International Journal of Fuzzy Logic and Intelligent Systems, vol. 2, no. 2, June 2002 pp. 100-108

Collision Avoiding Navigation of Marine Vehicles Using Fuzzy Logic

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Abstract

A fuzzy logic for collision avoiding navigation of marine vehicles is proposed in this paper. VFF(Virtual Force Field) method, which is used widely in the field of mobile robots, is modifiel to apply to marine vehicles. The method is named MVFF *(Modified Virtual Force Field) mothod*. The MVFF consists of the determination of the heading angles for trach-keeping mode (Ψ_{ca})and collision avoidance mode (Ψ_{tk}). The operator can choose the pattern of the track-keeping mode in the proposed algorithm. The collision avoidance algorithm can handle static and/or moving obstacles. These functons are implemented using fuzzy logic. Various simulation results verify the proposed alogorithm.

Key words : MVFF, Track-keeping Mode, Collision Avoidance, Moving Obstacle, Fuzzy Logic

1. Introduction

Autonomous navigation of marine vehicles is an important field from the viewpoint of marine business since working in the marine vehicles is considered as a kind of 3D job. *Reliable autonomous navigation may reduce such difficulties* considerably. Most of the researches in the literature use the methods based on the modern control theory [1,2,3,4,5]. These methods require precise mathematical modeling of the dynamic behavior of marine vehicle itself and environment. However, practical environmental situation of marine vehicles is very complicated and dynamic modeling of the marine vehicle itself has a variety of uncertainties. Therefore, an approach using a sort of artificial intelligence may be a promising choice in order to adopt human expert"s knowledge. Some results can be found in the literature [6,7,8]. The authors think that a thorough investigation in applying artificial intelligence is, however, still in need. Most of all, fuzzy logic is considered as a proper choice among various existing techniques of the artificial intelligence in this paper.

VFF (Virtual Force Field) method is used successfully in the field of mobile robots, especially for the problem of obstacle avoidance[9,10]. The basic concept of this method is that the goal attracts the mobile robot and the obstacle repels the mobile robot as electric charges do. Figure 1 illustrates the concept. This method works well for the static obstacles. The marine vehicles face, however, moving objects frequently. Furthermore, there exists pre-determined desired track, which is the shortest path between neighboring way points, and the marine vehicles must follow the track as precisely as possible. These are different aspects of the marine vehicles to the mobile robots and the original VFF method is not flexible enough to handle these features.

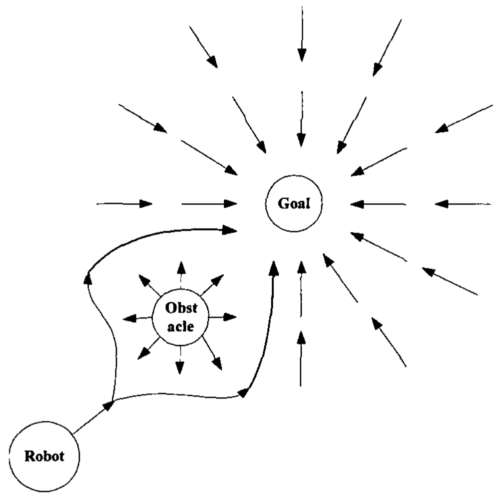


Figure 1. The basic concept of VFF method

The original VFF method is modified in this paper to yield MVFF (Modified Virtual Force Field) method. The MVFF method consists of two major modes. The first mode is named as 'track-keeping mode'. It defines the pattern of returning to the desired track when the marine vehicle is moved away from the desired track. It is investigated thoroughly in sections 2 and 3. Figure 2 represents the concept of the track-keeping mode.

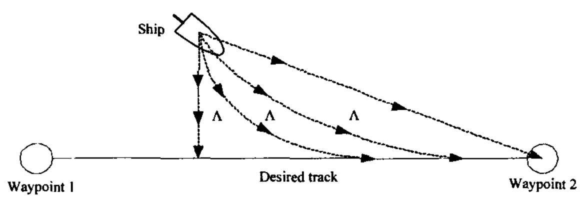


Figure 2. The concept of track-keeping mode

This work is supported by the Agency for Defense Development (ADD) through ADD-00-6-2.

The second mode is named as 'collision avoidance mode'. This mode can handle static and/or moving obstacles intelligently. Fuzzy logic is adopted to implement expert"s knowledge. Four linguistic variables are used in the premise part to include many cases of possible collisions. It is explained in the section 4. Many simulations are carried out to investigate the validity of the proposed algorithm and represented in the section 5. Section 6 concludes the paper.

2. Concept Of The Proposed MVFF Method

Marine vehicles are usually moving at a constant speed at the high seas and the control command is heading angle as shown in the figure 3.

