Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Cybernetics

Trajectory Planning in Cluttered Environments for Agile UAVs

Bachelor's Thesis

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Study programme: Cybernetics and Robotics
Supervisor: Ing. Matej Novosad

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BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

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II. Bachelor’s thesis details

Bachelor’s thesis title in English:

Trajectory Planning in Cluttered Environments for Agile UAVs

Bachelor’s thesis title in Czech:

Plánování trajektorií v prostředí s překážkami pro agilní bezpilotní letouny

Guidelines:

1. Study the state-of-the-art methods for path planning with different homotopy classes.
2. Study the state-of-the-art methods for real-time trajectory planning.
3. Implement a method which efficiently finds the fastest collision-free trajectory in a cluttered environment.
4. Verify functionality of the proposed algorithm in different environments.
5. Compare the performance of the proposed algorithm with performance of the state-of-the-art methods.

Bibliography / sources:

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Date of bachelor’s thesis assignment: **09.09.2024** Deadline for bachelor thesis submission: ___________

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prof. Dr. Ing. Jan Kybic	prof. Mgr. Petr Páta, Ph.D.
Head of department’s signature	Vice-dean´s signature on behalf of the Dean

III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt	Student’s signature

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Abstract

This paper is devoted to the problem of trajectory planning for maneuvering unmanned aerial vehicles (UAVs) in cluttered three-dimensional environments. The goal is to construct safe and time-minimal trajectories subject to constraints on the dynamics of motion. For this purpose, an approach combining two state-of-the-art algorithms has been implemented: Clustering Topological PRM (CTopPRM), which allows finding several homotopically different paths, and the time minimization method, which provides a time-optimal trajectory. Additionally, a system for path evaluation and selection based on metrics of length and sharpness of turns is proposed, and collision checking of trajectories with a local replanning procedure if necessary is implemented.

Keywords Unmanned Aerial Vehicles, Path Planning, Trajectory Planning

Abstrakt

Tento clanek se venuje problemu planovan trajektorie pro manevrovan bezpilotnch letadel (UAV) v neprehlednem trojrozmernem prostred. Clem je sestrojit bezpecne a casove minimaln trajektorie s ohledem na omezen dynamiky pohybu. Za tmto ucelem byl implementovan prstup kombinujc dva nejmodernejs algoritmy: Topologicky PRM se shlukovanm (CTop-PRM), ktery umoznuje nalezt nekolik homotopicky odlisnych drah, a metodu casove minimalizace, ktera poskytuje casove optimaln trajektorii. Krome toho je navrzen system pro vyhodnocovan a vyber cesty zalozeny na metrikach delky a ostrosti zatacek a je implementovana kontrola koliz trajektori s prpadnym postupem lokalnho preplanovan.

Klcova slova Bezpilotn prostredky, planovan cesty, planovan trajektorie

Abbreviations

UAV	Unmanned Aerial Vehicle
A	A star
RRT	Rapidly exploring Random Tree
RRT	Rapidly exploring Random Tree star
PRM	Probabilistic Roadmap Method
CTopPRM	Clustering Topological Probabilistic Roadmap Method
PMM	Point-Mass Model
RAPTOR	Robust and Perception-Aware Trajectory Replanning
TOP-UAV	Time-Optimal Trajectory Planner
ICRA	International Conference on Robotics and Automation
IROS	Intelligent Robots and Systems
RA-L	Robotics and Automation Letters
ESDF	Euclidean Signed Distance Field

Contents

Chapter 1

Introduction

This paper considers the problem of trajectory planning for a maneuverable unmanned aerial vehicle (UAV) in a complex cluttered three-dimensional environment. This problem is of key importance for autonomous navigation, as safe trajectory planning that allows the drone to avoid multiple obstacles is critical to the reliability of autonomous flight. This ability directly determines the success of UAV applications in tasks that require flying close to obstacles. For example, search and rescue operations in wooded areas, inspection of engineering structures, environmental monitoring and other scenarios involve autonomous flight through a limited space with a large number of obstacles. In such conditions, a collision with an obstacle can result in the loss of an expensive device or mission failure, so effective trajectory planning is of paramount importance.

Over the past decades, a wide range of path and trajectory planning approaches for autonomous robots and UAVs have been developed. Classical global planning methods include graph search algorithms (e.g., the A star (A) algorithm and its modifications) and sampling methods such as Probabilistic Roadmap (PRM) and Rapidly-Exploring Random Tree (RRT). These algorithms are capable of finding collision-free routes in configuration space and scale well to high dimensions. To improve the quality of solutions, optimal planning methods, such as the Rapidly exploring Random Tree star (RRT) extension of RRT, have been proposed to minimize path length or cost. A separate direction is represented by trajectory planning methods taking into account the dynamics of the vehicle, in which the trajectory is optimized according to time or energy consumption criteria. In addition, localized real-time obstacle avoidance algorithms are applied to respond to unforeseen environmental changes. A detailed review of existing approaches is given in the Related Work chapter.

Despite the variety of developed methods, trajectory planning for a maneuverable UAV in a highly cluttered environment remains a nontrivial task. Several aspects must be simultaneously considered: finding a global route through complex obstacles; generating a dynamically feasible trajectory that satisfies speed and acceleration constraints; minimizing flight time to improve mission effectiveness; and being able to adapt to changing conditions through operational replanning. Many existing algorithms focus on only one of these aspects. For example, some methods efficiently navigate through obstacles but do not guarantee that the trajectory can be traversed quickly given the drone's dynamics, while others optimize the dynamic trajectory but are limited to a single route option and may lead to a suboptimal solution. It is especially important to be able to find alternative topologically distinct paths in a complex environment, as choosing a single route may deprive the system of more efficient obstacle avoidance options.

This paper proposes an integrated path planning approach aimed at satisfying all the above requirements. The key idea is to combine the Clustering Topological PRM (Clustering Topological Probabilistic Roadmap Method (CTopPRM)) algorithm [2], which allows finding topologically different paths in a cluttered environment, with a time-of-flight optimization method that takes into account the dynamic constraints of the UAV [3]. This architecture combines global topological planning, local optimization, and replanning mechanism into a single, coordinated process. This ensures reliable and efficient UAV navigation in highly cluttered environments and makes the proposed approach practically applicable for autonomous flights in complex 3D environments. The overall structure is shown in Fig. 1.1. These steps are discussed in detail in the following chapters.