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Collision avoidance strategy optimization based on danger immune algorithm ☆

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ABSTRACT

Marine collision accidents cause a great loss of lives and property. As a possible solution, the danger immune algorithm is used to achieve ship collision avoidance strategy optimization, which is a multi-objective problem concerning safety and economy. Collision avoidance operations are encoded as the individuals of optimization algorithm. In the system, ship domain and ship arena, among others, are used for collision risk evaluation to assess the fitness of individuals. Through the optimization, the navigator will obtain the optimal collision avoidance strategy to achieve safe and efficient collision avoidance. The simulations indicate that the optimization algorithm is valid.

1. Introduction

With the appearance of new types of ships (e.g., large-scale ships), marine traffic environment has become increasingly complicated. Ship collision accidents often cause a great loss of lives and property, thus comprising one major safety concern at sea. Therefore, the issue of providing reasonable navigational information for navigators has been studied all over the world.

In the earlier navigation, ship collision avoidance depends on the experience of navigators. Such navigators evaluate collision risk according to data obtained by navigational equipment and visual watchkeeping. With the development of technology, the Automatic Radar Plotting Aid (ARPA) is widely used in collision avoidance system on most merchant ships (Statheros, Howells, & McDonald-Maier, 2008). Owing to the use of such tools, the decision of ship collision avoidance is progressively becoming more objective (Zeng, 2003). Currently, most of the ships' information can be obtained and displayed in the cab, thus the navigators can evaluate the motions of multiple moving-targets. The advanced data handling and graphic display capability of such equipments enhance the collision avoidance efficiency. Apart from providing a graphical display of the surrounding of the ship, the ARPA can also predict two important parameters values for the selected target ships, namely, distance at closest point of approach (DCPA) and time to closest point of approach (TCPA) (Chin & Debnath, 2009). The navigators can evaluate the validity of a collision avoidance strategy according to these parameters (Liao, 1998). The final decision is given by the navigators; thus, they must exhaust every collision avoidance scheme available in order to determine the optimal collision avoidance strategy from many choices. It is often difficult for navigators to obtain the optimal solution with the characteristics of safe, smooth energy conservation in limited time especially in complex environments. Moreover, it is impractical to determine the optimal collision avoidance strategy manually, and a wrong judgment while performing this intricate process will lead to costly errors. Thus, it is important to develop a collision avoidance supporting system that can prevent some human errors.

With the evolution of new navigation systems, such as global positioning system (GPS), automatic identification system (AIS) (Hsu, Witt, Hooper, et al., 2009; Mou, van der Tak, & Ligteringen, 2010), and other advanced navigation equipment, adopting a heuristic optimization algorithm to find the high efficiency and safe collision avoidance strategy has now become possible (Park, Kim, & Jeong, 2012; Skinner, Yuan, Huang, et al., 2013). The aim of the optimization is to find a reasonable operation to achieve a safe collision avoidance with minimal wastage. On the one hand, the passing distance that must be maintained between the two ships operates on the principle "the bigger, the better" in the collision avoidance process. On the other hand, a good collision avoidance strategy requires the ship to only slightly deviate from the original route especially in narrow waters. This is clearly a multi-objective optimization problem; therefore, many scholars use the heuristic optimization algorithms to achieve collision avoidance

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optimization (Harris, Hong, & Wilson, 1999; Jianmin & Gongbao, 2009; Sandler, Wahl, Zimmermann, et al., 1996; Szlapczynski, 2013; Tam & Bucknall, 2010a; Tam, Bucknall, & Greig, 2009). For example, Szlapczynski used an evolutionary algorithm to search the optimal trajectories set of the ships involved in the encounter (Szlapczynski, 2011, 2013). Smierzchalski and Michalewicz used a genetic algorithm to plan the route of the ship in a static or dynamic environment to avoid obstacles. Tran adopted an expert system to choose the safe route to achieve ship collision avoidance (Tran, 2001), and Cheng used the genetic algorithm to optimize the collision avoidance route in an urban river (Cheng & Liu, 2006a, 2006b, 2008). The safe collision avoidance route selection is considered as a nonlinear problem in these studies. In such a problem, the ship sails along the planning route to achieve safe collision avoidance; moreover, the kinetic characteristics of ships are omitted. Such omission is effective for robots that are more flexible in handling collision avoidance (Gemeinder & Gerke, 2003; Nearchou, 1999; Stafylopatis & Blekas, 1998; Ting, Lei, & Jar, 2002; Xiao, Michalewicz, Zhang, et al., 1997). However, for large modern ships, changing course within a short time and distance is difficult owing to the higher inertia coefficient requirement. Furthermore, they also consume greater energy if there is a frequent course change.