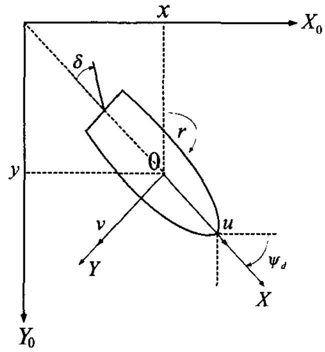


Figure 3. An illustration of the control command

$\{X_0, Y_0\}$and $\{X, Y\}$are the global and the body-fixed coordinate systems, respectively. (x, y) is the location of the center of gravity of the marine vehicle with respect to the global coordinate systems. u, v, and r are longitudinal, transversal, and angular velocities, respectively. δ is the rudder angle and Ψ_d is the desired heading angle.

Control of the marine vehicles is usually carried out by two-fold step. The control command is the desired heading angle Ψ_d and a course-keeping controller tries to follow the heading angle command. Deviation of the marine vehicle from the desired track doesn't matter to the course-keeping controller. There exists a track-keeping controller, which yields the desired heading angle continuously to follow the desired track of the marine vehicle. The course-keeping controller and track-keeping controller consist an inner loop and outer loop of the whole controller, respectively. The course-keeping controller is much faster than the track-keeping controller. The course-keeping controller is designed to follow the outer loop's heading angle command. Figure 4 illustrates the concept.

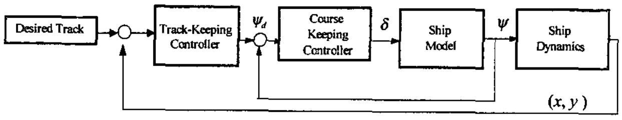


Figure 4. A typical scheme of the controller of marine vehicles

On the other hand, the basic idea of the proposed framework comes from VFF method. Direct application of the VFF method can be illustrated as figure 5.

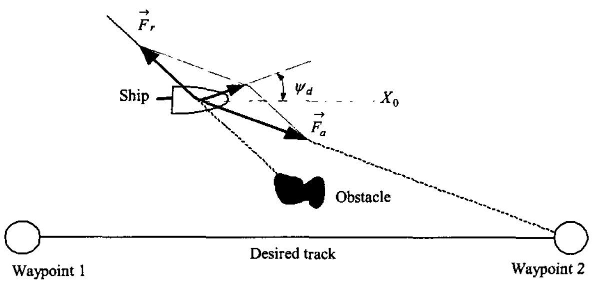


Figure 5 Direct application of VFF method

It consists of F_a (a force component approaching to the next way point) and F_r (a force component repelling from the obstacle). The original VFF method usually uses a closed-form function for those force components. It can be easily imagined that the requirement of track-keeping can not be accomplished flexibly. In the case of moving obstacle, the single function of F_r is not so flexible to handle all of the situations. Furthermore, the obstacles against the marine vehicles may approach from foreside or backside.

The proposed algorithm modifies the VFF method to yield MVFF method. The MVFF method consists of two major modes in order to accomplish track-keeping and collision avoidance in a unified framework. The first mode is named as "track-keeping mode". Figure 6 illustrates the concept of the track-keeping mode of the MVFF method.

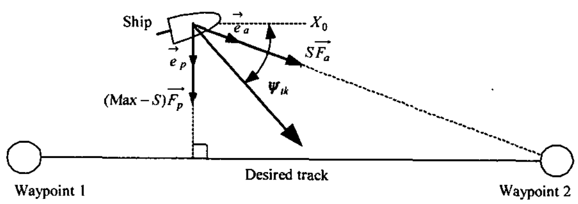


Figure 6. The concept of track-keeping mode of MVFF

It consists of F_a(a force component approaching to the next way point) and F_p(a force component which is perpendicular to the desired track). The mathematical expressions of these force components are different to those of VFF. Equations (1) and (2) represent those force components.

$$F_a = \alpha e_a \tag{1}$$

and

$$F_p = \beta e_p \tag{2}$$

where

e_a : unit vector heading the next way point,

e_p : unit vector heading the desired track perpendicularly,

and where α and β are constants which are determined from corresponding fuzzy rules. Properly designed set of fuzzy rules for α and β provides a <u>standard returning mode</u> of the marine vehicle to the desired track from its deviated location. If it is too far from the desired track, α is very small and β is very large. On the other hand, if it is very near to the desired track, α is very large and β is very small. The more detailed description about α and β is in the section 3.

Vector addition of F_a and F_p may provide new command for heading angle. More flexibility of choosing the returning mode is, however, designed in this paper by introducing the concept of *mode number*. Equation (3) explains this concept.

$$\Psi_{tk} = \angle(SF_a + (Max - S)F_p) \tag{3}$$

where S is the mode number and defined as $S \in [0, Max]$ and where Max is pre-determined off-line via simulation for the specific marine vehicle. angle($\cdot$) is a function which yields the angle of the vector input with respect to $\{X_0, Y_0\}$ and Ψ_{tk} is the heading angle command for the marine vehicle to keep the desired track. If S approaches to Max, then approaching to the next way point has more emphasis. If S goes to zero, then quick returning to the desired track has more emphasis. It implements the concept of the track-keeping mode in the figure 2 and the operator can select a proper mode subjectively.

