# An Automatic Collision Avoidance Strategy for Unmanned Surface Vehicles

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# AN AUTOMATIC COLLISION AVOIDANCE STRATEGY FOR UNMANNED SURFACE VEHICLES

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**Abstract.** Unmanned marine vehicles are useful tools for various hydrographical tasks especially when operating for extended periods and in hazardous environments. The autonomy of these vehicles depends on the design of robust navigation, guidance and control systems. This paper concerns the preliminary design of an automatic guidance system for unmanned surface vehicles based on standardised rules defined by the International Maritime Organisation. A guidance system determines "reasonable" and safe actions in order to complete a task at hand. Thus, autonomous guidance can be regarded as the mechanism that brings self-reliance to the whole system. The strategy here is based on waypoint guidance by line-of-sight coupled with a manual biasing scheme. Simulation results demonstrate the functioning of the proposed approach for multiple stationary as well as dynamic obstacles.

*Keywords*: Unmanned surface vehicles, obstacle detection and avoidance, navigation, guidance and control.

## 1 Introduction

Automatic unmanned systems are an integral part of everyday life, normally employed to perform repetitive chores quickly and efficiently which are too tedious for humans. Most are designed to operate in structured environments where the surroundings do not vary considerably. Developing a fully autonomous system which can work in any unstructured or unpredictable environment is a challenging task that requires robust guidance and control strategies. For unmanned mobile systems operating in fast changing surroundings, such as an automobile, aircraft or a humanoid robot, the automatic guidance system or path planner plays a cental role in bringing autonomy to the whole system. The guidance or mission commands are normally sent through a wired or wireless channel by a remote operator whose responsibility is to constantly oversee the system and act accordingly. The guidance system is thus essential to determine "reasonable" and safe actions that are required to accomplish a mission.

In what follows, a guidance system, or more precisely, an obstacle avoidance system (path planner) is developed for an unmanned (maritime) surface vehicle or USV. USVs are useful tools in tasks such as oceanography, weapons delivery, environmental monitoring, surveying and mapping. There are several worldwide

USV programs both in the defence and civil sectors such as the *Delfim* USV for mapping applications [1] and *Protector* USV [2] for maritime assets protection. Most of these programmes rely on remote operator guidance for sending mission commands and to constantly overlook the vehicle's status either by observation or via a wireless video link [3]. This adds to the operating cost of each mission and is not practical for extended periods. In order to fully benefit from this technology, a reliable obstacle detection and avoidance system is thus mandatory, a fact confirmed by leading researchers and industrialists in the field [3, 4]. It is also important that the USV behaves in a manner that is discernable by other ships in the vicinity. This attribute would aid in integrating the USVs with the ambient marine traffic. The coastguard regulations on prevention of collision at sea (COLREGs), defined by the International Maritime Organisation (IMO) [5], can usefully be integrated for this purpose.

The proposed approach employs a simple waypoint by line-of-sight (LOS) guidance strategy coupled with a manual biasing scheme. This is tested in simulations on the USV dynamic model described in Section 3. To this end, several mission waypoints are selected between the USV launching position and the destination. The vehicle is normally guided to stay on the direct LOS route when no obstacles are found. Assuming that a vision-based detection system is present onboard, a bias is added to the current reference heading angle should an object is found posing a threat. This manual bias deviates the course of the USV and thus the obstacle is evaded. Subsequently, the craft is again commanded to follow the direct LOS angle between its current position and the next waypoint. It is demonstrated that the addition of the bias angle generates evasive manoeuvres that satisfy the IMO requirements. Simulation results are presented showing USV trajectories between all the waypoints for the case of multiple stationary as well as a single dynamic obstacle. Section 2 explains the motivation of this research including a brief description of COLREGs. The *Springer* USV dynamic model employed here is briefly described in Section 3. The problem formation is then outlined in Section 4. Section 5 presents simulation results whilst concluding remarks follow in Section 6.

## 2 Motivation and Background

Recent statistics have shown that 60% of casualties at sea are caused by collisions [6]. It has also been found that human error is a major contributing factor to those incidents. Furthermore, it is reported [7] that 56% of collisions at sea include violation of COLREGs. The infamous *Titanic* tragedy was in fact as a result of the unwillingness of the crew to change the speed of the vessel [8] 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. A review of related research has revealed that very few USVs are equipped with an onboard detection and avoidance system. In addition, only a handful of research programmes have considered developing COLREGs-based avoidance systems. Examples include those at MIT [9] at MIT using behaviour-based control and the work at the Space and Naval

Warfare Systems Center in San Diego [10] employing a voting technique. Another collision avoidance method using fuzzy logic with reference to COLREGs was devised for the vessel traffic service (VTS) [11], but no experimental results were reported. Finally, a simulation study of COLREGs-based automatic collision avoidance for manned vessels at the Universities of Glasgow and Strathclyde [12] employed artificial potential field and speed vector for trajectory planning and collision avoidance.

