Proceeding of the IEEE
International Conference on Information and Automation
Hailar, China, July 2014

The Obstacle Avoidance Planning of USV Based on Improved Artificial Potential Field

Shaorong Xie, Peng Wu, Yan Peng, Jun Luo,
Dong Qu and Qingmei Li
Department of Mechatronic Engineering
Shanghai University, Shanghai, China
wuzong666666@126.com , {pengyan &luojun }@shu.edu.cn

Jason Gu
Department of Electrical & Computer Engineering
Dalhousie University, Halifax, NSB3H4R2, Canada
Jason.gu@dal.ca

***Abstract* - The autonomous obstacle avoidance planning of USV is the guarantee and the precondition of carrying out the performance. Obstacle avoidance planning is required to possess high accuracy and instantaneity due to a complex environment and faster speed. The algorithm of Artificial Potential Field has the advantage of sample mathematical model, which is easy to understand and implement, and facilitate the underlying control. However, application of traditional Artificial Potential Field has the problems of local minimum, destination unreachable, and poor accuracy of algorithm. Aiming at these issues, a method of the obstacle avoidance planning of Unmanned Surface Vehicle based on improved Artificial Potential Field is proposed in this article, and its feasibility is demonstrated using MATLAB simulation.**

Index Terms - obstacle avoidance planning;* Unmanned Surface Vehicle*; Artificial Potential Field; local minimum

I. Introduction

Unmanned Surface Vehicle (USV) has the features of highly intelligent, fast speed and small volume compared with conventional ships. USV equipped with different sensors and weapon systems can accomplish the tasks of detection, antisubmarine, mine clearance and so on. Many countries have developed a variety of military USV,, 'Spartan Scout' , 'Ghost Rider' , 'Stingray', for example . The obstacle avoidance planning of USV makes USV pass all obstacles safely without collision by selection of a path from zero to target on the premise of security. Among the research of obstacle avoidance planning for USV, the implementation of Artificial Potential Field is most widely used. The theory of Artificial Potential Field (APF) proposed by Khatib is one of most widely used algorithms for obstacle avoidance planning. Its essence is identification of the abstract potential field which consists of the repulsion potential field of obstacles and gravitational potential field of targets in the operational space. Forming a closed-loop control of the current path and the next-time environmental information projects a flowing obstacle avoidance path. However, there are many defects of the APF; the major defect is the problem of local minimum and destination unreachable for obstacles in the vicinity of the target. Thus, in order to acquire better result of obstacle avoidance, the improvement of shortcomings for traditional Artificial Potential Field is necessary when the algorithm of APF is applied to the obstacle avoidance planning of USV.

II. The Model of Traditional Artificial Potential Field

APF model proposed by Kahatib is a common field model at present (Fig.1). In the Artificial Potential Field model, T represent the target which produces the attraction to the USV, O represent obstacles which produce repulsion to the USV.

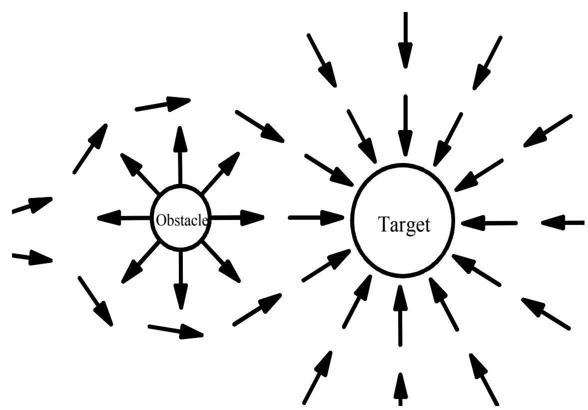

Fig. 1 The model of APF

In two-dimensional space, the collision avoidance problem of USV is relevant to a single obstacle O in Fig.1. If X_d represents the target position, the control of the USV with respect to the obstacle O can be carried out in the artificial potential [1]:

$$U_{art}(x) = U_{att}(x) + U_{rep}(x). \tag{1}$$

where U_{art}, U_{att}, U_{rep} represent artificial potential field, attraction potential energy, and repulsion potential energy respectively. Then its gradient function can be written as

$$F_{art} = F_{att} + F_{rep}, \tag{2}$$

$$F_{att} = -grad\,[U_{att}(X)], \tag{3}$$

$$F_{rep} = -grad[U_{rep}(X)]. \tag{4}$$

Where F_{att} is attraction making the USV reach the target position X_t, and F_O represents a force created by $U_{rep}(X)$ producing the repulsion from the obstacle. F_{att} is proportional