Collision avoidance in the proposed algorithm is quite different to that of the original VFF method. Figure 7 illustrates the basic concept of the proposed collision avoidance idea.

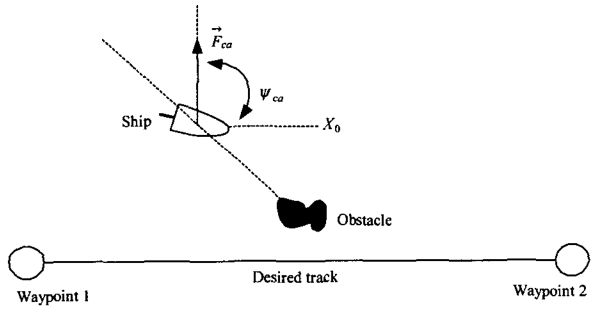


Figure 7. The concept of the proposed collision avoidance

F_r in the original VFF lies on the extended line between the marine vehicle and the obstacle as shown in the figure 5. The direction of F_{ca}, which plays the similar role of F_r in the VFF, in the MVFF is, however, determined from fuzzy rules. These fuzzy rules have four linguistic variables in the premise part and are designed to cope with a lot of different cases of collision. It is investigated thoroughly in the section 4. The heading angle for collision avoidance mode is

$$\Psi_{ca} = \text{angle}(F_{ca}) \tag{4}$$

where Ψ_{ca} is the heading angle to avoid collision.

Now, the combination of equations (3) and (4) yields the heading angle command for the marine vehicle as follows.

$$\Psi_d = \Psi_{tk} + \Psi_{ca} \tag{5}$$

Equation (5) provides the basis of the proposed unified framework for autonomous navigation of marine vehicles. Figure 8 shows the overall block diagram for the proposed algorithm. PID control scheme is used for the 'course-keeping controller' in the figure 8 and its sampling time is much faster (say, 10 times) than the outer loop 'track-keeping controller' with collision avoidance.

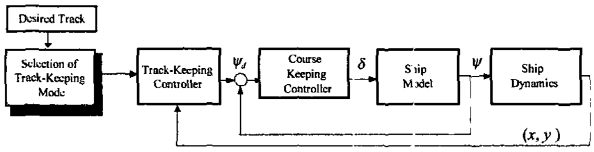


Figure 8. Block diagram for the proposed algorithm

3. Determination Of Ψ_{tk}

The space around the ship is classified as "danger region" and "safe region" as shown the figure 9. The danger region denotes that the marine vehicle is close to the border of the territorial waters of other country. The safe region represents that the ship is in the high seas. The patterns of autonomous navigation in these two regions must be different. The ship must return to the desired track as soon as possible in the danger region as shown in the figure 9. However, the marine vehicle may return to the desired track in various ways in the safe region according to the operator"s choice as explained in the equation (3).

As shown in equations (1), (2), and (3), parameters to be determined for Ψ_{tk} are α, β, and S. The values of α and β determine the representative behavior of the ship in danger and safe regions. Subjective choice of returning pattern in the safe region is implemented by selecting S. As mentioned in section 2, S is selected manually by an operator.

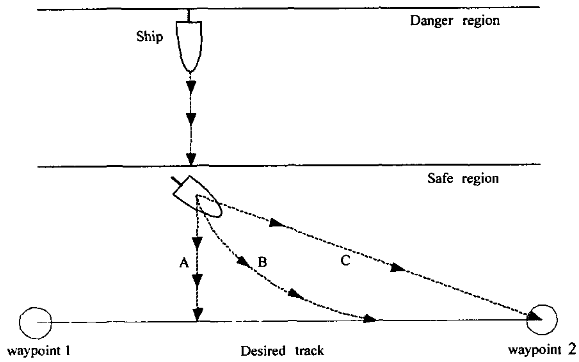


Figure 9. Danger region and safe region

Quick escape motion in the danger region is implemented by assigning $\alpha = 0$ and $\beta = 1$ as illustrated in the figure 10. α and β are, however, determined via fuzzy rules in the safe region. Equation (6) represents the designed fuzzy rules.

$$\begin{aligned} R_1 &: \text{IF } d \text{ is } Near \text{ THEN } \alpha \text{ is } B \text{ and } \beta \text{ is } S \\ R_2 &: \text{IF } d \text{ is } Middle \text{ THEN } \alpha \text{ is } M \text{ and } \beta \text{ is } M \\ R_3 &: \text{IF } d \text{ is } Far \text{ THEN } \alpha \text{ is } M \text{ and } \beta \text{ is } B \end{aligned} \tag{6}$$

where the linguistic variable d denotes the shortest distance of a marine vehicle from the pre-determined desired path and has {Near, Middle, Far} as its term set as shown in the figure 11.

