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An Evolutionary Artificial Potential Field Algorithm for Dynamic Path Planning of Mobile Robot

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Abstract - **The artificial potential field (APF) method is widely used for autonomous mobile robot path planning due to its simplicity and mathematical elegance. However, most researches are focused on solving the path-planning problem in a stationary environment, where both targets and obstacles are stationary. This paper proposes a new APF method for path planning of mobile robots in a dynamic environment where the target and obstacles are moving. Firstly, the new force function and the relative threat coefficient function are defined. Then, a new APF path-planning algorithm based on the relative threat coefficient is presented. Finally, computer simulation and experiment are used to demonstrate the effectiveness of the dynamic path-planning scheme.**

Index Terms -Artificial Potential Fields, Path Planning, Moving Obstacle Avoidance, Threat Coefficient

I. Introduction

RoboCup is an international research and education initiative. In RoboCup Middle-Size League (MSL) competition, the robot soccer players must navigate in a dynamic, partially unknown environment, cooperate with teammates and compete with opponents, track moving objects to protect the goal and kick the ball in the right direction, while performing real time visual perception tasks. For all the aforementioned tasks, accurate collision-free path planning is one of the most important challenges.

The goal of collision-free path planning is to find a continuous path for a robot from initial position to the goal position. Many algorithms for path planning have been studied and developed over the past few years [1, 2]. The main methods of path planning for mobile robot can be divided into two categories—artificial potential field (APF) approaches and artificial intelligence (AI) approaches [3].

The main AI-based approaches for robot path planning are the genetic algorithm, the fuzzy control algorithm and the Artificial Neural Network [4]. The computational complexity of these approaches limits real-time applications to only very simple cases, because their computation time increases exponentially with the number of robots and the complexity of the environment. This solution is unfeasible in the RoboCup competition, since the environment is unstructured and the robots need real-time path planning.

The basic idea of the APF approach is to fill the robot's workspace with an artificial potential field in which the robot is attracted to its target position and is repulsed away from the obstacles [5]. This method is particularly attractive because of its elegant mathematical analysis and simplicity. The application of APF for obstacle avoidance was first developed by Khatib [6]. In the past decade this method has been studied extensively for autonomous mobile robot path planning by many researchers [7-14].

In previous studies, APF methods have been used to deal with mobile robot path planning in stationary environments, where targets and obstacles are all stationary. However, in many real-world implementations, the environments are dynamic. In this kind of application, the traditional APF is not applicable as it would cause inefficient path planning or generate a local minimum problem. Ref. 9 proposes one evolutionary artificial potential field in which both the vector of velocity and acceleration are considered. This method can be efficiently applied in a dynamic environment to avoid moving obstacles. However in the RoboCup case, since the robots are moving in an antagonistic environment, the problem can not be solved by considering only the robot's and the obstacle's absolute velocity.

Therefore, a new evolutionary APF method based on relative threat coefficient is proposed in this research to deal with this antagonistic and unknown environment. This algorithm synthesizes the effect of the relative location and velocity among the robot, the obstacle and the goal to escape local minima.

The remainder of the paper is organized as follows: Section 2 presents the limits of a traditional APF method in dynamic environments. Section 3 discusses the force function in APF model in the RoboCup MSL soccer robot system. Section 4 discusses the new APF algorithm based on threat coefficient. Simulation and experimental results are described in Section 5 to demonstrate the effectiveness of the dynamic path-planning scheme. Section 6 concludes this paper with final remarks.

II. Problem Statement

The APF uses two types of potential field, namely a repulsive potential field to force a robot away from obstacles or forbidden regions and an attractive potential field to drive the robot to its goal. The robot moves under the action of a force that is equal to the negative gradient of that potential, and it is driven towards the positions with the lower potential.

In this paper, we consider the robot as one particle that moves under the action of the composition of forces $\vec{A}_r$, which is the summation of the goal's attractive force $\vec{F}_{rg}$ and the obstacle's repulsive force $\vec{F}_{or}$, as shown in Fig.1.

The traditional APF for robot path planning is often applied in static environments, where the obstacles and the goals are all stationary. In RoboCup competition, the opposing robots are the obstacles; the ball and the goal can be considered as the goals.

