Ocean Engineering 169 (2018) 110–124

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A COLREGs-based obstacle avoidance approach for unmanned surface vehicles

Yanlong Wang[a,*], Xuemin Yu[b,**], Xu Liang[a], Baoan Li[a]

[a] School of Automation Science and Electrical Engineering, Beihang University, Beijing, China
[b] Institute of Information Engineering, Chinese Academy of Sciences, Beijing, China

ARTICLE INFO

Keywords:
Obstacle avoidance
Unmanned surface vehicle
Local path planning
COLREGs
Normal distribution curve

ABSTRACT

This paper reports the preliminary research results of a novel automatic obstacle avoidance approach based on the COLREGs for unmanned surface vehicles (USVs). The approach presented is essentially a path searching-based algorithm called the local normal distribution-based trajectory, which plans viable avoidance trajectories in the presence of both static and dynamic obstacles. The proposed algorithm can generate a COLREGs-compliant suboptimal trajectory based on the bell-shaped curve of normal distribution and extract waypoints for the navigation controller to steer USVs safely. In addition, we discuss three key parameters and present a trajectory replanning strategy to improve the safety and flexibility of our approach. The common overtaking, crossing and head-on collision scenarios are each simulated in experiments. It is shown through simulations that the proposed approach considers multiple factors and can plan paths to avoid obstacles safely and smoothly. A comparison is also made with a reactive path planning algorithm which has been modified to follow the COLREGs.

1. Introduction

Unmanned surface vehicles (USVs) are autonomous marine vessels that can execute multiple tasks in a variety of cluttered marine environments without human supervision (Manley, 2008; Tang et al., 2015). USVs are characterized by small size, high mobility and good hiding capability; they can be used in many marine applications, including oceanography, remote sensing, environmental monitoring, surveying, weapons delivery, mapping and navigation, along with providing communication support for unmanned underwater vehicles and general robotics research (Naeem et al., 2012; Tang et al., 2015; Wang et al., 2018).

Technological development is driving USVs towards “persistent existence”. The future progress of USVs depends on the development of full autonomy, which would enable USVs to work in any unstructured or unpredictable environment without human intervention (Liu et al., 2016). One of the main challenges in enhancing USV autonomy is the simultaneous detection and avoidance of obstacles in either open or confined waters (Campbell et al., 2014). To overcome the obstacle avoidance challenge, hierarchical strategy-based obstacle avoidance approaches, composed of global path planning algorithms and local obstacle avoidance algorithms, have been proposed for USVs (Tang et al., 2015).

Global path planning for USVs is mainly designed to find the optimal global path to avoid static obstacles in a mapped environment. Global path planning can be conducted offline via common path finding heuristic algorithms such as A*, optimization theory such as linear programming, and evolutionary algorithms such as genetic algorithm. Wang et al. (2017) presented a novel path search algorithm for global path planning based on electronic charts and improved A* algorithm. This algorithm can generate safe and reasonable global path for USVs quickly. Kim et al. (2014) proposed a new approach based on Theta* algorithm to create paths in real-time, considering both angular rate and heading angle of USVs. Zhuang et al. (2011) presented a global path search algorithm for USVs based on improved Dijkstra algorithm, where planning time is reduced, and planning precision is improved. Wang et al. (2018) presented a global path search algorithm among multiple task points based on an improved A* algorithm, ant colony optimization and hexagonal grids, which can plan an optimal path to tour multiple task points safely and quickly.

Local obstacle avoidance for USVs is used to avoid static and dynamic obstacles by adopting a timely avoidance manoeuvre in which line-of-sight (LOS) and artificial potential field are widely employed (Campbell et al., 2012). Local obstacle avoidance algorithms are of two types: path searching-based local path planning, which can generate appropriate trajectories or waypoints followed by the vehicle, and the

* Corresponding author.
** Corresponding author.
E-mail addresses: wylloong@163.com (Y. Wang), yuxuemin@iie.ac.cn (X. Yu).

https://doi.org/10.1016/j.oceaneng.2018.09.012
Received 9 February 2018; Received in revised form 8 July 2018; Accepted 5 September 2018
0029-8018/

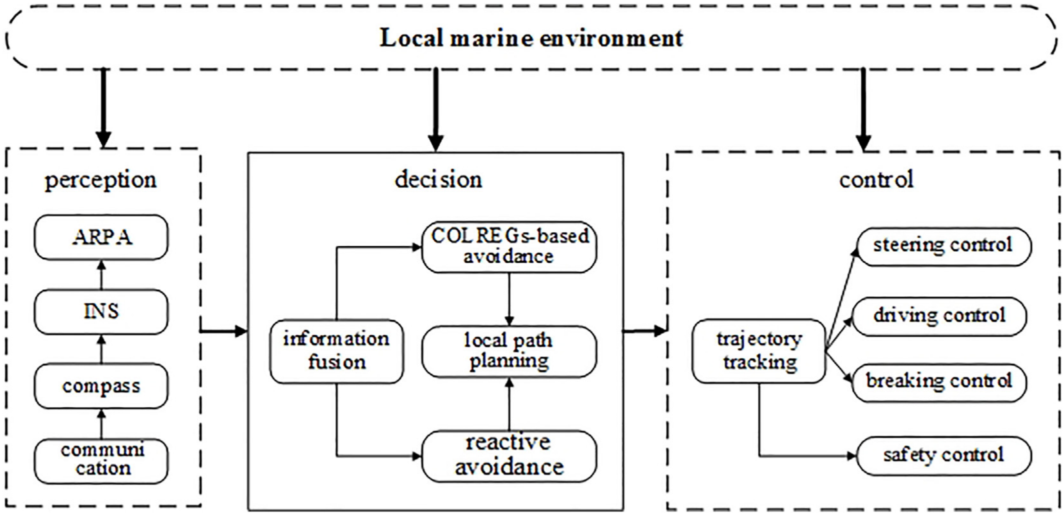

Fig. 1. The architecture diagram of obstacle avoidance.