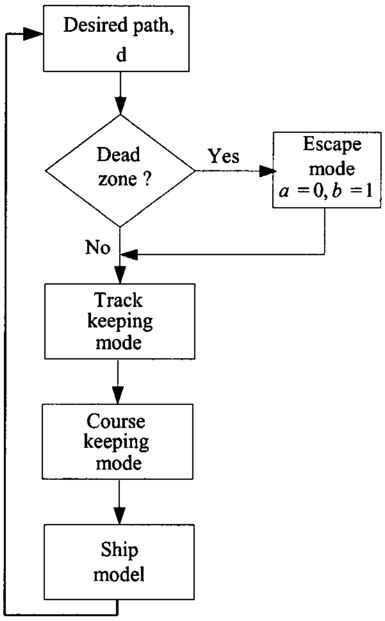


Figure 10. Escape motion in the danger region

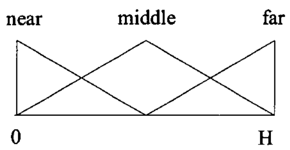


Figure 11. Term set for the linguistic variable d

The universe of discourse H is pre-determined and it determines the range where blending of fuzzy rules happens. Only the fuzzy rule about the term set 'far' fires when the deviation is beyond H.

The term set for α and β is {S(mall), M(edium), B(ig)} and the membership functions are represented in the figure 12.

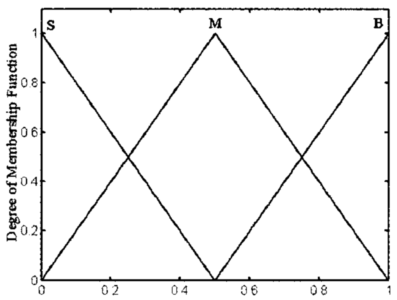


Figure 12. Term set for α and β

If α is much greater than β then the marine vehicle will head to the next way point as shown in the figure 6. On the other hand, if β is much greater than α then the marine vehicle will move toward the desired path as soon as possible. Therefore, the equation (6) means that the weight of the motion of the marine vehicle is given to the pre-determined desired path when the marine vehicle is moved away too far. The next way point gets more emphasis when the marine vehicle is near the pre-determined desired path. Fuzzy logic gives neat blending between these two extreme cases.

4. Determination Of ψ_{ca}

Basically, the VFF method yields good collision avoidance performance especially for static obstacles. However, situations of collision for marine vehicles are complicated. Figure 13 shows the space surrounding a marine vehicle.

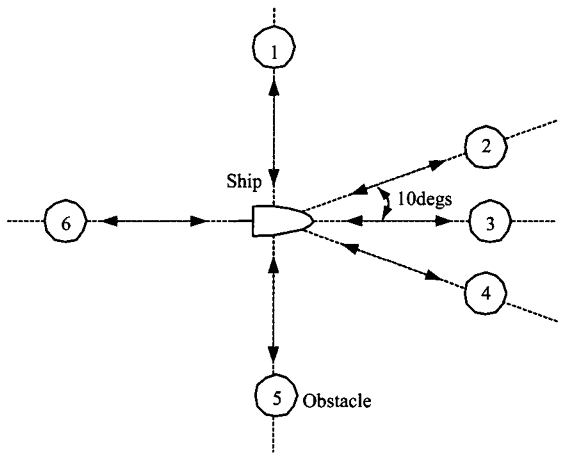


Figure 13. Representative locations of obstacles

Representative locations of possible static or moving obstacles are marked as circled numbers. Fuzzy rules for collision avoidance are designed for these locations.

The front half of the space to which the marine vehicle advances is divided more precisely than the rear half space since the most of the collisions happens in this half space. Fuzzy rules for the divided sectors are designed carefully and these rules are blended using fuzzy inference in order to cover all the space smoothly.

The obstacles can be static or dynamic. The direction of the moving obstacles can be toward or outward the marine vehicle. So, a lot of possible situations should be considered in these fuzzy rules. The original VFF is not so flexible to handle these complicated situations. The proposed MVFF method introduces the concept of the vector of collision avoidance F_{ca}. It is illustrated in the figure 7. This vector is determined via fuzzy rules which have four linguistic variables in the premise part. Equation (7) represents the i_{th} generic fuzzy rule yielding (F_{ca}).

$$\begin{aligned} &\text{IF } d_{obs} \text{ is } (LVd_{obs})_i \text{ and } \nu_{rel} \text{ is } (LV\nu_{rel})_i \\ &\quad \text{and } \theta \text{ is } (LVd\theta)_i \text{ and } \nu_{rel} \text{ is } (LV\phi)_i \\ &\quad \text{THEN angle is } (LV\,\text{angle}(F_{ca}))_i \end{aligned} \tag{7}$$

where ***LV*** is a linguistic value of the linguistic variable and

d_{obs} : distance between the ship and the obstacle,

ν_{rel} : absolute value of relative velocity between the ship and the obstacle,

θ : location of the obstacle with respect to the ship,

ϕ : moving direction of the obstacle measured with

respect to the local coordinate system attached to the ship. Figure 14 illustrates the meaning of θ and ϕ.

