COLLISION DETECTION AND COLLISION AVOIDANCE FOR UNMANNED SURFACE VESSELS

LIM Lian Nang, BAY Zi Jing, TAN Shu Jun

ABSTRACT

DSTA, together with Future Systems and Technology Directorate has progressively built up the component technologies to enable the operation of Unmanned Surface Vessels (USV) since the early 2000s. In view of the heavy maritime traffic in our waters, DSTA developed an advanced autonomous navigation capability that is equipped with a Collision Detection and Collision Avoidance (CDCA) algorithm to ensure safe navigation. The CDCA algorithm designed by DSO National Laboratories will allow the USV to be fully autonomous, replacing human operators in dangerous missions such as Mine Countermeasures and achieving manpower savings. This article presents the design of the CDCA algorithm, challenges in integration and validation, and spin-off applications.

Keywords: unmanned surface vessels, collision avoidance, autonomous

INTRODUCTION

In maritime security operations, defending the Sea Lines of Communications is vital to the well-being of Singapore's economy. This is especially so as maritime threats such as terrorist attacks and piracy are becoming increasingly widespread. The development of a fully autonomous Unmanned Surface Vessel (USV) would potentially allow dangerous missions to be carried out more quickly, effectively, safely and with reduced manpower.

When a USV navigates at sea, one of the greatest safety issues is the risk of collision. This is an especially challenging problem to tackle, given the high traffic density in the Singapore Strait. To overcome this, an on-board Collision Detection and Collision Avoidance (CDCA) algorithm is required. Since 2008, DSTA, together with Future Systems and Technology Directorate, has been engaging DSO National Laboratories (DSO) to develop and validate its CDCA algorithm tailored for the Republic of Singapore Navy's unique operations in the Singapore Strait (SS). The CDCA algorithm allows the USV to predict possible collisions with surrounding vessels and generate an avoidance command that abides to the guidelines of the International Maritime Organisation (IMO) International Regulations for Preventing Collisions at Sea (COLREGs) without the need for human intervention. In 2013, the CDCA algorithm has been successfully demonstrated by DSO under a Research and Technology project. Since then, the CDCA algorithm has been implemented on-board the Mine Countermeasures (MCM) USV.

CDCA ALGORITHM OVERVIEW AND DESIGN

The design of the CDCA algorithm leverages existing collision detection equipment used in manned maritime navigation. These include navigation charts to provide landmass information, the Maritime Automatic Identification System and Automatic Radar Plotting Aid to provide information and active sensing of static and dynamic obstacles in the environment, as well as the Differential Global Positioning System (DGPS) and heading sensors to provide the ownship position and orientation. Based on information on the USV and its surrounding vessels, the CDCA algorithm will predict possible collisions and generate avoidance manoeuvres to ensure safe navigation.

Prior to the design of the CDCA algorithm, comprehensive literature review was conducted and specific challenges were identified.

Literature Review: Deliberative vs Reactive Approaches for Obstacle Avoidance

There are two main approaches in designing collision avoidance algorithms. The first approach is a deliberative obstacle avoidance approach (Naeem, Irwin, & Yang, 2012; Pivtoraiko, Knepper, & Kelly, 2009), which involves path planning to avoid obstacles, taking into consideration the original user-defined route or end point (Larson, Bruch, Halterman, Rogers, & Webster, 2007). The ability to generate a global optimal path makes the path planning approach suitable for navigation in cluttered environments. However, using this approach to avoid both static and dynamic obstacles with bounded velocity is a Non-deterministic Polynomial-time hard (NP-hard) problem (Canny & Reif, 1987), which means that it is computationally expensive, especially when the environment becomes complex. The slow replanning rate hence limits the vessel's navigation speed. Moreover, deliberative obstacle avoidance would not guarantee collision-free navigation in situations where the USV inadvertently deviates from the planned path due to DGPS position error, or if the Inertial Navigation System position drifts over time (Larson, Bruch, & Ebken, 2006).

