Safety-Critical Ergodic Exploration in Cluttered Environments via Control Barrier Functions

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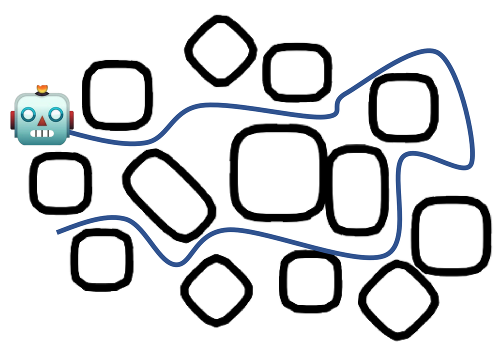
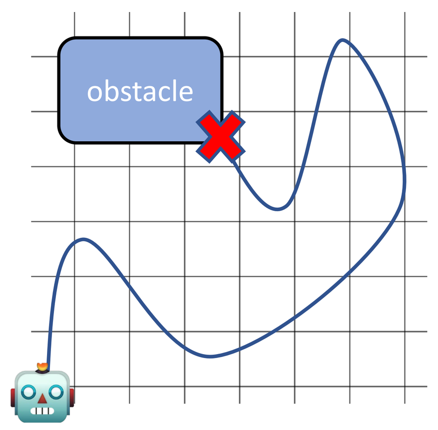
Introduction

- Want a robot to cover a cluttered environment autonomously
- Need to explore safely, without sacrificing coverage



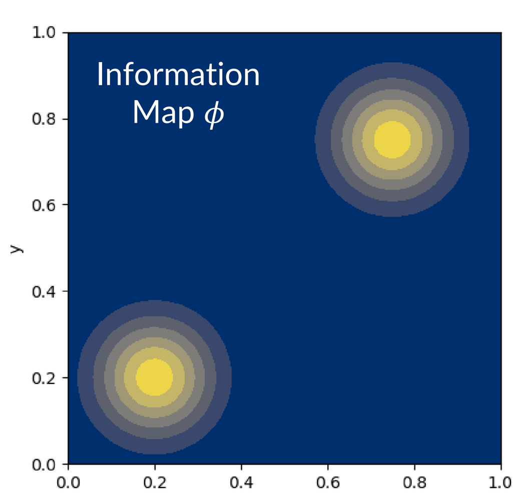


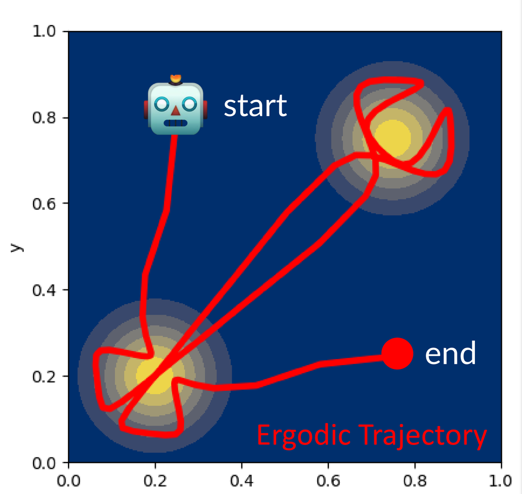
Ergodic Coverage[1-5]

Our approach: ergodic coverage methods

Time-averaged trajectory statistics $p(x(t)) = \frac{1}{T}\int_0^T F(x(t))dt$

$$\boxed{\lim_{T\to\infty} \frac{1}{T}\int_0^T F(x(t))dt = \mathbb{E}_{\phi(x)}[F(x)]}$$



