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Research article

Active disturbance rejection controller design for dynamically positioned vessels based on adaptive hybrid biogeography-based optimization and differential evolution

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ABSTRACT

Vessels with a dynamic positioning system (DPS) are widely applied in ocean resource exploration. Because of the inaccuracy and coupling of the vessel dynamic model, it is important to design a controller that performs well in an oceanic environment. The active disturbance rejection controller (ADRC) is introduced in this study to control the vessel movement and positioning in the DPS. The merit of the ADRC is that it does not need an accurate plant and disturbance model. In the proposed method, an adaptive hybrid biogeography-based optimization (BBO) and differential evolution (DE) are developed. The orthogonal learning (OL) mechanism is employed to achieve adaptive switching to different searching mechanisms between BBO and DE. The proposed adaptive hybrid BBO-DE (AHBBODE) algorithm is then used to optimize the parameters of ADRC; these parameters are not easy to determine by using the trial and error method. Finally, the proposed method is compared with the BBO- and DE-based methods. The results show that better performance is obtained by the proposed method.

1. Introduction

It is well-known that ocean exploration is becoming increasingly important because of the lack of resources from land. Extracting resources such as oil and gas from oceans should rely on special oceanic equipment. A vessel with a dynamic positioning system (DPS) is one type of equipment that is used in ocean exploration. Besides, DPS is also required for special tasks such as pipe laying, offshore wind farm, and offshore supply vessel. The thrusters are installed in such a vessel to keep it steady at a given position and yaw angle or predetermined track for marine operation purposes [1–4]. The thrusters should act in cooperation with each other to achieve the goal. The DPS is a closed-loop control system that mainly consists of a control subsystem, thrust allocation subsystem, propulsion subsystem and position/angle measurement subsystem. Those subsystems form a closed control loop. The DPS controller calculates the total force and moment the ship needs to arrive at the predetermined position according to the error between the actual position and the target from the position measurement system and the external interferences. Then, each thruster receives commands from the thrust allocation module; the commands contain the vectorial force that the thruster needs to produce. Finally, the force and moment from all thrusters make the ship move with a predetermined track or positioning [1–4]. The DPS has the advantages of great flexibility, easy operation and good positional accuracy. In addition, its capability will not be affected by the depth of the ocean or sea. Therefore, it is becoming more widely used.

The control subsystem plays a vital role in the DPS as the same as it is in the ground vehicle [5–8]. Because of the simple structure and obvious physical meaning, a traditional proportional–integral–derivative (PID) controller is generally adopted in the design of a DPS control subsystem. As the control theory has developed, many researchers utilized some relatively new controller design techniques such as back stepping control [9], neural network control [10], adaptive fuzzy technique [11], and dynamic surface control technique [12] to design the DPS controller. However, those methods have the disadvantage of a limited ability to defend external forces and uncertainties in model parameters. In addition, the engineering implementation is not easy. Therefore, Han [13] proposed a new nonlinear controller, namely the active disturbance rejection controller (ADRC), that has been used in many applications. The merits

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of ADRC include avoiding the complex modelling of disturbances and accurate plant model modelling [13].

In recent years, ADRC has also been applied in DPS and its good performance has been shown. For instance, Zhao et al. [14] presented an ADRC controller for a DPS; the effectiveness of the ADRC is verified by simulations. Lei et al. [15] also proposed an ADRC-based controller for vessels with DPS. However, the parameters of ADRC in the DPS are determined by trial and error. It is known that the ADRC's control capability depends on its control parameters to a great extent. Therefore, in our previous work [16], the biogeography-based optimization (BBO) algorithm [17–19] is utilized to adjust the ADRC parameters; its success and effectiveness was demonstrated when it was applied to the high level DPS controller.

In addition to the BBO algorithm, there is also a well-known optimization algorithm, namely Differential Evolution (DE) [20–22]. The hybrid intelligent optimization algorithms have the advantages of avoiding local minimums and speeding up the convergence rate compared with a single intelligent optimization method; therefore, several researchers proposed different hybrid BBO and DE algorithms. For instance, Lohokare et al. [23] proposed a BBOmDE in which the modified DE (mDE) is embedded as a neighborhood search operator to improve the convergence rate; the better performance is validated via several benchmarks. Zengqiang Mi et al. [24] proposed a hybrid BBO (HBBO) for constrained optimization. In HBBO, a modified DE mutation operator is used to generate a promising solution and is still integrated to update one half of the population to further lead the evolution towards the global optimum. The HBBO is verified on benchmark functions and engineering optimization problems. Jain et al. [25] proposed a hybrid BBO /DE in which the algorithm uses a novel hybrid DE with BBO and employs the sinusoidal migration model for strategic bidding. Therefore, DE exploration with BBO exploitation enhances global optimization for the proposed hybrid BBO/DE.