The second approach is a reactive obstacle avoidance approach. One of the state-of-the-art reactive obstacle avoidance methods is a modified version of the Velocity Obstacle approach (Kuwata, Wolf, Zarzhitsky, & Huntsberger, 2011) which has been integrated in the Office of Naval Research (ONR)'s autonomy suite – Control Architecture for Robotics Agent Command and Sensing (Huntsberger et al., 2008). Using that approach, ONR demonstrated the capability to control a swarm of USVs escorting a moving ship (Office of Naval Research (ONR, 2014) and protect a fixed harbour in a cooperative manner (FreedBerg, 2016). The reactive obstacle avoidance approach has a much faster replanning rate, which allows it to be used for vessels navigating at high speeds. The fast replanning rate would also allow the USV to be very reactive to highly manoeuvrable obstacles. However, the algorithm tends to generate local minima solutions and is more suitable for a sparse environment.

Challenges Identified

Besides considering the use of deliberative and reactive approaches, the CDCA algorithm also has to take into account several other challenges – uncertainties in sensor measurements and platform control, which are unique to the USV platform, as well as compliance with COLREGs.

Uncertainties in Sensor Measurements and Platform Control

One of the main challenges faced by the CDCA algorithm is the need to account for uncertainties in sensor measurements and platform control. Human operators on-board manned vessels are trained to handle noisy and incorrect data provided by the navigation sensors, and are able to correct the data easily using his/her own vision and prior memory. In order to replicate such performance and reduce the need for human intervention, the design of the CDCA algorithm has to take into account these uncertainties in perception, localisation and platform control.

Compliance with COLREGs

Vessels navigating in the sea are required to follow a set of guidelines for avoiding collisions, as defined in the IMO COLREGs. The design of the CDCA algorithm ensures that the USV will be able to avoid collisions while following these rules, in order to navigate the SS in a safe and predictable manner. For example, the CDCA algorithm adheres to COLREGs Rules 13 to 17 as illustrated in Figure 1.

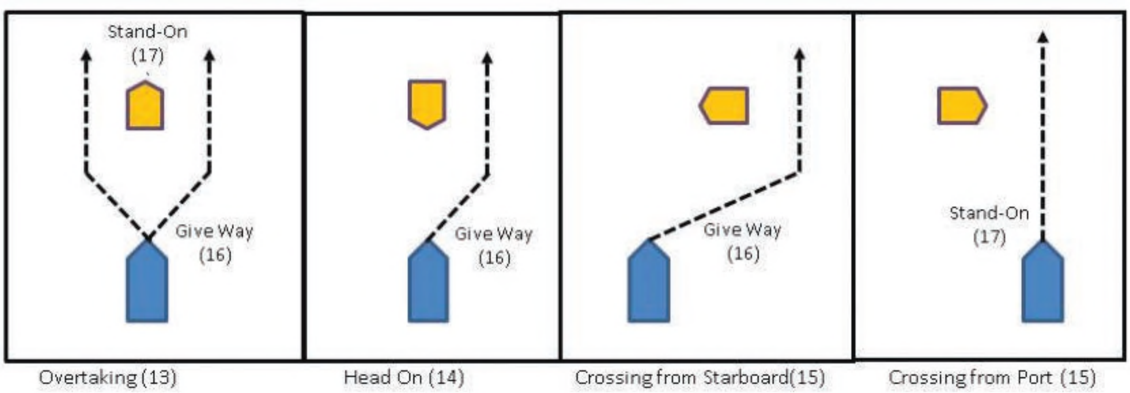

Figure 1. Collision avoidance behaviours complying with COLREGs (rule numbers within brackets)
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The CDCA algorithm was designed to generalise the COLREGs rules into a set of avoidance principles that would govern the collision avoidance behaviours generated. These principles can be incorporated into the CDCA algorithm's objective function to prioritise solutions which comply with COLREGs. In addition, to handle edge cases for which the avoidance behaviours required might not be clearly defined in the COLREGs rules, in-depth discussions have been conducted in order to customise the envisaged behaviours for each scenario.

