Artificial Potential Field Algorithm for Obstacle Avoidance in UAV Quadrotor for Dynamic Environment

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Abstract—**Artificial potential field (APF) is the effective real-time guide, navigation, and obstacle avoidance for UAV Quadrotor. The main problem in APF is local minima in an obstacle or multiple obstacles. In this paper, some modifications and improvements of APF will be introduced to solve one-obstacle local minima, two-obstacle local minima, Goal Not Reachable Near Obstacle (GNRON) and dynamic obstacle. The result shows that the improved APF gave the best result because it made the system reach the goal position in all of the examinations. Meanwhile, the APF with virtual force has the fastest time to reach the goal; however, it still has a problem in GNRON. It can be concluded that the APF needs to be modified in its algorithm to pass all of the local minima problems.**

Keywords—*Artificial Potential Field, Unmanned Aerial Vehicle, Path Planning, Obstacle Avoidance, Dynamic Environment*

I. INTRODUCTION

An unmanned Aerial Vehicle (UAV) is an unmanned flying vehicle that is usually controlled remotely or autonomous [1]. One kind of UAV is Quadrotor that has four rotors for flying [2][3][4]. The advantage of a Quadrotor is that it can take off and land in a vertical position or Vertical Take Off and Landing (VTOL) [5][6][7]. Because of that, many researchers researched quadrotor, and it is important to do.

One of the essential sub-systems in UAV is path planning that will guide and navigate the robot to reach the goal with obstacle avoidance [8][9][10][11]. Some path planning methods have been proposed, such as the iteration method and the real-time method [12]. The iteration method, or heuristic method, can give better path planning but needs more time for computing to find good path planning [13]. Thus it will need more time for processing in a larger area. Meanwhile, the real-time method, or classical algorithm, does not need iteration and has simple mathematical equations [14]. Thus, it will need less time for processing [15].

Some methods that can be categorized into iteration methods for path planning are Ant Colony [16], Genetic Algorithm [17][18], Particle Swarm Optimization [19], Differential Evolution [20][21], and Membrane Pseudo-Bacterial Potential Field [22], etc. [23]. Based on previous researches, it can be concluded that the iteration method can give good results for path planning; however, it is only applicable to a small area. If used in a large, dynamic environment and unknown area, it will need more time to process.

One of the real-time methods is Artificial Potential Field (APF) [24][25]. Khatib was the first to introduce the APF method for manipulators and mobile robots [26][27][28]. The APF can be implemented in mobile robots [29][30][31], flying robots [32], manipulator robots [33][34], and humanoid robot [35]. There are some modifications in APF that the researcher made. Based on those researches, it can be concluded that APF is good for real-time systems in a large, unknown environment and dynamic area but need some improvement [36][37][38][39].

APF have simple mathematic equation so that it need low computation. Thus it will suitable for real time application [40]. However, there is a main problem in the APF that is local minima [41]. There are some types of local minima, such as local minima in one obstacle, local minima in two obstacles [42], local minima in goal not reachable (GNRON) [43][44][45] and dynamic or moving obstacle. However, most researchers only consent to solve one of those problems by modifying the algorithm [46]. For instance, Khatib et al. only focused on collision avoidance and moving obstacles [26][27], which can be extended to two obstacle local minima and GNRON local minima problems were not included in the discussions. Rizqi et al. [47] took one-obstacle and two-obstacle local minima as its focused problem and did not consider the GNRON problem. Sun et al. [48] researched most local minima problems; unfortunately, two obstacle local minima were not discussed in the research.

Until now, the performance of those aforementioned methods to all local minima problems had not been studied yet. Therefore, this study aims to compare the performance of modified APF algorithms in challenging various obstacles with local minima. In the research, the conventional APF [26][27], modified APF [47], optimized APF [48], and APF with virtual force [49] will be compared to know its performances in navigating for a dynamic and unknown environment.

The paper will be written in the following structure. The first part is the introduction. Next, the second part is about the navigation process. The third part will discuss the Artificial Potential Field Algorithm. The fourth part contains simulation results and discussion. The last part is the conclusion.

