# TOPFLIGHT: Trajectory and Mission Planning for Agile Flight of Aerial Robots in Cluttered Environments

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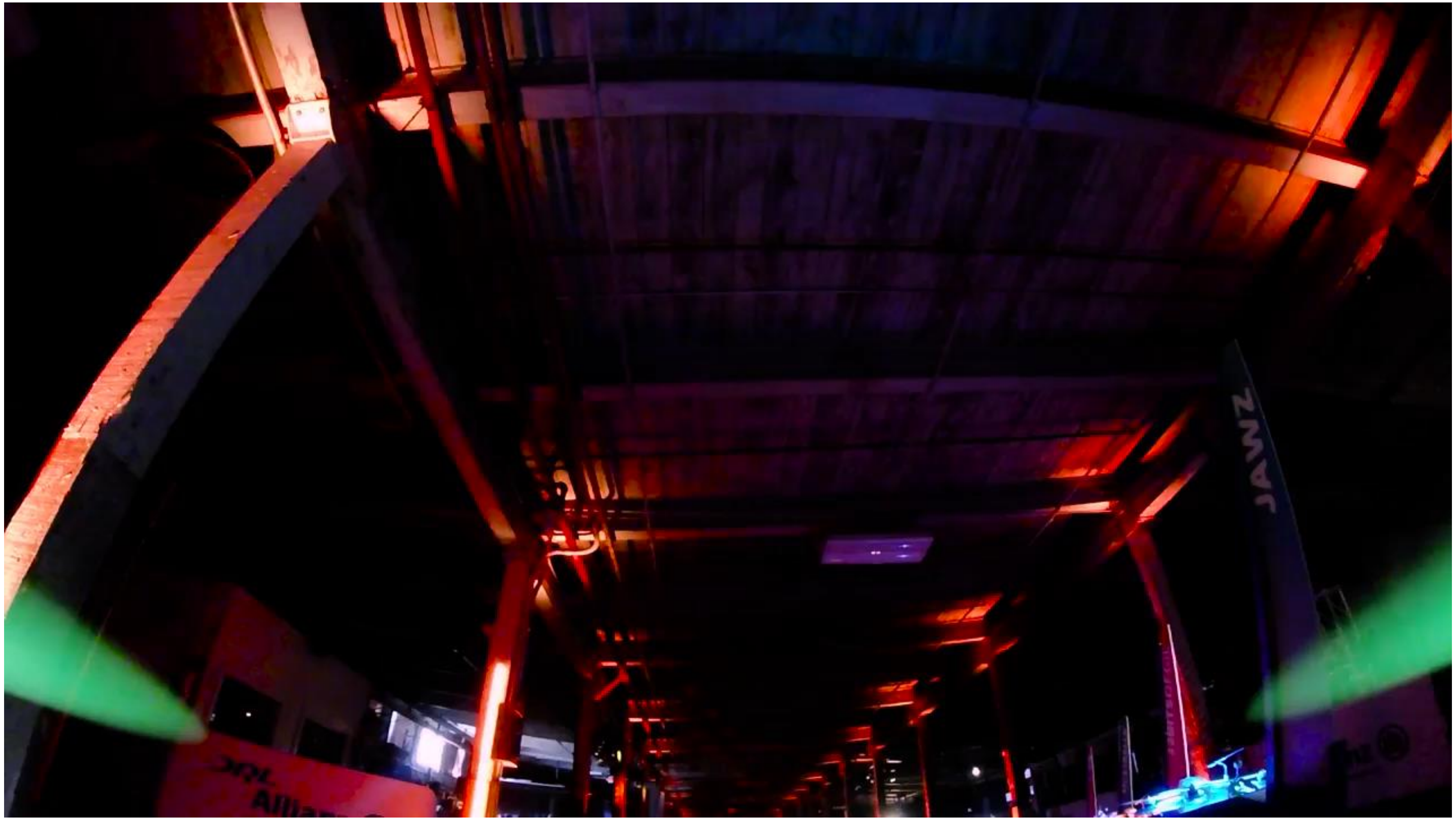
GROUP

