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A real-time collision avoidance learning system for Unmanned Surface Vessels

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ABSTRACT

A great amount of effort has been devoted to the study on Unmanned Surface Vehicles (USV) due to an increasing demand for their use in a variety of maritime applications. Real-time autonomous collision avoidance system is the pivotal issue here, in which reliable collision risk detection and the adoption of a plausible collision avoidance maneuver play a key role. Existing studies on this subject seldom integrate the COLREGS guidelines, however, and in order to ensure maritime safety, it is of fundamental importance that they should be obeyed at all times. In this paper, we presented an approach to real-time collision avoidance that complies with the COLREGS rules for USV. The Evidential Reasoning (ER) theory is employed to evaluate the collision risks with obstacles encountered and trigger a prompt warning of a potential collision. Then, we extend and adopt the optimal reciprocal collision avoidance (ORCA) algorithm so as to determine a collision avoidance maneuver that is COLREGS compliant. The proposed approach takes into consideration the fact that other obstacles also sense their surroundings and react accordingly, conforming to a practical marine situation when making a decision concerning collision-free motion. A number of simulations have been conducted in order to confirm the validity of the theoretic results obtained.

1. Introduction

USVs are powerful instruments used in a wide variety of maritime missions in civil, military or research applications including oceanography, remote sensing, weapons delivery, force multipliers, environmental monitoring, surveying, anti-submarine warfare, surface warfare, electronic warfare and maritime interdiction operations support, as illustrated in studies [1–4]. All of the missions listed above require safe navigation in open waters. The main challenges relating to this issue include reliable obstacle detection and effective collision avoidance [5]. Unfortunately, relevant research has focused to date predominantly on advanced control system design, for example, [6–8] and with little attention being paid to the field of collision avoidance as illustrated in [9]. The usability and expansibility of USVs are severely constrained in consequence. So as to take full advantage of USVs, an emphasis on obstacle detection and avoidance (ODA) is of paramount importance.

Collision risk assessment is the foundation behind an ODA system. Mou [10] pointed out that the timely and prompt alert of an impending collision is crucial so that a collision can be avoided, thus ensuring maritime safety and a reduction in potential casualties. Collision risk incidence (CRI), in which the probability of a collision with other vessels is evaluated, has three significant characteristics, namely ambiguity, uncertainty and instantaneity. The value of CRI is affected by various factors, among which key elements with a significant impact on CRI are Distance to Closest Point of Approach (DCPA), Time to Closest Point of Approach (TCPA), the distance from the threatening vessel (D), the Relative Bearing (B) and the ratio of speed (K) according to existing literature [11]. The weight method, based on DCPA and TCPA, was adopted early on by Kearon [12] and Imazu [13] in order to estimate the risk of collision. The weight method only takes into account the extent of DCPA and TCPA to obtain the risk. The units of the two factors are in fact inconsistent so that the estimated result is imprecise. With the rapid development of neural networks refer to [14–16], some new approaches in terms of CRI assessment based on neural networks, have been developed, the relevant work can be found in [17,18]. Due to the drawbacks of these neural networks, such as poor generalization ability and the ease with which it falls within a local optimal solution, this

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method is of limited use in practical marine navigation. The research conducted by [19] reveal that fuzzy theory is acknowledged to be the most reasonable approach for the evaluation of CRI, and there has been a successful body of research concerning this particular approach. There are, nevertheless, still some drawbacks restricting the widespread application of this approach owing to the fact that precise membership functions are difficult to establish, with the assessment of CRI being extremely sensitive to this type of function. Different assessments may thus be inferred owing to the disparity of membership functions.

This paper proposes a CRI assessment approach based on the ER theory and aims to provide an accurate estimation of the risk of collision. The ER theory is an analytic approach which can deal with the multiple attribute decision problem, it was first presented by Dempster [20] and subsequently extended by Shafer [21], has extensive applications in many areas. The ER theory has a well-established theoretical foundation and is able both to deal with uncertain information and to take full advantage of multisource information to obtain an accurate estimation. It has moreover been proved by Srivastava [22] that the ER theory is able to achieve fast convergence without a priori probability and conditional probability. Compared with fuzzy theory or neural networks, the ER theory is believed to represent a convincing and reliable algorithm for the evaluation of CRI in consequence of its outstanding performance in terms of dealing with indeterminate and real-time information.

