# Aerial Path Planning using Meta-Heuristics: A survey

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***Abstract*—Meta-heuristic algorithms have been known to solve complex problems which were once considered difficult to solve. They produce an optimal or near optimal solution with reduced computational complexity and are thus are considered where deterministic algorithms produce inefficient solutions. Robotics has been a disciplinary field where artificial intelligence is bestowed to robots for them to perform complex tasks similar to human beings. Many of tasks involve decision making removing the need for a human intervener. Robots can efficiently perform their tasks on the ground, air as well as underwater missions. To do so, a very important property required by the robot is to efficiently calculate its path in its surroundings. The path planning problem is a hard problem to solve using deterministic techniques and thus many heuristics based techniques are employed to solve this novel problem. This paper will review some the recent advancements in the path planning of unmanned aerial vehicles using meta-heuristic techniques. An extensive survey of the related research is presented with a stress on the major novelties of their work. At last, the research gaps inferred after analyzing the previous works are highlighted along with the future prospects in the field of research.**

**Keywords— UAV, Aerial Path Planning, Meta-Heuristics, Optimization, Robotics**

## I. INTRODUCTION

This Robotics is a field which is a combination of mechanical science and artificial intelligence [1]. The robots of the current era are expected to take decisions on their own without a human operator constantly giving them order. They are able to observe, navigate as well as manipulate their surroundings in the physical environment. They manage situations of uncertainty related to the environment and take actions autonomously using some form of decision making which is in their competence for the related task.

The unmanned aerial vehicles or drones of the todays world are a perfect example robots functioning autonomically. These vehicles are designed so as to complete tasks in areas which are unreachable through other modes of transport such as land and water, have the ability to travel at high velocity etc. To perform these tasks efficiently, a vehicle needs to have navigation and exploration abilities [2]. However, for UAVs one also needs to give additional importance to differential constraints like atmospheric turbulence which makes it difficult for the drone to follow its path. Keeping that in sense a robot is required to complete the task by finding a collision free path from its source location to the destination keeping a safe distance from the threats and obstacles in the way. This problem is forenamed as the path planning problem [3] in the literature and it deals with search based strategies for finding an optimal path for the vehicle evading obstacles or moving in an unknown terrain.

Path planning problem has been a widely researched topic for Unmanned Aerial Vehicles. The problem is usually implemented as an optimization problem where the problem statement is to obtain a solution that is the best solution among the possible solutions according to some constraints. There have been currently no deterministic algorithms that can be applied find the optimal path and practically implementable for the vehicles. Hence, path planning falls under the category of hard-optimization problems [4]. For these types of problems, the most logical solution would be to use algorithms which are not deterministic but their solutions are near optimal and not too hypothetical to be implemented. For solving the hard-optimization problems like path planning, the use of meta-heuristics has been universally appreciated. Meta-heuristics are problem independent solutions and they do not need to adapt to present a solution to a specific problem. Instead they approximately solve a wide range of hard-optimization problem. Meta-Heuristics are usually based on nature (principles of biology, physics, etc.), use random variables and have several parameters which are needed to be fitted according to the problem in hand. Some of the popular examples for these Nature Inspired Meta-Heuristic algorithms are Particle Swarm Optimization(PSO) [5], Artificial Bee Colony(ABC) [6], Genetic Algorithm [7], etc. The techniques behind these algorithms is to exploit the behavior of the individual agents to get attracted towards the behavior of the swarm collectively to find the desired solution for their problem. These algorithms work in a way so as to guide the individual search agents to improve the overall solutions. This way a near optimal solution is obtained with a feasible time complexity. Readers are advised to read about the recently published meta-heuristics in order to understand the technical and mathematical details of these algorithms to understand the due course of paper effectively [8].

The paper has been divided into sections as follows. The next section gives the background and analysis of the problem statement as well as describes the overview of the topic and similar work with this paper, and some important surveys previously conducted related to the problem. Section 3 provides solutions to the path planning problem based on

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single solution meta heuristics like simulated annealing, tabu search, etc as well as population based metaheuristics like PSO, ACO, Genetic Algorithm, etc. as well as discuss their applications to the problem. Section 4 presents the conclusion of the paper.

