Collision Avoidance of Moving Obstacles for Underwater Robots

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ABSTRACT

A fuzzy logic for autonomous navigation of underwater robot is proposed in this paper. The VFF(Virtual Force Field) algorithm, which is widely used in the field of mobile robot, is modified for application to the autonomous navigation of underwater robot. This Modified Virtual Force Field(MVFF) algorithm using the fuzzy logic can be used in either track keeping or obstacle avoidance. Fuzzy logics are devised to handle various situations which can be faced during autonomous navigation of underwater robot. A graphic simulator based on OpenGL for an autonomous navigation has been developed. The good performance of the proposed MVFF algorithm is verified through computer simulations on an underwater robot.

Keywords: Fuzzy Logic, Underwater Robot, MVFF, Obstacle Avoidance, Track Keeping, Navigation, Simulator

1. INTRODUCTION

Nowadays, as the development of ocean resources becomes very active, the demands for underwater work increase rapidly. Accordingly, underwater robots for the general inspection of ocean environment and resources emerge important subjects of research and development[1, 2].

Especially, obstacle avoidance for the underwater robots is a very important subject that has to be considered in order to prevent damages to the underwater robots due to collision with the hazardous objects[3, 4].

The autonomous navigation with obstacle avoiding ability is also very important subject to mobile robot researchers. One of the famous algorithms is the so-called virtual force field(VFF) algorithm. It has been applied to the mobile robots very actively and outstanding results have been reported in the literature [5-8].

The authors modified the VFF(MVFF) using the fuzzy logic in order to make the algorithm more sophisticated and applied to the autonomous navigation of a ship[9]. This paper is an extension of the MVFF to the underwater robots. The 2D problem is extended to 3D and the fuzzy logic became more sophisticated. This paper handles multiple moving obstacles.

Obstacle avoiding Navigation of underwater robots is divided into two consequent stages, which are going toward reference track and moving obstacles avoidance behaviors. The proposed algorithm modified the VFF method to provide track keeping capability in conjunction with obstacle avoidance in the presence of multiple moving obstacles intelligently. Fuzzy logic is adopted to implement export's knowledge. Eight linguistic variables are used in the premise part to include many cases of possible collisions.

In this paper a fuzzy logic for moving obstacles avoiding navigation of underwater robots is proposed. In section 2 of this paper we will discuss about the moving obstacles avoidance algorithm using MVFF. A fuzzy logic for moving obstacles avoidance is presented in section 3. Section 4 presents the 3D simulator packages. Section 5 is the simulation results for behavior of the underwater robots. Finally, section 6 presents a conclusion and a summary along with a discussion of future plans.

2. MOVING OBSTACLES AVOIDANCE ALGORITHM USING MVFF

The basic concept of the VFF algorithm which is applied to the mobile robots comes from the Coulomb's law. The goal attracts the mobile robot while the obstacle repels it, as in the case of electric charges [5-8]. Eq. (1) shows the concept of VFF. It can be seen that it has no function of track keeping, i.e., the mobile robot just goes to the goal from the present position.

$$\vec{R} = \vec{F}_a + \vec{F}_r \tag{1}$$

where $\vec{F}_a$ is the attractive force heading the goal, $\vec{F}_r$ is the repulsive force against the obstacle, and is the resultant of all forces. The magnitude of $\vec{F}_a$ and $\vec{F}_r$ are constants or simple fixed functions. This algorithm works well for static obstacles. Underwater robots, however, face moving objects. Moreover, there usually exists predetermined track(usually the shortest path between neighboring points), which the underwater robot has to follow as precisely as possible for some special applications. The operation of searching the sea bottom may be the example. The original VFF algorithm, however, also fail to offer the flexibility and robustness needed to address this concern, which is important in the navigation of underwater robots. Consequently, we offer a modified VFF, which is capable of operating in either 'track keeping' or 'moving obstacles avoidance'.

The MVFF adds one more force vector, i.e., $\vec{F}_p$, to the Eq. (1) which plays track keeping role. Figure 1 illustrates the concept of MVFF.

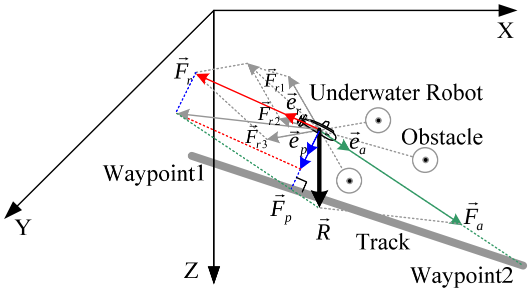


Fig. 1. The concept of MVFF.