II. THE NAVIGATION PROCESS

The proposed system is shown in Fig. 1. The APF algorithm has three inputs that are goal position, obstacle position, and robot position. In the research, the goal and obstacle position is written in the program. In real system, the goal position and robot position can be known by using an IMU sensor or GPS. The obstacle position can be known by using a distance sensor.
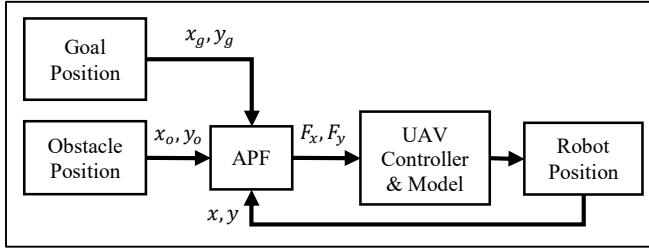

Fig. 1. Proposed System

The APF gives the robot reference position (setpoint). In the UAV, there are controllers that help the robot to reach the set point from APF. It can be a PID control [50], state feedback [49], fuzzy logic [51][52], or another controller [53][54][55].

III. ARTIFICIAL POTENTIAL FIELD

A. Attractive Force of APF

Commonly, APF consists of two forces; the first is the attractive force, and the second is the repulsive force. Attractive Force is the force that is used to navigate the robot to the goal. Suppose the $\mathbf{x} = [x \quad y]^T$ is the xy-coordinate of the robot, the attractive function is

$$U_{att}(\mathbf{x}) = \frac{1}{2}k_a(\mathbf{x} - \mathbf{x}_d)^2 \tag{1}$$

where, k_a is the attractive gain, $\mathbf{x}$ is the robot position vector, $\mathbf{x}_d$ is the goal position vector.

The attractive force is the gradient of attractive potential function as

$$\begin{aligned} F_{att}(\mathbf{x}) &= -\nabla U_{att}(\mathbf{x}) \\ &= -k_a(\mathbf{x} - \mathbf{x}_d) \end{aligned} \tag{2}$$

B. The Repulsive of APF

The repulsive force is the force that is used to avoid the obstacle. The repulsive potential function is

$$U_{rep} = \begin{cases} \frac{1}{2}k_r\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)^2, & \text{if } \rho \le \rho_0 \\ 0, & \text{if } \rho > \rho_0 \end{cases} \tag{3}$$

where, k_r is the repulsive gain, ρ is the distance between robot and obstacle, ρ_0 is the robot minimal distance which has a repulsive effect.

The distance between robot and obstacle ρ is

$$\rho = \sqrt{(\mathbf{x} - \mathbf{x_0})^2} = \sqrt{(x - x_o)^2 + (y - y_o)^2} \tag{4}$$

Where $\mathbf{x_0} = [x_O \quad y_O]^T$ is the obstacle position vector.

The repulsive force is the gradient of the repulsive potential function as

$$F_{rep}(\mathbf{x}) = -\nabla U_{rep}(\mathbf{x})$$

$$F_{rep}(\mathbf{x}) = \begin{cases} -k_r\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)\frac{1}{\rho^2}\frac{\partial \rho}{\partial \mathbf{x}}, & \text{if } \rho \le \rho_0 \\ 0, & \text{if } \rho > \rho_0 \end{cases} \tag{5}$$

where

$$\frac{\partial \rho}{\partial \mathbf{x}} = \left[\frac{\partial \rho}{\partial x} \quad \frac{\partial \rho}{\partial y}\right]^T = \frac{\mathbf{x}_O - \mathbf{x}}{\rho}, \tag{6}$$

where, $\mathbf{x}_O$ is the position obstacle in xy-coordinate system.

Rizqi et al. [47] defined a modified artificial potential field with the repulsive force in (3) as

$$F_{rep}(\mathbf{x}) = -\nabla U_{rep}(\mathbf{x})$$

$$= \begin{cases} -k_r\left(\frac{1}{\rho_m} - \frac{1}{\rho_0}\right)\frac{1}{(\rho_m)^2}, & \text{if } \rho \le \rho_m \\ -k_r\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)\left(\frac{\mathbf{x}_O - \mathbf{x}}{\rho^3}\right), & \text{if } \rho_m < \rho < \rho_0 \\ 0, & \text{if } \rho > \rho_0 \end{cases} \tag{7}$$

where ρ_m is the minimal distance where the force is constant.