CDCA Algorithm Design

The CDCA algorithm communicates with the USV Autopilot via a priority interface. It receives the course and speed commands generated by the Autopilot for collision detection, and sends out collision avoidance manoeuvres to the Autopilot via the same priority interface. The Autopilot priority interface allows the collision avoidance commands to override the course and speed commands of the current navigation mode. However, if the CDCA algorithm does not detect any collision, it will allow the Autopilot to follow its original intended course and speed.

Due to considerations of the overall USV system software architecture, the reactive obstacle avoidance approach has been adopted for the CDCA algorithm design, allowing the CDCA algorithm to control the Autopilot directly using course and speed commands. The reactive approach allows the USV to avoid other boats more quickly while travelling at high speeds due to its fast replanning rate. The reactive approach also allows the USV to follow user-defined waypoint tracks more closely, as compared to a deliberative planning approach which generates paths that tend to deviate from user-defined waypoints.

The algorithm design of the reactive obstacle avoidance approach is based on the Velocity Obstacle concept as well as the sampling approach in control space for avoiding both static and dynamic obstacles (Kuwata, Wolf, Zarzhitsky, & Huntsberger, 2011; Wilkie, van den Berg, & Manocha, 2009).

Each iteration of the CDCA algorithm can be broken down into two phases: the collision detection phase and the collision avoidance phase. In the collision detection phase, the CDCA algorithm will predict the USV trajectory and check for potential collision with surrounding obstacles, based on the USV's current and intended course and speed commands. The collision detection is achieved by calculating the Euclidean distance from the USV to all obstacles for each time step up to a pre-defined Time to Closest Point of Approach (TCPA) in the predicted trajectory. At any time step, if the Closest Point of Approach (CPA) between the USV and the obstacle is less than the pre-defined safety distance, a possible collision will be flagged. Once possible collision with any obstacle is detected, the collision avoidance phase will be activated.

In the collision avoidance phase, the CDCA algorithm generates a sample of ownship trajectories within the control space for evaluation. Trajectories for which the USV is predicted to collide with surrounding obstacles will be removed first. For the remaining trajectories, an objective function cost will be calculated. This objective function is used to achieve the desired USV behaviours, by penalising trajectories that violate COLREGs, deviate from current course and speed, deviate from intended course and speed, or are in close proximity with the obstacles. The trajectory with the least cost will be selected and the collision avoidance course and speed commands will be sent out to the Autopilot.

Moving forward, the CDCA algorithm will be improved to integrate both deliberative path planning and reactive obstacle avoidance methods. This has been similarly implemented in the Space and Naval Warfare Systems Center USV (Larson, Bruch, & Ebken, 2006). The path planner will first be used to continuously generate a path that avoids static obstacles and landmasses, to the destination. The USV will follow this path and avoid dynamic obstacles using the reactive obstacle avoidance method. This ensures that the USV manoeuvre and behave in a way that is more efficient, since the deliberative approach ensures that the avoidance solutions generated are more optimal. The integration of both deliberative and reactive approaches allows the USV to plan its avoidance manoeuvres in advance, reducing undesirable behaviours such as U-turns.

INTEGRATION AND VALIDATION CHALLENGES

The CDCA algorithm has been integrated into the MCM USV. For laboratory simulations, hundreds of scenarios have been tested with varied ranges of target and own ship speeds, clocking hundreds of hours of simulation hours without any collision. For at-sea validation, more than a thousand hours have been clocked thus far. Nevertheless, DSTA faced several integration and validation challenges, which will be described in this section.

Integration Challenges

There were several challenges identified for the integration of the CDCA algorithm on the MCM USV platform. As the CDCA algorithm is dependent on the perception sensors (to obtain an accurate situational awareness) and the control system (to predict collision and execute the avoidance manoeuvres required), integration problems with the perception sensors and control system could affect the performance of the CDCA algorithm. Furthermore, CDCA algorithm performance could also be degraded due to the difference in boat manoeuvrability and performance characteristics linked to specific boat payloads.