In a dynamic environment, the common predigesting model considers the robot and the ball as in the static state in one proceeding cycle period. However, this method ignores the trend of moving obstacles, leading to inefficient robot paths. In the example reported in Fig.2, since the obstacle is moving away from the robot, the robot's path should not be affected by the obstacle (blue line). Instead, the traditional APF method takes into account the presence of the moving obstacle, the resulting robot's path (blue dashed line) is clearly sub-optimal.

III. Force Function In Apf Model

In the RoboCup soccer robot system, the reasonable repulsive force should be configured as follows: it should increase when the robot gets closer to the obstacle in order to repel the robot away from the obstacles. It should increase quickly in some range of distance so that the robot can avoid collision effectively; and it should increase slowly outside this range. Finally, if the obstacle is far enough from the robot, it should not affect the robot's path. Therefore, after comparing several repulsive forces' characteristics as shown in Fig.3, we choose the repulsive force as shown in (1).

$$\vec{F}_{or} = \left(\eta\sqrt{D_{ro}^{-1} + (D_{ro})_{\max}^{-1}}\,\overrightarrow{OR}\right) \Big/ (D_{ro})^2 \tag{1}$$

where η is the proportional gain of the function; D_{ro} is the Euclidean distance between the robot and the obstacle; $(D_{ro})_{\max}$ represents the Euclidean distance limit of influence between the robot and the obstacle, the selection of the distance $(D_{ro})_{\max}$ depends on the maximum speed of the robot and the control period [6]; and $\overrightarrow{OR}$ is the vector from the robot to the obstacle.

For what concerns the choice of the attractive force, the principle is that the robot should rush to the goal as quickly as possible. Therefore we construct the attractive force $\vec{F}_{rg}$ as (2) shown.

$$\vec{F}_{rg} = \xi\,\overrightarrow{RG} \tag{2}$$

where ξ is the proportional gain of the function; $\overrightarrow{RG}$ is the vector from the robot to the goal in Euclidean metric.

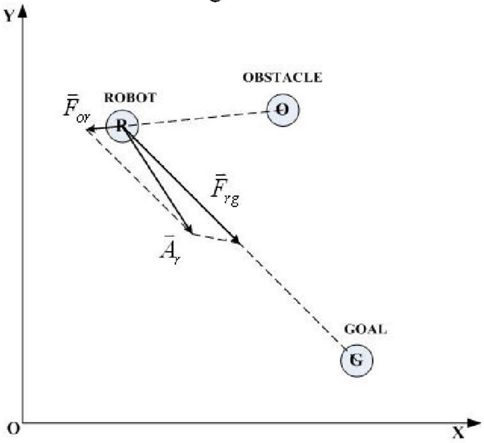

Fig. 1 Virtual attractive force of robot in APF

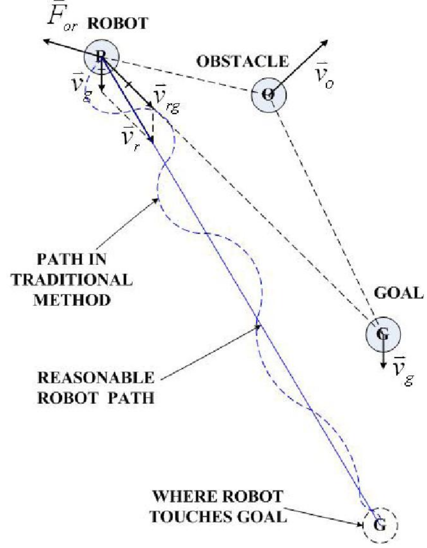

Fig. 2 The problem of traditional APF method in dynamic environment

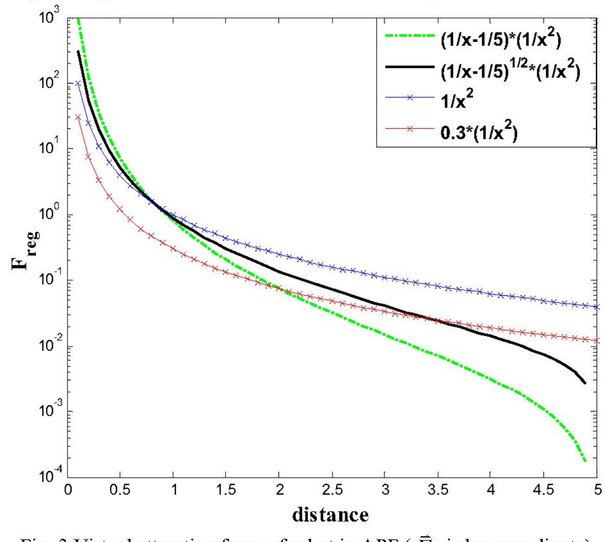

Fig. 3 Virtual attractive force of robot in APF ($\vec{F}_{or}$ is log coordinate)