# How can we fly robustly through cluttered environment in minimum time?



**WARNING!** This drone is NOT autonomous; it is operated by a human pilot.

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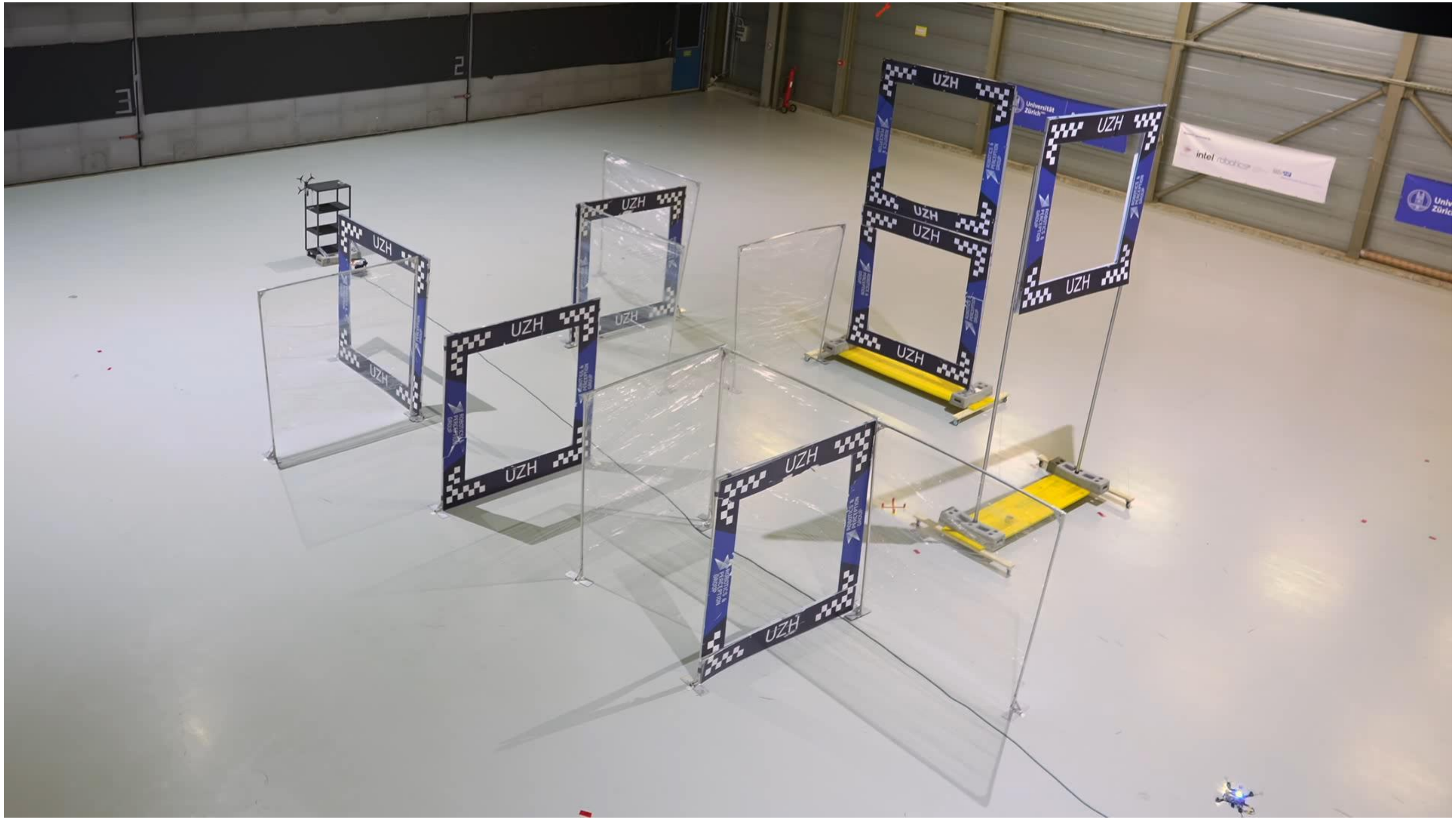


This drone is autonomous!