This paper is sponsored by Shanghai Municipal Science and Technology Commission Project (No.12140500400，12111101200) and Shanghai Rising-Star Program (12QH1400900)

to the distance between the USV and the target. Then gain factor of attraction k_p is also taken into account, and the attractive potential field $U_{att}(X)$ is simply written as

$$U_{att} = \frac{1}{2} k_p (X - X_t)^2, \quad (5)$$

In addition, $U_{rep}(x)$ is a non-negative continuous and differentiable function [2]. And the influence of this potential field must be limited to a given region surrounding the obstacle without undesirable perturbing forces [3]. Thus the equation of $U_{rep}(x)$ is written as

$$U_{rep}(X) = \begin{cases} 0.5\eta(\frac{1}{\rho(X, X_0)} - \frac{1}{\rho})^2 & \rho(X, X_0) \le \rho_0, \\ 0 & \rho(X, X_0) > \rho_0. \end{cases} \quad (6)$$

Where $X=(x, y)$ is the position of the USV, $X_0=(x_0, y_0)$ is position of obstacles, $X_t=(x_t, y_t)$ is the position of the target. $\rho(X, X_t) = \|X_t - X\| = \sqrt{(x - x_t)^2 + (y - y_t)^2}$ is the shortest distance between the USV and the target in two-dimensional space. η is the gain factor of repulsion.

$\rho(X, X_0) = \|X_0 - X\| = \sqrt{(x - x_0)^2 + (y - y_0)^2}$ is the shortest distance between the USV and obstacles in two-dimensional space. $\rho(X_0)$ represents safe distance. According to kinetic theory, we select $\rho(X_0) \ge V_{\max} / 2a_{\max}$, where V_{max} represents the maximum speed of the USV, a_{max} represents the maximum capacity of deceleration, η is the gain factor of repulsion [4]. Thus the function of attraction and repulsion are written as

$$F_{att} = -\nabla\left[\frac{1}{2} k_p \rho^2 (X, X_t)\right] = k_p \rho(X, X_t), \quad (7)$$

$$F_{rep} = \begin{cases} \eta(\frac{1}{\rho(X, X_0)} - \frac{1}{\rho^2(X, X_0)})\frac{1}{\rho^2(X, X_0)} & \rho(X, X_0) \le \rho_0, \\ 0 & \rho(X, X_0) > \rho_0. \end{cases} \quad (8)$$

It is supposed that β is an included angle between X-axis and the line from a way point to an obstacle. Then the two components of the repulsion in the direction of X-axis and Y-axis can be obtained. According to an included angle α between X-axis and the line from the target point to the position of the USV, we can get the components of the attraction on X-axis and Y-axis [5].

$$F_{repx}(X, X_o) = F_{rep}(X, X_o)\cos\beta \quad (9)$$

$$F_{repy}(X, X_o) = F_{rep}(X, X_o)\sin\beta \quad (10)$$

$$F_{attx}(X, X_t) = F_{att}(X, X_t)\cos\alpha \quad (11)$$

$$F_{atty}(X, X_t) = F_{atty}(X, X_t)\sin\alpha \quad (12)$$

First the resultant force of the repulsion and the attraction on X-axis and Y-axis is computed. Second the included angle θ, between the resultant force and X-axis, is calculated, which is the steering angle of the USV at present.

$$\theta = \arctan \frac{F_{atty}(X, X_t) + F_{repy}(X, X_o)}{F_{attx}(X, X_t) + F_{repx}(X, X_o)} \quad (13)$$

The next waypoint can be computed constantly according to the following function, until meeting the condition of convergence.

$$\begin{cases} x^* = x + l \times \cos\theta \\ y^* = y + l \times \cos\theta \end{cases} \quad (14)$$

Where l represents step size, x^* and y^* are the position of the next waypoint. Then the traditional APF model is used to make the USV reach the target point safely in the case of obstacles simplified into particles.