Therefore, the total force $\vec{A}_r$ can be obtained by adding the attractive force $\vec{F}_{rg}$ and the repulsive force $\vec{F}_{or}$, as shown in (3).

$$\vec{A}_r = \vec{F}_{rg} + \vec{F}_{or} = \eta \frac{\sqrt{D_{ro}^{-1} + (D_{ro})_{\max}^{-1}}}{(D_{ro})^2} \overrightarrow{OR} + \xi \overrightarrow{RG} \tag{3}$$

IV. AMELIORATIVE APF ALGORITHM BASED ON THREAT COEFFICIENT

A. Robot and Environment Coordinates

As shown in Fig.4, suppose that at a generic instant of time T_0, the velocity of the goal is $\vec{v}_g$, the velocity of the robot is $\vec{v}_r$, and the relative velocity between goal and robot is $\vec{v}_{rg} = \vec{v}_r - \vec{v}_g$. The angles of these vectors are defined as:

$$\theta = \angle\vec{v}_{rg} - \angle\vec{v}_g \tag{4}$$

$$\beta = \begin{cases} \arcsin(\sin\theta \times |v_r| / |v_g|) & \text{if } v_g \neq 0 \\ 0 & \text{if } v_g = 0 \end{cases} \tag{5}$$

The velocity of the obstacle $\vec{v}_o$ is

$$\vec{v}_o = \vec{v}_{og} + \vec{v}_g = \vec{v}_{or} + \vec{v}_r \tag{6}$$

$$\gamma = \angle\vec{v}_{or} - \angle\overline{OB} \tag{7}$$

where the $\vec{v}_{og}$ is the relative velocity from the obstacle to the goal; $\vec{v}_{or}$ is the relative velocity from the obstacle to the robot.

When $\gamma \in [\pi, 2\pi)$, the obstacle is moving away from the robot, so the collision-avoiding action is not necessary.

Therefore, we can build the reference frame as shown in Fig. 5: the X–Y reference frame is the robot's global coordinate system; X'–Y' reference frame is the robot's local coordinate system. Suppose the X' axis is aligned with $\vec{v}_r$. α is the angle between RO and RG; β is the angle between RG and $\vec{v}_r$; γ is the angle between $\vec{v}_{or}$ and RO; δ is the angle between $\vec{v}_{or}$ and Y'. All these angles take counter-clockwise as positive direction except δ. And the relationship of these angles can be described as shown in (8):

$$\delta = \pi/2 - \alpha - \beta - \gamma \tag{8}$$

B. Analysis of the Threat Coefficient Function

In the RoboCup scenario, the robots are moving in an antagonistic and dynamic environment. As stated before, the problem can't be solved by considering only the robot's and the obstacle's absolute velocity. Therefore, a new evolutionary potential field method based on relative threat coefficient is proposed in this paper. This threat coefficient, defined as e_{or}, is determined by synthesizing the effect of the relative position and velocity among the robot, the obstacle and the goal. When the obstacle is far away from the robot or it is moving away from the robot, this obstacle makes no threat to the robot, i.e. $e_{or} = 0$; if the robot is close enough to the obstacle or it is moving toward the obstacle, then $e_{or} = 1$.

At first, we should define the maximum threat range $(D_{threat})_{\max}$, exceeding which the obstacle makes no threat to the robot, i.e. $e_{or} = 0$, as shown in (9).

$$(D_{threat})_{\max} = T_{action} \times v_{or} \times \cos\gamma \quad \text{if } \gamma \in [0, \pi/2) \text{ and } \vec{v}_{or} > 0 \tag{9}$$

where T_{action} is the time that the obstacle takes from moving into the threat range to impacting with the robot. This parameter depends on the robot's capability.