# What I mostly focused on in my proposal

| | |
|---|---|
| • Selling the topic and its impact to wider public | • Drones can help in many industries, e.g. search and rescue |
| • Selling the high-risk high-gain factor of the proposed research | • I want the drones to be able to fly autonomously in minimum time |
| • I am the ideal candidate to solve it given my background | • The project needs combination of skills from my PhD and my postdoc |
| • I have great project team and great international experience | • My postdocs are experts for WPs and I had excellent postdoc prof. |

Only difference from writing a paper is that additionally you have to sell yourself.

- **Paper** has four *parts*, *title*, *abstract*, *introduction* and *the rest*. Spend same time on each of them. Reviewers decide acceptance internally after reading introduction.
- **Proposal** has only title, <u>*introduction*</u> and the rest …..

Czech Science Foundation — Part C1 — Project Description
**Applicant:** Ing. Robert Pěnička, Ph.D.

### **TOPFLIGHT**: **T**rajectory and Missi**o**n **P**lanning for Agile **Flight** of Aerial Robots in Cluttered Environments

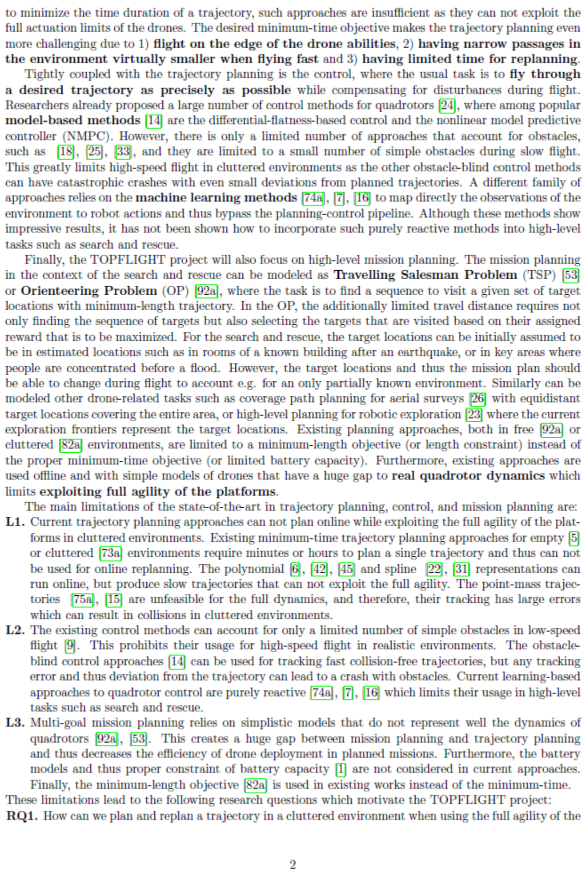
### 1 Introduction

Aerial Robots, also known as drones, belong to one of the most agile and maneuverable machines ever built by humans [70]. They are already changing and will continue to change many industries like package delivery, inspection, or search and rescue. Especially for search and rescue applications, the agility and speed of the considered quad- or multi-rotor drones can play a huge factor when searching as fast as possible for survivors after natural disasters like earthquakes or floods. The drone industry itself is predicted to significantly grow in the next years [2], especially in fields like agriculture, construction, and law enforcement. Nowadays, there is even a drone that flies on another planet. On Mars, the Ingenuity helicopter shows that aerial robots can be used not only in many industries on Earth but also for exploration and science on other worlds. Both drones for industrial applications on Earth and also for future science on Mars, however, need **high level of autonomy** to complete their missions efficiently without human intervention.