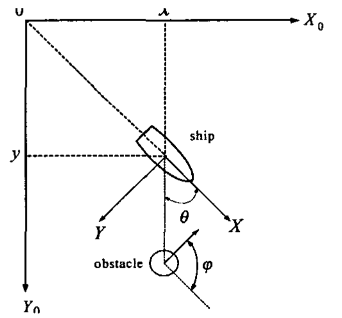


Figure 14. Meaning of θ and ϕ

The term sets of the four linguistic variables are illustrated in the figures 15 ~ 18. Figure 15 represents the term set for the linguistic variable d_{obs}.. It consists of {Near, Far}.

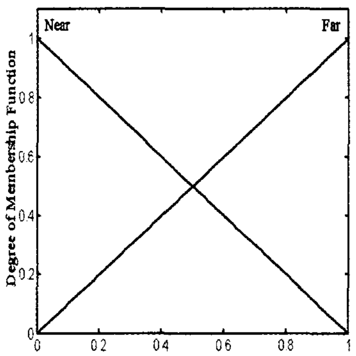


Figure 15. Term set for d_{obs}(nm)

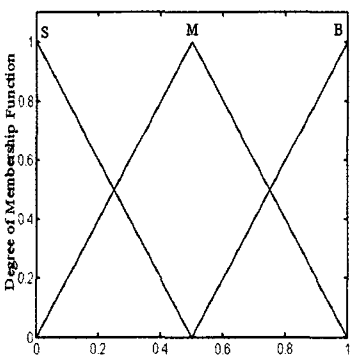


Figure 16. Term set for ν_{rel}(nm/min)

Figure 16 represents the term set for the linguistic variable ν_{rel}. It consists of {S(mall), M(edium), B(ig)}.

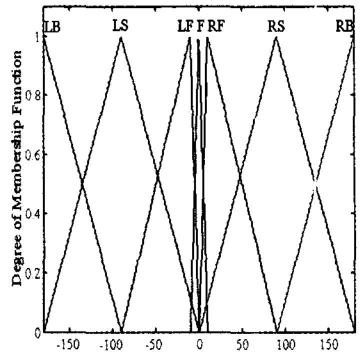


Figure 17. represents the term set for the linguistic variable θ. It consists of {LB, LS, LF, F, RF, RS, RB}. L and R denotes 'Left' and 'Right' B, S, and F mean 'Backside', 'Side', and 'Front', respectively.

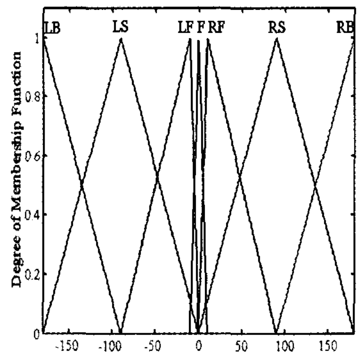


Figure 17. Term set for θ (degree)

Figure 18 represents the term set for the linguistic variable ϕ. It consists of {LB, LS, F, RS, RB}.

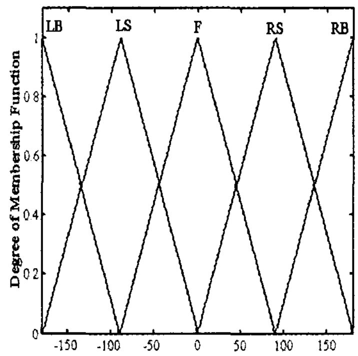


Figure 18. Term set for (degree)

There exist 210 fuzzy rules in total. Note that multiplication of numbers of all the term set yields 210. Table 1 shows consequent parts of the collision avoidance fuzzy rules. The number of each rule is numbered from left to right in the Table 1 sequentially. As an example, a rule

