Supplementary Material
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AMSwarm: An Alternating Minimization Approach for Safe Motion Planning of Quadrotor Swarms in Cluttered Environments

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1 Experimental Setup

This section presents experimental demonstrations on our Crazyflie 2.0 swarm testbed operated in an overhead motion capture system. The quadrotors' trajectories are computed on a single computer, and we send position and velocity trajectories to the underlying lower controller based on [1]. The computer specifications and parameters of the algorithm are the same as described in Sec. IV of the submitted paper with a few exceptions. We set $\overline{v} = 1.5ms^{-1}$, increased κ to 15, and we penalized snap ($q = 4$) trajectory. We observed that these parameter changes resulted in smooth, agile, and aggressive motions that the lower controller could easily track. We inflated the collision avoidance ellipsoid with neighbouring quadrotor to $\mathbf{\Theta}_{ij} = \text{diag}(0.16m\ 0.16m\ 0.49m)$ so that our custom estimator package could reliably track the positions of the quadrotor swarm in our difficult handpicked configuration. The dimension for collision avoidance with static obstacles is chosen according to our available setup. The generated trajectories at each planning step are upsampled at $0.016s$ and sent to the swarm at 60Hz. We also incorporated an event-triggered replanning strategy as proposed in [2].

1.1 Transitions without Static Obstacles

In the first scenario, we considered a swarm of 12 quadrotors placed in a square-like formation. One quadrotor is placed in the centre, and the rest are placed on the boundary of the square. The quadrotors perform two transitions: one head-on and one random transition. In head-on transition, each quadrotor on the square's boundary is assigned an antipodal goal position, and the centre quadrotor is assigned to stay at its initial position. This configuration brings all of the quadrotors in conflict with each other. Our algorithm navigated the quadrotor swarm safely to their desired goal positions for each transition in a smooth and agile fashion with a maximum reported speed of $1.51ms^{-1}$, and the reported RMSE tracking error is $4.4cm$. As the trajectories for all the quadrotors are computed on a single computer, the time taken to generate all the trajectories at each planning step was $9.9ms$ on average, with a standard deviation of $18.1ms$.

1.2 Transitions with Static Obstacles

We considered a similar setup to Sec. 1.1 with the same transitions but with an addition of 6 cylindrical static obstacles in the environment. The quadrotors could quickly negotiate around the obstacles and reach their desired goal position in each transition. The average time and standard deviation to compute all the trajectories at each planning step are reported to be $9.86ms$ and $26.95ms$. The reported RMSE tracking error is $4.7cm$ and the maximum reported speed is $1.51ms^{-1}$ again indicates that the generated trajectories were smooth and agile even in a cluttered setting.

1.3 Transition with different Safe Behaviours

In this scenario, there are 12 quadrotors that will make a grid-like formation. We highlight two quadrotors in the video, blue and red. The quadrotors with $\gamma = 0.85$ go to their respective position in a highly conservative/safer behaviour than the quadrotors with $\gamma = 1.0$. The quadrotors with conservative γ dive into the centre of the grid formation.

1.4 Shared Workspace with a Human

In this scenario, we consider a swarm of 8 quadrotors operating in a shared space with a human. Each quadrotor applies BF constraints with $\gamma = 1$ for the neighbouring quadrotors. In contrast, a highly conservative BF constraint with $\gamma = 0.6$ is applied for the non-cooperative agent, the human. The quadrotors have instantaneous position and velocity information of the human, and while optimizing for a new trajectory, the quadrotor assumes a constant velocity prediction. With the help of BF constraints, the quadrotors could safely navigate around the unpredictable human.

References

[1] D. Mellinger and V. Kumar, "Minimum snap trajectory generation and control for quadrotors," in *2011 IEEE international conference on robotics and automation*, pp. 2520–2525, IEEE, 2011.

[2] C. E. Luis, M. Vukosavljev, and A. P. Schoellig, "Online trajectory generation with distributed model predictive control for multi-robot motion planning," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 604–611, 2020.