The concept of the MVFF can be represented as

$$\vec{R} = \vec{F}_a + \vec{F}_p + \vec{F}_r = \vec{F}_a + \vec{F}_p + (\vec{F}_{r1} + \vec{F}_{r2} + \cdots + \vec{F}_{ri}) \quad (2)$$

where

$\vec{F}_a$: the attractive force heading next waypoint,

$\vec{F}_r$: the repulsive force against obstacles, $i = 1,2,\ldots,n$.

$\vec{F}_p$: the perpendicular force returning to the predefined track,

$\vec{R}$: the resultant of all forces.

One of the novel ideas of the MVFF is in determination of the force terms in the Eq.(2). Eq. (3) shows the way of determining the force terms in the MVFF algorithm.

$$\begin{cases} \vec{F}_a = \alpha \vec{e}_a \\ \vec{F}_p = \beta \vec{e}_p \\ \vec{F}_r = \gamma(\vec{e}_{r1} + \vec{e}_{r2} + \cdots + \vec{e}_{ri}) \end{cases} \quad (3)$$

where $\vec{e}_a$ is the unit vectors directed towards the next way point, $\vec{e}_p$ is orthogonal to predefined track and is directed towards the predefined track. $\vec{e}_{r1}$, $\vec{e}_{r2}$ and $\vec{e}_{ri}$ are unit vectors directed away from the given obstacles. α , β , and γ are parameters which determine the magnitudes of each force terms. Now, sophisticated fuzzy logics determining the parameters are devised to handle various situations which can be faced during autonomous navigation of underwater robots.

Figure 2 shows the overall block diagram for the proposed algorithm. Control of underwater robots is usually carried out via a combination of inner and outer loops. The inner, course-keeping controller attempts to follow the heading angle command(ψ_d , θ_d). Where ψ_d is the desired yaw, θ_d is the pitch angle. A simple PID control scheme is used for the 'course-keeping controller'. The outer, MVFF determines the moving obstacle avoidance and track-keeping control.

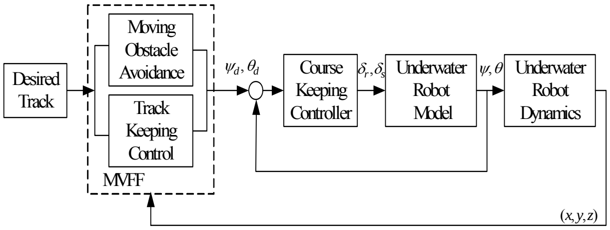


Fig. 2. Block diagram for the proposed algorithm.

It is assumed that the behavior of the underwater robot is controlled by horizontal fin(or stern plane) and vertical fin(or rudder plane). The two fins operate independently of each other. In this paper, the authors designed a simple submarine-type underwater robot just mathematically for this research using the reference[10-12], so the dynamic behavior may not be good. It was enough, however, for this research since the purpose of the research was the feasibility study of the proposed algorithm.

3. FUZZY LOGIC FOR MOVING OBSTACLE AVOIDANCE

In this paper, the gains α , β , and γ for vector $\vec{F}_a$, $\vec{F}_p$, and $\vec{F}_r$ are obtained from the fuzzy logic. These algorithms have the ability to handle track keeping and moving obstacle avoidance in various obstacles environment.

Properly designed set of fuzzy rules for α and β provides efficient track keeping of the underwater robot to the desired track from its deviated location.

Figure 3 represents the term set for the linguistic variable d_α . It consists of {Z(ero), S(mall), B(ig)}. Figure 4 represents the term set for the linguistic variable v_α . It consists of {S(mall), M(edium), B(ig)}. Figure 5 represents the term set for the linguistic variable α . It consists of {Z(ero), S(mall), B(ig)}. Table I shows rule table for α . The universe of discourse is represented normalization. This means that if d_α is small then α is big, if d_α is big then α is small without velocity. It is applied to identical term set and fuzzy rule in horizontal plane control and vertical plane control. It is a different scaling factor.