Sun et al. [48] proposed about optimized artificial potential field algorithm. The repulsive field function is

$$\begin{aligned} & U_{rep}(\mathbf{x}) \\ & = \begin{cases} \frac{1}{2}k_r\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)^2(\mathbf{x} - \mathbf{x}_d)^n, & \text{if } \rho \le \rho_0 \\ 0, & \text{if } \rho > \rho_0 \end{cases} \end{aligned} \tag{8}$$

The repulsive force is

$$F_{rep}(\mathbf{x}) = \begin{cases} F_{rep_1}(\mathbf{x}) + F_{rep2}(\mathbf{x}), & \text{if } \rho \le \rho_0 \\ 0, & \text{if } \rho > \rho_0 \end{cases} \tag{9}$$

where

$$F_{rep1}(\mathbf{x}) = -k_r \left(\frac{1}{\rho(x)} - \frac{1}{\rho_0} \right) \frac{1}{\rho^2(x)} (\mathbf{x} - \mathbf{x}_d)^n \frac{\partial_\rho(\mathbf{x})}{\partial(\mathbf{x})}$$

$$F_{rep2}(\mathbf{x}) = -\frac{n}{2} k_r \left(\frac{1}{\rho(x)} - \frac{1}{\rho_0} \right)^2 (\mathbf{x} - \mathbf{x}_d)^{n-1} \frac{\partial(\mathbf{x} - \mathbf{x}_d)}{\partial(\mathbf{x})}$$

where

$$(\mathbf{x} - \mathbf{x}_d)^n = |(x - x_d)^n| + |(y - y_d)^n|$$

$$\frac{\partial_\rho(\mathbf{x})}{\partial(\mathbf{x})} = \frac{\mathbf{x} - \mathbf{x}_O}{\rho(\mathbf{x})}$$

$$\frac{\partial(\mathbf{x} - \mathbf{x}_d)}{\partial(\mathbf{x})} = \frac{\mathbf{x} - \mathbf{x}_O}{\mathbf{x} - \mathbf{x}_d}$$

where the variables $F_{rep1}(\mathbf{x})$ and $F_{rep2}(\mathbf{x})$ are two-component forces of $F_{rep}(\mathbf{x})$. The variable n is constant value such as $n = 0, 0.5, 1, 2$.

The repulsive force with virtual force algorithm is proposed in [49] that was used to avoid the local minima. It can be written as

$$F_{rep}(\mathbf{x}) = \begin{cases} F_{rep_1}(\mathbf{x}) + F_{vir}(\mathbf{x}), & \text{if } \rho \le \rho_0 \\ 0, & \text{if } \rho > \rho_0 \end{cases} \quad (10)$$

where

$$F_{rep1}(\mathbf{x}) = -k_r \left(1 - \frac{\rho}{\rho_0} \right) \left(\frac{\mathbf{x}_O - \mathbf{x}}{\rho^3} \right)$$

$$F_{vir}(\mathbf{x}) = -k_v \frac{1}{\rho}$$

where k_v is the virtual force gain.

C. Total Force of APF

The total force of APF is the sum of the attractive force and the repulsive force of n obstacles as

$$F_{total}(\mathbf{x}) = F_{att}(\mathbf{x}) + \sum_{i=1}^{n} F_{rep_i}(\mathbf{x}) \quad (11)$$

The total force will be a set point reference for the quadrotor in x-axis and y-axis, respectively, as

$$F_{total\_x}(\mathbf{x}) = F_{att\_x}(\mathbf{x}) + F_{rep\_x}(\mathbf{x}) \quad (12)$$

$$F_{total\_y}(\mathbf{x}) = F_{att\_y}(\mathbf{x}) + F_{rep\_y}(\mathbf{x}) \quad (13)$$

IV. SIMULATION RESULT

The simulation used the Simulink Matlab. In this section, some examinations were conducted. The first examination is about local minima in one obstacle. The second examination focused on local minima in two obstacles. Last, the third examination is about the goal not reachable (GNRON). The

methods that will be compared are the traditional artificial potential field, modified artificial potential field, optimized artificial potential field, and artificial potential field with wall following. Finally, the analysis will conclude whether the UAV can avoid the obstacle and reach the goal.

A. Local Minima in One Obstacle

In the sub-section, local minima in one obstacle examination is presented. The result is shown in Fig. 2. The starting position was used in (-7, -7), and the goal position was in (8, 8). The obstacle position is in (0, 0). It can be known that all of the algorithms can make the robot reaching the goal position.

