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A mixed probabilistic–geometric strategy for UAV optimum flight path identification based on bit-coded basic manoeuvres

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A B S T R A C T

This paper presents a novel algorithm identifying optimal flight trajectories for Unmanned Aerial Vehicles compliant with environmental constraints. Such constraints are defined in terms of obstacles, fixed waypoints and selected destination points. Optimality is evaluated taking the minimum path length as the specific objective function. The proposed path planning strategy is based on an original trajectory modelling coupled with a Particle Swarm optimizer (PSO). Flight paths starting from a specified point and ending at a selected destination point are divided into a finite number of segments made up of circular arcs and straight lines. In the proposed approach such a geometrical sequence is replaced with a finite sequence of binary-coded basic manoeuvres. This novel formulation allows to easily handle the manoeuvres sequence with a fixed number of integer variables taking advantage of PSO capability in handling discrete variables; moreover the use of mixed-type variables provides the optimization procedure a useful flexibility in the "decision making" modelling and operational scenarios definition as well. Specific geometric-based linear obstacle avoidance models have been implemented in addition to suitable penalty functions. The use of these models forces each path to be consistent with the environmental constraints favouring the identification of feasible trajectories with a reduced number of iterations and particles. The path planning model has been developed with particular care devoted to reduce computational effort as well as to improve algorithm capability in handling general-shaped obstacles both in 2-D and 3-D environments. Various applications have been performed in order to test the effectiveness of the proposed flight path generator. Applicability of the proposed optimization model also to vehicles with VTOL and hovering capabilities has been preliminarily assessed.

0. Introduction

Unmanned air vehicles (UAVs) are being extensively used for different civil and military applications especially to replace the presence of human pilot aboard in dangerous/dull missions or to reduce operational costs. In the frame of a careful mission planning, identification of feasible flight trajectories, consistent with mission objectives, operational scenarios and vehicles performance, certainly plays an important role.

A wide literature exists regarding trajectory optimization methodologies applied to different operational scenarios and vehicles. The variational approach is the most rigorous one for this class of problems though unfit to solve complex problems. Numerical methods based on the solution of Non Linear Programming (NLP) problems are presented by Betts [1]. Feasible trajectories can be also generated following a geometrical approach based on topological techniques creating a sequence of waypoints. This sequence can derive from probabilistic or potential methods [2]. A classical geometric approach guaranteeing optimality conditions in terms of paths length and smooth trajectories compliant with curvature constraint was proposed by Dubins [3] and refined by Anderson et al. [4], Chitsaz and LaValle [5] and Shanmugavel et al. [6]. An interesting technique, taking into account flight dynamics, is based on the so called "motion primitives" [7], where flight paths are defined through a sequence of trim conditions and manoeuvres. Recently, novel path planning strategies work by quickly sampling the 3-D free space to get a grid of points which are connected with specific smooth curves. An interesting paper is proposed by Ching-Huei Huang et al. [8], where Rapidly Random Tree (RRT) technique is employed with A* algorithm to get the optimal trajectory connecting the starting and the ending points. Bezier curves are used to get the final smooth path. A variant of the classical RRT method uses 3-D Dubins curves for tree expansion [9]. An improved RRT, using D* Lite algorithm for solving the dynamic path planning problem, is proposed by Liu Yang et al. [10]. Probabilistic Roadmap Method (PRM) together with A* algorithm used to as-

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sist PRM for path planning during the query phase is presented by Fei Yan et al. [11] whereas an Improved PRM with D* Lite algorithm is proposed by Qian Xue et al. [12] for online re-planning. Another approach is presented by Mattei et al. [13] where the trajectory optimization problem is converted into a minimum cost path search by defining a weighted and oriented graph called CPG. A parallel and distributed implementation of CPG algorithm is proposed by Pascarella et al. [14] providing a preliminary assessment of algorithm suitability for real time operations.

Non-conventional, nature-inspired optimization methods have shown their effectiveness and robustness in the field of path planning too. Specific examples can be found in Hu et al. [15], Yufeng He et al. [16] and Nuri Özalp et al. [17]. Among evolutionary computational techniques, optimization methods based on Swarm Theory (PSO) certainly are of great importance having the advantage of a simpler implementation than other population-based optimization methods (e.g. genetic algorithm) providing in some cases better results as well [18]. Examples of PSO applications in the field of path planning can be found in Raja and Pugazhenhi [19] where PSO algorithm is used to refine the shortest path identified using a Dijkstra algorithm. In Shibo et al. [20] a mixed fuzzy-PSO technique is applied to identify the optimum path over a meshed planning area. In Saska et al. [21] a PSO-based procedure is used to optimize cubic splines parameters describing smooth trajectories. In H. Min et al. [22] a mathematical collision model is developed and coupled with a Particle Swarm Optimizer. Such a procedure is successfully applied in finding optimum path with respect to a simulation environment composed by one robot and multiple circular obstacles. Results are then compared with both potential and hybrid potential-genetic algorithm. Another PSO-based obstacle avoidance path planner is developed and successfully applied by Wang et al. [23]. Recent works deal with trajectory optimization using parallel GA and PSO for real time application in the field of UAV path planning [24].