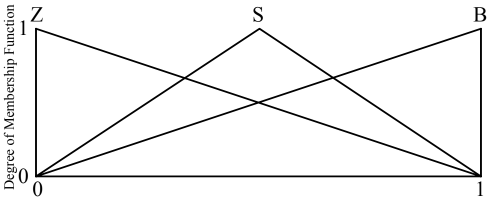


Fig. 3. Term set for d_α

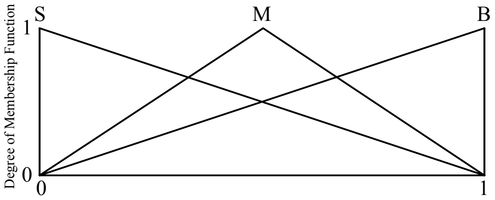


Fig. 4. Term set for v_α

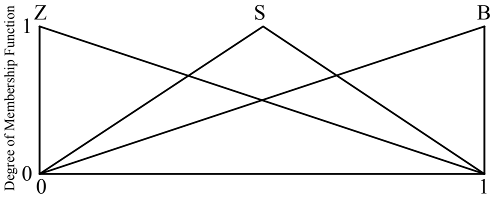


Fig. 5. Term set for α

TABLE I
RULE TABLE FOR α

d_α \ v_α	S	M	B
Z	B	B	B
S	S	S	S
B	Z	Z	Z

β consists of the shortest distance between the underwater robot and predetermined track (e_β) and it's rate(Δe_β). The purpose of this fuzzy rule is to reduce oscillation and return reference track.

Figure 6 represents the term set for the linguistic variable e_β. It consists of {N(egative), Z(ero), P(ositive)}. Figure 7 represents the term set for the linguistic variable Δe_β. It consists of {N(egative), Z(ero), P(ositive)}. Figure 8 represents the term set for the linguistic variable β. Table II shows rule table for β. Table II illustrates the fuzzy rule about set-point regulation.

Basically, the VFF algorithm yields good obstacle avoidance performance, particularly for static obstacles. However, collision situations for underwater robots are generally complicated. The original VFF algorithm is not so flexible to handle these complicated situations. In this paper, space allocation between underwater robot and obstacle are constructed. These are solved by fuzzy logics.

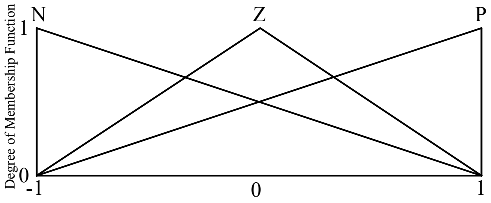


Fig. 6. Term set for e_β and Δe_β .

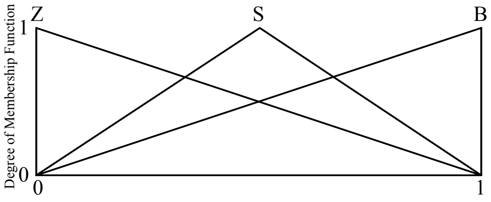


Fig. 7. Term set for β

TABLE II
RULE TABLE FOR β

e_β \ Δe_β	N	Z	B
N	B	S	Z
Z	S	Z	S
B	Z	S	B

Figure 8 shows the space surrounding a underwater robot. Representative locations of possible moving obstacles are marked as circle. Fuzzy rules for collision avoidance are designed for these locations. The front half of the space to which the underwater robot advances is divided more precisely than the rear 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.

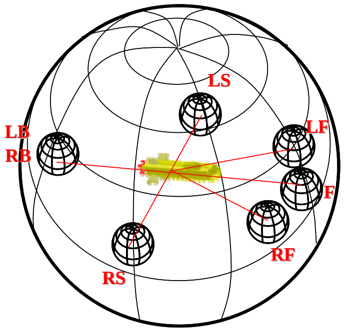
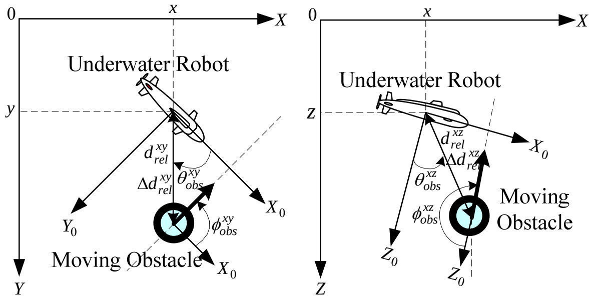


Fig. 8. 3D Representative locations of obstacles.