It can be seen from the aforementioned work that the hybrid BBO/DE generally adopts an improved operator either in BBO or DE and then hybridizes the BBO and DE. However, the hybridization introduces several additional parameters to make the hybrid algorithm complicated. In addition, the hybridization can't fully utilize the advantages of both BBO and DE algorithm. In this study, the strategy of adaptively switching to different search mechanisms between BBO and DE is proposed. Therefore, the hybrid algorithm doesn't introduce several additional parameters and the benefits of BBO and DE algorithm can be fully exploited so that the global optimum can be obtained.

Inspired by Zhan et al. [26], an adaptive hybrid algorithm based on BBO and DE (AHBBODE) is proposed based on the orthogonal learning (OL) mechanism. Zhan et al. [26] is an improvement of the single PSO algorithm. In the proposed method, improvement is made by using an orthogonal design for the hybrid BBO/DE algorithm. Then, the proposed AHBBODE is employed to adjust the parameters of the ADRC controller.

The rest of this paper is organized as follows. In Section 2, the vessel mathematical model with DPS is presented as the basis for the following development. In Section 3, the Active Disturbance Rejection Controller is presented. In Section 4, the AHBBODE algorithm is proposed and the procedure of the algorithm is given. In Section 5, comparisons are conducted to verify the feasibility and effectiveness of our proposed method. Our concluding remarks and future work are in the final section.

2. Vessel mathematical model

The DPS mainly consists of position measurement system, control system, thrust allocation (TA) and propulsion system. The structure of a DPS is illustrated in Fig. 1. It can be seen from Fig. 1 that the vessel model is the basic plant for ADRC controller design. Therefore, this section provides a basic explanation of the vessel model. The mathematical model of a vessel with DPS consists of a kinematics model and a dynamic model. They are given in the following sections.

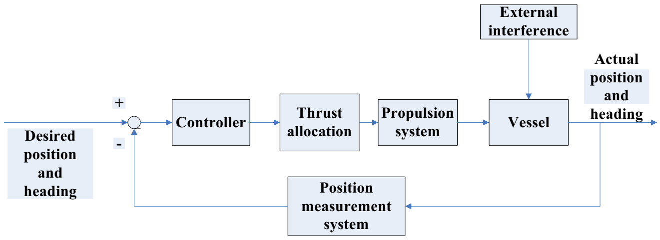

Fig. 1. Block diagram of dynamic positioning system.

2.1. Vessel kinematic model

For a vessel with DPS, it moves on the ocean surface at a relatively low velocity in general. In other words, the roll and pitch motions of the vessel are neither monitored nor compensated. The kinematic model of the vessel can be changed to a relatively simply style by means of limiting it to the planar position and orientation of the vessel.

To establish the vessel mathematical model, two right-hand coordinate frames are firstly defined as given in Fig. 2. $OX_0Y_0Z_0$ is the earth-fixed frame. Any point on the earth's surface can be taken as the origin O. In the earth-fixed frame, the axis OX_0 and OY_0 points to the north and east directions respectively while the axis OZ_0 is directed toward the center of the earth. $AXYZ$ is the body-fixed frame, which is fixed to the vessel. The axis AX points from aft to fore, AY points to starboard, and AZ is directed from top to bottom.

The velocity of the vessel is described in $AXYZ$ coordinate system. The velocity vector ν consists of components u, v, r, that describe the velocity in three directions. The relationship between the position and the velocity of the vessel is purely geometric, and is described as:

$$\dot{\eta} = R(\psi)v \tag{1}$$

where $R(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$, and it can be found that $R(\psi)R^{\mathrm{T}}(\psi) = I$.

$\eta = [x, y, \psi]^T$ is the radius vector of the vessel, and x, y, ψ represent the accurate position and heading angle. $v = [u, v, r]^T$ is the velocity vector of the vessel, and u, v, r represent the speed of the surge, sway and heading motion, respectively.

2.2. Vessel dynamic model

There are several force sources including control force and oceanic environmental forces acting on the vessel. Those forces working together resulting to their vector sum. Several thrusters equipped in the vessel working together lead to the control force. Other forces acting on the vessel include hydrodynamic drag, waves, and wind. The forces created by waves and wind are determined by the oceanic environment.

The velocity and angular rotation speed are expressed in a coordinate frame fixed to the vessel. This coordinate frame may be rotating. For low speeds, a linearization of the hydrodynamic drag is also reasonable. The dynamic mathematic model of a vessel with DPS is as follows:

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