Title	UAV Dynamic Path Planning for Intercepting of a Moving Target: A Review
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Citation	Communications in Computer and Information Science, 376: 206-219
Issue Date	2013-08
Type	Journal Article
Text version	author
URL	http://hdl.handle.net/10119/12206
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Description	16th FIRA RoboWorld Congress, FIRA 2013, Kuala Lumpur, Malaysia, August 24-29, 2013.

UAV Dynamic Path Planning for Intercepting of a Moving Target: A Review

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Abstract. An Unmanned Aerial Vehicle (UAV) has to possess three abilities to function autonomously. The three abilities are localization, mapping and path planning. Path planning guides the UAV to find a feasible path, meaning a path that meets safety, kinematic and optimization constrains. In order to intercept a moving target, dynamic path planning must be used due to target movement. To produce a feasible path, many approaches had been used in path planning algorithms. The current approach of path planning is divided into three kinds of algorithm. The first approach is an algorithm which is based on grid. Second approach is algorithm which is based on evolutionary algorithm. The last is algorithm which is based on curves. This paper presents short review of these algorithms and gives a critical analysis of each approach. The review used literature from book, conference and journal publication. The result shows that implementation of curved path planning in dynamic condition becomes a great opportunity in the UAV field.

Keywords: Unmanned Aerial Vehicle; Path Planning Algorithm; Moving Target

1 Introduction

Three abilities that have to be possessed for establishing an autonomous UAV are localization, mapping and path planning. Localization is defined as the position of the UAV from surrounding aviation. Mapping is how to convert the real environment into a modeling environment. Path Planning chooses the feasible route and gives guidance for low level control.

UAV Path planning is divided into dynamic and static path planning. The static path planning is a path planning that constructs in one time from the initial position into the final position of the UAV. Differently from static path planning, dynamic path planning requires path planning construction which can be changing in discrete time. For interception of a moving target, dynamic path planning must be done due to movement of the target.

There are many algorithmic approaches that have been developed to produce either dynamic or static path planning. Major considerations relating to path planning system are optimization and a flyable path which meets safety constraints. Optimization means the algorithm has to find the shortest distance to reach the target. A flyable path which meets the safety constraint relates to the path that enables the UAV to fly without neglecting kinematic constraints and surrounding aviation.

This paper presents the state of the art of current path planning algorithms and gives a critical analysis of each approach. The presentation will be organized as follows. Section 2 explains the taxonomy of the path planning algorithm and gives an analysis of the advantages and disadvantages of each approach. This section includes the conceptual framework of each approach. Section 3 focuses on comparison of the result and analysis. The analysis underlines the opportunities for an affordable path planning algorithm. The last section is the conclusion and discussion for further research.

2 Taxonomy of the path planning algorithm

The taxonomy is developed to map current approaches of path planning algorithms. As seen in Fig. 1, the path planning system consists of one or more algorithms [1].

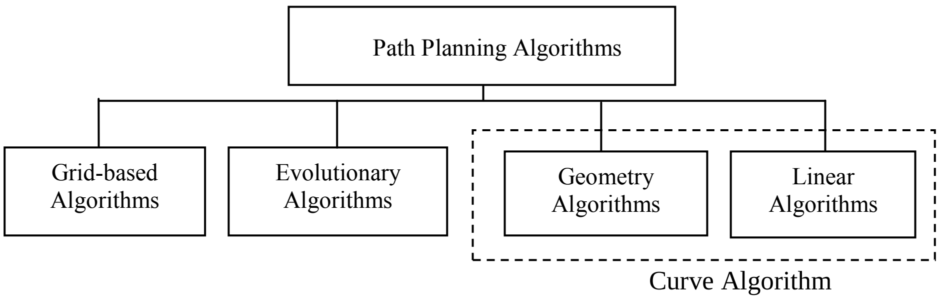

Fig. 1. Taxonomy of path planning algorithm

The algorithms are divided into four fields. Each field has various algorithms for path planning construction. The geometry and linear algorithms can be integrated into one field, which can be called curve algorithms. Afterward, the fields can be reduced into three fields. The algorithm on each field and the methodology on each algorithm are described as follows.

2.1 Grid-based algorithm framework

A path planning framework which is based on a grid can be illustrated as seen in Fig. 2.

