated Path following Controller. The coordinated path following task is performed by switching between the two controllers designed above. Based on the analysis in [15], we know that the problem can be solved with two different switching methods. One is a hard switching from formation controller to path following controller. The other adds an extra sliding dynamics controller which including the above two controllers. Considering the property of great inertia of surface vessels, hard switching is inapplicable for

coordination maneuver. Thus, we propose an appropriate weighting function which enables slipping from formation controller to coordination path following controller slowly. The weighting function is defined as α, and it should satisfy the following properties:

(i) $\alpha \rightarrow 1$ when the synchronization error vector of formation reference positions between two vessels approaches 0;

(ii) $\alpha \rightarrow 0$ when the synchronization error vector of formation reference positions between two vessels is very large;

(iii) α varies slowly.

Then the weighting function can be chosen as

$$\alpha\left(\mathbf{z}^T\mathbf{L}\mathbf{z}\right) = \exp\left[-2.5(\mathbf{z}^T\mathbf{L}\mathbf{z})\right], \tag{20}$$

where $\mathbf{L} = \mathbf{L}^T > 0$.

We define the formation controller and path following controller for each vessel as ${\tau_i}^1$ and ${\tau_i}^3$, respectively. The transformation from formation to path following is defined as ${\tau_i}^2$. Then we have ${\tau_i}^2 = (1-\alpha){\tau_i}^1 + \alpha{\tau_i}^3$.

3.2. Coordinated Dynamic Positioning Controller. In this section, a coordinated dynamic positioning controller is designed by introducing formation reference point (FRP). The desired position of each vessel is represented by the relative position vector between actual position and FRP. Then the coordinated dynamic positioning controller can be designed using the backstepping method. First, we assign the position of FRP as $\eta_d = [n_d \quad e_d \quad \psi_d]^T$ and the relative position vector as l_i. The desired position of each vessel is

$$\eta_{di} = \eta_d + \mathbf{R}\left(\psi_d\right) l_i. \tag{21}$$

And the positioning error of each vessel is

$$\mathbf{e}_{1i} = \eta_i - \eta_{di}. \tag{22}$$

Differentiating the position error gives that

$$\dot{\mathbf{e}}_{1i} = \mathbf{R}\left(\psi_i\right)\mathbf{v}_i + \dot{\eta}_{di}. \tag{23}$$

If we choose the desired velocity of each vessel as

$$\mathbf{v}_{di} = \mathbf{R}(\psi_i)^T\left(\dot{\eta}_{di} - \mathbf{Q}\mathbf{e}_{1i}\right), \tag{24}$$

where $\mathbf{Q}$ is a positive definite matrix, then the velocity error is

$$\mathbf{e}_{2i} = \mathbf{v}_i - \mathbf{v}_{di}. \tag{25}$$

We choose the distributed coordinated dynamic positioning control law as

$$\tau_i = \mathbf{C}_{vi}\mathbf{v}_i + \mathbf{D}_{vi}\mathbf{v}_i + \mathbf{M}_{vi}\dot{\mathbf{v}}_{di} - \mathbf{K}\mathbf{e}_{2i}, \tag{26}$$

where $\mathbf{K}$ is a positive definite matrix and

$$\dot{\mathbf{v}}_{di} = -r_i\mathbf{S}\mathbf{v}_{di} - \mathbf{R}(\psi_i)^T\left(\ddot{\eta}_{di} - \mathbf{Q}\dot{\mathbf{e}}_{1i}\right). \tag{27}$$

A positive definite Lyapunov function is designed as

$$V_b(\xi) = \sum_{i=1}^{n}\frac{1}{2}\mathbf{e}_{1i}^T\mathbf{e}_{1i} + \sum_{i=1}^{n}\frac{1}{2}\mathbf{e}_{2i}^T\mathbf{M}_{vi}\mathbf{e}_{2i}. \tag{28}$$

