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Flight path planning for unmanned aerial vehicles with landmark-based visual navigation

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HIGHLIGHTS

- The flight performance and the navigational capabilities are considered.
- The airspace is discretized by a network depending on the UAV characteristics.
- The time-consuming tasks are performed in a preprocessing step.
- It is demonstrated that a flight path is calculated within few seconds.

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ABSTRACT

In this paper we present an algorithm to determine a shortest trajectory of a fixed-wing UAV in scenarios with no-fly areas. The innovative feature is that not only the kinematic and dynamic properties, but also the navigational capabilities of the air vehicle are taken into account. We consider a UAV with landmark-based visual navigation, a technique which can cope with long-term GPS outages. A navigation update is obtained by matching onboard images of selected landmarks with internally stored geo-referenced images. To achieve regular updates, a set of landmarks must be identified which are passed by the air vehicle in a proper sequence and with appropriate overflight directions.

The algorithm is based on a discretization of the airspace by a specific network. Each path in the network corresponds to a trajectory which avoids the no-fly areas and respects the flight performance of the air vehicle. Full functionality of the navigation can be ensured by dynamically adapting the network to the environmental conditions. A shortest trajectory is then obtained by the application of standard network algorithms.

1. Introduction

Unmanned Aerial Vehicles (UAVs) are increasingly deployed in civilian and military domains. Civil applications include search and rescue, border interdiction, traffic monitoring, law enforcement, disaster and emergency management, wild fire suppression, communications relay, and many others. In the military field, UAVs play a key role within the concept of information dominance. They are widely used for intelligence, reconnaissance and surveillance missions. A survey of UAV applications is given by Sarris [1].

A UAV mission planning system is intended to assist an operator to plan and manage missions which satisfy the operational requirements while taking into account the limitations of the air vehicle, airspace control regulations, rules of engagement, etc. The main component of an automated mission planning system is the flight path algorithm. The task is to find an optimal or near-optimal route from a start point to a destination point in a complex and challenging scenario. This problem is further complicated by the need of a fast planning. Modern mission planning systems must support quick reactions to changing operational requirements, tactical considerations, or environmental conditions.

An advanced flight path algorithm should consider *differential constraints* which arise from the kinematic and the dynamic behavior of the air vehicle. Limitations of the velocity are often called *kinematic constraints* in order to distinguish them from *dynamic constraints* which refer to the acceleration capabilities. For an air vehicle, the kinematic constraints (first order derivative of motion) are usually expressed by its minimum and maximum velocity. The dynamic constraints (second order derivatives) reflect that the air vehicle is not able to instantaneously change its velocity or perform sharp turns. Motion planning problems with velocity and acceleration bounds are also known as *kinodynamic problems* (see Donald et al. [2]). Planning under differential constraints is intensively discussed in the textbook of LaValle [3].

Equally important, however, is to involve the *navigational capabilities* of the UAV. A successful mission of an autonomous air vehicle strongly depends on an accurate and reliable navigation.

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Navigation data (position, velocity, and attitude) are needed for guidance and control. They are usually obtained by inertial navigation systems which are based on measurements of the vehicle's angular velocity and acceleration. In order to correct the inevitable drift, the systems are aided by external non-inertial navigation data. These data are often provided by a satellite-based system such as the Global Positioning System (GPS). Since GPS is not always available, visual (image-based) navigation is establishing more and more as a cheap and robust additional measurement method. In a landmark-based approach, an onboard camera takes images of selected landmarks during flight. By matching these images with geo-referenced landmark data, the position and attitude of the air vehicle relative to the landmark can be estimated.

This paper investigates the problem of finding a flight path of minimal length in the horizontal plane, from a start point with release velocity vector to a destination point with approach velocity vector. The flight path must avoid no-fly zones (densely populated areas, threat regions, obstacles due to topography, etc.) and must consider the performance of the air vehicle. This means that the trajectory should be sufficiently smooth (obeying the kinematic and dynamic constraints of the air vehicle) and should ensure full functionality of the navigation system. The latter includes the identification of a set of suitable landmarks which have to be passed by the air vehicle in a proper sequence. The distances between consecutive landmarks and the overflight directions must be controlled in order to guarantee regular navigation updates. The problem is aggravated by the fact that the quality of navigation updates is strongly depending on (rapidly changing) weather conditions.

Finding a flight path which avoids no-fly zones is strongly related to the problem of finding a collision-free path of a robot in an environment with obstacles. Different techniques have been used to solve that problem, among them are mixed integer linear programs, the potential field method, cell decomposition, the roadmap method, the mass–spring–damper method, and several network-based approaches with discretizations of the space by visibility graphs, Voronoi diagrams or regular grids. We refer to the reviews of Latombe [4] and LaValle [3].

