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Motion Planning of USV Based on Marine Rules

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Abstract

In order to achieve a high level of autonomy in a highly dynamic and unpredictable world, obstacle avoidance is required to ensure the safety of other vessels, people, and property. Discussed here is the integration of the Coast Guard International Regulations for Avoiding Collision as Sea (COLREGS), or the "Marine Rules of the Road", with an autonomous motion planning method based on the relative coordinate. The simulation results provide obstacle avoidance capability, that complies with COLREGS, to an Unmanned Surface Vehicle (USV).

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Keywords: Unmanned Surface Vehicle (USV); motion planning; marine rules

1. Introduction

Unmanned surface vehicles (USVs) is one of four unmanned vehicle kindred including unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs) and unmanned ground vehicles (UGVs). In fact, US Navy release its first USV Master Plan in 2007, where a USV is defined as a vehicle which displaces water at rest and operates with near continuous contact with the water surface, capable of unmanned operations with varying degrees of autonomy. It will play a key role in merchant, naval and scientific fields in the future. Its applications include military purpose, surveillance of territorial waters, exploration and exploitation of hydrocarbon, environmental monitoring, research of ocean scientific, and so on [1, 2]. The typical USVs in the world are: Protector (Israel), Spartan (America), Charlie (Italy) [3], Springer (Britain) [4], Delfim (Portugal) etc.

The increased use of USVs presents new law and policy issues that have not been addressed. Current law does not specifically address the use of unmanned vehicles in a marine environment. The use of such vehicles presents a risk of injury and property damage. A natural and prudent solution is for the designer

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to follow the International Collision Regulations (COLREGS) [5] until more precise law regulating USVs is enacted.

The complexity and uncertainty of modeling marine vehicles and their surrounding environment led Lee et al. [6], to use a fuzzy logic approach to satisfying the COLREGS. Two groups, who have done actual testing on the water, are Benjamin et al. [7] and Larson et al. [8]. In Benjamin et al., they use interval programming based multiobjective optimization to implement a COLREG compliant system. Larson et al. use a projected obstacle area to develop an estimate of possible future locations of an obstacle. The choice of vehicle action is then discretized into three possible actions based on the vehicles location relative to the obstacle.

In this paper, integration with the evolutionary path planner, of a method based on the relative coordinate for obeying the marine rules, is discussed.

2. Marine Rules of The Road

A graphical interpretation of the rules of the road is shown in Fig. 1. The focus is on two scenarios, head-on collision and crossing collision. The definitions of the rules, how we interpret them and the angles that define whether we are in a head-on or crossing collision scenario are discussed in subsequent sections.

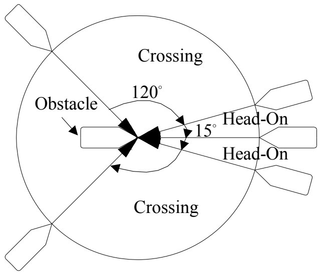

Fig. 1. Collision scenario definition

2.1. Head-on collision definition

A pictorial interpretation of the head-on collision is shown in Fig. 2(a)and Fig. 2(b). It was decided to use the rule shown in (1). is shown in (2), $_1$ and $_2$ are our vehicles heading and the obstacles heading respectively. When the condition is true we will consider our vessel to be in a head-on configuration with another moving obstacle.

$$|180 \quad | \quad 15$$

(1)

$$_1 \quad _2 \qquad (2)$$

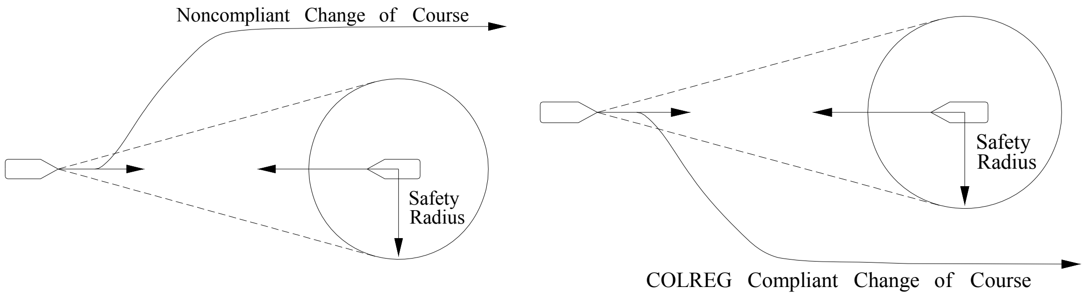

Fig. 2. (a) Complies with COLREGS; (b) Does not comply with COLREGS

2.2. Crossing collision definition

The crossing collision has been interpreted as the relation shown in (3), where is the same as in the head-on scenario. When the condition is true we are in a crossing situation.