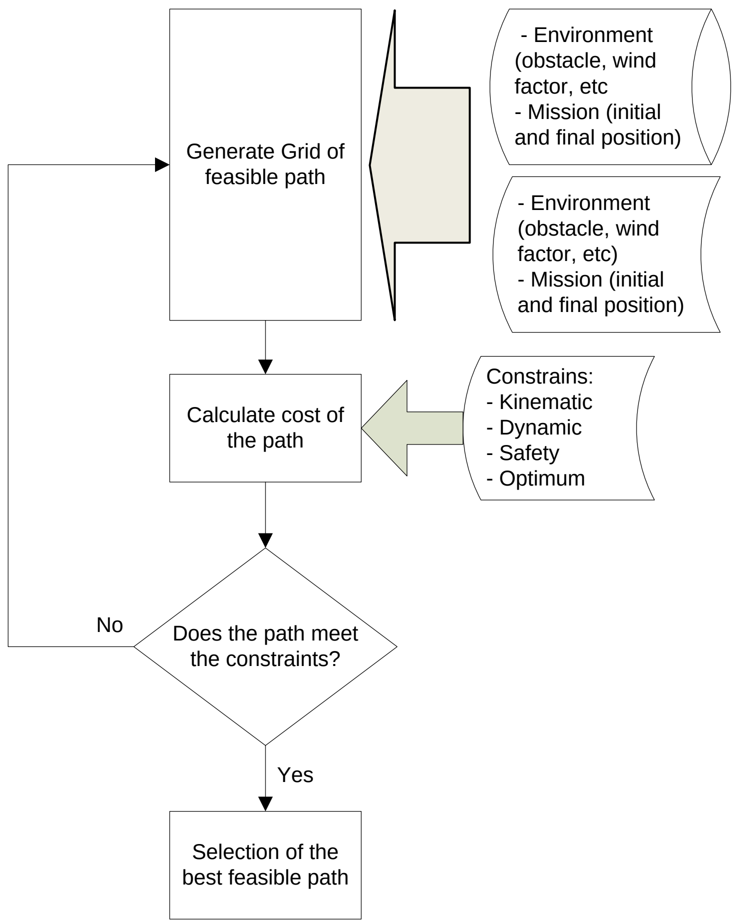

Fig. 2. General framework of path planning which is based on grid algorithm

The general framework in Fig 2 shows that the three processes for constructing path planning are generation of grid of feasible path, calculation of cost of the path, and selection of a feasible path. In order to generate a grid of the feasible path, environment and mission objectives have to be considered. Due to usage of grid-based path planning which can be used for static and dynamic conditions, environment data can be given as on-line or off-line data [2]. On-line means that the data of the environment acquired is continuous and processed in real time. In contrast, off-line data is a condition whereby the data is in storage. The off-line and on-line data are shown in Fig 2 by different shapes of the input environment. Mostly, the grid yields a polygon shape which means a safety path between the initial position and the final position [3]. Constraints which influence this process are kinematic, dynamic, safety and optimum. The constraints are used to calculate the cost of the path from the initial position until the final position. Therefore, the cost result will used to select the best path among all possibilities of path planning. It has to be noted that the method of grid-based algorithm is using iteration to find the feasible path as seen in Fig 2. Consequently, initial and final position depends on the condition of path planning. For static condition, path planning will be created through fix waypoints. In this case, the calculation of the cost will be done from initial until final waypoints. For dynamic condition, discrete time of path required loop close calculation for determining waypoints in certain time. According to off-line and on-line data, it is proven that path planning which is based on a grid can be used for dynamic and static path planning.

2.2 Previous research of grid-based algorithms

Firstly, an algorithm which is based on Delanuay triangulation was used for the UAV using camera vision [4-5]. Three main parts of the UAV path planning algorithm were grouping, an optimal circular path, and an optimal transition to the path. The visible targets were connected by Delanuay triangulation into one group. Afterward, the group was divided into subgroups or modules, which was explained by Newman [6]. After the group was divided into subgroups, the centroid of each subgroup could be determined by calculating the region of each subgroup. Therefore, based on the centroid of each subgroup, the UAV's path planning was optimum if the path was circular in the range of the camera and in the minimum turning radius. The algorithms built optimal path planning which was robust according to the target movement and kept the target in the range of camera vision. Thus, the disadvantage of the algorithms was the limitation of area because of the capturing capability of the camera. This algorithm was only used for tracking or reconnaissance the target but it could not be used to intercept the target in a vast area.