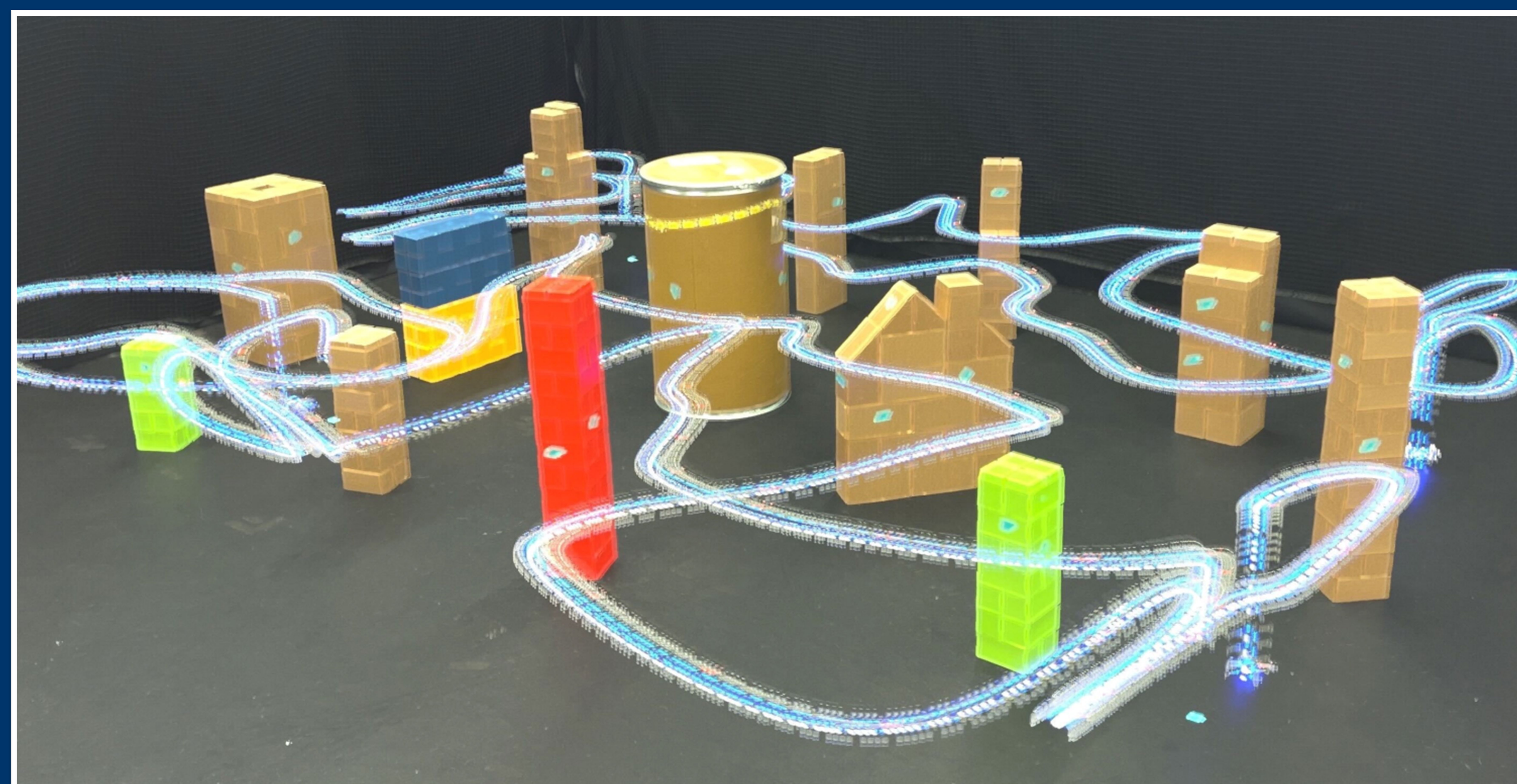


Ergodic Metric

computes distance between $p(x(t))$ and $\phi(x)$

$$\varepsilon(x(t), \phi) = \sum_{k\in\mathbb{N}^v}^{T} \Lambda(c_k(x(t) - \phi_k)^2$$

We demonstrate a planning method that **guarantees safe**, continuous **coverage** trajectories for search in **cluttered environments**.



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[1] L. M. Miller and T. D. Murphey, "Trajectory optimization for continuous ergodic exploration," American Control Conference, 2013, doi: 10.1109/ACC.2013.6580484
[2] L. M. Miller and T. D. Murphey, "Trajectory optimization for continuous ergodic exploration on the motion group SE(2)," CDC, 2013, doi: 10.1109/CDC.2013.6760585
[3] E. Ayvali, H. Salman and H. Choset, "Ergodic coverage in constrained environments using stochastic trajectory optimization," IROS, 2017, doi: 10.1109/IROS.2017.8206410
[4] D. Gkouletsos, A. Iannelli, M. H. de Badyn and J. Lygeros, "Decentralized Trajectory Optimization for Multi-Agent Ergodic Exploration," RA-L, 2021, doi: 10.1109/LRA.2021.3094242
[5] H. Coffin, I. Abraham, G. Sartoretti, T. Dillstrom and H. Choset, "Multi-Agent Dynamic Ergodic Search with Low-Information Sensors," ICRA, 2022, doi:10.1109/ICRA46639.2022.9812037

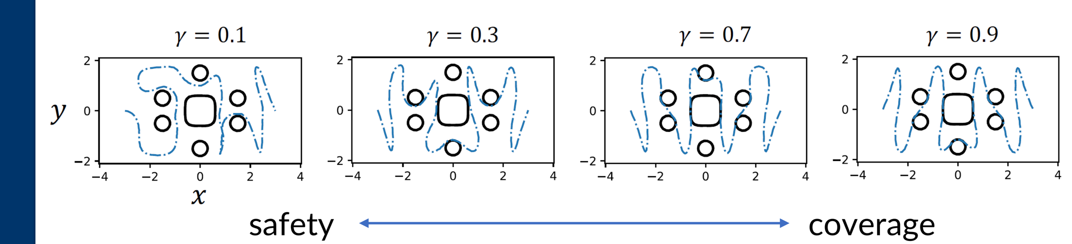
Main Contribution

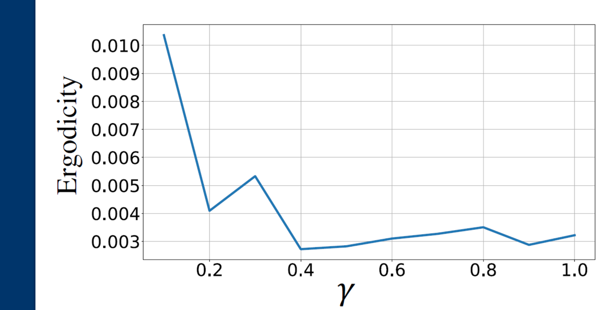
Safety-Critical Ergodic Trajectory Optimization (SC-ETO)