Performance of Perception Sensors

The CDCA algorithm is dependent on the perception sensors to provide situational awareness, in order to generate feasible collision avoidance manoeuvres. It is thus important to ensure that the perception sensors are robust and tuned to the specific operating environment, to detect and track obstacles accurately and consistently. For the MCM USV, DSTA had conducted many sea trials to tune the perception sensors in order to ensure its performance when integrating it with the CDCA algorithm.

Performance of USV Control System

The CDCA algorithm predicts trajectories and detects collisions based on assumptions on the USV's kinematic and dynamic model. Another challenge identified was the difficulty in modelling the USV control system accurately. To tackle this problem, DSTA led the effort to collect and analyse log files from the MCM USV sea trials to characterise the USV control system, in terms of parameters such as turn rate and reaction time for incorporation into the CDCA algorithm.

Performance of CDCA Algorithm given Payload Constraints

When the USV tows MCM payloads, such as the Towed Synthetic Aperture Sonar and the Expendable Mine Disposal System, the boat's manoeuvrability is reduced. Simulations ran by DSO showed that a low turn rate makes it difficult for the USV to avoid collisions safely when obstacles appear too near to the USV. To address this, DSTA recommended that the CDCA algorithm be configured to have a "Towing Mode", which will detect and avoid obstacles using a larger safety distance. In this mode, the CDCA algorithm will also predict collisions and compute avoidance solutions based on reduced USV manoeuvrability.

Validation Challenges

In order to further stress test the algorithm to ensure that the CDCA algorithm can enable the USV to avoid collisions effectively, a Verification and Validation (V&V) simulator set-up (see Figure 2) has been designed. The V&V set-up aims to speed up virtual simulations to run the CDCA algorithm for millions of kilometres along the SS without any collisions.

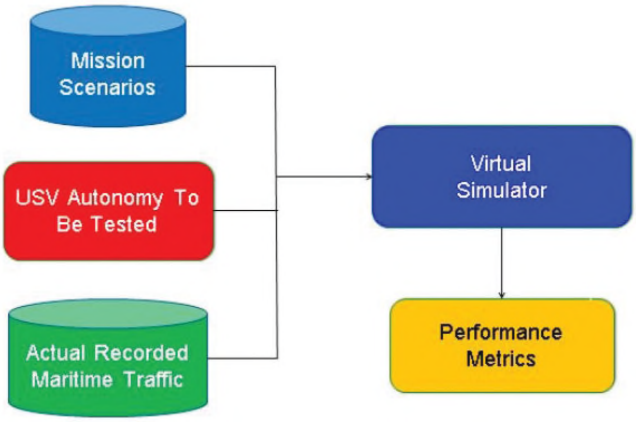

Figure 2. V&V Simulator Set-up
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To create a realistic model of the USV and its operating environment, a Virtual Simulator was set up by making use of actual recorded maritime traffic in the SS to generate obstacles, and modelling both the USV platform and surrounding obstacles with appropriate sensor and control errors. After simulations are completed, the results are evaluated using a set of performance metrics. The performance metrics evaluate the CDCA algorithm's behaviours based on the number of collisions, degree of compliance to COLREGs, smoothness of course and speed changes, as well as the necessity of movements made.

Achieving the targeted number of virtual simulation runs would take more than 60 years (assuming an average USV speed of 12 knots) based on real time simulation running on a single computing platform which was impractical. The V&V simulation was thus accelerated through hardware and software solutions.

In terms of hardware, the simulation was accelerated by setting up multiple computers to run multiple different scenarios in parallel (see Figure 3). In terms of software, the Virtual Simulator was sped up by integrating each component in the simulator through the use of static libraries such that the main logic in the Virtual Simulator would engage each module sequentially through function calls. This design eliminates "sleep time" in the code, and allows it to run as quickly as the computer's Central Processing Unit allows.