In the absence of obstacles, the waypoint guidance scheme generally works very well. However, in practice, the real-world is full of unpredictable situations, so it is not possible to leave the unmanned vessel unattended during a mission. This paper introduces a simple, yet effective, technique for obstacle avoidance based on IMO regulations. The IMO rules or COLREGs suggest particular manoeuvres in various obstacle encounter settings. For instance, in the head-on collision scenario presented (Rule 14), both the vessels involved must turn towards their respective starboard sides. Also, Rule 15 defined the crossing situation, which is akin to the right of way rule in the automobile driving regulations.

The difficulty with the COLREGs is that they were written for humans and thus are subjective in nature. For instance, Rule 8($b$) states that any change in the vehicle's course should be discernable by the ambient traffic and must not include a series of small changes. For a human captain, say a $28^0$ starboard-side manoeuvre is no different than a $30^0$ turn as long as it is avoiding the collision. This is clearly not optimal in any sense. Hence an automatic path planning system may also be useful for (the captain of) a manned vessel.

## 3 *Springer* USV

The *Springer* USV is a catamaran-shaped research vessel which was primarily designed to carry out pollutant tracking and environmental and hydrographic surveys in rivers, reservoirs, inland waterways and coastal waters. It is a low cost vehicle which is also intended to be used as a test bed for researchers involved in environmental data gathering, designing alternative energy sources, sensor and instrumentation technology and control systems engineering.

Each hull of *Springer* is divided into two watertight compartments containing some of the onboard sensors and electronics including battery packs. Pelicases are placed within the bay areas between the two cross beams, as depicted in Figure 1. These house the computers and the remaining onboard electronics and control circuitry. A GPS receiver and wireless router were also installed on the mount shown in Figure 1. The onboard computers are all linked through an *ad-hoc* wireless network providing an external intervention capability in the case of erratic behaviour or simply for monitoring purpose. For the interested reader, the detailed hardware development of the *Springer* USV is described in [13].

*Springer's* steering mechanism is based on differential thrust and the dynamic equations can be manipulated to generate the following single-input single-output state space model:

$$\mathbf{x}(k+1) = \begin{bmatrix} 1.002 & 0 \\ 0 & 0.9945 \end{bmatrix} \mathbf{x}(k) + \begin{bmatrix} 6.354 \times 10^{-6} \\ -4.699 \times 10^{-6} \end{bmatrix} u(k) \tag{1}$$

**Fig. 1.** *Springer* USV during trials at Roadford Reservoir, Devon

$$y(k) = \begin{bmatrix} 34.13 \; 15.11 \end{bmatrix} \mathbf{x}(k) \tag{2}$$

where $u = n_d$ is the differential thrust input (excitation signal) in rpm given by Equation 3 in terms of the individual thruster velocities, $n_1$ and $n_2$. The controlled variable, $y = \psi$, is the output heading angle of the USV in radians.

$$n_d = \frac{n_1 - n_2}{2} \tag{3}$$

It is obvious that when $n_d = 0$ i.e. $n_1 = n_2$, the vessel traverses in a straight line in the absence of external disturbances. The above dynamic model was obtained by applying system identification techniques to the input-output data acquired through trials carried out at a fixed speed.

## 4 Problem Formulation

In order for the automatic collision avoidance to work, a reliable detection system is mandatory. The detection system is responsible for keeping track of any changes in the vicinity of the vessel and reporting to the avoidance (guidance) module. For many reported applications, it is normally assumed that the location of the obstacles is known in advance. A map of the environment is also available which defines location of all the fixed infrastructure present around a sea port or a harbour. It is assumed that a camera and LIDAR (light detection and ranging) system is present onboard which can reliably detect any obstacles and provide their distance from the USV. The vision processing software detects the vertices of an object whose distance from the ship is accurately calculated using a LIDAR. Although this method of detection has some obvious disadvantages, it is only being used in this paper to demonstrate the viability of the proposed approach.

It is common to employ a virtual safety zone around the obstacles as well as the ship being controlled which must not be breached at any time unless necessary. The size of these zones depend on the dynamics (minimum turning radius and speed etc.) of the vessel. Here, a circular safety zone called the circle-of-rejection (COR) is assumed around each obstacle. A circle-of-acceptance (COA) is also assumed around each waypoint which flags the arrival of the ship at each one and the mission planner then selects the next waypoint. The COA is normally taken to be twice the length of the vessel being commanded.

The methodology adopted here has two distinct planning stages. Firstly, the vehicle must never enters the safety zone around the obstacle. Secondly, in order comply with COLREGs, the vehicle must pass by from the starboard side of the obstacle. This is true for both stationary and mobile obstacles. As explained earlier, the proposed approach employs a simple waypoint guidance by LOS coupled together with a manual biasing scheme. This strategy changes the current heading angle of the vehicle towards the starboard side when the distance of the ship to the obstacle is less than or equal to, the radius of COR thus avoiding the obstacle in accordance with coastguard regulations.