behaviour-based reactive obstacle avoidance method, which can generate the guidance angle and guidance velocity realized by the navigation controller in real time.

Many researchers make efforts to address the local obstacle avoidance problem over the years. Tang et al. (2012) proposed a near-field reactive static obstacle avoidance method for USVs based on a dynamic window, and the excellent navigation angle, rotational velocity, and translational velocity can be gotten by solving the constraint problem of static obstacles. Zhuang et al. (2013) designed a reactive obstacle avoidance method based on the relative velocity modelling, where the obstacle avoidance of USVs is completed by changing speed and course. Tang et al. (2015) presented a novel general local reactive obstacle avoidance algorithm for high-speed USVs, which is verified by experiments in simulations and sea trials in real marine environments, and the motion of USVs depends on the guidance angle and guidance translational velocity during navigation. Kuwata et al. (2011) put forward a meritorious motion planning approach for USVs in which the Velocity Obstacles (VO) algorithm is adopted to generate a collision-free path while obeying the COLREGS rules. Naeem et al. (2012) adopted a strategy consisting of waypoint guidance by LOS coupled with a manual biasing scheme under COLREGs, and this algorithm is able to generate a non-optimal viable trajectory in the presence of both stationary and dynamic obstacles.

Although many novel algorithms for better real-time implementation of obstacle avoidance in a cluttered environment have been proposed over the years, the local obstacle avoidance problem still limits the wide application of USVs. For example, there are still drawbacks associated with LOS and artificial potential field methods, such as the potential to overshoot and a lack of consideration of the next manoeuvre. Additionally, USVs must behave in a manner that is discernible by other vessels in the vicinity, so the obstacle avoidance approach should integrate marine traffic rules. However, only a few studies have successfully integrated those rules into the obstacle avoidance process, and few obstacle avoidance approaches can simultaneously avoid both static and dynamic obstacles.

Based on the premise that the existing literature does not sufficiently address obstacle avoidance problems and that much effort is still required to optimize these obstacle avoidance approaches, a novel path searching-based algorithm called the local normal distribution-based trajectory (LNDT) is proposed in this paper to address the local obstacle avoidance problem of USVs in complicated encounter situations. This algorithm can generate a suboptimal collision-free path and determine a real-time collision avoidance manoeuvre based on a set of waypoints. The avoidance manoeuvre in the LNDT algorithm includes diverting around static geographical obstacles and avoiding collision with approaching vessels, in compliance with the COLREGs.

The overall scheme of obstacle avoidance is illustrated in Fig. 1. The decision-making module in the dashed frame includes a two-layered distributed architecture of obstacle avoidance; we primarily study the COLREGs-based obstacle avoidance approach.

The remainder of this paper is organized as follows: the next section describes the basic collision avoidance design of USVs. Section 3 presents the LNDT algorithm in detail. Section 4 presents the algorithm flow of the LNDT. Section 5 verifies the algorithm on a local obstacle avoidance simulation platform. Finally, the conclusion and future work are discussed in section 6.

2. Basic obstacle avoidance design

The primary need with regard to obstacle avoidance is increasing autonomy in terms of obstacle detection and appropriate avoidance manoeuvres with minimal or no supervision from a human operator. The obstacle avoidance approach we propose is able to assess collision situations and avoid obstacles automatically by generating trajectories for USVs to minimize their dependency on human intervention, which is a vital element for a fully autonomous surface vehicle.

2.1. COLREGs-based obstacle avoidance rules

Given that there cannot be any verbal communication between the two vessels when a USV takes evasive manoeuvres to avoid an approaching vessel, the USV must take obstacle avoidance measures that are discernible by other vessels in the vicinity. Furthermore, recent statistics show that 60% of casualties at sea are caused by collisions and that 56% of collisions are caused by COLREGs violations (Liu et al., 2016; Campbell et al., 2014). Hence it is necessary for both USV and manned vessels to abide by some pre-defined rules in the course of obstacle avoidance.

The international regulations for preventing collisions at sea (COLREGs), defined by the International Maritime Organization (IMO) in 1972, is designed to maintain a high level of safety at sea. It defines universal and definitive guides for executing standard avoidance manoeuvres, and applies to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels (IMO, 1972).

COLREGs are designed to be followed by navigators while operating all types of vessels or watercrafts. Although there is no relevant maritime navigation laws or regulations for USVs, COLREGs rules must be obeyed if USVs sail at sea lawfully. Otherwise, unpredictable or