$$45 \quad | \quad | \quad 165 \qquad (3)$$

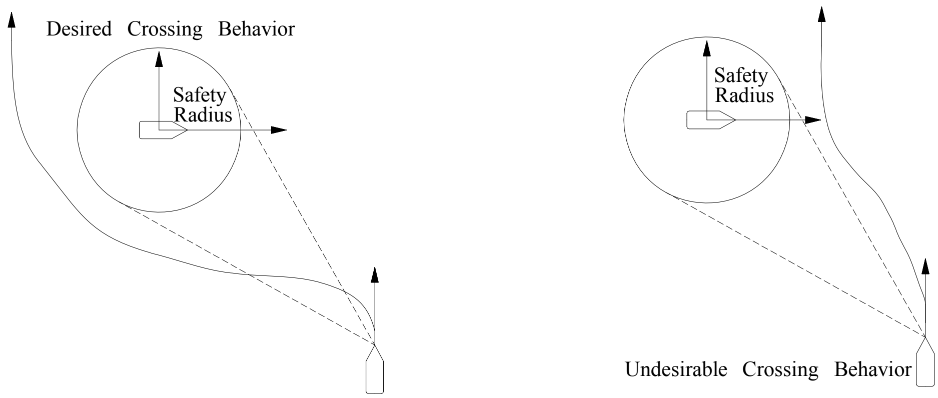

Fig. 3. (a)Desired crossing behavior; (b) Undesired crossing behavior

2.3. Determination of possible collision

Deciding when to take action to follow the Rules of the Road can be difficult for an autonomous vehicle. Fig. 4(a) shows the relation model of USV and obstacle.

In Fig. 4(a), A is a point object, which presents USV, while B is a circle of radius R and with center at B, which presents obstacle. The velocities of A and B are denoted by V_A and V_B respectively. The behavior of the line-of-sight (LOS) is characterized by the following kinematics, equations:

$$\begin{aligned} V_s \quad & v_a \cos \qquad v_b \cos \\ V \quad & v_a \sin \qquad v_b \sin \end{aligned} \qquad (4)$$

Where V_s and V are the relative components along and perpendicular to the LOS respectively. V is the relative velocity of A with respect to B, $V \quad V_A \quad V_B$. is the angle between V and LOS, and is the angle between V and V_A.

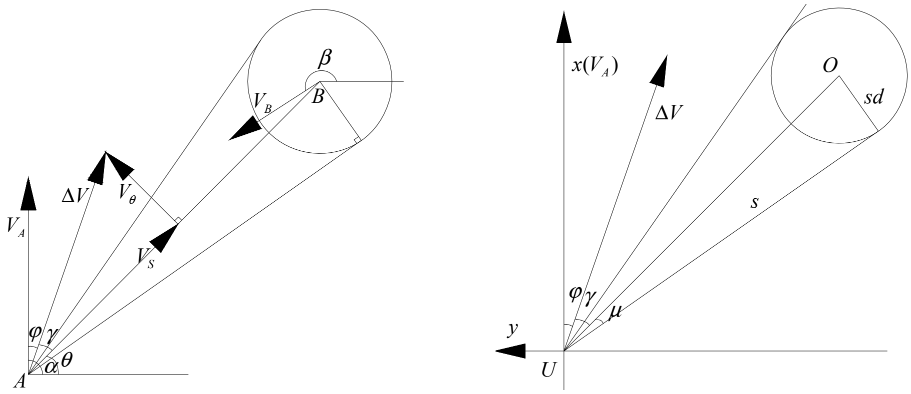

Fig. 4. (a) The relation model of USV and obstacle; (b) The relative coordinates

In Fig. 4(b), U is the USV as the origin of coordinates, the heading of velocity V_A is x axes, and the perpendicular to it is the y axes. The obstacle that the USV met with is denoted by O. The distance between the USV and the obstacle is denoted by s which can be measured by radar. We define that sd is the safe distance and denotes the safe angle or collision angle, which is get by $tg^{\ 1} \ sd \big/ \sqrt{s^2 \quad sd^2}$. If the angle is outside the angle , the USV is safe or else it probably collides with the obstacle.