IF d_{obs} is ***Near*** and ν_{rel} is ***S***

and θ is ***LF*** and ϕ is ***LF***

Table 1. Consequent parts of the 210 fuzzy rules

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0.0	0.0	-22.5	0.0	0.0	67.5	0.0	0.0	45.0	-67.5	0.0	0.0	22.5	0.0	0.0	0.0	-22.5	0.0	0.0	67.5	0.0
2	0.0	22.5	45.0	22.5	22.5	67.5	-45.0	0.0	67.5	90.0	67.5	0.0	22.5	0.0	0.0	22.5	45.0	22.5	0.0	67.5	-45.0
3	22.5	0.0	0.0	-22.5	0.0	22.5	0.0	67.5	0.0	0.0	-67.5	0.0	0.0	0.0	22.5	0.0	0.0	-22.5	0.0	0.0	0.0
4	-22.5	-45.0	-22.5	0.0	45.0	-67.5	0.0	-67.5	-90.0	-67.5	0.0	0.0	-22.5	0.0	-22.5	-45.0	-22.5	0.0	45.0	-67.5	0.0
5	0.0	22.5	0.0	0.0	0.0	-67.5	0.0	0.0	67.5	-45.5	0.0	0.0	-22.5	0.0	0.0	22.5	0.0	0.0	0.0	-67.5	0.0
6	0.0	45.0	0.0	0.0	22.5	-45.5	0.0	0.0	90.0	0.0	0.0	0.0	0.0	0.0	0.0	45.0	0.0	0.0	22.5	-45.0	0.0
7	22.5	45.0	-22.5	0.0	45.0	67.5	45.0	22.5	90.0	-67.5	0.0	0.0	22.5	0.0	0.0	45.0	-22.5	0.0	45.0	67.5	45.0
8	0.0	22.5	0.0	45.0	0.0	0.0	-45.0	22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.0	0.0	0.0	-45.0
9	22.5	-45.0	0.0	-45.0	-67.5	-45.0	0.0	67.5	-90.0	0.0	0.0	-22.5	0.0	0.0	22.5	-45.0	0.0	-45.0	-67.5	-45.0	0.0
10	0.0	-45.0	0.0	0.0	45.0	22.5	0.0	0.0	-90.0	0.0	0.0	0.0	0.0	0.0	0.0	-45.0	0.0	0.0	45.0	-22.5	0.0

THEN angle (F_{ca}) is -22.5

means that if the distance to the obstacle is 'Near', the relative velocity between the ship and obstacle is 'Small', the obstacle is located at 'Left Front', and the moving object is approaching from 'Left Front' then the vector for collision avoidance is directing -22.5 degree.

5. Simulations

A marine vehicle used for verification of the proposed algorithm is modeled as follows,

$$
\begin{aligned}
x &= u\cos\Psi - \nu\sin\Psi \\
y &= u\sin\Psi - \nu\cos\Psi \\
\Psi &= r \\
r &= -ar - br^3 + c\delta \\
u &= -fu - Wr^2 + S \\
\nu &= -g_1 u - g_2 \nu^{3_1}
\end{aligned}
\tag{8}
$$

where a, b, c, f, W, S, g_1, and g_2 are ship model parameters and given as $a = 1.084/\text{min}$, $W = 0.067\,\text{nm/rad}^2$, $S = 0.215\,\text{nm/min}^2$, $g_1 = -0.0375\,\text{nm/min}$, and $g_2 = 0$

This model is cited from [4]. Angle and rate of rudder is limited as -35 ~ 35 degree and -120 ~ 120 degree/min for simulation. It is assumed that there exist only surge, sway, and yaw motions.

5.1 Simulations for Track-keeping Mode

Track-keeping ability of the proposed algorithm is investigated in this subsection. Way points used are as follows,

Way Point 1: $x = 10\text{nm}$, $y = 10\text{nm}$
Way Point 2: $x = 60\text{nm}$, $y = 60\text{nm}$
Way Point 3: $x = 50\text{nm}$, $y = 50\text{nm}$

and they are marked as small circles. Simple P-controller with gain $K_p = 0.08$ is used as a course-keeping controller for all the simulations. Figure 19 shows defined danger and safe regions. Width of danger and safe regions are set to 5 nm and 10 nm, respectively.

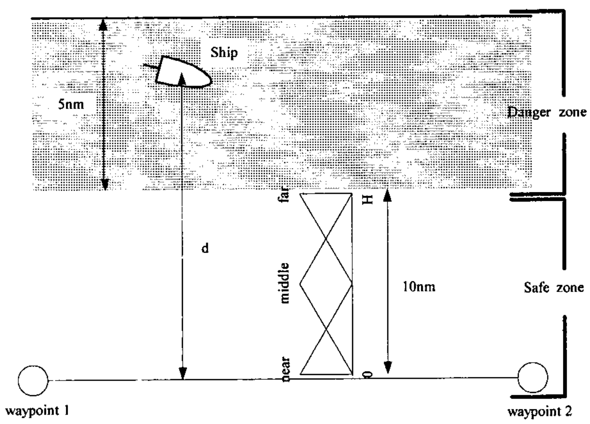


Figure 19. Danger and safe regions

Simulation A. Escaping from the danger region and various returning mode at single initial location of the marine vehicle

The purpose of this simulation is to investigate the performance of escaping from the danger region with various returning mode. The location of the marine vehicle is set to $x = 15\text{nm}$, $y = 25\text{nm}$. S is selected in [0, 10] to show the gradual transition of the returning mode from A to C. Max is set to 10. Figure 20 represents the simulation results. It can be seen that the marine vehicle escapes at the danger region very quickly and various returning modes are performed well as expected.