However, there are several problems. First, the resultant force of the repulsion and the attraction is zero at a certain point in the process of motion, the USV can stop moving or wander around the point, which is called local minimum of USV. Second, the path can not converge and the USV can not reach the goal when the goal is surrounded by obstacles.

III. THE MODIFIED POTENTIAL FIELD METHOD

A. Background

Scholars all over the world have researched the imperfections of traditional APF, and proposed a variety of improvement strategies. For examples, Simulated Annealing Algorithm combined with APF is used to solve the problems of local minimum and destination unreachable. Its weaknesses are that it requires a large amount of calculation and is time-consuming. Otherwise, there was an algorithm based on circuit scanning, which drove the USV to escape from the local minimum. In this article a regulatory factor was added to improve traditional APF aiming at the case of local minimum and destination unreachable. When the USV is close to the target, this regulatory factor controls attraction for decreasing as a linear function, and repulsion is decreased as a higher-order function (n⩾2) [6]. It avoids no convergence of motion paths.

B. The model of modified potential field method

In two-dimensional space, the function of modified attraction field is identified as

$$U_{att} = \frac{1}{2} k\rho(X, X_t) \quad (15)$$

The function of modified repulsion field is written as

$$U_{rep}(X) = \begin{cases} 0.5\eta(\frac{1}{\rho(X, X_0)} - \frac{1}{\rho})^2 \rho^n(X, X_t) & \rho(X, X_0) \le \rho_0, \\ 0 & \rho(X, X_0) > \rho_0. \end{cases} \quad (16)$$

Where $X=(x, y)$, $X0=(x_0, y_0)$ and $X_t=(x_t, y_t)$ are also the position of the USV, obstacles and the target respectively.

ρ(X, Xt) is also the shortest distance between the USV and the target in two-dimensional space. $\rho_n(X, X_t)$ is the regulatory factor [7]. It is similar to the traditional model; the function of attraction is the negative gradient of attraction field which is written as

$$F_{att} = -\nabla\left[\frac{1}{2}k_p\rho^2(X, X_t)\right] = k\rho(X, X_t) \quad (17)$$

In a similar way, the function of repulsion is the negative gradient of repulsion field which is written as

$$F_{rep} = \begin{cases} \eta F_{rep1}(X) + \dfrac{n}{2}\eta F_{rep2}(X) & \rho(X, X_0) \le \rho_0, \\ 0 & \rho(X, X_0) > \rho_0. \end{cases} \quad (18)$$

In the modified model, F_{rep} can be decomposed into F_{rep1} and F_{rep2}. Where F_{rep1} is the component force in the direction of the line between the USV and the obstacle [8], and F_{rep2} is the component force in the direction of the line between the USV and the target.

$$\begin{cases} F_{rep1} = \left(\dfrac{1}{\rho(X, X_o)} - \dfrac{1}{\rho_o}\right)\dfrac{\rho^n(X, X_t)}{\rho^2(X, X_o)} \\ F_{rep2} = \left(\dfrac{1}{\rho(X, X_o)} - \dfrac{1}{\rho_o}\right)^2\rho^{n-1}(X, X_t) \end{cases} \quad (19)$$

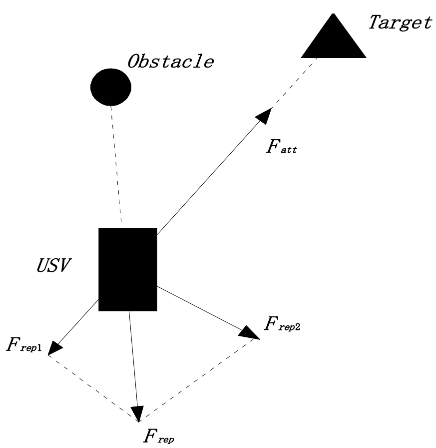

Fig.2 Force analysis of the USV

Where ρ_0 is the safe distance of obstacles, $\rho(X, X_o)$ is the distance between the USV and the obstacle, $\rho(X, X_t)$ is the distance between the USV and the target [9]. It is similar to the calculation of the traditional model, the two components of the repulsion and the attraction in the direction of X-axis and Y-axis can be obtained.