3. Motion planning algorithm

The motion planning approach for USV can roughly be divided into two categories: global and local. The global techniques, such as road-map, cell decomposition and potential field methods, generally assume that a complete model of the USV's environment is available.

The local path planning techniques, also known as the obstacle avoidance methods, are potentially more efficient in USV navigation when the environment is unknown or only partially known. A approach is introduced based on the Velocity Obstacle (V-obstacle) Concept, it allows to efficiently select a single velocity by the robot that avoids any number of moving obstacles (if such solution exists) [9, 10, 11]. The motion planning method based on relative coordinates which is ideally suited for USV [12].

From Fig. 4(a) and equation (4) we can get:

$$tg \qquad \frac{V}{V_s} \qquad \frac{v_a \sin \qquad\qquad v_b \sin}{v_a \cos \qquad\qquad v_b \cos}$$

(5)

We define a function about the magnitude and direction angle of the velocity:

$$f \ \ v_a, \ \ , v_b, \qquad tg$$

And we can get: $tg^{\ 1} f \ \ v_a, \ \ , v_b,$

$$d \qquad \frac{1}{1 \quad f^2} df \tag{6}$$

Where

$$\frac{1}{1 \quad f^2} \qquad \frac{K^2}{v_a^2 \quad v_b^2 \quad 2v_a v_b \cos}$$

$$K^2 \quad v_b \cos \qquad v_a \cos \qquad ^2$$

$$df \quad \frac{f}{v_a} dv_a \quad \frac{f}{} d \quad \frac{f}{v_b} dv_b \quad \frac{f}{} d$$

(7)

Because we can just control the USV and not the obstacle in any time, or the varieties of obstacle's magnitude and direction of velocity is too small in a very small interval that the varieties of obstacle's can be approximated to zero, so (7) is near to:

$$df \quad \frac{f}{v_a} dv_a \quad \frac{f}{} d \quad dV_a \tag{8}$$

Where: $\frac{f}{v_a} \quad \frac{v_b \sin}{K^2}$

$$\frac{f}{} \quad \frac{v_a \; v_a \quad v_b \cos}{K^2}$$

So we rewrite (6) as:

$$d \quad \frac{v_b \sin \qquad dv_a \quad v_a \; v_a \quad v_b \cos \qquad d}{v_a^2 \quad v_b^2 \quad 2v_a v_b \cos}$$

Instead of the differential with difference, the equation above can rewrite as:

$$\frac{v_b \sin \qquad v_a \quad v_a \; v_a \quad v_b \cos}{v_a^2 \quad v_b^2 \quad 2v_a v_b \cos}$$

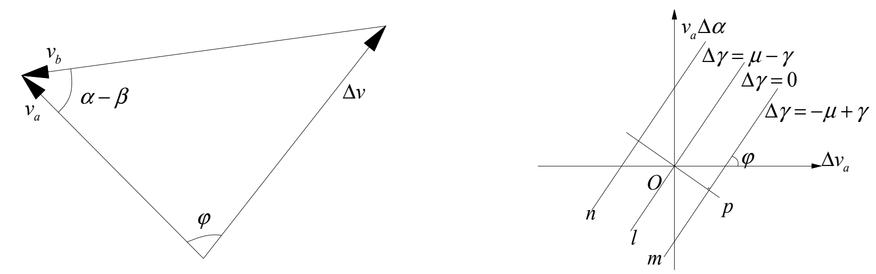

Fig. 5. (a) The relation of velocities;. (b)The acceleration space coordinates

From Fig. 5(a), we get:

$$v_b \sin \qquad v \sin$$

$$v_a \quad v_b \cos \qquad v \cos$$

$$v_a^2 \quad v_b^2 \quad 2v_a v_b \cos \qquad v^2$$

Then $$\frac{v_a \sin \quad v_a \quad \cos}{v}$$ *(9)*

And $v_a \quad tg \quad v_a \quad v \quad / \cos$

(10)

v is the variety of relative velocity respectively and is the variety of velocily's magnitude. From Fig. 4(b) and equation (10), we need take the angle out of the angle , the variety range of is between and which is a strip whose width is 2 , and this range is called collision field. Along the path p is the best way for v out of the collision field.