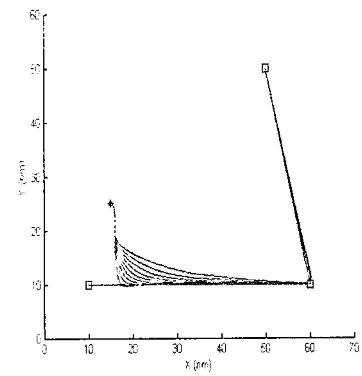


Figure 20 . Escaping from danger region with various returning mode

5.2 Simulations for Collision Avoidance Mode

This subsection investigates the collision avoidance performance of the proposed algorithm. Escaping from the danger region and selection of returning mode are still maintained. In other words, collision avoidance mode is added to the algorithm in the subsection 5-1 and it makes the proposed algorithm good for autonomous navigation of marine vehicles.

Obstacles are classified as 'static' and 'moving'. For the moving obstacles, 8 different situations are examined.

Simulation B. Static Obstacles

The location of the ship is set to $x=15$nm and $y=25$nm for this simulation. As defined before, this location is within the danger region. Mode number are S and Max set to 1 and 10. Therefore, the track-keeping mode is very close to the mode A.

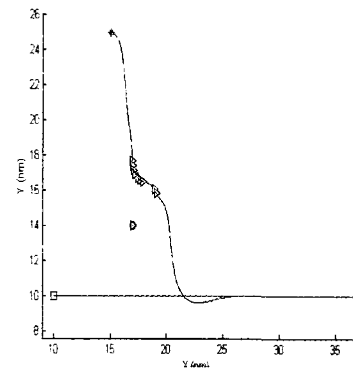
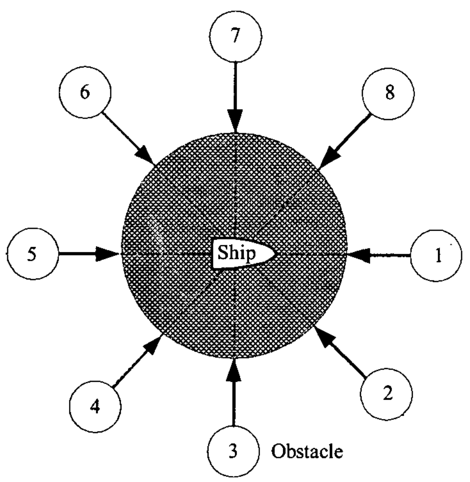


Figure 21. Collision avoidance against a static obstacle at (20, 10) nm

Figure 21 shows that the proposed algorithm works very well for the static obstacles which are placed at arbitrary location.

Simulation C. Moving Obstacles

The proposed collision avoidance algorithm is designed to handle various situations of moving obstacles. Figure 22 illustrates 8 different cases of a moving obstacle. The circled numbers represent moving obstacle and arrows mean their moving directions. Simulations are performed for each obstacle. The ship is moving forward along the desired track.



Figurer 22. An illustration of moving obstacle

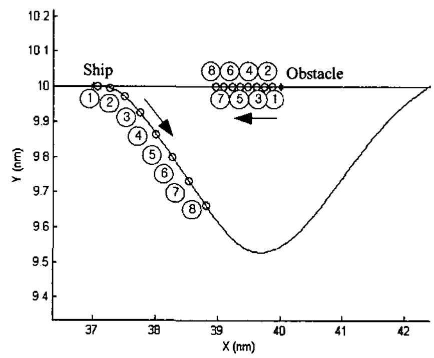


Figure 23. Avoiding an obstacle approaching from the front

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (40, 10)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (-0.13, 0)$nm. Figure 23 shows that the proposed algorithm avoids well the moving obstacle approaching from the front.

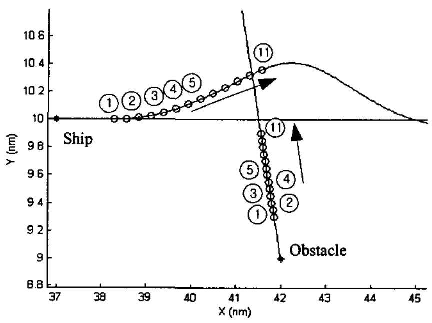


Figure 24. Avoiding an obstacle approaching from right front

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (42, 9)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (-0.01, 0.02)$nm. Figure 24 shows that the proposed

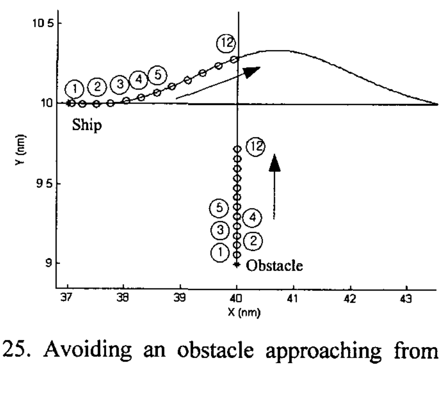


Figure 25. Avoiding an obstacle approaching from right side

algorithm avoids well the moving obstacle approaching from the right front.

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (40, 9)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (0, 0.06)$ nm. Figure 25 shows that the proposed algorithm avoids well the moving obstacle approaching from the right side.