Figure 9 shows the meaning of premise part term set for γ. The obstacles can be dynamic. The direction of the moving obstacles can be toward or outward the underwater robot. 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 algorithm introduces the concept of the vector of obstacle avoidance $\vec{F}_r$. It is illustrated in the Figure 1. This vector is determined via fuzzy rules which have eight linguistic variables.



(a) xy-plane (b) xz-plane

Fig. 9. Meaning of premise part term set for γ .

Eq. (4) represents the i_{th} generic fuzzy rule yielding γ. It can be applied to horizontal control and vertical control.

$$\begin{aligned}&\text{IF } d_{rel} \text{ is } (LVd_{rel})_i \text{ and } \Delta d_{rel} \text{ is } (LV\Delta d_{rel})_i \\ &\text{and } \theta_{obs} \text{ is } (LV\theta_{obs})_i \text{ and } \varphi_{obs} \text{ is } (LV\varphi_{obs})_i \\ &\text{THEN } \gamma \text{ is } (LV\gamma)_i\end{aligned} \quad (4)$$

where $LV*$ is a linguistic value of the linguistic variable $*$., d_{rel} is the distance between the underwater robot and the obstacle, Δd_{rel} is the rate of d_{rel}, θ_{obs} is the location of the obstacle with respect to the underwater robot, φ_{obs} is the moving direction of the obstacle measured with respect to the local coordinate system attached to the underwater robot.

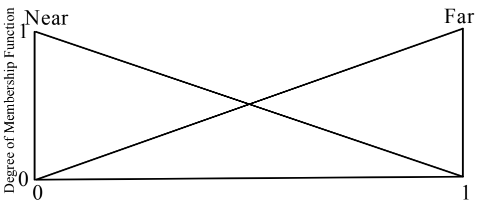


Fig. 10. Term set for d_{rel}

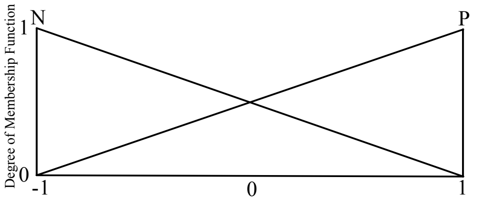


Fig. 11. Term set for Δd_{rel}

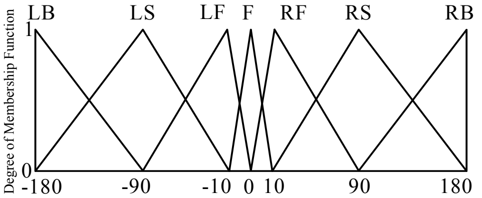


Fig. 12. Term set for θ_{obs}

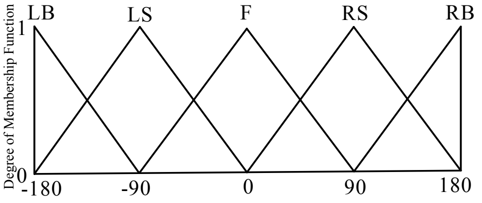


Fig. 13. Term set for φ_{obs}

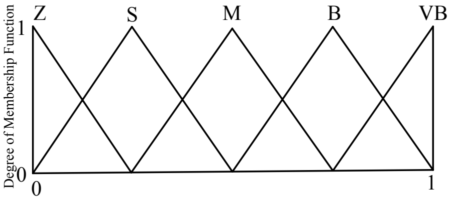


Fig. 14. Term set for γ

TABLE III
RULE TABLE FOR γ

IF d_{rel} is *Near* and Δd_{rel} is *N*,

θ_{obs} φ_{obs}	LB	LS	LF	F	RF	RS	RB
LB	Z	M	M	VB	M	M	Z
LS	S	S	S	B	VB	VB	S
F	M	B	B	M	B	B	M
RS	S	VB	VB	B	S	S	S
RB	Z	M	M	VB	M	M	Z