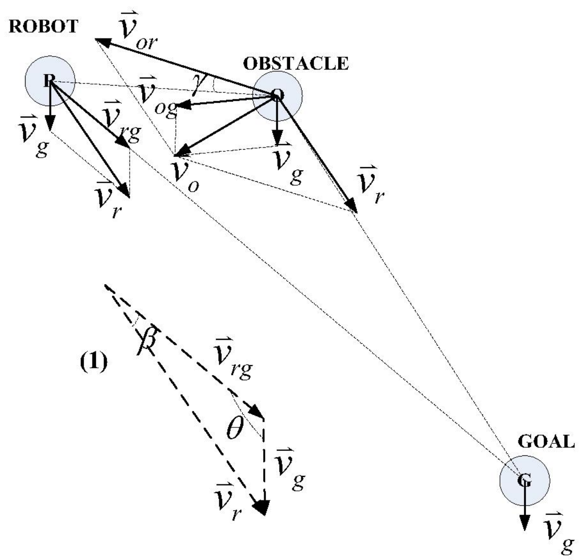

Fig.4 Decomposition of velocity vectors of the robot and obstacle

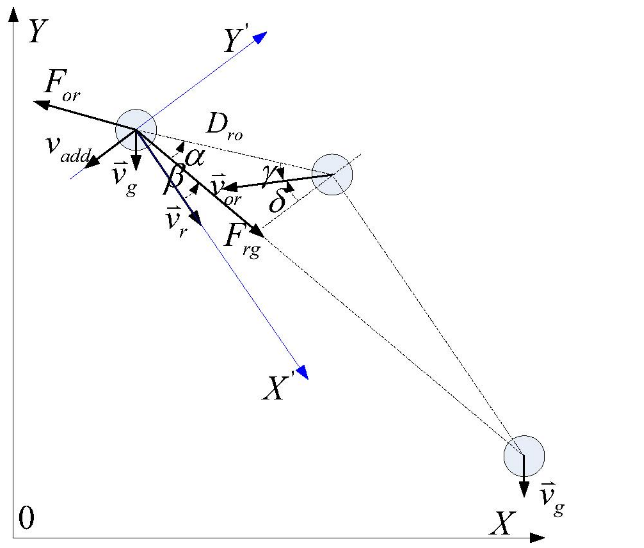

Fig. 5 Decomposition of velocity vectors of the robot and obstacle

Secondly we define the minimum threat range $(D_{threat})_{\min}$, which can be defined by (10).

$$(D_{threat})_{\min} = T_{cycle} \times (v_{or})_{\max} \quad (10)$$

where T_{cycle} is the complete command cycle.

$(D_{ro})_{\max}$ in (1) (which should satisfy the condition $(D_{ro})_{\max} \geq (D_{threat})_{\max}$) can be calculated as:

$$(D_{ro})_{\max} = T_{action} \times ((v_r)_{\max} + (v_o)_{\max}) \quad (11)$$

Therefore we can write the following relationship:

$$D_{ro} > (D_{threat})_{\max} \rightarrow e_{or} = 0 \quad (12)$$

$$D_{ro} \leq (D_{threat})_{\min} \rightarrow e_{or} = 1 \quad (13)$$

The relative position of the obstacle and the robot can be described by parameter $(\alpha + \beta)$. Namely we define three possible regions:

(1) When $(\alpha + \beta) \in (\pi/2, 3\pi/2)$, the obstacle is behind the robot's moving direction, then $e_{or} = 0$ obviously;

(2) When $(\alpha + \beta) \in [-\pi/2, 0) \uplus (0, \pi/2]$, the obstacle is in front of the robot, e_{or} should be confirmed by other parameters;

(3) When $(\alpha + \beta) = 0$, the obstacle is directly ahead of the robot, e_{or} also should be confirmed by other parameters.

Firstly, we discuss the case in region 2. In this space, the vector $\overrightarrow{RO}$ affects e_{or} directly, and the vector $\vec{v}_{or}$ affects $\overrightarrow{RO}$ directly. Therefore, e_{or} is a function of $(D_{ro}, v_{or}, \alpha, \beta, \gamma)$, i.e.:

$$e_{or} = f(D_{ro}, v_{or}, \alpha, \beta, \gamma) \quad (14)$$

Through analyzing, we can find that when $\|\overrightarrow{RO}\|$, i.e. D_{ro} decreases, e_{or} increases; when $\angle\overrightarrow{RO}$, i.e. $(\alpha + \beta)$ decreases, e_{or} increases. And the change of $\overrightarrow{RO}$ can be decided by $\vec{v}_{or}$.