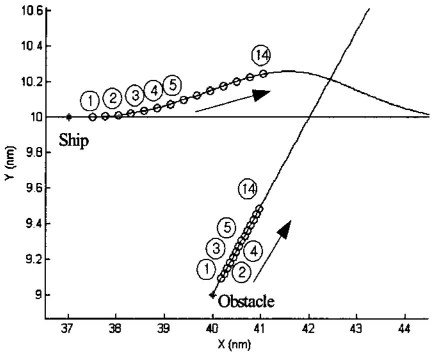


Figure 26. Avoiding an obstacle approaching from right backside

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (40, 9)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (0.06, 0.03)$ nm. Figure 26 shows that the proposed algorithm avoids well the moving obstacle approaching from the right backside.

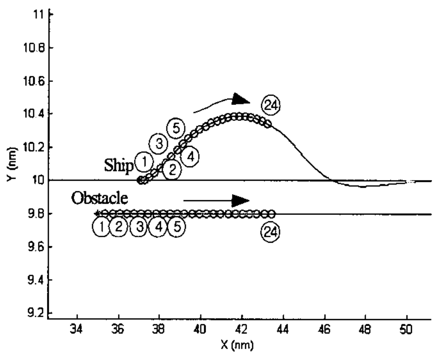


Figure 27. Avoiding an obstacle approaching from backside

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (35, 9.8)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (0.35, 0)$ nm. Figure 27 shows that the proposed algorithm avoids well the moving obstacle approaching from the backside.

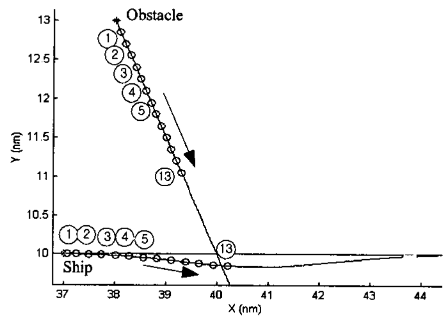


Figure 28. Avoiding an obstacle approaching from left backside

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$nm and $(x, y)_{obs} = (38, 13)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (0.1, -0.15)$nm. Figure 28 shows that the proposed algorithm avoids well the moving obstacle approaching from the left backside.

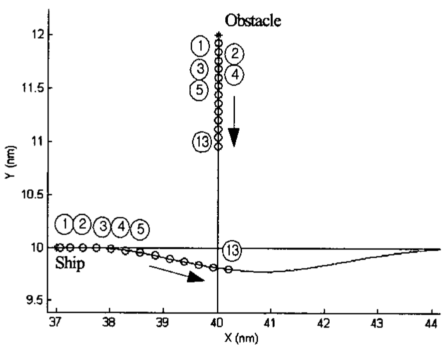


Figure 29. Avoiding an obstacle approaching from left side

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (40, 12)$ nm, respectively. The corresponding velocities are $v_{ship} = (0.275, 0)$ nm/min and $v_{obs} = (0, -0.08)$nm. Figure 29 shows that the proposed algorithm avoids well the moving obstacle approaching from the left side.

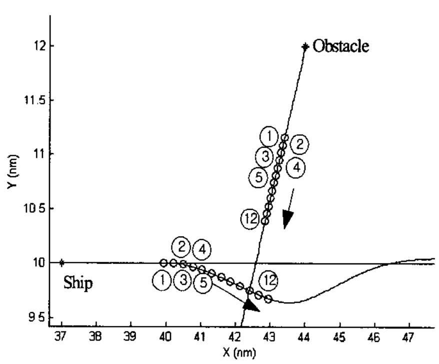


Figure 30. Avoiding an obstacle approaching from left front

The locations of the ship and the obstacle are $(x, y)_{ship} = (37, 10)$ nm and $(x, y)_{obs} = (44, 12)$ nm , respectively. The corresponding velocities are $\nu_{ship} = (0.275, 0)$ nm/min and $\nu_{obs} = (-0.05, -0.07)$ nm Figure 30 shows that the proposed algorithm avoids well the moving obstacle approaching from the left front.

Figures 23 ~ 30 show that the proposed collision avoidance algorithm works well against moving obstacles.

6. Concluding Remarks

An algorithm for new collision avoiding navigation of marine vehicles is proposed in this paper. MVFF (Modified Virtual Force Field) method is newly devised to yield the framework.

Introduction of the concept of α, β, and mode number S gives flexibility on the selection of track-keeping mode. A typical behavior of the ship in the danger region and safe region is implemented by designing fuzzy logic which yields α and β. Furthermore, the concept of mode number S makes possible the operator"s selection of returning mode.

Static or moving obstacles can be avoided with the proposed algorithm. Two hundreds and ten fuzzy rules with four linguistic variables in the premise part are devised deliberately. The moving obstacle can have any direction.

Various simulation results are presented to verify the validity of the proposed algorithm.

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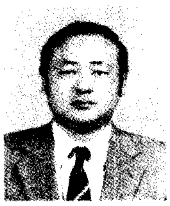

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