The other grid-based algorithms were heuristic A* and graph Voronoi diagram [7-10]. The researchers improved the algorithm by considering the minimum turning radius and maximum course angle variety rate. The improvement extended the node which fulfills the maneuverability requirements.

As well as the A* Algorithm, the other researchers used a Voronoi diagram to construct a Voronoi map [11]. The edge of the Voronoi map considered terrain, radar, and missile threat. After the Voronoi map had been constructed, the graph theory such as Dijkstra was used to find the optimal path.

2.3 Critical analysis of the grid-based algorithm

The grid-based algorithm is an effective path planning algorithm that seeks minimal cost between two nodes. There are waypoints in between the nodes where the UAV flies through. Optimal path planning was obtained by computing iteratively all of the waypoints. Because of the iterations, computational time would be the disadvantage. Meanwhile, the advantage of the algorithm is the ease of implementation on static path planning although it can be used as dynamic path planning. However, the original grid-based algorithm cannot solve discontinuation problem. The algorithm has to be integrated with the curve algorithm to solve the non-discontinuation problem. Although the grid-based algorithms are very effective to build static path planning, most of the algorithms had not been used for intercepting of a moving target.

2.4 Evolutionary algorithm framework

A path planning framework which is based on an evolutionary algorithm can be illustrated as seen in Fig. 3.

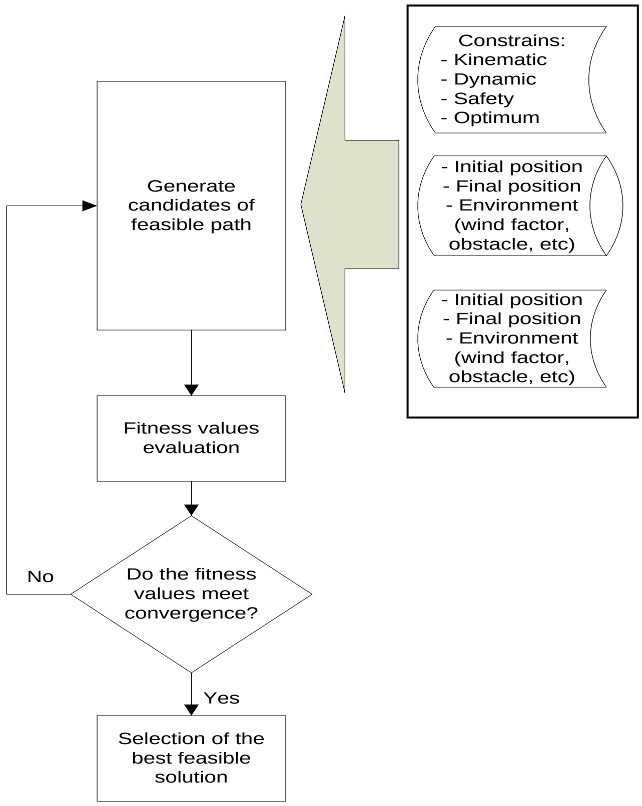

Fig. 3. General framework of path planning which is based on evolutionary algorithm

Fig 3 shows that there are three processes for constructing a path planning algorithm which is based on evolutionary algorithm. The processes are generating candidates of the feasible path, evaluating fitness values, and selecting the best solution from among possibilities of the feasible path. Generating candidates of feasible path is influenced by several constraints and surrounding aviation. Several constraints that influence path planning are kinematic, dynamic, and safety. Surrounding aviation is divided into two conditions, i. e. online and offline conditions [2]. The online condition means that the conditions are inserted in real time dynamically. In contrast, the offline conditions mean that the input conditions have been saved in the data storage.

In the beginning, the process of path planning which is based on an evolutionary algorithm generates all the possible candidates of path planning. Afterward, all the candidates will be calculated the fitness values by using several parameters as seen in the dashed line blocks of Fig 2. The best path planning is obtained if the calculation meets convergence and assumes that the chosen path has optimum fitness value. It means that the path is the best solution path. Consequently, the UAV will fly through the chosen path.

2.5 Previous research on the evolutionary algorithm

The next algorithms were evolutionary computation algorithms. Here, famous algorithms such as genetic algorithms, particle swarm optimization (PSO) and Artificial Immune Algorithm (AIA), as well as the Ant Colony Algorithm (ACA) were used to produce the UAV path planning. The algorithms choose optimal path planning from among path planning possibilities. All possible path planning were represented by the chromosome in GA as well as the particle in PSO.