B. Local Minima in Two Obstacle

In the sub-section, local minima with two obstacles examinations are presented. The result is shown in Fig. 3. The obstacle position is in (-1, 1) and (1, -1). Based on the result, the traditional APF and modified APF cannot make the robot reach the goal position. It is because of the local minima located in front of the two obstacles. Meanwhile, the optimized APF and APF with virtual force can make the quadrotor reach the goal position.
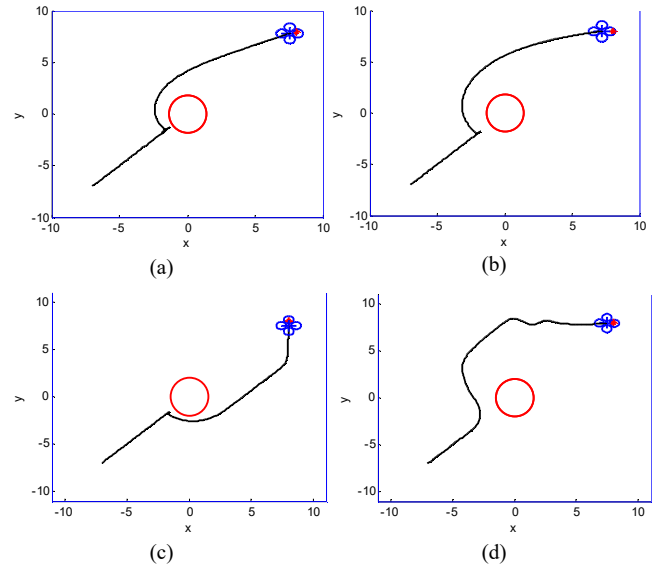

Fig. 2. One Obstacle Result (a) traditional APF (b) modified APF (c) optimized APF (d) APF with virtual force

C. Goal not Reachable (GNRON)

In the sub-section, examination for local minima in goal not reachable (GNRON) is presented in Fig. 4. The obstacle position is near the goal position. The goal is in the coordinate of (8, 8), and the obstacle is in the coordinate of (6, 6). It can be shown that the traditional APF and the modified APF can avoid the obstacle. However, it cannot reach the goal because the repulsive from the obstacle makes the quadrotor unable to reach the goal.

D. Dynamic Obstacle

In the sub-section, examination for local minima in goal not reachable (GNRON) is presented in Fig. 5. The static obstacle position is in the coordinate (0, -1) and the dynamic

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obstacle is moving from the coordinate (6, 4) with horizontal movement. The goal is in the coordinate of (8, 8). It can be known that all of the algorithms can make the robot avoid the static and dynamic obstacle then reaching the goal position.
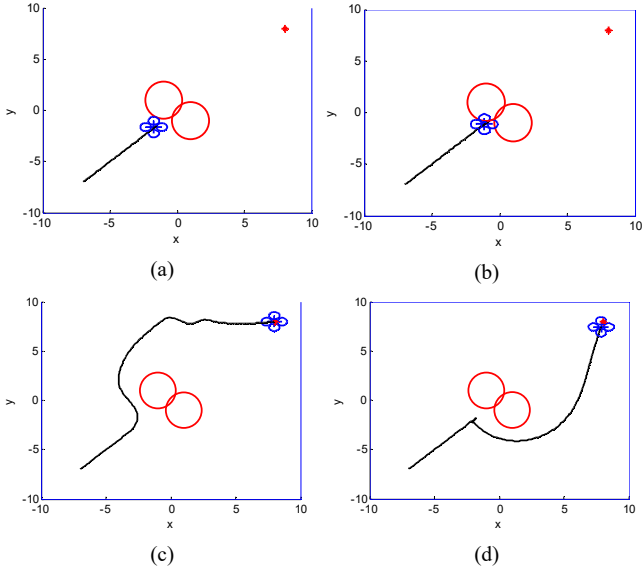