Suppose that t_1 and t_2 are the instants of time when $D_{ro} = 0$ and $(\alpha + \beta) = 0$ respectively. Assuming $v_{or} \neq 0$, we can write:

$$t_1 = D_{ro} / (v_{or} \cos\gamma) \quad \text{when } D_{ro} > (D_{threat})_{\min} \quad (15)$$

$$t_2 = (\alpha + \beta) D_{ro} / (v_{or} \sin\gamma) \quad \text{when } (\alpha + \beta) \neq 0 \quad (16)$$

Therefore, we can simplify the function of e_{or} as $f(t_1, t_2)$. Based on the practical experience, we can get one predigested model of e_{or}:

$$e_{or} = k_1 T_{cycle} / t_1 + k_2 / t_2 + k_3 \quad (17)$$

Combining (15), (16) and (17), we can calculate e_{or} as follows:

$$e_{or} = k_1 T_{cycle} \times v_{or} \cos\gamma / D_{ro} + k_2 v_{or} \sin\gamma / ((\alpha + \beta) D_{ro}) + k_3$$
$$\text{when } (\alpha + \beta) \in [-\pi/2, 0) \uplus (0, \pi/2] \quad (18)$$

k_1, k_2, k_3 are scaling factors to ensure $e_{or} \in (0,1)$.

Secondly, we discuss the case in region 3, as shown in Fig.5.When $\gamma \in [\pi/2, 3\pi/2]$, or $v_{or} = 0$, the obstacle moves away from the robot or the change of its relative position to the robot is negligible. We therefore can assume $e_{or} = 0$.When $\gamma \in (-\pi/2, \pi/2)$, through similar analysis, we can define the function of e_{or}' as:

$$e_{or}' = k_1' T_{cycle} \times v_{or} \cos\gamma / D_{ro} + k_2' / (v_{or} |\sin\gamma|) + k_3'$$
$$\text{When } D_{ro} > (D_{threat})_{\min} \text{ and } (\alpha + \beta) = 0 \quad (19)$$

k_1', k_2', k_3' are scaling factors to ensure $e_{or} \in (0,1)$.

Therefore, the function of the threat coefficient can be defined as follows:

$$e_{or} = \begin{cases} k_1 \dfrac{T_{cycle} \times v_{or} \times \cos\gamma}{D_{ro}} + \dfrac{k_2 \times v_{or} \times \sin\gamma}{(\alpha + \beta) D_{ro}} + k_3 \\ \quad \text{if } D_{ro} > (D_{threat})_{\min}, (\alpha + \beta) \in [-\pi/2, 0) \uplus (0, \pi/2], \\ \quad \text{and } \gamma \in [0, \pi/2) \\ k_1' \dfrac{T_{cycle} \times v_{or} \cos\gamma}{D_{ro}} + \dfrac{k_2'}{v_{or} |\sin\gamma|} + k_3' \\ \quad \text{if } D_{ro} > (D_{threat})_{\min}, (\alpha + \beta) = 0, \gamma \in (-\pi/2, \pi/2) \\ 1 \\ \quad \text{if } D_{ro} \leq (D_{threat})_{\min} \\ 0 \quad \text{otherwise} \end{cases} \quad (20)$$

C. Application of the Threat Coefficient in APF

When $e_{or} = 0$, the obstacle does not influence the robot's path, and the collision-avoidance mechanism is not necessary. When $v_g = 0$, then $v_r = (v_r)_{\max}$, $\angle\vec{v}_r = \angle\vec{v}_{rg}$; when $v_g \neq 0$, then $v_r = (v_r)_{\max}$, $\angle\vec{v}_r = \angle\vec{v}_{rg} - \beta$, where β is calculated using (5).

When $e_{or} \in (0,1)$, the obstacle threats the robot's path. The Y'-axis projection of $\vec{v}_{or}$ is defined as $\vec{v}_{add}$, as shown in Fig. 6 and (21).