$$\begin{aligned}
&\min_{\mathbf{x},\mathbf{u}} \mathcal{E}(\mathbf{x}, \phi) + \sum_0^{T-1} u_t^\top R u_t dt \\
&\text{s.t. } x_{t+1} = f(x_t, u_t), x_t \in \mathcal{X}, u_t \in \mathcal{U} \\
&x_0 = \bar{x}_0, x_{T-1} = \bar{x}_f, g(x) \in \mathcal{W} \\
&\underbrace{\Delta h(x_t, u_t) \geq -\gamma h(x_t)}_{\text{inequality constraint for safety}}
\end{aligned}$$

- Discrete control barrier function implemented as an inequality constraint
- Jointly consider coverage and safety during trajectory optimization
- Guarantee safe trajectories while ensuring effective ergodic coverage

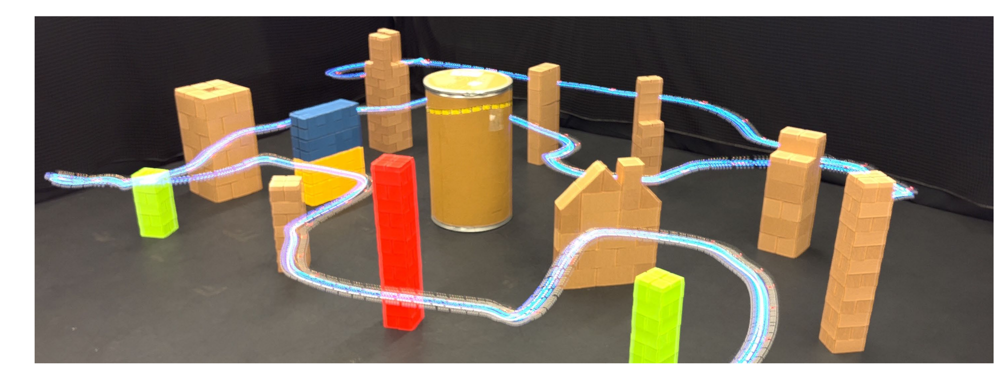
Results: Ablation Study

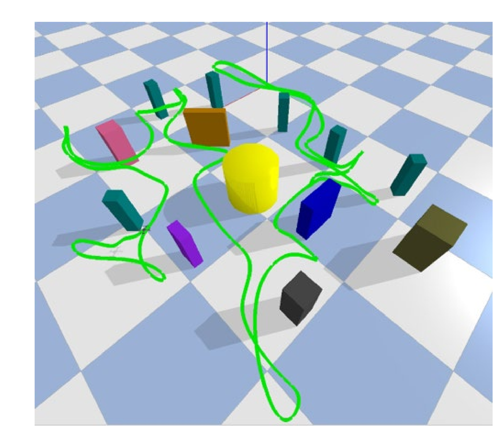




The benefit of our approach is that we have a single value that can tune the trade-off between safety and exploration.

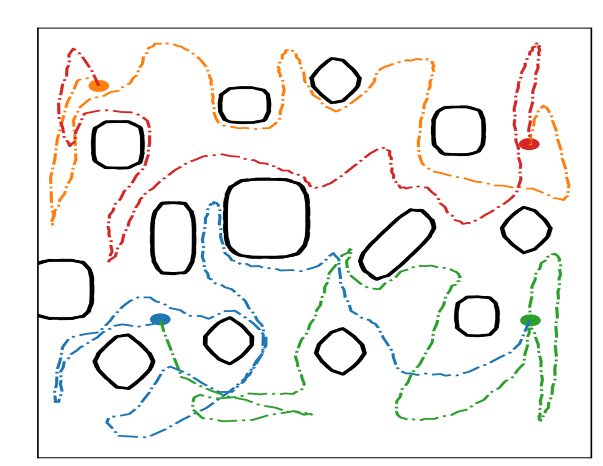
Results: Single Drone





Method	Success %
Safety-Critical ETO	100.0 %
ETO w/ Constr.	38.0%

Results: Multi-Robot Exploration



Used inter-robot CBF's between each pair-wise set of drones in the ergodic trajectory optimization

This research was supported with funding through Yale University and the NSF-GRFP program.