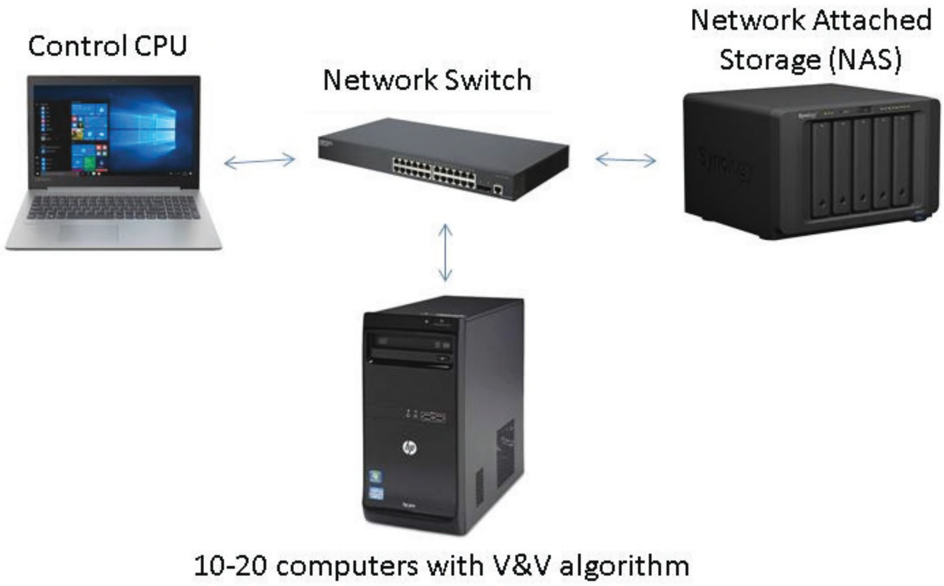

Figure 3. V&V hardware set-up to accelerate simulation
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SPIN-OFF APPLICATIONS

The CDCA algorithm developed for the USV can be modified to be used as an advisory on board manned vessels. It is observed from history that most maritime accidents such as the USS John McCain collision, occurred due to human error (Department of Navy [DoN], 2017; Apostol-Mates & Barbu, 2016). DSTA is currently leading the development of a Maritime Collision Avoidance Advisory System based on the CDCA algorithm (see Figure 4), which could warn sailors of potential collisions in advance and suggest possible avoidance manoeuvres that are collision-free within the user-configurable CPA and TCPA for enhanced safety. Its implementation is currently being explored for manned vessels.

Figure 4. Maritime Collision Avoidance Advisory System
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CONCLUSION

The CDCA algorithm has allowed the USV to be fully autonomous, replacing human operators in dangerous missions such as Mine Countermeasures and achieving manpower savings. This article has presented the design of the CDCA algorithm, integration and validation challenges, as well as the spin-off application of the Maritime Collision Avoidance Advisory System for manned vessels.

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BIOGRAPHY

LIM Lian Nang is the Head Information for Innovation (Naval Systems), leading the Unmanned Maritime Systems Programme Office in DSTA. He also oversees the Unmanned Surface Vessel (USV) projects. He is currently a member of the Committee for Maritime Autonomous Surface Ships (CMASS) working group responsible for the development of local MASS rules and regulations. Lian Nang graduated with a Diplôme d'Ingénieur in Mechanical Engineering (Master equivalent) and a Master in Business Administration from the École Nationale des Ponts et Chaussées, France, in 2006.

BAY Zi Jing is a Senior Defence Engineer from DSO National Laboratories (DSO). He is currently leading the research on USV Autonomy. With over 10 years of experience in designing algorithms for unmanned systems, he has delivered several unmanned systems to MINDEF including the first USV that is able to detect and avoid collision autonomously in Singapore waters. Zi Jing graduated with a Bachelor of Engineering (Electrical and Electronic Engineering) from Nanyang Technological University and Master in Computer Science (MSc) from Imperial College, London. He started his career in DSO in 2007.

TAN Shu Jun is an Engineer (Naval Systems) in the Unmanned Maritime Systems Programme Office in DSTA. She is currently working on projects to deliver the USV to the RSN. She was previously been seconded to DSO to design and develop a Verification and Validation framework to test the CDCA algorithm. Shu Jun graduated from the National University of Singapore with a Bachelor of Engineering (Mechanical Engineering), and obtained her Master in Engineering (Mechanical Engineering) (Product Design) from the University of California, Berkeley in 2017.