Differentiating the above equation yields

$$\begin{aligned}\dot{V}_b(\xi) &= \sum_{i=1}^{n}\mathbf{e}_{1i}^T\dot{\mathbf{e}}_{1i} + \sum_{i=1}^{n}\mathbf{e}_{2i}^T\mathbf{M}_{vi}\dot{\mathbf{e}}_{2i}\\ &= -\sum_{i=1}^{n}\mathbf{e}_{1i}\mathbf{Q}\mathbf{e}_{1i} - \sum_{i=1}^{n}\mathbf{e}_{2i}^T\mathbf{K}\mathbf{e}_{2i}\\ &\le 0.\end{aligned} \tag{29}$$

Let $\mathbf{e}_1 = [\mathbf{e}_{11}^T, \ldots, \mathbf{e}_{1n}^T]^T$ and $\mathbf{e}_2 = [\mathbf{e}_{21}^T, \ldots, \mathbf{e}_{2n}^T]^T$, we can know that the error vector $[\mathbf{e}_1^T, \mathbf{e}_2^T]^T = 0$ is globally asymptotically stable.

3.3. Transformation between the Coordinated Dynamic Positioning Controller and the Coordinated Path following Controller. Considering the great inertia of surface vessels, an appropriate weighting function that enables slipping smoothly between two different controllers is quite desirable. For this need, the weighting function is defined as σ, and it should satisfy the following properties:

(i) $\sigma \rightarrow 1$ when a certain task controller is active in the coordination maneuver;

(ii) $\sigma \rightarrow 0$ when another task controller is active in the coordination maneuver; and the existing controller is suspended.

(iii) σ varies slowly.

Here we can choose the weighting function as

$$\sigma(U) = \exp\left[-(2.5U)^{10}\right], \tag{30}$$

where $U = \sqrt{u^2 + v^2}$ is the vessel speed. u and v are the surge and sway velocity, respectively.

We define the coordinated dynamic positioning controller and coordinated path following controller for each vessel as ${\tau_i}^5$ and ${\tau_i}^3$, respectively. Then the controller for transformation between coordinated dynamic positioning and coordinated path following is

$${\tau_i}^4 = \sigma{\tau_i}^3 + (1-\sigma){\tau_i}^5. \tag{31}$$

3.4. Supervisory Switching Control. Coordination tasks of multiple vessels are often performed by switching between various controllers designed above. In order to ensure the security of coordination operations of vessels in arbitrary initial locations, the supervisory switching control method is employed in the integrated coordination control system where all the controllers are governed by a supervisor. Figure 1 shows the block diagram of the system designed in this paper. In Figure 1, Controller 1 is the formation controller; Controller 3 is the coordinated path following (CPF)

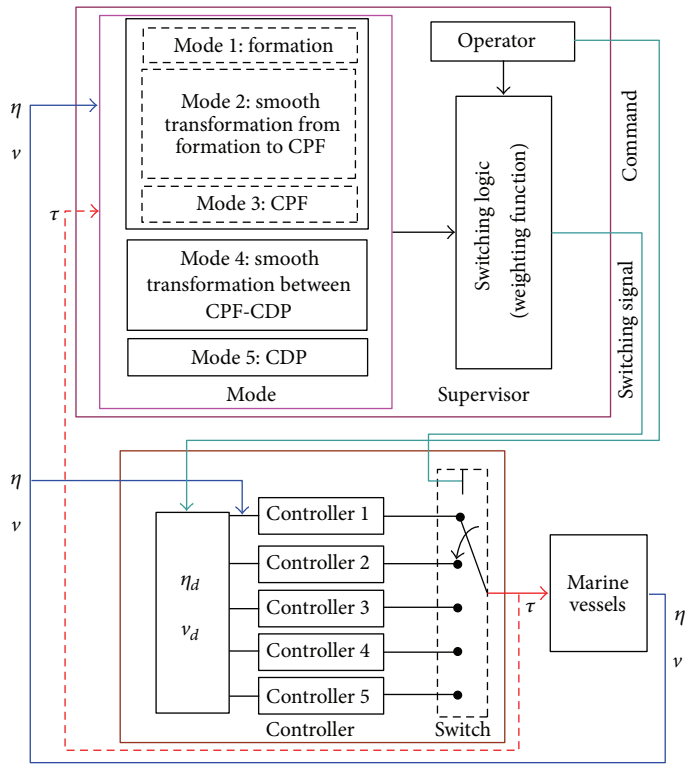

Figure 1: The block diagram of integrated coordination control system.

controller; Controller 2 is the switching controller used to transform from formation to CPF; Controller 5 is the coordinated dynamic positioning (CDP) controller; and Controller 4 is the switching controller used to switch between CPF and CDP. The supervisor decides the actions of all these controllers according to the command from the operator; thereby it determines the current operational mode. The details of stability analysis of supervisory switching control can be found in [21].

