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A Reactive COLREGs-Compliant Navigation Strategy for Autonomous Maritime Navigation

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Abstract: This paper reports the development of an automatic collision avoidance technique for unmanned marine vessel incorporating standard collision regulations or COLREGs, defined by the International Maritime Organisation. Like any ship, all unmanned vessels must adhere to COLREGs at all times in order to minimise or eliminate the risk of collisions. The proposed approach is essentially a reactive path planning algorithm based on a modified well known Artificial Potential Fields (APF) framework. It is shown through simulations that the proposed strategy is able to generate COLREGs-compliant trajectories in the presence of both stationary and dynamic obstacles. Rules 13, 14 and 15 of the COLREGs, which apply to the overtaking, head-on and crossing scenarios respectively, are simulated for multiple dynamic vessels in an environment inclusive of land features.

Keywords: Artificial Potential Fields, COLREGs, Unmanned Surface Vehicles, Autonomous, Navigation, Path Planning.

1. INTRODUCTION

There has been a growing interest in the use and application of unmanned marine vehicles (UMVs). UMVs are generally classified into underwater and surface vehicles with underwater vehicles currently taking the lion's share of the market because of their range of applications including subsea pipeline/infrastructure surveying and inspection, search and rescue to name a few. Unmanned surface vehicles (USVs) have also gained a widespread interest for applications ranging from oceanography, remote sensing, weapons delivery, force multipliers, environmental monitoring, surveying and mapping, and providing navigation and communication support to underwater vehicles. In particular, the USV industry has seen a widespread surge when in 2012, DARPA released the USV Master Plan which entailed \$3 billion funding for projects involving surface vehicle development for submarine tracking (Doyle, 2011). Currently, DARPA (Defense Advanced Research Project Agency) is carrying out at-sea trials of its brand-new 132-foot-long Autonomous Submarine Hunter vessel[1]. Some of the other worldwide USV programs both in the defence and civil sectors include the *Delfim* USV for mapping applications (Pascoal et. al., 2000) *Autosea* Project for unmanned USV (Loe, 2008) and *Protector* USV (Protector, 2010) for maritime assets protection.

Most of these systems rely on remote operator guidance for sending mission commands and to constantly overlook the vehicle's status either by direct observation or via a wireless video link (Corfield and Young, 2006). This adds to the operating cost of each mission and is not practical for extended periods of time. In order to fully benefit from this technology, a reliable obstacle detection and avoidance (ODA) system is thus mandatory (Caccia, 2006; Corfield and Young, 2006). Besides developing a system that generates evasive manoeuvres to avoid an object, it is important that the USV behaves in a manner that is discernible by other ships in the vicinity. This attribute would aid in integrating the USVs with the surrounding marine traffic. The coastguard regulations on prevention of collision at sea (COLREGs), defined by the International Maritime Organisation (IMO) (Cockcroft and Lameijer, 2003; Commandant, 1999), can usefully be incorporated for this purpose. It should be noted that all manned vessels are required to adhere to these regulations at all times in order to avoid a collision. The DARPA's Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV[2]) has shown to be capable of operating the ship in compliance with maritime laws and conventions for safe navigation.

Here, an Artificial Potential Field (APF) method has been adapted to generate a collision free COLREGs-compliant path for an USV. Whilst the principle of using potential energy fields remains consistent with the original works of Khatib (1986), significant adaptation is required for automatic implementation in any arbitrary encounter scenario, rather than those predetermined.

APFs have been investigated, under limited circumstances previously for COLREGs avoidance for USVs (Lee et. al. 2004; Xue et. al, 2009) due to their potential suitability and characteristic merits. However, no additional significant

[1] http://www.engadget.com/2016/04/08/darpa-christens-actuv-sea-hunter/

[2] http://www.darpa.mil/news-events/2016-04-07

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related research has been identified, thus there are still opportunities to shape and develop this method. The well-known limitations of APFs mainly pertaining to a need for more robust exceptions handling, addressing the local minima issues and a need for more complex encounter scenarios will also be considered.

The structure of the paper is as follows. Section 2 outlines the background and motivation of the research including a summary of the IMO collision regulations. In Section 3, the APF algorithm fundamentals are presented along with the proposed adaptation to this well-known reactive path planning technique. The method of defining COLREGs zones within the APF framework and gain tuning is also provided in Section 3. Simulation results are presented in Section 4 followed by concluding remarks in Section 5.