Nowadays drones are still mostly controlled by human pilots, rely on simple GPS navigation, or in case of the Ingenuity use visual inertial odometry to fly between waypoints of pre-planned missions. A typical system for autonomous aerial robots consists of four main modules that solve (a) **perception and mapping** of the environment, (b) **localization** of the robot, (c) mission and trajectory **planning** in the environment, and (d) **control** of the robot to traverse planned trajectory. In this project, we want to push the boundaries in the last two problems, i.e. the **planning and control** that would allow using the full **agility** of the drones in **cluttered environments**. The planning and control are one of the most important features of fully autonomous drones, and also one of the core elements of the robotic research [59]. Though astonishing agility of current quadrotor planning and control has been demonstrated in many research labs [5]–[7], [12], [22], [16], [19], [29], [52], solving both planning and control problems in cluttered environments on-the-fly while using the maximum agility of the drones is still an open problem. It is challenging mainly due to the tradeoff between the computational speed required for online planning and the feasibility of the trajectories for control, which influences how agile the flight can be. Solving this problem can significantly improve deployment of the drones in many fields. For example in the search and rescue scenario, which motivates this project, it can **decrease the time to find survivors and thus save lives**.

Figure 1: Motivation and examples of drone applications of the proposed project (a) Ingenuity drone flying on Mars [4], (b) Minimum-time flight in cluttered environments [74a] where the drone racing serves as a proxy scenario for search and rescue (c) Multi-goal mission planning in cluttered environments [92a] (d) Mission planning for data collection with multiple drones [85a].

One of the topics of the proposed TOPFLIGHT project is trajectory planning, where the task is to **plan a collision-free sequence of robot states** (i.e. the trajectory) for a quadrotor, between two given states. One of the holy grails of planning for the quadrotors is, however, to plan a collision-free trajectory online while flying in unknown or partially unknown environments. The challenges of the **online planning** arise mainly from the fact that the nonlinear dynamics of the quadrotors would require solving non-trivial differential equations to plan optimal trajectories. At the same time, trajectory planning has to be fast to allow online adaptation of a plan during flight. The researchers, therefore, relied so far on rather simple trajectory representations such as polynomial representation [6], [42], [45], spline representation [22], [31] or point-mass trajectories [75a], [15]. Thanks to the differential flatness of quadrotors [49], such representations can be used for trajectory planning rather than solving the otherwise too complex differential equations. However, for the scenarios like search and rescue, where the objective is



to minimize the time duration of a trajectory, such approaches are insufficient as they can not exploit the full actuation limits of the drones. The desired minimum-time objective makes the trajectory planning even more challenging due to 1) **flight on the edge of the drone abilities**, 2) **having narrow passages in the environment virtually smaller when flying fast** and 3) **having limited time for replanning**.

Tightly coupled with the trajectory planning is the control, where the usual task is to **fly through a desired trajectory as precisely as possible** while compensating for disturbances during flight. Researchers already proposed a large number of control methods for quadrotors [24], where among popular **model-based methods** [14] are the differential-flatness-based control and the nonlinear model predictive controller (NMPC). However, there is only a limited number of approaches that account for obstacles, such as [18], [25], [33], and they are limited to a small number of simple obstacles during slow flight. This greatly limits high-speed flight in cluttered environments as the other obstacle-blind control methods can have catastrophic crashes with even small deviations from planned trajectories. A different family of approaches relies on the **machine learning methods** [74a], [7], [16] to map directly the observations of the environment to robot actions and thus bypass the planning-control pipeline. Although these methods show impressive results, it has not been shown how to incorporate such purely reactive methods into high-level tasks such as search and rescue.