In the frame of PSO-based procedures performing off-line trajectories generation, this paper represents a considerable evolution of authors' previous work [25]. The proposed path planning strategy is based on an original trajectory modelling coupled with a Particle Swarm optimizer. Flight paths start from a specified point with a fixed direction ending at a selected destination point. We assume that trajectories are divided into a finite number of segments made up of circular arcs and straight lines resembling in some way the Dubins curves proposed for free space trajectory generation [3]. Besides this similitude, in our probabilistic guided-search process criteria for switching between arcs and straight lines follow a completely different rationale compared with Dubins approach. In the proposed novel path planner, such a sequence of circular arcs and straight lines is replaced with a finite sequence of binary-coded basic manoeuvres. This way flight path can be described with a fixed number of integer-type variables taking advantage of PSO capability in handling discrete variables; moreover the use of mixed-type variables provides the optimization procedure a useful flexibility in the "decision making" modelling and operational scenarios definition as well. Specific geometric-based linear obstacle avoidance models have been implemented in addition to suitable penalty functions. The use of these models forces each path to be consistent with the environmental constraints favouring the identification of feasible trajectories with a reduced number of iterations and particles. Various kinds of test have been performed to verify the effectiveness of the proposed novel flight path generator as well as to assess solutions reliability with respect to different initial populations. Compared to authors' previous work [25], the new algorithm shows an higher effectiveness providing comparable or in some cases better results with a smaller swarm size and a less iterations number; moreover, algorithm capability in handling general-shaped obstacles in a 3-D environment has been verified. Finally a preliminary assessment of algorithm applicability to vehicles with VTOL and hovering capabilities has been carried out too.

The present paper is organized as follows: Chapter 1 presents the proposed new trajectory modelling and briefly recalls PSO methodology; Chapter 2 describes some additional features we have implemented to further improve algorithm effectiveness; Chapter 3 presents numerical results obtained with operational scenarios of different complexity; finally conclusions are reported in Chapter 4.

Table 1
Bit-coded basic manoeuvres in the horizontal plane.

Turn right	0	1
Turn left	1	0
Straight flight	0	0
Alignment to target	1	1

1. The path planning strategy

The problem we have investigated in this paper consists in the identification of flight paths minimizing trajectory length in the presence of obstacles and targets both in 2-D and 3-D environments. The proposed path planning strategy is based on an original trajectory modelling coupled with a Particle Swarm optimizer. The choice of a PSO strategy naturally follows from the optimization problem formulation that takes full advantage of PSO capability in handling mixed-type variables. Assuming simple circular obstacles, specific geometric-based linear obstacle avoidance models have been implemented. These models allowing the algorithm to select suitable trajectory parameters (e.g. turn radius or path angle) force each path to be consistent with the environmental constraints strongly supporting the optimization process.

1.1. 2-D trajectory modelling

All candidate trajectories start from a specified starting point (SP) with a given initial direction ending at the destination point (DP); if required, flight paths can pass over fixed waypoints whose optimum sequence can be selected by the algorithm. We assume that flight paths are divided into a finite sequence of n segments made up of circular arcs and straight lines whose length is Δs; such a geometrical sequence is replaced with a sequence of n manoeuvres chosen within a finite set and represented by means of two bit-coded numbers. In particular, Table 1 shows the set of basic manoeuvres defined in the horizontal plane with the related binary coding:

In order to identify a sequence of n manoeuvres (i.e. n pairs of binary numbers) we define two integer variables, namely $VP_{1\mathrm{m}}$ and $VP_{2\mathrm{m}}$, varying in the range $[0, 2^n - 1]$ whose binary coding provides two n-tuples of binary numbers representing the manoeuvres sequence. This way we can easily describe trajectory by means of two design variables (i.e. $VP_{1\mathrm{m}}$, $VP_{2\mathrm{m}}$) regardless the actual number of path segments, n.

Table 2 shows an example of manoeuvres sequence ($n = 10$) resulting from $VP_{1\mathrm{m}}$ and $VP_{2\mathrm{m}}$ specific values.

The segments number, n, is fixed *a priori* by the user on the basis of problem complexity. As a general criterion the higher the environment complexity is, the higher the number of segments, n, should be. Practically, if n is sufficiently high, destination point can be reached with a number of segments less than n.

In case of an "alignment to target" manoeuvre, a circular arc with r_t radius is traced turning trajectory direction to the target (Fig. 1). In this regard the "alignment to target" manoeuvre