## II. Background

The path planning problem is classified as an NP-hard problem by the researchers working in the field of computational complexity [9]. The difficulty increases as the degrees of freedom for the problem increases. Therefore, to solve this problem meta-heuristic techniques are widely recognized in literature and present quite good results. The purpose of this paper is to provide a survey of the meta-heuristic approaches executed till date on the path planning problem so as to facilitate the future researchers by having a detailed overview about the solution available to them. Majority of the algorithms developed are based on the decomposition approach in which researchers first develop the solution to a problem, apply path smoothing techniques, form a trajectory which is achievable by the vehicle, and then applies a control algorithm for the vehicle to follow the path. In the case of UAV cruising in 3D space, various parameters are to be taken into account before making the mathematical problem statement. The aircraft may have different velocity and acceleration constraints, sensor capabilities, knowledge of the environment, manoeuvrability. In the survey conducted it has been found that the there is a need for some benchmark constraints for the problems so as to have constant results on the application of a problem statement. However, due to difference in environmental conditions and aircraft properties there has been difficulty in maintaining the standards. For example, it is seen that the fixed-wing and rotary-wing aircrafts show different properties in environments [10]. Hence, it has been difficult to provide a comparison even in the case of state-of-the-art approximation algorithms. This paper also tries to specify the constraints and conditions for the solution proposed, so as to make the reader aware about the hypothesis of the problem.

### A. Similar Work

There have been a quite a lot of previous surveys on the path planning problems in robotics as well as on meta-heuristic techniques. They are published in the forms of books, journals, etc and provide a good deal of knowledge. The book Complexity of Robot motion planning [11] explains several initial concepts of path planning like voronoi diagrams, roadmap methods, etc that are used till date. The article by Hwang and Ahuja [12] surveyed several motion planning algorithms for robots in different environments. For UAVs there has been an extensive research done till date. Several notable surveys have been published which outlines the previous contributions done in the field of aerial path planning. [13] provided a review of existing cognition strategies related to decision making in drones. [14] presented several motion planning problems and discussed the solutions available for the problems during the time taking care of the factors of the surroundings of the UAVs. A more recent work includes a book named 'Cooperative path planning of unmanned aerial vehicles' [15] is a very extensive literature on all the path planning problems and related techniques for solving including path planning for multi-uav systems in 2D and 3D environments. Several notable reviews have also been done using meta-heuristics as a solution for the aerial path planning problems. [16] performed a performance comparison of several notable evolutionary algorithms on UAV planning by calculating a dominance evaluation function. Among their set of chosen algorithms, the DE algorithm performed the best performance and generated most optimal path. The book 'Planning and decision making for aerial robots [17] also explains several meta heuristic methods for aerial robot decision making in its Chapter 3. These surveys have been of extremely important to any researcher for getting to know about the existing experiments and results in the literature. In this review paper, a brief summary is provided about various meta heuristic algorithms that have been applied on the field of path planning for unmanned aerial vehicles in either 2D or 3D dimensions with static or dynamic obstacles.

## III. Path Planning and Meta-Heuristics

The complex NP-Hard problem of path planning is a very challenging issue in the research community. Several deterministic and meta-heuristic algorithms have been used in order to have an efficient method for an Aerial Vehicle to generate a path from source to destination. Many of these methods will be discussed in this section with a critical understanding of them highlighting their strong points and weak points. The division of these algorithms is done on the basis of their implementation for their optimization agents. The next section discusses solutions based on two types of meta-heuristics: Single solution based meta-heuristics and population based metaheuristics

### A. Single Solution based Meta-heuristics

Single solution meta-heuristics are also known as trajectory methods [8]. They involve only a single solution which moves in the search space making a trajectory and considered intelligent versions of the local search methods. Some major single solution meta-heuristics for the UAV path planning are discussed as follows:

*1) Simulated Annealing:* Simulated annealing method was first introduced by Kirkpatrick and Scott [18]. This method is useful to find global best in large discrete search space. It is known to show improved results over methods like gradient descent when it is feasible to find approximate global best over precise local best solution A few researchers have tried to implement the simulated annealing approach over the 3D Path planning problem. In [19] the authors applied simulated annealing neural network to solve 3D path planning and obtained improved results than previous potential field algorithm in terms of path obtained and memory used. In [20] the authors used modified simulated annealing technique for path planning of small UAVs. They tested the algorithm to solve the multiple Travelling Salesman Problem (mTSP) [21]. The algorithm showed promising results on Raspberry Pi

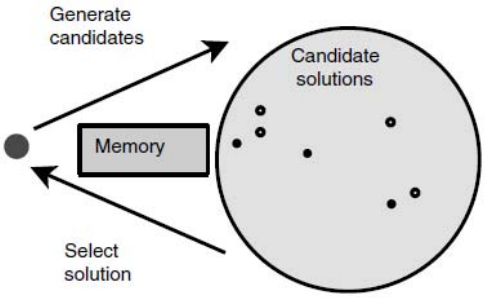


Fig. 1. Single Solution meta-heuristics [8]

platform and field tests were to be done to verify the optimality of the algorithm.

*2) Tabu Search:* Tabu search was introduced by Fred Glover [22]. It is a meta-heuristic method which uses local search procedures for finding the optimal solution to the problem. It takes its name as tabu as it forbids the previously visited solutions to be visited again by using memory structures. In [23] the authors suggested a routing method for UAVs by first solving the problem on Travelling salesman problem using tabu search and then extending the solution by introducing the parameters required for the UAV routing problem.

### *B. Population Based Meta-heuristics*

In the initialization of population based meta-heuristics [8] multiple (population of) solutions are initialized. At each step they use the properties of the population in order to guide the solution to the optimality. The most popular population based meta-heuristics are either based on evolutionary strategies or on swarm intelligence. The paper discusses both types of meta-heuristics as well as the implementation of their algorithms in the Aerial Path planning problem.

*I. Evolutionary computation:* These techniques are developed from the natures characteristics that the things that show the best adaptive behavior in the environment thrive while the ones which do not show perish. The algorithms which are developed from EC are also known as Evolutionary Algorithms(EA). They are usually grouped as Evolutionary Programming [24], Evolutionary Strategies [25], Genetic Programming [26], Genetic Algorithm [7] and Differential Evolution [27]. There has been an extensive research by the use of these strategies for the UAV path planning as they produce optimal results without having any assumption about the fitness landscape. A brief overview of all the related work done in the field is given in Table 1.

TABLE I. EVOLUTIONARY META-HEURISTICS

| S. No | Evolutionary Meta-heuristics | | | |
|---|---|---|---|---|
| | *Author( Year)* | *Meta-heuristic* | *Result* | *Comments* |
| 1 | Ioannis K. Nikolos (2005) [28] | Differential Evolution | The algorithm produced feasible solutions within 100 generations with coordination from 3-4 UAVs. | 2D path planning for multi UAV coordination in offline environment. Large number of waypoints leads to increased computational time. |
| 2 | Y. Volkan (2007) [29] | Vibrational GA | The VBA created a path length effectively taking care of the constraints. The path is smoothed using Bezier Curves. | 3D terrain model used. Effective model of applying VGA with Bezier curve to obtain smooth path trajectory. |
| 3 | Hasircioglu (2008) [30] | Genetic Algorithm | Applied algorithm on two terrains. Good performance after several generations. | 3D Path planning using EA. No comparison with other solutions. Path represented as B-spline curves. |
| 4 | Si-Yao Fu (2012) [31] | Modified GA | Radars were introduced in the path of the UAV. The UAV effectively retraces the path in 15-20 generations. | A new method based on genetic algorithm is introduced. Its effectiveness proves GA to be promising for UAV path planning. 2D path planning done which can be implemented in 3D. |
| 5 | N. Ozalp (2013) [32] | Parallel GA | The algorithm obtained improved results over GA by utilizing multi core properties of today's CPU. | 3D path planning with no environmental constraints used. Introduced parallel version of GA on multi core machines. Comparison done with only the GA on single core machine. |
| 6 | Vincent Roberge (2013) [33] | PSO and Parallel GA | Parallel GA produced better trajectories than PSO in 25 out of 40 scenarios and PSO better in P-GA in 3 out of 40 scenarios. | 3D path planning in dynamic environment. Needs multiple core CPU to perform parallel processing. No comparison with algorithms other than PSO. |
| 7 | Yangguang Fu (2013) [34] | Hybrid DE and Quantum behaved PSO | The trajectory obtained by DEQPSO is better than that of DE, PSO, DEPSO, QPSO on comparing tests. | A new hybrid meta-heuristic was introduced which is a combination of two algorithms. Solution approach applied to path planning of UAV in the sea. |