It is worth noticing that when the robot and the obstacle are aligned, the sum of the vectors may be equal to zero. In order to prevent the emergence of a local minimum problem, we add one constant C in the function of $\vec{v}_{add}$.

$$\vec{v}_{add} = \begin{cases} \vec{v}_{or} // Y' + c & \text{if sum of all vectors is 0} \\ \vec{v}_{or} // Y' & \text{else} \end{cases} \quad (21)$$

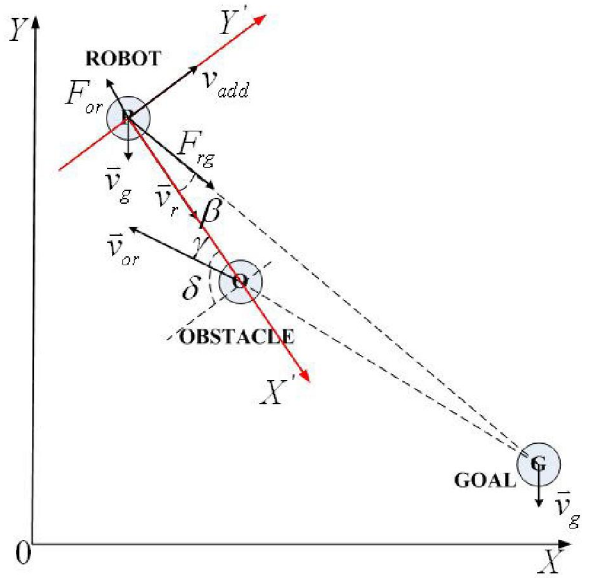

Fig. 6 Improvement of APF method when the obstacle is in front of the robot

Finally the APF force function based on threat coefficient can be defined as follows, where n_1, n_2, n_3, n_4 are practical parameters.

$$\vec{A}^* = n_1\vec{F}_{rg} + n_2 e_{or}\vec{F}_{or} + n_3\vec{v}_g + n_4 e_{or}\vec{v}_{add} \quad (22)$$

V. Simulation And Experiment

In this section, we present the simulation and experimental studies on the new path-planning scheme in the 2-dimensional RoboCup environment. In the operational space, there is one moving target (the orange cycle one), one moving robot (the black cycle one) and one moving obstacle (the black pane one), as shown in Fig.7. The flow diagram of the path planning algorithm is shown in Fig.8. In Fig.9, the black hollow cycle represents the robot's trajectory, the black pane represents the obstacle's trajectory, and the orange solid cycle represents the goal.

Suppose that the robot's initial position is (2750,1500) (mm), ad its max velocity is 1.5m/s; the obstacle's initial position is (5000, 2250) (mm), and its max velocity is 1.5m/s; the ball's initial position is (8000,750) (mm), and its velocity is zero. Also suppose that $n_1 = 0.6$, $n_2 = 0.7$, $n_3 = 0.4$, $n_4 = 0.3$, $c = 0.035$, $t_{action} = 1s$. The simulation results of the robot path planning are shown in Fig.9. This algorithm was also used in our "JiaoLong" soccer robots, which took part in the RoboCup2005 in Osaka, Japan (see Fig.10) achieving satisfactory performances.