4. Simulation Results

In this section, experimental simulations will be carried out to evaluate the effectiveness of the proposed approach. Three marine vessels are considered to perform the coordination tasks. Detailed parameters of these vessels are presented in literature [8]. The experimental process is divided into five stages to cover all the possible coordination modes. The five stages are as follows.

Stage 1. The vessels perform path following while maintaining the desired formation pattern using Controller-1, Controller-2 and Controller-3.

Stage 2. The vessels transform from path following to dynamic positioning using Controller-4.

Stage 3. The vessels realize tracking pause at an appropriate location; that is, the vessels will keep the fixed position and heading while maintaining the desired formation pattern using Controller-5.

Stage 4. The vessels transform from dynamic positioning to path following using Controller-4.

Stage 5. The vessels will continue realize coordinated path following using Controller-3.

For the sake of simplicity, we applied the switching signals based on time scale instead of command velocity from the operator. All the designed controllers mentioned previously were utilized in the simulation.

The initial positions of the three vessels are $\eta_1 = [80 \quad 831 \quad -7\pi/30]^T$, $\eta_2 = [85 \quad 782 \quad -\pi/3]^T$, and $\eta_3 = [75 \quad 753 \quad -\pi/4]^T$, respectively. The desired formation pattern of the coordinated path following is described by $l_{01} = [0 \quad 80 \quad 0]^T$, $l_{02} = [0 \quad 0 \quad 0]^T$, and $l_{03} = [0 \quad -80 \quad 0]^T$. The desired path for the formation is chosen as $\eta_d(\theta) = [n_d(\theta) \quad e_d(\theta) \quad \psi_d(\theta)]^T$, and the parameterized forms is $n_d(\theta) = \theta$, $e_d(\theta) = 300\sin(\theta/400)$, and $\psi_d(\theta) = \arctan(\dot{e}_d(\theta)/\dot{n}_d(\theta))$. The incidence matrix of the topology graph for the communication among the three vessels is as

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}. \tag{32}$$

The control parameters of the coordinated path following controller are chosen as $\mathbf{K}_{di} = 10^5 * \mathrm{diag}(6.5, 6.5, 1350)$,

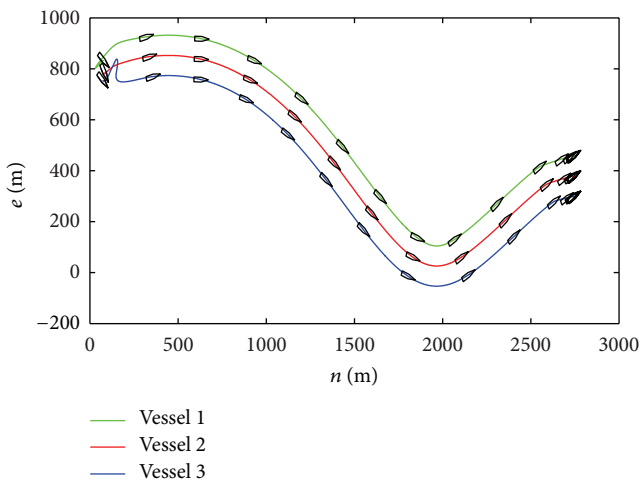

Figure 2: The movement curve of each vessel.