| | | | | |
|---|---|---|---|---|
| 8 | M. Cakir (2015) [35] | Genetic Algorithm | Path planning algorithm with Forbidden zones in the 2D map using GA. | 2D path planning can be improved to 3D with dynamic differential constraints. No comparison performed with other solutions. |
| 9 | Xiangyin Zhang (2015) [36] | Improved constrained Differential Evolutional (DE) | The route obtained has short length and low altitude. The algorithms show better results than several state of the art solutions for constraint optimization. | Path planning in 2D and 3D path. Combines DE based local search ability and constraints handling techniques based on level comparison. |
| 10 | Mrcio da Silva (2016) [37] | Hybrid GA (HGA) | Solution is obtained quickly (in about 10 seconds). Compared against a heuristic (Customized Search Approach) and exact(CPLEX) method. | Hybrid GA combines Multi Population GA with visibility graph to obtain high quality solution in less computational time. Future research included application in real time 3D environment. |
| 11 | YANG Xiaoyu (2016) [38] | Genetic Programming | GP method shows both better fitness and path generated than GA. GP methods have less reliance on threats position than GA. | Path Planning in 2D space. GP methods shows promising results over GA methods. Need to compare results with modified GA methods. |

*2) Swarm Intelligence:* Swarm intelligence refers to the intelligent behavior by a collection of population. They are usually decentralized and self-organized systems. The term was first introduced by Gerardo Beni and Jing Wang [39]. In swarm intelligence the agents do not follow any centralized control structure, but local and random interactions between these agents lead to intelligent behavior among them. These algorithms are widely used in many optimization problems and also have a huge significance in the field of path planning. The paper now discusses several major swarm intelligence algorithms in context to the UAV path planning problem.