Gao et. al. and Obermeyer used basic GA as a 2D path planning algorithm [12-15]. The chromosome represented a sequence of speed and heading transitions. Gao et. al. also added two operators in GA which were insertion and deletion. In 2005, Zeng et. al. developed a path planning system using evolutionary algorithms which had linked list data structure in the chromosome [16]. In this research, the chromosome was filled with the UAV's flight route which contained (x,y,z) coordinates of each node, information on feasibility of the point and the following route segment.

The difference in GA implementation between Zeng et. al. and Gao et. al. was in the operators. Zeng et. al. had seven operators in the implementation of GA. In addition, the operators were added to by threesome operators that were swap, smooth and fixed vector mutators. The additional operator made the flight route more feasible by avoiding discontinuation path. The research that used basic GA and evolutionary algorithm had not solved the dynamic path problem.

The other evolutionary algorithms that were used to produce path planning were PSO [17-22]. Each particle represented potential solution that was evaluated by three factors: position, velocity and adaptability. The equation of PSO was expressed by Eq. (2) which derived from Eq. (1).

$$P_i(K+1) = P_i(K) + V_i(K) \tag{1}$$

$$V_i[k+1] = w * V_i[k] + C_1 * Rand1() * (P_{best\,i}(k) - P_i(k)) +$$
$$C_2 * Rand2() * (G_{best}(k) - P_i(k)) \quad (2)$$

Vi(k) represented the velocity of the particle, P(k) presented particle position, Pi(k) represented best position in its past experience, and Gbest was the best position among all particles in the population. Rand1 and rand2 were two uniform random functions with a range [0,1]. Notation C1 and C2 were the cognitive and social parameters respectively. In the implementation of the PSO, PSO is used to produce both static and dynamic 3D path planning. The PSO algorithm has benefit of minimum computation but is easily trapped into local optima in high dimensional complex issues [23].

The ACA could be applied in path planning systems [24-30]. The ACA mainly comprises two basic steps: the adaption stage and the cooperation stage. In the adaption stage, the candidate solutions continued to readjust their structure on the basis of information accumulating. In the cooperation stage, the candidate solutions exchanged information to produce better solutions [27]. In ACA, an ant left a pheromone which could be felt by the next ant as a signal to affect its action. The pheromone that the following one left would enhance the original pheromone. Within certain time, a shorter trajectory would be visited by more ants, thus it would accumulate more pheromone and the possibility which was selected by other ants. Using the rule of choosing nodes, the probability that an ant k was located in node i in the network was expressed by Eq. (3).

$$P_{ij}^{k} = \begin{cases} \dfrac{(\tau_{ij}^{k})^{\alpha}(\eta_{ij}^{k})^{\beta}}{\sum_{l \in N_i^k}(\tau_{il}^{k})^{\alpha}(\eta_{il}^{k})^{\beta}} & if \quad j \in N_i^k \\ 0 & if \quad j \notin N_i^k \end{cases} \quad (3)$$

where pheromone levels were denoted by τ_{ij}^{k}. Both α, β, and η_{ij}^{k} were usually in a dependent condition; where η_{ij}^{k} represented the heuristic information, and the values of α and β were weight for the importance of the pheromone and heuristic values.

The other evolutionary computation algorithm which was used to construct UAV’s path planning was Artificial Immune Algorithm [23]. An antibody was represented with a decimal string which is a possible solution (UAV's flight path) in the feasible airspace. Affinity functions were equivalent to the cost of the whole path and comprehensively expressed the influential scope and the size of all threats.

The affinity function value of li meant the distance from p(i) to p(i+1) in a certain flight path. Liu and Zhang used AIA to choose optimal solution coordinates of the flight path. Therefore, the curve of the path planning was constructed by 3 orders of

B-spline curves to smooth the 3D path. This means the algorithm integrated AIA with 3 orders of B-Spline curves.