IF d_{rel} is *Near* and Δd_{rel} is *P*,

θ_{obs} φ_{obs}	LB	LS	LF	F	RF	RS	RB
LB	Z	S	S	B	S	S	Z
LS	Z	Z	Z	M	B	B	Z
F	S	M	M	S	M	M	S
RS	Z	B	B	M	Z	Z	Z
RB	Z	S	S	B	S	S	Z

IF d_{rel} is *Far* and Δd_{rel} is *N*,

θ_{obs} φ_{obs}	LB	LS	LF	F	RF	RS	RB
LB	Z	Z	Z	M	Z	Z	Z
LS	Z	Z	Z	S	M	M	Z
F	Z	S	S	Z	S	S	Z
RS	Z	M	M	S	Z	Z	Z
RB	Z	Z	Z	M	Z	Z	Z

IF d_{rel} is *Far* and Δd_{rel} is *P*,

θ_{obs} φ_{obs}	LB	LS	LF	F	RF	RS	RB
LB	Z	Z	Z	S	Z	Z	Z
LS	Z	Z	Z	Z	S	S	Z
F	Z	Z	Z	Z	Z	Z	Z
RS	Z	S	S	Z	Z	Z	Z
RB	Z	Z	Z	S	Z	Z	Z

The term sets of the four linguistic variables are illustrated in the figure 10 ~ 13. Figure 10 represents the term set for the linguistic variable d_{rel} . It consists of {Near , Far}. Figure 11 represents the term set for the linguistic variable Δd_{rel} . It consists of {N(egative), P(ositive)}. Figure 12 represents the term set for the linguistic variable θ_{obs} . It consists of {LB, LS, LF, F, RF, RS, RB}. L and B denotes 'Left', and 'Right'. B, S, and F mean 'Backside', 'Side', and 'Front', respectively. Figure 13 represents the term set for the linguistic variables φ_{obs} . It consists of {LB, LS, F, RS, RB}. Figure 14 shows the term set of consequent part. It consists of {Z(ero), S(mall), M(edium), B(ig), V(ery)B(ig)}.

The resulting combinations of linguistic variables and their associated term sets result in 140 fuzzy rules as listed in Table III. Fuzzy rules are obtained by designer's intuition and trial and error method.

The proposed algorithm in this paper is able to set the obstacle avoiding distance *r* (Refer to Fig.8 and Fig. 9). The position of the underwater robot is the center of the circle of radius *r* and the circle plays the role of the onset of the obstacle avoidance action. This means that the algorithm ignores obstacles outside the circle but it activates its obstacle avoiding action whenever the obstacles are inside the circle. The radius *r* can be set by the operator appropriately. Therefore, with the assumption of no existence of obstacles within the circle at the onset of the obstacle avoiding algorithm, the collision can always be avoided.

4. SIMULATION PACKAGE

A computer simulator of the physical behavior of underwater robot is developed. The developed simulator was made for user convenience by Microsoft Visual C++ 6.0 that can develop a program supplying graphic user interface environment and by OpenGL of the Silicon Graphics as a graphic library to embody 3D graphic environment. Figure 15 shows a 3D simulator for autonomous underwater robot.

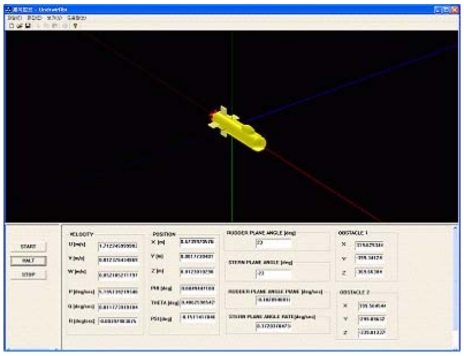


Fig. 15. 3D Simulator

5. SIMULATIONS

In this paper, an extensive simulation study is performed to verify the validity of the proposed algorithm. This model is cited from [10-12]. It is assumed that the underwater robot is following the predefined track which is made by connecting two adjacent waypoints. Multiple moving obstacles are placed around the track. It is also assumed that the real time position of the obstacles can be sensed. The angle and rate of the rudder and stern is limited as -23 ~ 23degrees and -10 ~ 10 degree/s for simulation. The radius of the obstacle avoiding circle of underwater robot and obstacle are 20meters and 60meters. The surge velocity of underwater robot is set to 3meter/s.
Waypoints used are as follows,