$$\begin{bmatrix} F_{repx}(X, X_o) \\ F_{repy}(X, X_o) \\ F_{attx}(X, X_t) \\ F_{atty}(X, X_t) \end{bmatrix} = \begin{bmatrix} F_{rep}(X, X_o)\cos\beta \\ F_{rep}(X, X_o)\sin\beta \\ F_{attx}(X, X_t)\cos\alpha \\ F_{atty}(X, X_t)\sin\alpha \end{bmatrix} \quad (20)$$

We can compute the resultant force of the repulsion and the attraction on X-axis and Y-axis, and the included angle θ' between the resultant force and X-axis is calculated, which is the steering angle of the USV at present. The next waypoint is calculated until the convergence of the path [10-15].

$$\dot{\theta} = \arctan\frac{F_{atty}(X, X_t) + F_{rep1y}(X, X_o) + F_{rep2y}(X, X_o)}{F_{attx}(X, X_t) + F_{rep1x}(X, X_o) + F_{rep2x}(X, X_o)} \quad (21)$$

$$\begin{cases} x' = x + l^* \times \cos\theta \\ y' = y + l^* \times \cos\theta \end{cases} \quad (22)$$

Where l^* represent step size, x and y' are the position of the next waypoint. Then the model of modified potential field method is used to make the USV reach the target point safely in the case of obstacles simplified into particles [16-22].

The regulatory factor $^{n}(X, X_o)$ is added up in the modified model in this article, if the USV can not reach the target and 0<n<1, F_{rep1} will tend to infinity as the USV is close to the target. The path of convergence is only caused by F_{rep2} and F_{att}. If n=1, F_{rep2} will tend to constant, and F_{rep1} will tend to zero. The path of convergence is also only caused by F_{rep2} and F_{att}. If n=0, F_{rep1} and F_{rep2} all will tend to zero. The path of convergence is also only caused by the attraction [23-26]. Above all, if n is a positive real number, the USV will not encounter the case of local minimum or destination unreachable [27-28].