The last evolutionary computation algorithm was the differential evolution algorithm (DE). The Differential evolution (DE) was an evolutionary algorithm developed on the framework of genetic algorithm [31-32]. The difference between GA and DE was mutation strategy in speeded-up convergence. The mutation strategy was expressed by Eq. (5) which was derived from Eq. (4).

$$k1 = k_{1\min} + (k_{1\max} - k_{1\min}) \cdot (\frac{g}{n})^2, k2 = k_{2\max} - (k_{2\max} - k_{2\min}) \cdot (\frac{g}{n})^2 \quad (4)$$

where g was the current generation and N was the maximum number of generations.

$$v_i^G = a \cdot x_{r1}^G (1-a) \cdot x_{best}^G + k1 \cdot (1-a) \cdot (x_{best}^G - x_{r1}^G) + k2 \cdot a \cdot (x_{r2}^G - x_{r3}^G) \quad (5)$$

where x was the target vector, G was the current generation index, and r1, r2 and r3 were chosen randomly from the index set. The foremost important factor to be noted in this research is that the proposed DE is more convergent than other optimization algorithms (PSO and GA).

2.4 Critical analysis of the evolutionary algorithm

Generally, the advantage of evolutionary computation is that it can be used to create both static and dynamic path planning. ACA was a powerful tool for developing the UAV’s path planning but the algorithm was prone to stagnation and converged slowly. PSO is very fast to find optimum solution but PSO has disadvantage whereby it can fall in local optima.

Similar to the grid-based algorithm, evolutionary computation finds a feasible solution by iteration. Iteration is used to find optimum solution based on fitness value function. On the other hands, for the moving target interception problem, the UAV often changes direction in discrete time because of target movement. According to target movement, iteration would be happened in discrete time. Consequently, the disadvantage of evolutionary computation is the computation cost in producing path planning.

2.5 The curve algorithm

A path planning framework which is based on the curve algorithm can be illustrated as seen in Fig. 3.

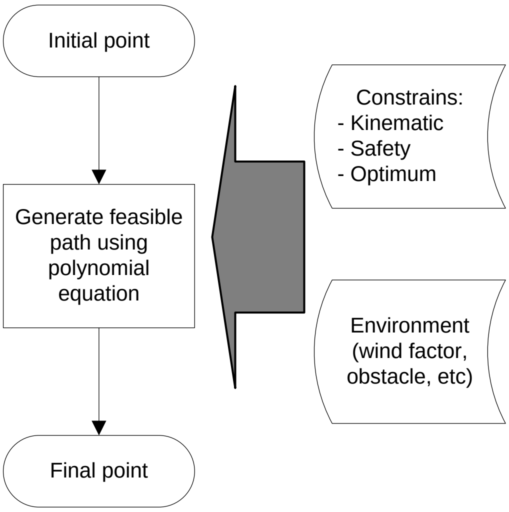

Fig. 3. General framework of path planning which is based on curve algorithm

The main process in the curve algorithm is defined as a polynomial equation. The equation builds a path planning from an initial position until the final position. Similar to the other algorithms, the curve algorithm is influenced by kinematic, safety, and optimum constraints. Due to static condition, this algorithm merely uses off-line inputs. The inputs are pertaining to the environment, which include the initial position, final position, and environment.

2.6 Previous work on the curve algorithm

The last current approaches were algorithms which were based on the curve. It started with Dubins path planning [33]. In this algorithm, the UAV was assumed as a simple car. Enhancement of the Dubins path planning had been done by using altitude and wind as additional parameters [34-35]. The other enhancement had been done by adding clothoid arcs to make the curve path smoother than the basic Dubins [36-37]. For a clothoid arc, the arc angle varying along the trajectory was given by Eq. (6).

$$\theta(t) = \int_0^t K \frac{\tau}{s} d\tau = \frac{K}{2s} t^2 \tag{6}$$

where k was the curvature at arc length s and t the arc length variable, such that $s = |\vec{v}|t$, where $\vec{v}$ was the velocity.

Dubins with clothoid arcs was expressed by Eq. (7).

$$C(s) = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)!(4n+3)} s^{4n+3} \quad (7)$$

The benefit of Dubins with clothoid arcs was a non-discontinuous path solving problem to construct curve path planning.