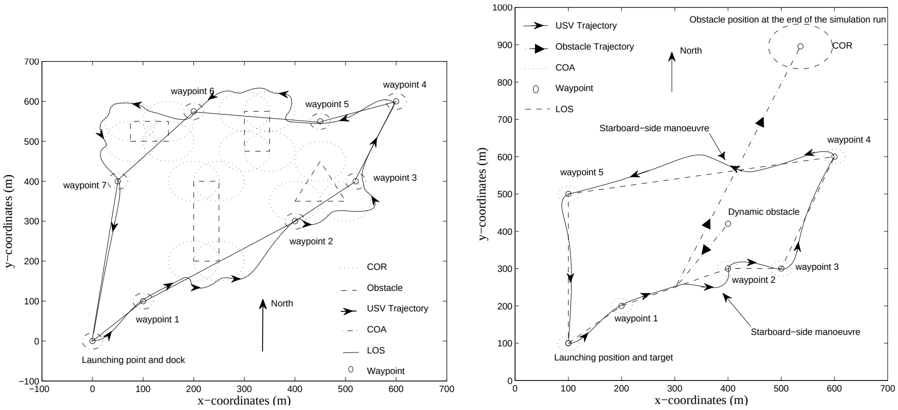
## 5 Simulation Results

Simulations have been carried out both for static and dynamic obstacles. As stated previously, the detection system determines the vertices of the obstacles and a COR is defined around each of them. Based on the waypoint guidance strategy, the vessel follows the LOS angle between its current position and the next waypoint. If there is a breach of the COR, the added bias in the current heading angle alters the course of the vessel towards the starboard side in order to avoid the collision as well as complying with the COLREGs. When the obstacle is fully avoided, the vehicle heads back to the current LOS to the next waypoint. The parameters, COR, COA and bias angle are chosen as $50m$, $10m$ and $75^0$ respectively. In addition, a simple PID controller integrated with the path planner maintains the desired heading. The PID autopilot ensures that the vehicle stays on course as required by the guidance system.

The USV was assumed to have been launched at $(0, 0)$ where it eventually docked after completing the mission. There were seven waypoints and four obstacles (three rectangle and one triangle-shaped) in a field of 700 by 700 metres. The co-ordinates of the waypoints were chosen randomly taking care that no waypoint be located within any of the obstacle's boundary. The obstacle avoidance simulation is presented in Figure 2(a) which shows the USV's trajectory through all the waypoints.

From the plot, the effect of vessel dynamics is evident. Several evasive actions have evidently been generated by the path planner. From waypoint 1 to 2, the craft had to navigate away from the obstacle twice before arriving at the waypoint. There was a starboard side turn on the way to waypoint 3, whereas the trajectory from waypoint 5 to 6 consisted of several avoidance manoeuvres including a very sharp starboard turn. The path taken by the USV from waypoint 6 to 7 also contained COLREGs-compliant manoeuvres to avoid running into the obstacle. Note that waypoints 2, 3 and 6 are very close to the boundary of the COR and hence a breach was unavoidable. The vehicle finally docked at the launching point.

Next, a single mobile obstacle, comprising a ship initially considered to be moving in the South-Westerly direction at a fixed speed of $1m/s$ was examined. A COR of radius $50m$ was assumed around the obstacle. The USV launch coordinates were $(100, 100)$ which was also the final docking location. It is clear that the initial USV orientation would have been towards the North-East direction and therefore on a direct collision course with the oncoming ship. In order to create an interesting scenario, the direction of the oncoming ship was altered towards the North-East after the USV evaded its first encounter. This provided a practical situation or could also be regarded as two dynamic obstacles encountered during a mission. The complete USV route depicted in Figure 2(b) shows two evasive actions from waypoint 1 to 2 and from waypoint 4 to 5. In both cases, the USV passed on from the right-hand side of the moving ship and avoided the collision. The remaining trajectory consisted of approximately straight line or LOS paths. The relative speed limitation of the USV with the obstacle is a potential problem with this simulation as it may require a large COR so that appropriate action can be taken well in advance.



(a) COLREGs-based collision avoidance simulation for multiple static obstacles

(b) COLREGs-based collision avoidance trajectory for a dynamic obstacle

**Fig. 2.** COLREGs-based simulation analysis of collision avoidance in the presence of static and dynamic obstacles

## 6 Concluding Remarks

Preliminary simulation results have been presented on the development of an obstacle avoidance strategy for USVs. A simple manual biasing scheme was implemented together with the waypoint by LOS guidance technique. The highlight here is the integration of standardised IMO regulations or COLREGS in the path planning. The dynamics of an actual USV were also incorporated, providing realistic trajectories which are closely followed by the autopilot. In the proposed strategy, the USV must enter within the COR before the heading bias is introduced which diverts its heading towards the starboard side. It should be noted that manned vessels could also benefit from autonomous path planning, thus helping to eliminate the subjective nature of human decision making and safeguarding the onboard personnel. In the future, other motion planning strategies will be investigated for COLREGs-compliance using evolutionary algorithms such as genetic algorithms and particle swarm optimisation. Furthermore, automation of additional IMO rules will be carried out and the performance analysed in the presence of sea disturbances.

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