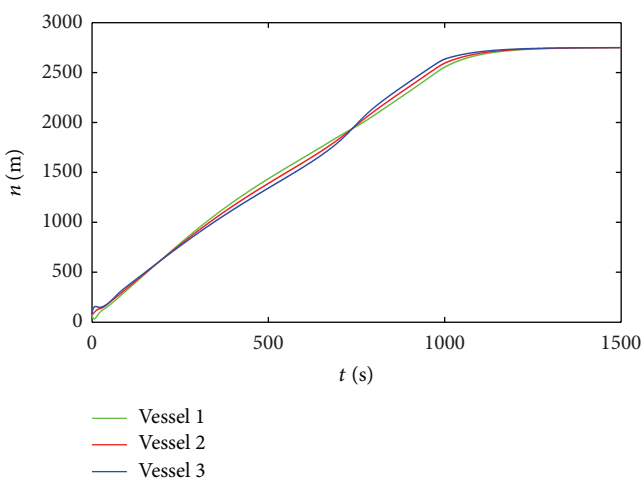

Figure 3: The north position curve of each vessel.

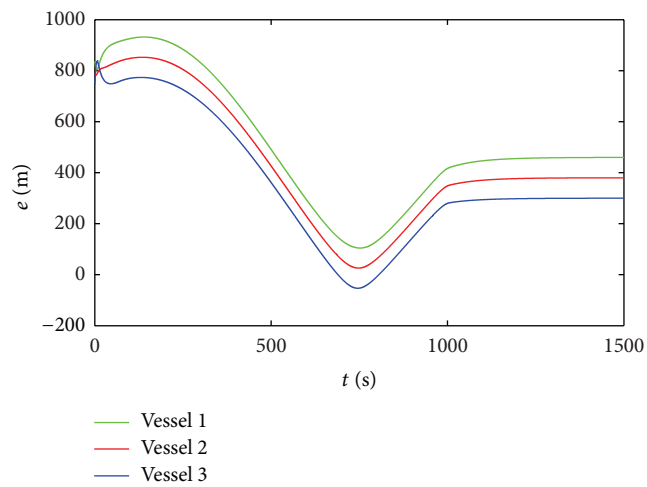

Figure 4: The east position curve of each vessel.

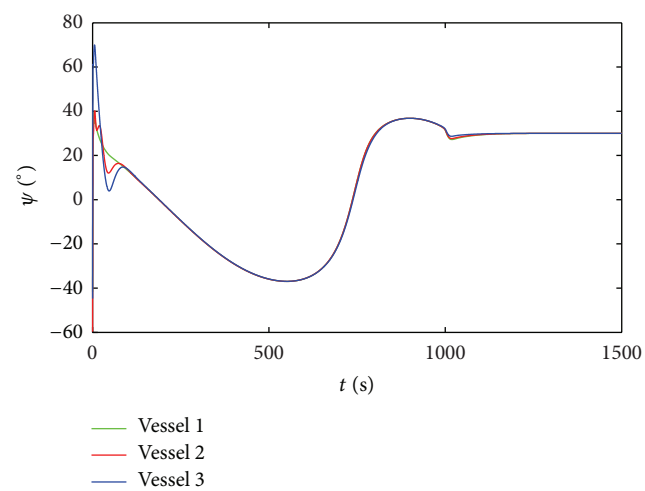

Figure 5: The heading curve of each vessel.

$\mathbf{\Lambda} = \mathrm{diag}(0.001, 0.001, 2.8)$, $a_k = 3000$, $b_k = 6 * 10^5$, $\mathbf{L} = \mathrm{diag}(1, 1, 2500, 1, 1, 2500, 1, 1, 2500)$, $u_d = 3\,\mathrm{m/s}$, and $\lambda = \mu = 20$.

Assume that the switching action from coordinated path following to coordinated dynamic positioning occurs at $t = 1000\,\mathrm{s}$. After implementing the coordinated dynamic positioning task, the desired position of the formation reference point is chosen as $\eta_d = [2750 \quad 380 \quad -\pi/6]^T$. The desired formation pattern of the coordinated dynamic positioning is described by $l_{01} = [0 \quad 80 \quad 0]^T$, $l_{02} = [0 \quad 0 \quad 0]^T$, and $l_{03} = [0 \quad -80 \quad 0]^T$. Then the desired positions of the three vessels are $\eta_{d1} = [2750 \quad 460 \quad -\pi/6]^T$, $\eta_{d2} = [2750 \quad 380 \quad -\pi/6]^T$, and $\eta_{d3} = [2750 \quad 300 \quad -\pi/6]^T$. The control parameters of the coordinated dynamic positioning controller are chosen as $\mathbf{K} = 10^5 * \mathrm{diag}(6.5, 6.5, 6.5)$ and $\mathbf{Q} = \mathrm{diag}(0.01, 0.01, 0.2)$.