IV. Simulation Analyses

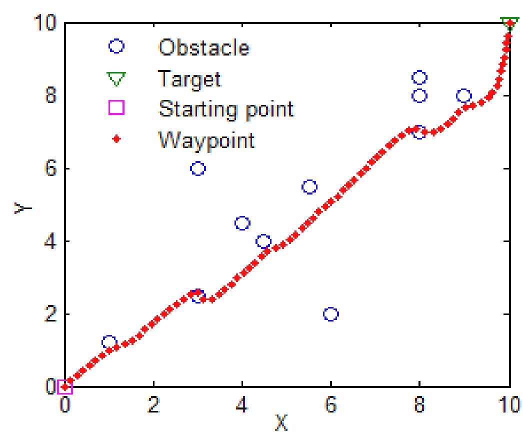

Fig. 3 Simulation result of traditional APF

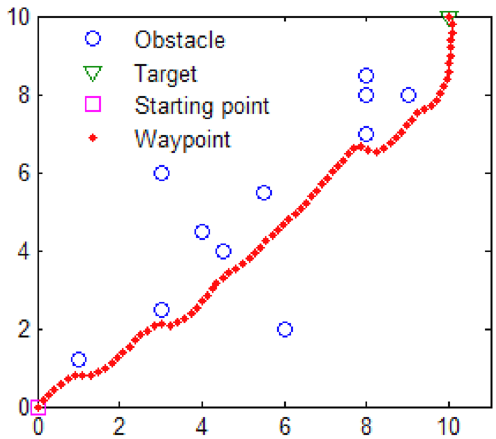

Fig. 4 Simulation result of modified APF

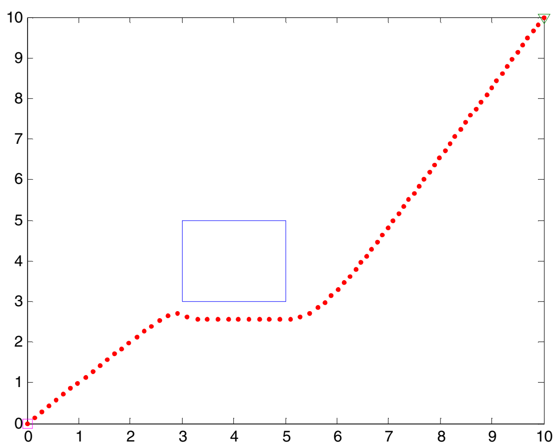

Fig. 5 Simulation result of rectangular obstacles in modified APF

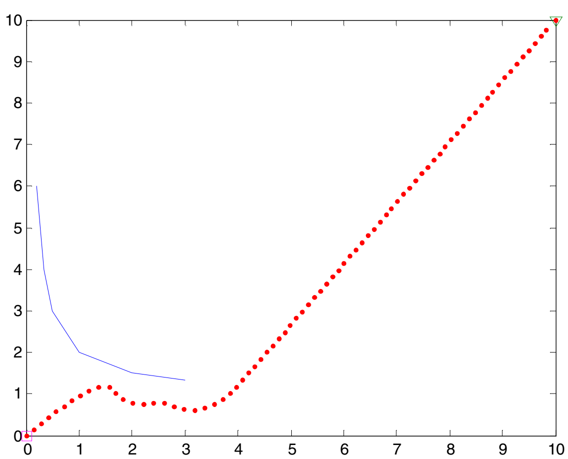

Fig. 6 Simulation result of curved obstacles in modified APF

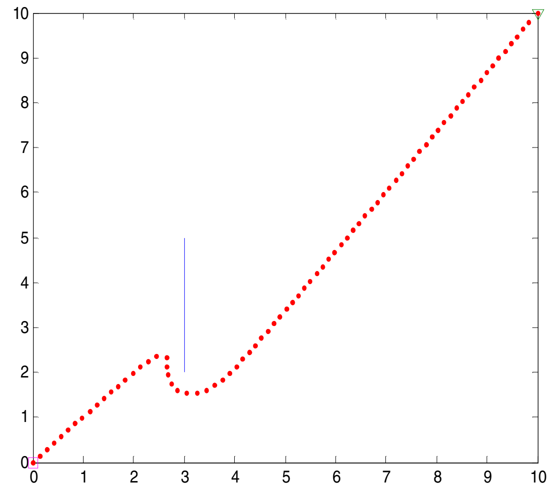

Fig. 7 Simulation result of straight obstacles in modified APF

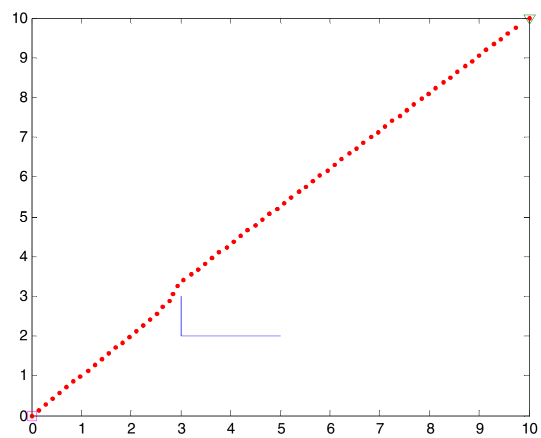

Fig. 8 Simulation result of broken line obstacles in modified APF

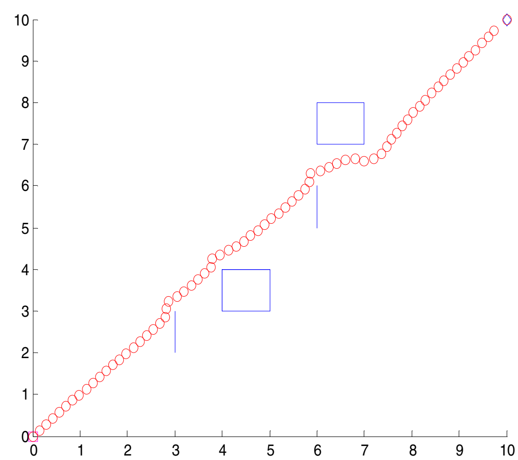

Fig. 9 Simulation result of rectangular and straight in modified APF

TABLE I
THE DIFFERENT STEPS OF THE TWO ALGORITHMS

Traditional APF		Modified APF	
Step size	Steps	Step size	Steps
0.05	305	0.05	306
0.10	153	0.10	154
0.15	102	0.15	103
0.20	76	0.20	78

The process of the algorithm of the obstacle avoidance planning of USV based on modified APF is as follows:

Building the environmental map; detecting the data of the position with the sensors and calculating the attraction and repulsion in the space; defining the next waypoint by the resultant force and steering angle, and reaching the target when meeting the condition of convergence.