Waypoint1: $x = 100$m, $y = -100$m, $z = -100$m
Waypoint2: $x = 500$m, $y = -500$m, $z = -500$m

and they marked as small circles. PID-controller for rudder with gain KpDR = -1.3, KdDR=-2.7 and KiDR = -0.0001 is used as a course-keeping controller for all the simulations. PID-controller for stern with gain KpDS = -7, KdDS=-4.3 and KiDS = -0.013 is used as a course-keeping controller for all the simulations. Where, KpDR, KpDS denote P gain values. KdDR, KdDS denote D gain values. KiDR, KiDS denote I gain values.
In this paper, We compared the MVFF using fuzzy logic with constant and fixed equation at track-keeping and obstacle avoidance. In figure 16, the location of underwater robot is set to $x = 120$m, $y = -150$m, $z = -120$m. The location of obstacle is set to $x = 300$m, $y = -300$m, $z = -300$m. The radius of the obstacle avoiding is marked as black circle.
Figure 16 shows the ability of the MVFF algorithm from the view point of track keeping accuracy over the so-called VFF algorithm which has been used widely in the field of obstacle avoidance of mobile robots. It can be seen easily that the well-designed MVFF outperforms the conventional VFF algorithm.

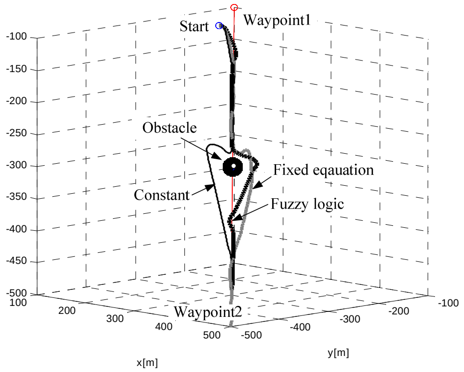


Fig. 16. Performance comparison of the MVFF and VFF algorithms.

In figure 17, the location of underwater robot is set to $x = 120$m, $y = -150$m, $z = -120$m. The location of first moving obstacle is set to $x = 300$m, $y = -327$m, $z = -310$m. The velocity of first moving obstacle is set to $v_{obsx} = -2.5$m/s, $v_{obsy} = 1$m/s, $v_{obsz} = 2$m/s, The location of second moving obstacle is set to $x = 300$m, $y = -327$m, $z = -310$m, The velocity of second moving obstacle is set to $v_{obsx} = -0.6$m/s, $v_{obsy} = 2$m/s, $v_{obsz} = 1.2$m/s. Small circle and big circle is represented the radius of the underwater robot and the obstacle, respectively. The solid line shows the track-keeping and the circle shows the moving obstacle avoidance.
Figure 17 illustrates the ability of the MVFF algorithm in avoiding multiple moving obstacles. It shows the proposed algorithm avoids two moving obstacles nicely while keeping the predetermined track as close as possible.

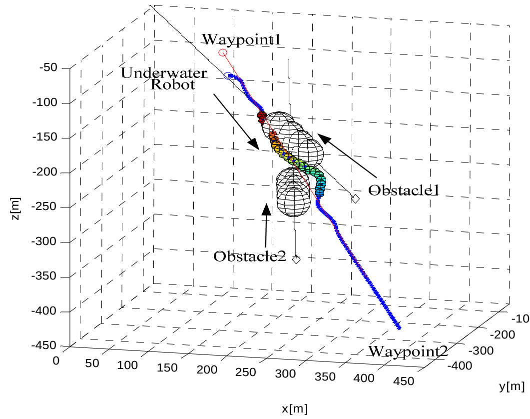


Fig. 17. Obstacles avoidance of the MVFF algorithm in presence of two moving obstacles

Fig. 16 and Fig. 17 show the proposed algorithm avoids multiple moving obstacles nicely while keeping the predetermined track as close as possible.

6. CONCLUSIONS

An algorithm for multiple moving obstacles avoiding autonomous navigation of underwater robots is proposed in this paper. The MVFF (Modified Virtual Force Field) algorithm is newly devised to yield the track keeping and obstacle avoidance. The novel idea of using three parameters α, β, and γ with sophisticated fuzzy logic provides great flexibility in handling more complicated situations of autonomous navigation of underwater robots. Multiple moving obstacles can be avoided with the proposed algorithm. The complete system involves one hundreds and forty fuzzy rules with four linguistic variables in the premise part, which presents a certain challenge from a computational standpoint. Various simulation results are presented to verify the validity of the proposed algorithm.

ACKNOWLEDGEMENT

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