- *Particle Swarm Optimization(PSO):* PSO was introduced by James Kennedy in 1995 [5]. It is a metaphor describing an optimization method based on the flocking of birds. Several notable researches are done on the Path planning for UAVs using PSO technique and its variants. [40] is among the first attempts to do 3D path planning of UAVs using the PSO technique. A VR system named Virtual Battlespace was used to implement the solution developed through PSO. The planner was successfully able to generate paths in real time. Two constraints namely threat avoidance and fuel cost were included in the optimization problem. [41] uses Discrete-PSO technique along with voronoi diagrams to have coordinated timing attacks using multi-uav. Initial paths are obtained using Voronoi-diagram and Waypoint Path Planner and then attack is planned using Particle Swarm Optimization. The results show that the PSO based planner works effectively for managing timing and control for UAVs. [42] uses a modified version of PSO named as Fitness-Scaling Adaptive Chaotic PSO. The performance of the approach was found to be better than elite GA, PSO, Simulated annealing and Chaotic ABC for the UCAV path planning problem. They also extended their experiments on dynamic path planning for 2D map as well as 3D path planning and FAC-PSO showed superior results in all the cases. [43] uses the Adaptive Chaotic PSO method to do Real-Time path planning of UAVs in dynamic environment. The improved PSO is used with variable structure strategy to make the path planning more effective.
- *Ant Colony Optimization(ACO):* ACO was first introduced by M. Dorigo et al. [44] as a solution of hard optimization problem. It takes into use the foraging behavior of ants to perform a model based search [45]. In the topic of UAV path planning [46] used ACO algorithm for creating a path from source to destination in discrete space. The path generated was short and efficient however the authors did not apply any path smoothing algorithms which was required according to real life motion of UAVs. [47] used a hybrid ACO-DE algorithm for 3D path planning of UAVs. The new method showed better results over normal ACO algorithm in terms of speed as well as path length. [48] used parallelized ant colony algorithm for solving UAV path planning problem in CUDA architecture. The algorithm here produced a path from source to destination even in large solution space due to its parallel nature. However, much stress was not given to smoothing of path, and creating a dynamic environment for the UAVs. In [49] ACO with a multi colony approach is used to tackle weakness of ACO i.e. premature convergence. The multi colony approach results into creation of multi paths during the simulation and thus there is less chance for getting stuck in one path. In the future they planned to make a parallel version of the same algorithm for better performance.
- *Artificial Bee Colony(ABC):* ABC optimization algorithm was invented by Karaboga in 2005 [6]. This algorithm takes into use the foraging behavior of honey bee swarm. [50] presented a chaotic Artificial Bee Colony approach for Unmanned combat aerial vehicle path planning in dynamic environment with pop up threats. The chaos variable introduced in the algorithm helped to the solution to prevent getting stuck in local optimum unlike normal ABC approach. [51] solves the UAV path planning in 2 dimensions using improved ABC approach. Improvements were applied at every stage of ABC algorithm. The results obtained showed better convergence rate the

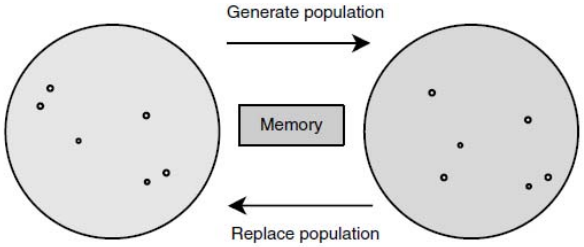


Fig. 2. Population Based meta-heuristics [8]

standard ABC approach. [52] introduced a novel probability density model based on ABC for UCAV path planning. Even when the threats are in major part of the map (inflexible to avoid), the Probability density model minimized the risk cost effectively. The results are to be verified for 3D path planning and parallel versions in multi-core CPU is also to be developed. [53] used balanced evolution strategy to improve the performance of ABC in the UCAV path planning problem. They also compared the proposed algorithm with conventional as well as several other variants of ABC to prove the new methods superiority.

*3) Miscellaneous Meta-Heuristics:* Several researchers introduced novel meta-heuristic methods which can be applied to obtain an optimal path for the unmanned aerial vehicles. Many of these algorithms are quite new and their novelty for the problem is yet to be verified by future researches. This section will give an overview of few of the new meta-heuristic methods which have been used on the UAV path planning problem along with a review on the results obtained by them. The inference is provided in Table 2.