A simulation experiment is carried out by MATLAB. The USV moves from the starting point to the target. The gain of attraction and repulsion selected are 20 and 6 respectively. Safe distance $\rho0$ is 3, and the initial step size l is 0.2. If there are obstacles in the vicinity of the target, in the two-dimensional space, the USV may collide with the obstacles near the target in the method of traditional APF (Fig.3), and it can not reach the goal. In the same case, the USV can avoid the obstacles and reach the goal successfully in the method of modified APF (Fig.4). In Table 1, we can conclude that the time of the method of modified APF is approximately the same as the traditional APF. However, in the same case, the method of modified APF can control the USV to avoid obstacles smoothly to reach the goal. In spite of different figurate obstacles, the USV can still bypass such obstacles to reach the goal.

V. CONCLUSION

The planning of obstacle avoidance is among the most important research for USV, allowing the robot to find a safe and collisionless motion path from the starting point to the terminal according to the given algorithm when there are obstacles around the target. APF is a comparatively mature method, which is used widely for its concise and explicit mathematical calculation. However, because of the inherent boundedness in traditional APF, the USV can not apply directly, so aiming at solving the problem that the robot can not reach the target in the algorithm of traditional APF, This article puts forward a modified algorithm of obstacle avoidance. The USV can bypass the obstacles around the target and reach the terminal successfully in the modified APF; meanwhile it wastes the same time as the original algorithm. The goal of the modified traditional APF is to overcome its inherent boundedness, but it is not the optimal motion path. It is necessary to continue research to find an optimal path for solving the local minimum or destination unreachable in the modified algorithm.

REFERENCES

[1] O. Khatib, “Real-time obstacle avoidance for manipulators and mobile robots,” *Intl J of Robotic Research*, vol. 5, no. 1, pp. 90-98, Spring 1986.

[2] J. Borenstein, Y. Koren, “Real-time obstacle avoidance for fast mobile robots,” *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 19, no. 5, pp. 1179-1187, April 1989.

[3] C. Fang and J. Zhao, “New Dynamic Obstacle Avoidance Algorithm with Hybrid Index Based on Gradient Projection Method,” *Journal of Mechanical Engineering*, vol. 46, no.19, pp. 30-37, October 2010.

[4] Z. Zhao, N. Wang, and Z. Zhang, “Implementation of Sensor-based Navigation on Mobile Robots Using Non-360°Range Sensor,” *Journal of Mechanical Engineering*, vol. 46, no. 19, pp. 44-52, October 2010.

[5] M. Wang and J.N.K. Liu, “Fuzzy logic-based real-time robot navigation in unknown environment with dead ends,” *Robotics and Autonomous Systems* vol. 56, no. 7, pp. 625-643, April 2008.

[6] S.K. Pradhan, D.R. Parhi, and AK. Panda, “Fuzzy logic techniques for navigation of several mobile robots,” *Applied Soft Computing*, vol. 9, no.1, pp. 290-304, September 2009.

[7] J. Yang, Z. Cai, and J. Yang, “Efficient Method of Obstacle Avoidance Based on Behavior Fusion for Mobile Robots,” *Journal of Mechanical Engineering*, vol. 48, no. 5, pp. 10, March 2012.

[8] R. Simmons “The curvature-velocity method for local obstacle avoidance,” *IEEE Intl. Conference on Robotics and Automation Minneapolis*, pp. 3375-3382, April 1996.

[9] B. Huang, J. Zhao, and Y. Yao, “Analytical Approach for the Motion Planning of Mobile Manipulator upon the Obstacle Avoidance Region,” *Journal of Mechanical Engineering*, vol. 46, no. 15, pp. 8-16, April 2010.