2. MOTIVATION AND BACKGROUND

Statistics have shown that 60% of casualties at sea are caused by collisions (Jingsong and Wilson, 2008). Furthermore, it is reported in Statheros et al. (2008) that 56% of collisions at sea include violation of COLREGs with the majority occurring due to human error. The infamous Titanic tragedy was in fact as a result of the unwillingness of the crew to change the speed of the vessel (Lord, 1955) as required by the rules of obstacle encounter at that time. Although these studies are compiled for manned ships, unmanned vessels without any form of onboard intelligence could even be more vulnerable. For this very reason, there is an ongoing legal debate about providing cover for these types of vessels. A review of related research has revealed that very few USVs are equipped with an onboard collision avoidance system. In addition, only a handful of research programmes have considered developing COLREGs-based navigation systems. In one instance, Benjamin and others at MIT (Benjamin and Curcio, 2004; Benjamin *et. al.* 2006) have investigated COLREGs-based navigation using a multi-objective optimisation and interval programming to generate a behaviour-based control algorithm. The proposed strategy was implemented on two kayak-based SCOUT vehicles each with the capability to communicate its position to the other. The Space and Naval Warfare Systems Center in San Diego (SSC San Diego) have developed an ODA system which provides optimal trajectories based on the COLREGs. The distance to the object is measured using an onboard camera system mounted on a SEADOO Challenger 2000 sport boat (Larson *et. al.* 2006; Larson *et. al.* 2007). Another collision avoidance method using fuzzy logic with reference to COLREGs is devised for vessel traffic service (VTS) (Kao, 2007), however, no experimental results have been reported. A simulation study of COLREGs-based automatic collision avoidance for manned vessels at the Universities of Glasgow and Strathclyde (Xue et. al., 2009) employed an artificial potential field and a speed vector for trajectory planning and collision avoidance. Results were presented to demonstrate path planning for various obstacle encounter scenarios. More recently, Kuwata *et.al.* (2014) from the Jet Propulsion Lab proposed a velocity obstacle method to generate COLREGs-compliant trajectories. A series of on-water experiments involving up to four vessels has been conducted implementing three fundamental COLREGs rules (crossing, overtaking and head-on). These are further described in the following.

2.1 The International Regulations for Avoiding Collisions at Sea

COLREGs were set out in 1972 by the IMO as a set of guidelines for vessel encounters at sea. It is expected that all vessel operators comply with these regulations, which outline procedures for determining right of way and correct avoidance manoeuvres. Thus, if intelligent autonomous marine vessels can operate in accordance with these guidelines, many traffic-related accidents at sea caused by human error could be avoided.

Without a human operator or crew physically present onboard the vessel, the rules must still be obeyed if an unmanned ship is to be lawfully operational at sea. Otherwise unpredictable or incorrect actions may lead to confusion and potentially catastrophic collisions amongst other marine traffic. In the case of remotely operated vessels, the operator shall implement all manoeuvring decisions. Conversely, an autonomous vessel should have the ability to make these same decisions based largely on sensor information. The regulations are comprised of three main sections:

- General (Part A): Outlining the applicability and responsibilities of the regulations.
- Steering and Sailing Rules (Part B): Part B consists of two sections, where Section I refers to the conduct of vessels in any visibility conditions and Section II regards the conduct of vessels in sight of one another.
- Lights and Shapes (Part C): Covers protocols for issuing indicating, warning or distress signals etc. and safe guidelines for the use of lighting.

Although rules from all sections are applicable, the Steering and Sailing Rules in particular, of vessels in sight of one another present perhaps the greatest challenge in achieving full autonomy. The fundamental rules/practices for ships in sight of one another are defined as follows.

Rule 13 - Overtaking: Any vessel overtaking any other shall keep out of the way of the vessel being overtaken.

Rule 14 - Head-on Situation: When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other.

Rule 15 - Crossing Situation: When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

3. APF FUNDAMENTAL THEORY AND ADAPTATION

In this section, the foundations and basic concept of APFs will be provided first to provide a basis of understanding, which enables the reader to follow the development of the APF COLREGs path planner. Unlike grid-based heuristics