The simulation results are shown in Figures 2–7. Figure 2 shows the trajectory of each vessel. Figures 3 and 4 show the north position and the east position of each vessel, respectively. The heading change curve of each vessel is shown in Figure 5. From these figures, we can see that the position and heading of each vessel change smoothly when the operation transforms from coordinated path following to coordinated dynamic positioning.

Figures 6 and 7 show the surge velocity and the sway velocity of each vessel during the switching process, which also change smoothly. In addition, the surge velocity and the sway velocity of each vessel cannot achieve consensus when the vessels move to the inflexion of the path curve. This phenomenon appears due to the vessel speed regulates to maintain the desired formation pattern. After completing the coordinated dynamic positioning task, the speed of each vessel approaches to zero finally. With the analysis of the simulation results, we can conclude that the vessels can accomplish all the coordination tasks considered in this paper with acceptable performance, which means that the proposed coordination control approach is successful and satisfactory.

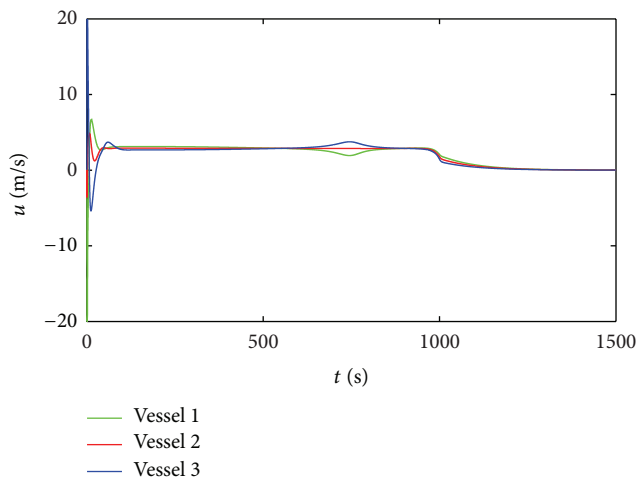

Figure 6: The surge velocity curve of each vessel.

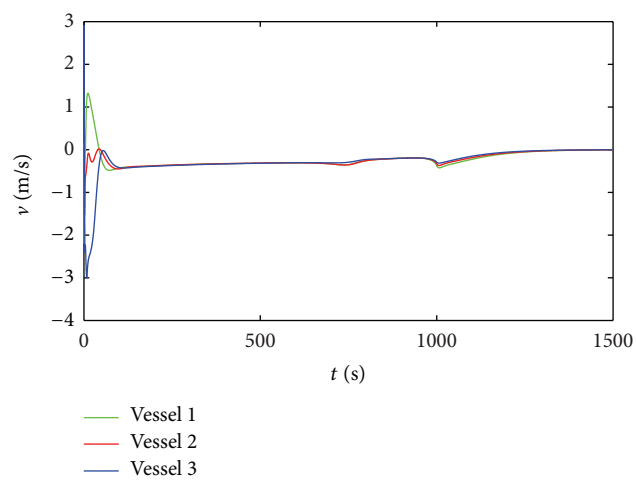

Figure 7: The sway velocity curve of each vessel.

5. Conclusion

This paper has presented a novel coordinated control approach for multiple vessels based on hybrid control theory. Several controllers have been designed for different operational tasks/modes, and an appropriate weighting function is given to switch smoothly between these controllers according to initiated commands. For security purposes, all these controllers are integrated into one control system and governed by a supervisor. Finally, the effectiveness of the proposed coordination control approach is demonstrated by experimental simulations.

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