In adapting these methods to the flight path problem, some authors completely neglect the maneuverability of the air vehicle. In a number of papers, the flight performance is indeed considered, but in a rather simplified form. For instance, the network-based methods of Carlyle [5], Rippel [6] and Zabarankin [7] generate a polygonal path from a regular grid discretization of the airspace. The flight performance is restricted to the implementation of turn radius constraints. They allow consecutive edges on a path only if these edges include a sufficiently small angle. Other authors perform a path smoothing after having found a collision-free path in a first step. For instance, Bortoff [8] determines a shortest path in a network based on Voronoi polygons and achieves a smoothing of the path by a springs and masses approach. Judd and McLain [9] use a series of cubic splines to smooth the straight-line segments.

Newer approaches try to solve the flight path problem while, at the same time, accounting for no-fly zones and differential constraints. These include sampling-based methods based on rapidly exploring random trees, model predictive control methods, and mathematical programming methods which treat the route planning problem as a numerical optimization problem. A review is given by Goerzen et al. [10]. On the other hand, we are not aware of any research that also considers the navigational capabilities of the air vehicle.

In this paper we introduce a flight path algorithm which considers no-fly zones, differential and navigational constraints for a fixed-wing UAV equipped with land-mark-based visual navigation. The algorithm is based on a discretization of the airspace by a specific network. The edges of the network represent shortest obstacle-avoiding trajectories between the landmarks. Each of them respects the differential constraints which are given in the form of velocity and acceleration bounds. The generation of the trajectories adopts an idea from Babel [11]. By deleting certain edges, we obtain a subnetwork where the trajectories additionally comply with the navigational constraints. While the basic network is static, the subnetwork can be considered as dynamic in the sense that it depends on the environmental conditions of the current mission. The approach allows the application of standard network methods to find a shortest path. In order to realize a quick planning we split the algorithm into a preprocessing and an online planning phase. The preprocessing phase gathers the time-consuming preparatory work, thus allowing an online planning within a few seconds.

Section 2 briefly describes the concept of landmark-based visual navigation. Section 3 outlines how to find a shortest flight path with differential constraints in a scenario with no-fly zones. Section 4 contains the main contribution of the paper, the route planning algorithm for air vehicles with navigational constraints. Section 5 continues with implementation details. Computational results for different scenarios are discussed in Section 6. We conclude with final remarks in Section 7.

2. Landmark-based navigation

Today, most air vehicles are equipped with an inertial navigation system. The main component of an inertial navigation system is the inertial measurement unit (IMU), an electronic device which usually consists of three accelerometers and three gyroscopes. Measurements of the current rate of acceleration and changes in angular velocities (of pitch, roll and yaw) are integrated over time, thus providing an estimation of the velocity, orientation and position of the vehicle.

A major drawback of inertial navigation systems is that they suffer from integration drift. Small measurement errors of acceleration and angular velocity are integrated into increasing errors in velocity which are accumulated into still greater errors in position. This provides an ever-increasing difference between the estimated position of the air vehicle and its true position (see e.g. Britting [12], Titterton and Weston [13]).

For that reason the position must be periodically corrected by an input from some other source. This can be accomplished by a satellite-based system (such as the Global Positioning System GPS) or some other type of navigation system. An aided system fuses the inertial navigation data with the GPS data (or data from some other source), hence bounding the error and providing a higher degree of accuracy than is possible with the use of any single system (see e.g. Farrel and Barth [14], Grewal et al. [15]).

However, for UAVs with GPS-aided inertial navigation system a loss of GPS signals can be extremely problematic and, in the worst case, end up with a complete failure of the mission. Reasons for GPS outages might be that satellite services are temporarily unavailable or satellite signals are jammed. Recently, spoofing has also come into the focus of unmanned flight systems (a spoofing attack attempts to deceive a GPS receiver with manipulated GPS signals hence pretending a false position). Both jamming and spoofing have become a major concern of GPS users due to the easy availability of technology on the market (see e.g. Wright et al. [16]).

To overcome these problems, visual navigation is getting more and more common for aiding inertial navigation systems (for reviews of the applied techniques see e.g. Bonin-Font et al. [17], DeSouza and Kak [18]). Visual navigation can cope with long-term GPS outages. A significant advantage – compared to other active approaches – is that visual navigation does not send out any signals. Hence there is no danger of being detected by hostile