The danger immune algorithm is an immune algorithm inspired by the danger theory (Xu, Wang, & Zhang, 2012), which imitates the biological gene and immunology mechanisms. Compared with other optimization algorithms, the danger immune algorithm is a special immune algorithm that focuses on some important solutions to increase the convergence process. In the algorithm, two special parts are used, danger zone and danger operator. The danger zone is used as the division criteria of interested candidate and inferior solution, and the danger operator is used to operate the inferior solution to improve the performance of this solution. Moreover, it is suitable for solving complex engineering problems. The danger immune algorithm can be used to solve both single- and multi-objective problems, and it is suitable for ship collision avoidance strategy optimization, which is a multi-objective problem. In the optimization, the collision avoidance operation can be encoded as the individual component of the optimization algorithm, which can identify the optimal operation. The system will consider the kinetic characteristics of the ships. In the collision avoidance system, the encounter situation and collision risk can be evaluated according to the ships' information. If the collision avoidance is required, the optimization module will be initiated to obtain the optimal strategy. Then, the navigators can use the optimal strategy to achieve the collision avoidance.

This paper is organized by several sections. Section 2 presents the construction of the ship collision avoidance system and the calculation of ship motion parameters. Section 3 presents the application of the danger immune algorithm in collision avoidance strategy optimization. Section 4 tests the strategy optimization system. Section 5 concludes the paper.

2. The structure of the system and the ship motion model

2.1. Information system

Fig. 1 shows the structure of ship information system. There are several steps to be followed by the ship collision avoidance supporting system in order to complete the ship operation. The first is the gathering of information using navigational equipment (e.g., ARPA, GPS, and AIS etc.). The second step occurs when the ship navigators initiate ship encounter judgment and collision risk evaluation. Finally, the dynamic information display is used to operate the ship.

Fig. 2 shows the flowchart of ship collision avoidance operation. Collision avoidance is implemented according to the encounter situation. The optimization module can be realized between the modules "Danger?" and "Navigator operation?" The safe and economic collision avoidance strategy comes from numerous collision avoidance strategies, which follow the requirement of the International Regulations for Preventing Collisions at Sea (COLREGS) with higher fitness. It is important to accurately obtain and handle GPS information, which can be obtained from other equipment (Tam & Fung, 2011; Wu, Tao, Li, et al., 2013).

2.2. Ship motion model and parameter calculation

The ship motion mathematical model can be experimental and experiential depending on the complexity of the ship itself and the particular environment. A complicated and delicate ship model may contain too many parameters, which are difficult to estimate and analyze. Therefore, the mathematical model of the ship is always an approximate model. In deducing a ship motion model, a number of hypotheses are presented (Xue, Clelland, Lee, et al., 2011) as follows: (1) the ship is a rigid body, (2) the earth reference coordinate frame is an inertia reference, and (3) the power and frequency of the water have no relations of ship motion, that is, the surface of water is just a body wall. The famous two-freedom Nomoto model is the most popular one in the ship movement control system, and is given by

$$T\ddot{\phi} + \dot{\phi} = K\delta. \tag{1}$$

where φ is the yaw angle which is the heading of the ship, and δ is the rudder angle. K is the gain constant and T is the time constant.

The transfer function is given by

$$G_{\phi\delta}(s) = \frac{K}{s(Ts+1)}, \tag{2}$$

where K and T are the constant parameters coming form the velocity V of the ship as Eq. (3).

$$\begin{cases} K = K_0(\frac{V}{V_0}) \\ T = T_0(\frac{V_0}{V}) \end{cases}, \tag{3}$$

where K_0 and T_0 come from the spiral test (Van Amerongen & Udink Ten Cate, 1975).

In this study, we adopt the Nomoto model to simulate the ship. The ship course controller uses a PID controller. The system is always in automatic control mode in normal sailing and achieves a closed-loop control. The manual and automatic control modes can be switched freely. Fig. 3 presents the diagram of the closed-loop control.

Through the Nomoto model, we can simulate the navigational information of ships, including the static and dynamic data. Static parameters contain ship length, breadth, and K T parameter (Eq. (2)). The dynamic parameters contain the velocity of the ship being navigated and that of the target ship, as well as the location and course.

Suppose the location of local ship S_0 is (x_0, y_0), the heading of the ship is φ_0, and the velocity is v_0. The location of the target ship S_T is (x_T, y_T), the heading of the ship is φ_T, and the velocity is v_T. Consequently, in the ship motion simulation system, the ship motion parameters can be calculated as shown below.

(a) The true motion velocity vector of the location ship is given by

$$\begin{cases} v_{x0} = v_0 \cdot \sin(\phi_0) \\ v_{y0} = v_0 \cdot \cos(\phi_0) \end{cases}, \tag{4}$$