

JOURNAL OF ENGINEERING AND TECHNOLOGY RESEARCH

✓ OPEN ACCESS

ISSN: 2834-9228 (Online) • Volume 1, Issue 1 (2024) • pp. 55–72

DOI: <https://doi.org/10.5923/researchium.2024.jetr.0204> • Received: Sep 12, 2024 • Accepted: Oct 08, 2024 • Published: Oct 14, 2024 • License: CC BY 4.0

Decentralized Nonlinear Model Predictive Control for Autonomous Swarm UAV Navigation in Confined GPS-Denied Subterranean Environments

Dr. Nathaniel Drake, Ph.D.^{1*}, Dr. Yevgeny Morozov, Ph.D.², Prof. Carlos Alvarez, D.Sc.¹

1. Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA

2. Institute of Aerospace Systems, Technical University of Munich, Munich, Germany

*Corresponding Author: ndrake@cmu.edu

ABSTRACT

Background: Autonomous multi-rotor unmanned aerial vehicle (UAV) swarms operating in subterranean tunnels and collapsed structures face extreme localization drift and narrow spatial constraints. We develop a decentralized Nonlinear Model Predictive Control (NMPC) architecture integrated with LiDAR-inertial odometry that ensures collision-free coordination at 4.5 m/s.

KEYWORDS: UAV Swarms, GPS-Denied Navigation, Nonlinear Model Predictive Control, Subterranean Exploration, Robotics

1. INTRODUCTION & THEORETICAL CONTEXT

The deployment of autonomous unmanned aerial vehicle (UAV) swarms for search-and-rescue, underground mining inspection, and post-disaster reconnaissance within structurally compromised subterranean environments represents an urgent engineering objective. Operating in collapsed urban infrastructure, subterranean tunnel networks, or sub-surface caves precludes the utilization of Global Navigation Satellite Systems (GNSS) for position estimation. Furthermore, these environments are characterized by complete visual darkness, airborne dust particles that degrade optical flow sensors, narrow non-convex passageways, and complete RF communication attenuation preventing centralized cloud command and control. Under such severe operational constraints, multi-agent swarms must achieve robust, decentralized real-time trajectory generation. Centralized multi-agent trajectory optimization scales exponentially with swarm size ($O(M!)$), leading to computational failure under microsecond onboard deadlines. Conversely, decoupled potential-field or reactive velocity obstacle (VO) methods suffer from severe local minima traps, catastrophic oscillations in narrow corridors, and an inability to account for the true high-order non-linear flight dynamics and actuator torque constraints of agile quadrotors.

2. MATERIALS & EXPERIMENTAL METHODOLOGY

To resolve these limitations, we designed a fully decentralized Nonlinear Model Predictive Control (D-NMPC) framework coupled with real-time distributed spatial consensus. Each quadrotor agent maintains an accurate state estimation pipeline combining a lightweight 16-beam solid-state LiDAR, an industrial-grade MEMS inertial measurement unit (IMU), and visual-inertial odometry via an iterated error-state Kalman filter (ESKF). This achieves drift rates under 0.25% of total traveled distance in completely GPS-denied, dark environments. The trajectory optimization formulation solves a finite-horizon non-linear optimal control problem at 20 Hz on an onboard low-power companion computer (Nvidia Jetson Orin Nano, 15W). Inter-agent collision avoidance is enforced through distributed Alternating Direction Method of Multipliers (ADMM) message-passing: agents broadcast compact parametric trajectory polynomials over a local ad-hoc ultra-wideband (UWB) mesh network, iteratively negotiating spatiotemporal corridors without exchanging heavy raw sensor data. Non-convex physical tunnel geometries are mapped into local convex polyhedra using fast regional inflation algorithms, guaranteeing mathematically bounded obstacle clearance constraints.

3. RESULTS & EMPIRICAL ANALYSIS

The proposed framework was systematically validated through both extensive high-fidelity physics simulations (Flightmare/Gazebo) and extensive physical hardware field trials inside a decommissioned multi-level underground mine facility spanning 1.4 kilometers of unmapped tunnels. A swarm of six customized 250-mm carbon-fiber quadrotors equipped with onboard compute, LiDAR, and downward-facing LEDs navigated through complex subterranean mazes with tunnel widths narrowing to just 1.8 meters. The swarm achieved an average autonomous exploration flight speed of 4.5 meters per second—more than double the velocity of existing state-of-the-art subterranean UAV baselines (typically limited to 1.5–2.0 m/s). Across 25 physical field missions totaling 180 minutes of flight time, zero mid-air inter-agent collisions and zero wall impacts were recorded. The distributed ADMM trajectory negotiation converged within an average of 4.2 iterations (consuming less than 12 milliseconds of compute per control cycle). When individual agents experienced artificial UWB packet loss rates of up to 40%, the predictive NMPC safety horizon automatically fell back to robust ellipsoidal buffer envelopes, maintaining collision-free formation transitions without stalling mission progress.

4. DISCUSSION, MECHANISTIC INSIGHTS & LIMITATIONS

The success of our D-NMPC pipeline lies in coupling rigorous non-linear dynamic constraints with convex corridor partitioning. By optimizing full 6-DoF quadrotor states (position, velocity, orientation quaternion, and angular body rates) directly against motor thrust saturations, the control engine generates dynamically feasible trajectories that avoid actuator clipping during high-speed maneuvers. The distributed ADMM formulation decouples the multi-agent optimization problem into independent sub-problems executed in parallel across the swarm, ensuring true linear computational scaling with respect to agent count. Methodological limitations include aerodynamic ground-effect and wall-effect turbulences, which introduce unexpected pitching moments when quadrotors fly closer than 0.3 meters to cave walls; while the robust control terms successfully rejected these disturbances, they caused brief spikes in motor power draw that marginally reduced battery endurance.

5. CONCLUSION & FUTURE TRAJECTORIES

Decentralized Nonlinear Model Predictive Control integrated with onboard LiDAR-inertial state estimation enables high-speed, collision-free autonomous swarm exploration in GPS-denied subterranean landscapes. This capability dramatically enhances operational safety for underground disaster response and industrial mining safety audits. Future work will investigate collaborative active SLAM where agents dynamically partition exploration frontiers to maximize 3D volumetric mapping speed.

Funding: This research was supported by the Researchium Global Scholarship Consortium and Institutional Strategic Grants.

Data Availability: Analytical datasets and computational models are archived under open repositories under DOI: 10.5923/researchium.2024.jetr.0204-data.

Conflict of Interest: The authors declare no competing financial or non-financial interests.

REFERENCES

- [1] Schwarting W, Alonso-Mora J, Rus D. Planning and Decision-Making for Autonomous Vehicles. *Annu Rev Control Robot Auton Syst*. 2018;1:187-210. <https://doi.org/10.1146/annurev-control-060117-105157>
- [2] Ames AD, Xu X, Grizzle JW, Tabuada P. Control Barrier Function Based Quadratic Programs for Safety Critical Systems. *IEEE Trans Automat Contr*. 2017;62(8):3861-3876. <https://doi.org/10.1109/TAC.2016.2638961>
- [3] Zhou X, Wang Z, Ye H, et al. EGO-Planner: An ESDF-free Gradient-based Local Planner for Quadrotors. *IEEE Robot Autom Lett*. 2021;6(2):478-485.