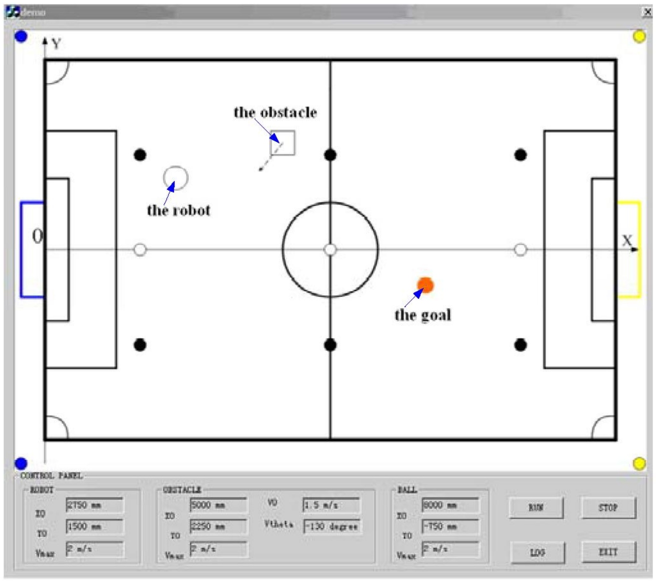

Fig7. User interface of the program

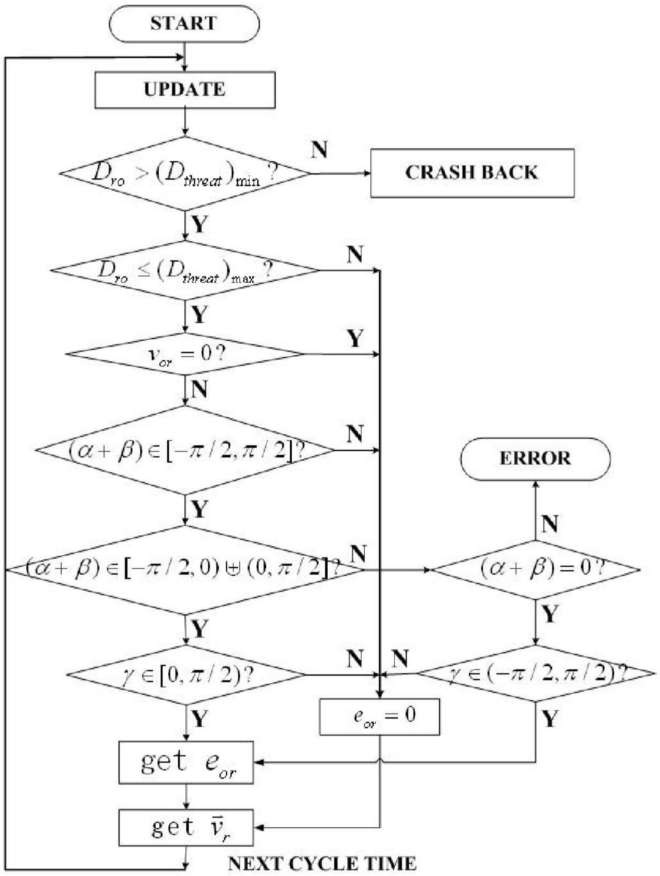

Fig8. Flow diagram of the proposed path planning scheme

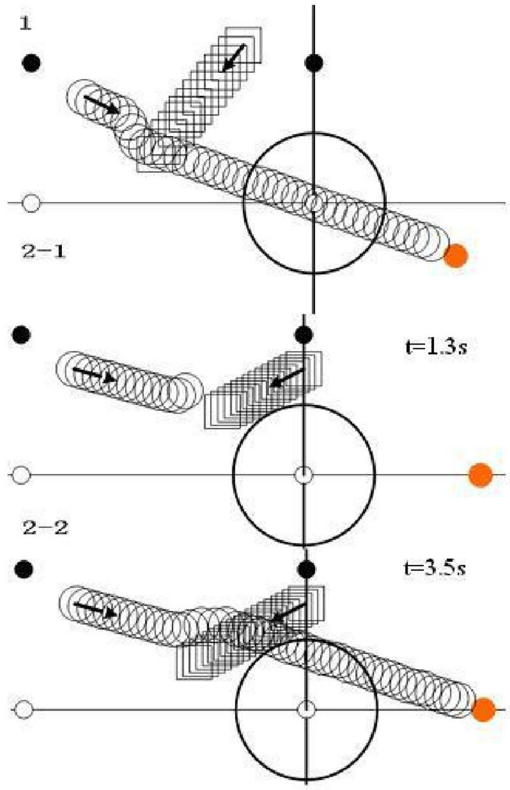

Fig9. Simulation results of robot's path using the proposed path planning approach

Fig.10 The experiment result of dynamic robot path planning

VI. CONCLUSION

In this paper, a new APF method has been proposed for mobile robot path planning in a dynamic environment where the target and the obstacles are moving. The threat coefficient is defined by taking into account the relative velocities of the target with respect to the robot and the relative velocities of the robot with respect to the obstacles. The new potential force functions are defined based on the threat coefficient with respect to both relative position and velocity of the robot, the goal and the obstacle. The combination of the threat coefficient and the new force function makes simultaneous target tracking and moving obstacle avoidance feasible. Computer simulations and real-world experiments demonstrate the effectiveness of the proposed mobile robot path-planning scheme.

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