Finally, the TOPFLIGHT project will also focus on high-level mission planning. The mission planning in the context of the search and rescue can be modeled as **Travelling Salesman Problem** (TSP) [53] or **Orienteering Problem** (OP) [92a], where the task is to find a sequence to visit a given set of target locations with minimum-length trajectory. In the OP, the additionally limited travel distance requires not only finding the sequence of targets but also selecting the targets that are visited based on their assigned reward that is to be maximized. For the search and rescue, the target locations can be initially assumed to be in estimated locations such as in rooms of a known building after an earthquake, or in key areas where people are concentrated before a flood. However, the target locations and thus the mission plan should be able to change during flight to account e.g. for an only partially known environment. Similarly can be modeled other drone-related tasks such as coverage path planning for aerial surveys [26] with equidistant target locations covering the entire area, or high-level planning for robotic exploration [23] where the current exploration frontiers represent the target locations. Existing planning approaches, both in free [92a] or cluttered [82a] environments, are limited to a minimum-length objective (or length constraint) instead of the proper minimum-time objective (or limited battery capacity). Furthermore, existing approaches are used offline and with simple models of drones that have a huge gap to **real quadrotor dynamics** which limits **exploiting full agility of the platforms**.

The main limitations of the state-of-the-art in trajectory planning, control, and mission planning are:

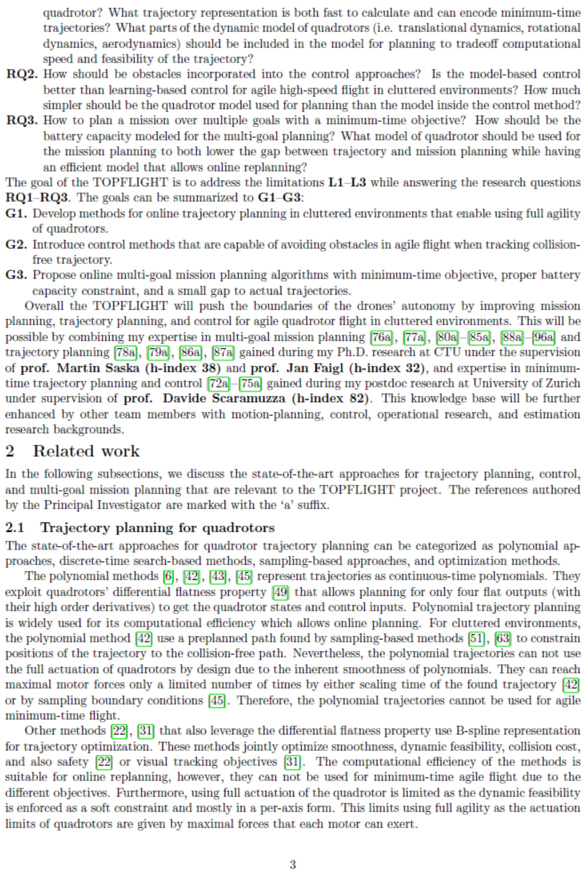
**L1.** Current trajectory planning approaches can not plan online while exploiting the full agility of the platforms in cluttered environments. Existing minimum-time trajectory planning approaches for empty [5] or cluttered [73a] environments require minutes or hours to plan a single trajectory and thus can not be used for online replanning. The polynomial [6], [42], [45] and spline [22], [31] representations can run online, but produce slow trajectories that can not exploit the full agility. The point-mass trajectories [75a], [15] are unfeasible for the full dynamics, and therefore, their tracking has large errors which can result in collisions in cluttered environments.

**L2.** The existing control methods can account for only a limited number of simple obstacles in low-speed flight [9]. This prohibits their usage for high-speed flight in realistic environments. The obstacle-blind control approaches [14] can be used for tracking fast collision-free trajectories, but any tracking error and thus deviation from the trajectory can lead to a crash with obstacles. Current learning-based approaches to quadrotor control are purely reactive [74a], [7], [16] which limits their usage in high-level tasks such as search and rescue.

**L3.** Multi-goal mission planning relies on simplistic models that do not represent well the dynamics of quadrotors [92a], [53]. This creates a huge gap between mission planning and trajectory planning and thus decreases the efficiency of drone deployment in planned missions. Furthermore, the battery models and thus proper constraint of battery capacity [1] are not considered in current approaches. Finally, the minimum-length objective [82a] is used in existing works instead of the minimum-time.