TABLE II. OTHER NEW META-HEURISTICS

| S. No | Evolutionary Meta-heuristics | | | |
|---|---|---|---|---|
| | *Author( Year)* | *Meta-heuristic* | *Result* | *Comments* |
| 1 | Haibin Duan et al. (2008) [54] | Intelligent Water-Drops Optimization | Where basic IWD failed to generate a path, improved IWD Successfully generated a minimum threat path between source and destination. | Basic IWD showed below satisfactory results. Path planning done in 2D radar environment Comparisons not performed with other solutions. |
| 2 | Ma et. al (2012) [55] | Artificial Fish School Algorithm | Comparisons made with improved versions of PSO generated better worst cases for AFS algorithm. AFS generated satisfactory results even in the worst case while others could not. | Path planning for 2D radar environment. No inclusion of obstacles for collision avoidance schemes. AFS showed strong global search ability. Resulted in shorter flight distance. |
| 3 | Wang et al. (2012) [56] | Modified Firefly Algorithm | MFA algorithm performed better than original FA, ACO, ES, GA, PSO, Probability based Incremental Learning and stud GA. | Path planning for combat environment. There was less need to fine tune the parameters of MFA to obtain the best solution unlike FA. |
| 4 | Zhang et al. (2014) [57] | Predator Prey Pigeon Inspired Optimization | PPPIO produced better trajectory than PIO and PSO algorithms in 2D and 3D environments. | UAV 3D path planning in complex environment. They performed tests on both 2D and 3D environment and obtained better results for PPPIO. |
| 5 | Zhu et al. (2014) [58] | Chaotic predator prey biogeography based optimization | Algorithm prevented jumping into local minima by basic BBO algorithm by using ergodic properties of chaos variable and predator-prey behavior | A Novel method for UCAV path planning in 2D environment. Used static obstacles with threats having different radius. |
| 6 | Yu et al. (2014) [59] | Teaching Learning Based Optimization | TLBO algorithm performed better that ABC, PSO, GSO algorithm in complicated combating environment and produced second best results after DE. | A new method based on the behavior of teachers and learners in the classroom. It efficiently produced a path for UAV and obtained better results than many solutions. Good scope with improvement. |
| 7 | Tang et al. (2015) [60] | Glowworm Swarm Optimization | Results are better than 10 other algorithms on some parameters. On other parameters a better performance than 6-7 other algorithms. | 2D path planning in combating environment. Robust Comparison performed using Wilcoxon-Signed Ranked Tests [61]. |
| 8 | Gai-Ge Wang (2016) [62] | Improved bat algorithm | The results improved over normal BA as it prevented it to converge into local minima. The results were similar to modified DE/CS (Cuckoo Search) algorithm. | 3D path planning algorithm in combating environment. Used mutation operation of DE to enhance bat selection algorithm. |
| 9 | Huang et al. (2016) [63] | Improved Cuckoo Search Algorithm | Algorithm performed good results in high threat points and control points. Improved performance over normal Cuckoo Search. | Hybrid Cuckoo Search algorithm improved with GA operators to prevent falling into local optimum. More improvement in result expected. |

## IV. RESEARCH GAPS

The research for the path planning algorithms using meta-heuristics has been expanded a lot during the last decade. Several modifications of the general algorithms as well as new methods are introduced for solving the problem every year. However, some of the research gaps are felt that are needed to be solved in the near future researches. The lack of benchmark conditions for performing experiments and simulations leads to heterogeneity of results which creates an inconsistency when a comparison is done between multiple algorithms. We found researchers using different objective functions, parameters, initial assumptions for multi objective optimization problem. The results obtained were found to be satisfactory for their objective however the real life path planning might include several other factors that are needed to be taken care of. Most of the researches were ignoring the differential constraints when applying their algorithm using simulation as they focused more on the solution part than formulation of the problem.

Some of the future prospects in this field that that can be expected are:

- Several improvements on the pre-existing meta-heuristic algorithms as well as new novel meta-heuristic methods resulting performance improvement.
- Parallelization of the algorithms using multi-core CPUs is also seen as a novel approach to improve the performance of the algorithm and is expected to be researched further.
- Researchers in the area should develop benchmark problem conditions for other researches to develop and test their solution so that comparisons between different solutions can be made efficiently.
- A more robust environment formulation by researches is also expected which resembles real world environment as much as it can.

## V. CONCLUSION

A broad discussion of several meta-heuristic applications has been done which have been applied to solve the path planning problem of Unmanned Aerial Vehicles. Importance is given to the novelty of the algorithm and its potential for solving future problems of real time UAV path planning. The algorithms were compared using various simulation softwares or graphs which cater the need of the researcher by formulating a real time environment related to the problem. The algorithms generated a path in the solution space, which was then made flyable by the UAVs using path smoothing strategies also discussed in the paper. After this review it can be concluded that the use of modified meta-heuristic algorithms has good scope for being implemented in real time motion planning of the Unmanned Aerial vehicles for completing complex tasks implemented in parallel or in a hybrid way taking into the best features of several algorithms.

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