Trajectory Planning for Heterogeneous Robot Teams

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***Abstract*— We describe a method for trajectory planning for heterogeneous mobile robot teams in known environments. We consider two core problems that arise with heterogeneous robot teams: 1) asymmetric inter-robot collision constraints and 2) varying dynamic limits. Asymmetric collision constraints complicate the spatial coordination and are important for close-proximity flight of rotorcraft because of the downwash effect. Varying dynamic limits complicate the temporal coordination between robots and must be taken into account during planning.**

I. INTRODUCTION

Trajectory planning for heterogeneous teams of robots is a core problem for many potential applications of multi-robot systems. In order to accomplish complex tasks it could be beneficial for a team to be composed of different types of robots with varied capabilities. This complicates trajectory planning due to each robot having different dynamics and mixed requirements for allowed interactions with each other. Fig. 1 shows an example of a physical experiment in which many quadrotors of different sizes must fly in close proximity and thus be aware of other quadrotors' downwash while also considering the motion of ground robots.

Consider a team of N robots, each of which are one of M types. Each robot is denoted by $r^{(i,k)}$ with $i \in \{1 \ldots N\}$ and $k \in \{1 \ldots M\}$. The operating environment is defined by a set of N_{obs} convex obstacles and a convex boundary. The obstacles and boundary are used to define M configuration spaces $\mathcal{F}^k$. We are given a set of starting locations $s^{(i,k)}$ and goal locations $g^{(i,k)}$ for each robot. We seek to find the time T in which the last robot in the team reaches its goal and collision free trajectories $f^{(i,k)} : [0,T] \to \mathcal{F}^k$ for each robot such that $f^{(i,k)}(0) = s^{(i,k)}$ and $f^{(i,k)}(T) = g^{(i,k)}$.

The presented method is an extension to prior work done on downwash-aware trajectory planning for large quadrotor teams [1]. The high-level structure of the original approach is retained. First, a graph-based planning method is used to compute a collision-free discretized schedule for all robots in the team. We consider spatial and temporal differences of the given robot types by constructing an annotated *super roadmap*. The discrete solution is then used to partition the free space for each robot in a parallelizable trajectory optimization stage. Spatial partitioning is generalized to consider asymmetric collision constraints and a new method of temporal scaling is used to address varied dynamic limits. Our method scales well with respect to the number of robot types and with respect to the total number of robots.

Fig. 1. A robot team with 10 small UAVs (blue, 8 visible), 2 medium UAVs (red), 1 large UAV (green), and 2 ground robots (yellow) is tasked with navigating a cluttered environment.

Motion planning for heterogeneous robots have employed a variety of methods including optimization-based methods [2], graph-based methods [3], and reactive planning [4]. In contrast to the mentioned work, our method demonstrates better scalability as well as the ability to account for asymmetric collision constraints.

II. APPROACH

We generalize the hybrid planning approach to account for the additional difficulties with spatial and dynamic heterogeneity. In the discrete scheduling phase we first construct a *super roadmap* that is used for multi-agent path-finding. In the trajectory optimization phase we generalize the spatial partitioning and trajectory scaling steps. Fig. 2 shows an example of the entire approach for the case of two types of UAVs.

A. Heterogeneous Collision Model

Trajectory planning for heterogeneous teams requires the ability to account for non-uniform inter-robot collision constraints. For example, due to the downwash effect a large quadrotor is likely able to fly underneath a smaller one without difficulty, but the opposite is not true.

To account for these kinds of asymmetric collision constraints, we define independent collision volumes for each pair of types in the team. Specifically, for each pair of types we define a cylindrical collision volume $\mathcal{R}^{(k,l)}, k, l \in \{1 \ldots M\}$ that is parameterized by a tuple $\langle r, a, b \rangle$. The parameter r specifies the safe horizontal distance between the positions of robots that are of k, l types, and the parameters a, b specify the distance that a robot of type l must maintain above and below a robot of type k. This collision model is used to check for conflicts during the discrete scheduling phase, and to compute free-space partitions during the trajectory optimization phase.

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