Besides Dubins, development of the phytagorian hodograph (PH) is used to make a curve path [38-39]. The derivatives $\dot{x}$ and $\dot{y}$ were called hodographs. The hodographs could be formulated using polynomials u(q), v(q) and w(q) as in Eq. (8).

$$\begin{aligned} \dot{x}(q) &= [u(q)^2 - v(q)^2]w(q) \\ \dot{y}(q) &= 2u(q)v(q)w(q) \end{aligned} \quad (8)$$

On the other hand, a Cornu spiral (CS) was used to construct the UAV's path planning which is based on a curve [40]. The CS was a well-known curve whose curvature was defined as a polynomial function of its arc length s as in Eq. (9).

$$K(s) = \sum_{i=0}^{n} \alpha_i S^i \quad (9)$$

The position of the points on this curve was calculated by Eq. (10).

$$\begin{aligned} x(s) &= \int_0^s \cos(\theta(s))ds \\ y(s) &= \int_0^s \sin(\theta(s))ds \end{aligned} \quad (10)$$

The curvature of a planar curve was defined by Eq. (11).

$$K(t) = \frac{\dot{x}(t)\ddot{y}(t) - \dot{y}(t)\ddot{x}(t)}{(\dot{x}(t)^2 - \dot{y}(t)^2)^{3/2}} \quad (11)$$

The linear curve that was used for developing UAV path planning used Mix Integer Linear Programinng (LP) [41]. The linear curve connects the initial position to the final position. A linear programming problem may be defined as the problem of maximizing or minimizing a linear function subject to linear constraints. The constraints may be equalities or inequalities. In UAV path planning for the dynamic target, the cost is obviously time dependent.

2.7 Critical analysis of the curve algorithm

Most of the curve algorithm can meet kinematic constraints. The path planning is constructed by determining polynomial equation. The equation will yield path planning which is met kinematic constrain. This becomes an advantage of a path planning algorithm which is based on the curve.

The problem of the curve algorithm is its difficulty to be employed in dynamic path planning. The difficulty occurs since the curve algorithm is designed to construct static path planning from the initial position until the final position. Thus, these algorithms are mostly used to produce static path planning and still cannot be used for intercepting a moving target. The complexity of the algorithm depends on the equation that builds the path planning.

3. Result and Analysis

Based on the state in the aforementioned, a summarization of the comparison between each path planning algorithm can be seen in Table 1.

Table 1. Comparison of path planning approaches

Approach	**Algorithm**	**Concept**	**Minimum Computational Complexity**	**Path Planning Constrains**
Grid	A*, Triangulation, Voronoi Diagram	Iteration, minimum cost between two nodes	$O(n^2)$	static and dynamic
Evolutionary	GA, PSO, AIA, DE, ACA	Iteration	$O(n^2)$	static and dynamic
Curve	Dubins, PH, CS, Clothoid Arcs	Polynomial equation	Depend on the polynomial equation	static and kinematic

Table 1 shows that the $O(n^2)$ of computation cost generated by the iteration is the disadvantage of grid-based and evolutionary computation algorithms. This computation occurs due to the algorithm find optimum feasible path by iteratively while seeking the target. Although some researchers utilized the grid based algorithms for tracking a moving target, the algorithms were lacking in ability when applied in a vast area scenario. The algorithms were only applied within camera range. Evolutionary computation could produce dynamic path planning but most algorithms were not usable for intercepting of a moving target.

On the other hand, the curve algorithm which was based on geometry is very effective to construct static path planning with discontinuation path solution. Satisfied kinematic constraint is one of the advantages of the curve algorithm. Since the curve algorithm is designed to construct a fixed path planning from the initial position until the final position, then the difficulty to implement the algorithm in dynamic path planning would be the disadvantage. Hence, the implementation of curved path planning in a dynamic condition becomes very challenging.

4 Conclusion and discussion

A path planning system is one of the important parts within the autonomous UAV field. Current researches of the path planning algorithms are divided into three kinds of algorithm. Firstly, the algorithms which are based on a grid are the A* algorithm and the Voronoi diagram. Secondly, the algorithms which are based on evolutionary computation are GA, PSO, DE, AIA and ACA. The last is the algorithm which is based on a curve. The grid-based algorithm and evolutionary computation used iteration to select among possibilities of candidates for path planning solution. Although it can be used to construct dynamic path planning, the iteration leads to high computational complexity. On the other hand, a path planning algorithm which is based on a curve has advantages to cope with the kinematic constraint. Nonetheless, the curve algorithm had been used in dynamic condition especially for intercepting a moving target. Thus, implementation of curved path planning in dynamic condition becomes a great opportunity in the UAV field.

Acknowledgement

This research is supported by Ministry of Higher Education Malaysia research grant scheme number FRGS/1/2012/SG05/UKM/02/12 and ERGS/1/2012/STG07/UKM/02/7.

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