After confirming a potential conflict, the next step is to adopt a timely avoidance maneuver. Previous studies have attempted to resolve this issue; Svec [23], for instance, employed a nominal trajectory planner to generate a collision free trajectory between the current state of a USV and its motion goal and, in the work of Soltan [24], ordinary differential equations were used to define transitional trajectories able to avoid obstacles. Phanthong [25], meanwhile, adopted a numerical solution procedure based on an A* algorithm to compute near-optimal paths; he then used a robust real-time path re-planning technique to avoid moving obstacles. Nevertheless, these studies focused solely on the computation of a collision-free path without respecting CORLEGS compliancy. However, as Statheros et al. [26] report, 56% of all collisions at sea involve a violation of the COLREGS rules. In consequence, it is important for USV to maintain a strict adherence to the COLREGS at all times.

There are a few studies that successfully integrate the COLREGS rules into collision avoidance techniques for USVs. One significant study can be found in the work undertaken by Benjamin [27], who applied Interval Programming in a behavior-based control framework to represent the navigation rules for safe navigation. Tam et al. [28] proposed a deterministic path planning algorithm able to compute a practical and COLREGS compliant navigation path so that output consistency can be maintained. An automatic obstacle avoidance system for USV emerged in relevant literature [9], in which the R-RA* method was developed for path re-planning when a ship is confronted with multiple approaching vessels. The proposed R-RA* algorithm is able to incorporate the necessary COLREGS rules. Similarly, Naeem et al. [1] established a collision avoidance strategy that consists of a real-time path-planning scheme using the biased line-of-sight method and an offline trajectory generation with a DPSS algorithm able to produce COLREGS-compliant paths. Breitsprecher [29] posited a decision rule induction algorithm in order to build a COLREGS knowledge database and implement it to form an expert decision support system. A framework for a decision-action execution model was introduced by Perera in [19] to facilitate intelligent collision avoidance while respecting the COLREGS rules, in which the Fuzzy-Bayesian-based decision/action formulation process was used to avoid a situation in which a complex collision occurred. The author also presented a fuzzy logic-based intelligent decision making system to improve the safety of marine vessels. In this study, the intelligent decision making rules were formulated in accordance with the COLREGS guidelines to avoid collisions [30]. However, most of the previous methods in which the COLREGS rules are taken into account have failed to handle situations in which there is congestion, with the kinematical constraints of USV being ignored. Kuwata et al. [31] put forward a meritorious approach to motion planning in which the Velocity Obstacles (VO) algorithm [32] was adopted to generate a collision-free path while obeying the COLREGS rules. This approach has the advantage of guaranteeing the safe navigation of USV in cluttered environments. However, this approach, based as it is on the assumption that the vessels encountered are passive — in other words, the reactive actions of the encountered vessels are neglected — while, in fact, in an actual marine situation, the encountered vessels also sense their ambience and change their trajectories accordingly. As a consequence, the path generated by this approach may in fact be unreliable.

Inspired by the approach proposed by Kuwata et al., in which the issue of generating a collision-free path while incorporating the COLREGS rules and simultaneously taking into consideration the reactive action of encountered vessels is taken into account, this paper presents a real-time collision avoidance strategy based on a generalized ORCA algorithm [33]. The ORCA algorithm is the extensional formulation of the VO concept. The VO algorithm was first proposed by Fiorini in 1998 and has been successfully used for a variety of applications in order to avoid collisions with moving obstacles, with several modified approaches based on VO being presented in [34–36]. Among these formulations, one significant method is the RVO [34], which can ensure both collision-free and oscillation-free navigation. Furthermore, it takes into account the reactive behavior of the obstacles. Consequently, it is an appropriate method for handling the problem of reactive collision avoidance. This method can, however, only guarantee collision-free navigation under specific conditions. To overcome this limitation Berg et al. [33] defined ORCA to provide a condition appropriate for multiple robots, and which is adopted and extended in this paper in order to achieve reactive collision avoidance.

In this paper, we intend to develop a real-time autonomous collision detection and avoidance learning system that complies with the COLREGs rules for USV. Firstly, the ER theory is adopted to provide an efficient CRI assessment, in which the weights of the elements corresponding to the value of CRI are assigned through the Analytic Hierarchy Process (AHP) method. The ORCA algorithm is then extended to determine a collision avoidance maneuver at the same time as respecting the COLREGs rules. The rest of paper is organized as follows. Section 2 clarifies the problem this paper intends to solve as well as outlining the general procedure for the approach adopted. In Section 3, the CRI assessment approach is explained specifically. A detailed process for the implementation of the COLREGs compliant collision avoidance method is presented in Section 4. Simulated traffic situations are illustrated followed by a discussion and analysis in Section 5 in order to verify the validity of the proposed approach. The paper is finally concluded with suggestions for further avenues of research related to the approach adopted here.

2. Problem statement and general procedure

2.1. Problem statement

The problem considered in this paper is as follows:

The navigation information of the target ships surrounding the USV and constituting a threat of potential collision is treated first