The equation of the perpendicular line p is:

$v_a \quad ctg \quad v_a$

(11)

From (10) and (11), we get the varieties of the magnitude and direction angle of velocity in each interval time T:

$v_a \quad v \quad \cos$

$v_a \quad v \quad \sin$

(12)

4. Simulation results

We give the simulation results to demonstrate the effective implementation of the rules of the road and show the validity of the motion planning method. The obstacle is the gray ellipse, the boundary represents the safety radius which we do not want our USV to enter. The 'G' marks the goal location and the 'S' marks the start location. The path is the red line.

Fig. 6 shows the results of a head-on collision scenario.

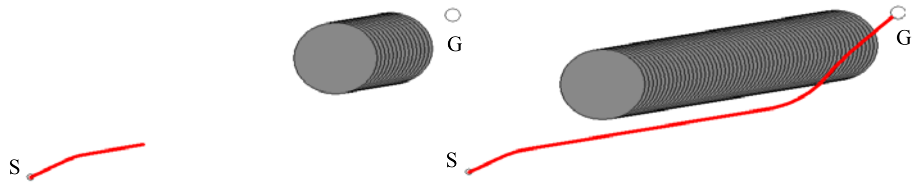

Fig. 6. Simulation of a head-on collision scenario. (a) Pass across the larboard side of the obstacle; (b) Safely past the obstacle.

In Fig. 6(a), the initial plan is to pass with starboard sides facing each other. To comply with the COLREGS we must make a maneuver to our starboard such that our ports are facing each other. Fig. 6(b) shows that we indeed make it safely past the oncoming obstacle.

Fig. 7 shows the results of a crossing collision scenario.

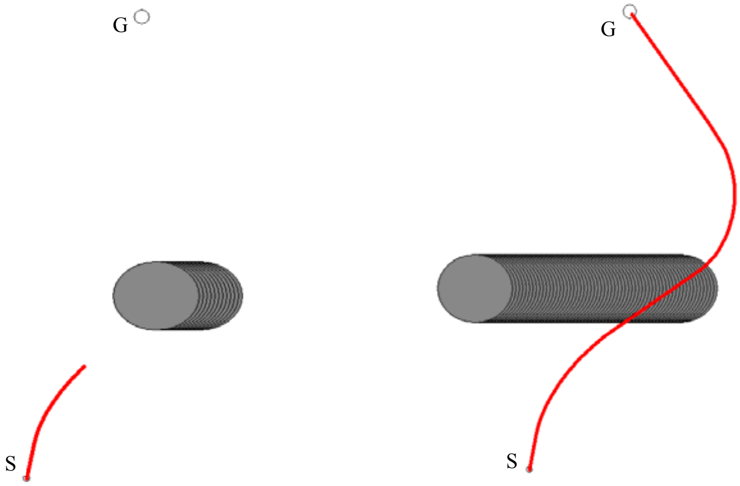

Fig. 7. Simulation of a crossing collision scenario. (a) Pass across the stern of the obstacle;(b) Safely past the obstacle.

In Fig. 7(a), we can see that our vehicle's initial path is crossing the bow of the obstacle. This is unexpected. Once the vehicle enters the motion planning, the planned path is altered to go to the stern of the crossing vehicle. Fig. 7(b) shows that our vehicle is able to safely pass behind the crossing obstacle.

5. Conclusion

In recent years the science of UAVs has reached a high level of technical maturity. Meanwhile USVs have lagged behind in technical development. The need for an improvement in USV technology to a level comparable with their airborne counterparts is clear.

In order to achieve satisfactory performance of obstacle avoidance a motion planning method based on relative coordinate is used. Presented here is the path planner to comply with the marine rules of the road as defined by the COLREGS. The simulation results prove that the USV can avoid moving vehicles and obey the marine rules.

Acknowledgements

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