These limitations lead to the following research questions which motivate the TOPFLIGHT project:

**RQ1.** How can we plan and replan a trajectory in a cluttered environment when using the full agility of the



quadrotor? What trajectory representation is both fast to calculate and can encode minimum-time trajectories? What parts of the dynamic model of quadrotors (i.e. translational dynamics, rotational dynamics, aerodynamics) should be included in the model for planning to tradeoff computational speed and feasibility of the trajectory?

**RQ2.** How should be obstacles incorporated into the control approaches? Is the model-based control better than learning-based control for agile high-speed flight in cluttered environments? How much simpler should be the quadrotor model used for planning than the model inside the control method?

**RQ3.** How to plan a mission over multiple goals with a minimum-time objective? How should be the battery capacity modeled for the multi-goal planning? What model of quadrotor should be used for the mission planning to both lower the gap between trajectory and mission planning while having an efficient model that allows online replanning?

The goal of the TOPFLIGHT is to address the limitations **L1**–**L3** while answering the research questions **RQ1**–**RQ3**. The goals can be summarized to **G1**–**G3**:

**G1.** Develop methods for online trajectory planning in cluttered environments that enable using full agility of quadrotors.

**G2.** Introduce control methods that are capable of avoiding obstacles in agile flight when tracking collision-free trajectory.

**G3.** Propose online multi-goal mission planning algorithms with minimum-time objective, proper battery capacity constraint, and a small gap to actual trajectories.

Overall the TOPFLIGHT will push the boundaries of the drones' autonomy by improving mission planning, trajectory planning, and control for agile quadrotor flight in cluttered environments. This will be possible by combining my expertise in multi-goal mission planning [76a], [77a], [80a]–[85a], [88a]–[96a] and trajectory planning [78a], [79a], [86a], [87a] gained during my Ph.D. research at CTU under the supervision of **prof. Martin Saska (h-index 38)** and **prof. Jan Faigl (h-index 32)**, and expertise in minimum-time trajectory planning and control [72a]–[75a] gained during my postdoc research at University of Zurich under supervision of **prof. Davide Scaramuzza (h-index 82)**. This knowledge base will be further enhanced by other team members with motion-planning, control, operational research, and estimation research backgrounds.

### 2 Related work

In the following subsections, we discuss the state-of-the-art approaches for trajectory planning, control, and multi-goal mission planning that are relevant to the TOPFLIGHT project. The references authored by the Principal Investigator are marked with the 'a' suffix.

#### 2.1 Trajectory planning for quadrotors

The state-of-the-art approaches for quadrotor trajectory planning can be categorized as polynomial approaches, discrete-time search-based methods, sampling-based approaches, and optimization methods.

The polynomial methods [6], [42], [43], [45] represent trajectories as continuous-time polynomials. They exploit quadrotors' differential flatness property [49] that allows planning for only four flat outputs (with their high order derivatives) to get the quadrotor states and control inputs. Polynomial trajectory planning is widely used for its computational efficiency which allows online planning. For cluttered environments, the polynomial method [42] use a preplanned path found by sampling-based methods [51], [63] to constrain positions of the trajectory to the collision-free path. Nevertheless, the polynomial trajectories can not use the full actuation of quadrotors by design due to the inherent smoothness of polynomials. They can reach maximal motor forces only a limited number of times by either scaling time of the found trajectory [42] or by sampling boundary conditions [45]. Therefore, the polynomial trajectories cannot be used for agile minimum-time flight.

Other methods [22], [31] that also leverage the differential flatness property use B-spline representation for trajectory optimization. These methods jointly optimize smoothness, dynamic feasibility, collision cost, and also safety [22] or visual tracking objectives [31]. The computational efficiency of the methods is suitable for online replanning, however, they can not be used for minimum-time agile flight due to the different objectives. Furthermore, using full actuation of the quadrotor is limited as the dynamic feasibility is enforced as a soft constraint and mostly in a per-axis form. This limits using full agility as the actuation limits of quadrotors are given by maximal forces that each motor can exert.

# My suggestions, recommendations

- Research experience abroad
- Twitter science
- Do as much reviews as possible
- Push for the best journals first

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