[10] H.G. Tnnaer and K.J. Kyriakopoulos, “Nonholonomic motion planning for
mobile manipulators, ” *IEEE Intl. Conference on Robotics and Automation*, pp. 1 233-1238, April 2000.

[11] P. Khosla and R. Volpe, “Superquadric artificial potentials for obstacle avoidance and approach,” *IEEE Conf: Robotics Automat*, pp. 1778-1784. March 1988.

[12]A. A. Maciejewski and C. A. Klein, “Obstacle avoidance for kinematically redundant manipulators in dynamically varying environments,” *Int. J. Robotics Res.*, vol. 4, no. 3, pp. 109-117, Fall 1985.

[13]E. Rimon and D.E. Koditschek, “Exact robot navigation in geometrically complicated but topologically simple spaces.” in *Proc. IEEE Int. Conj Robotics Automat.*, pp. 1937-1942, 1990.

[14] V.J. Lumelsky and A.A. Stepanov, “Path-planning strategies for a point mobile automaton moving amidst obstacles of arbitrary shape,” *Algorithmica*, vol. 2, pp. 403-430, 1987.

[15] V.J. Lumelsky, “Algorithmic and complexity issues of robot motion in an uncertain environment.” *J. of Complexity*, vol. 3, no. 2, pp. 146-182, 1987.

[16]I. Kamon and E. Rivlin, “Sensory-based motion planning with global proofs,” *IEEE Trans. Robotics and Automation*, vol. 13, no. 6, pp. 1058-1068, 1997.

[17]V.J. LUMELSKY and T. Skewis, “Incorporating rangesensing in the robot navigation function,” *IEEE Trans. Syst. Man. Cybern.*, vol. 20, no. 5, pp. 1058-1069, 1990.

[18]T. Fraichard and P. Garnier, “Fuzzy control to drive car-like vehicles,” *Robotics and Autonomous Systems*, vol. 24, pp. 1–22, 2001.

[19]H. Seraji and A. Howard, “Behavior-based robot navigation on challenging terrain: a fuzzy logic approach,” *IEEE Transactions on Robotics and Automation*, vol. 18, no. 3, pp. 308–321, 2002.

[20]T.L. Lee, C.J. Wu, “Fuzzy motion planning of mobile robots in unknown environments,” *Journal of Intelligent and Robotic Systems*, vol. 37, no. 2 , pp. 177–191, 2003.

[21]P. Vadakkepat, O.C. Miin, and X. Peng, “Fuzzy behavior-based control of mobile robots,” *IEEE Transactions on Fuzzy Systems*, vol. 12, no. 4, pp. 559–564, 2004.

[22]D.K. Pratihar, W. Bibel, and Near-optimal, “Collision-free path generation for multiple robots working in the same workspace using a genetic-fuzzy systems,” *Machine Intelligence and Robotic Control*, vol. 5, no. 2, pp. 45–58, 2003.

[23]Y. Iwakoshi, T. Furuhashi, and Y. Uchikawa, “A Fuzzy Classifier System for evolutionary learning of robot behaviors,” *Applied Mathematics and Computation*, vol. 91, no. 1, pp. 73–81, 1998.

[24]B.H. Krogh and F. Dai, “Dynamic generation of subgoals for autonomous mobile robots using local feedback information,” *IEEE Trans. Autom. Control*, vol. 34, no. 5, pp. 483-493,1989.

[25]F. Janabi-Sharifi and D. Vinke, "Integration of the artificial potential field approach with simulated annealing for robot path planning," *Proceedings of the 1993 IEEE International Symposium on Intelligent Control*, pp. 536-541, 1993.
[26]E. Rimon and D. E. Koditschek, "Exact Robot Navigation Using Artificial Potential Functions," *IEEE Trans. on Robotics and Automation*, vol. 8, no. 5, pp. 501-518, 1992.
[27] R.A. Rutenbar, "Simulated Annealing Algorithms: Anoverview," *IEEE Circuits and Devices Magazine*, pp. 19-26, January 1989.
[28]A. Elnagar and A.M. Hussein, "Motion planning using Maxwell's equations,"in *Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, vol. 3, pp. 2347–2352, Oct. 2002.