Fig. 3. Two Obstacle Result (a) traditional APF (b) modified APF (c) optimized APF (d) APF with virtual force
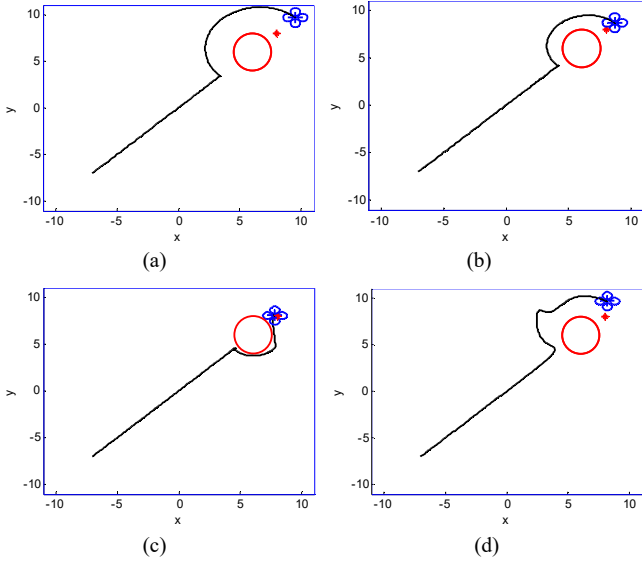

Fig. 4. Two Obstacle Result (a) traditional APF (b) modified APF (c) optimized APF (d) APF with virtual force

V. DISCUSSION

The time to reach the goal position is shown in Table 1. In local minima with one and two obstacles, the Virtual Force APF has the fastest time to reach the Goal however has a problem in GNRON. It can be known that the optimized APF can reach goals in each examination. There is a reason why the optimized APF can reach the goal in GNRON. It can be seen in Table 2 based on each APF formula in (5), (7), (9), and (10). The optimized APF has $(\mathbf{x} - \mathbf{x}_d)$ distance from robot and goal parameter in repulsive force equation. Thus, if the

goal is closest to the obstacle, then the parameter will decrease the repulsive force to make the robot reach the goal. Meanwhile, the APF with virtual force can have the fastest time reaching the goal because the virtual force will push the robot to the side when the robot is near the obstacle.
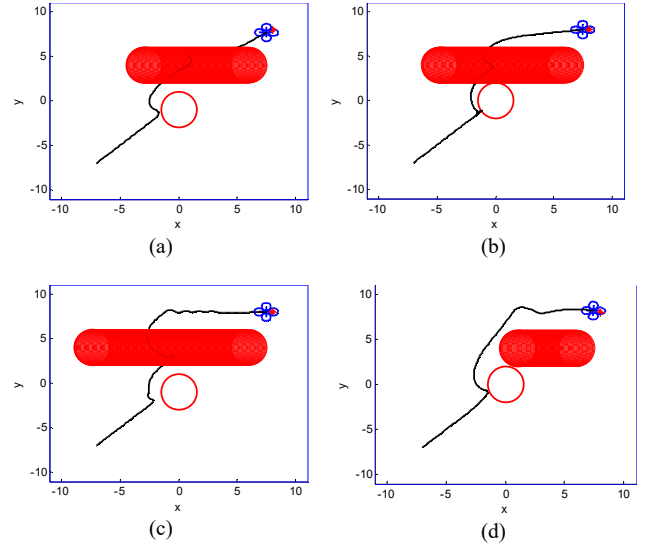

Fig. 5. Dynamic Obstacle Result (a) traditional APF (b) modified APF (c) optimized APF (d) APF with virtual force

TABLE I.   TIME TO REACH GOAL

Algorithm	Examination			
	One Obstacle	Two Obstacle	GNRON	Dynamic Obstacle
Traditional APF	6.370s	-	-	5.948s
Modified APF	6189s	-	-	5.944s
Optimized APF	9.514s	12.818s	11.614s	8.962s
Virtual Force APF	3.523s	4.507s	-	3.249s

TABLE II.   REPULSIVE FORCE COMPONENT

Algorithm	Repulsive Force Component		
	ρ	$(\mathbf{x} - \mathbf{x}_d)$	F_{vir}
Traditional APF	v	-	-
Modified APF	v	-	-
Optimized APF	v	v	-
Virtual Force APF	v	-	v

VI. CONCLUSIONS

The research proposes a performance comparison of Artificial Potential Field (APF) algorithms in UAV quadrotor in one obstacle local minima, two obstacle local minima, and GNRON. As a result, the optimized APF can reach goals in all of the examinations. Furthermore, the distance parameter between the robot and goal in repulsive force can decrease the repulsive force. The fastest method to reach the goal is APF with virtual force, but it still has a problem in GNRON. The Artificial Potential Field is suitable for robot navigation but still needs modification to pass all of the local minima problems. The important parameter in repulsive APF is the distance between robot and goal, and virtual force.

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