Safe Navigation for Autonomous Mobile Robots

Using Control Barrier Functions and Model Predictive Control

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Agenda

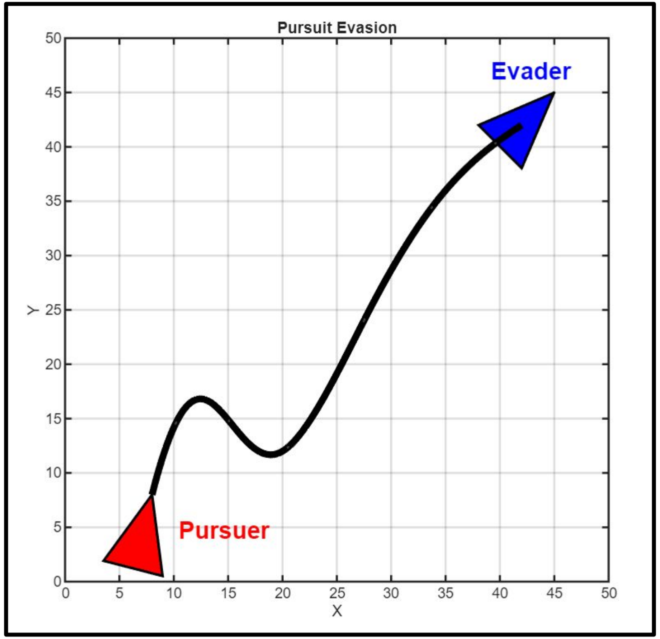
1. Project Overview
2. Literature Review
3. Safe Navigation Framework
4. Simulation Results
5. Future Work
6. Questions

TurtleBot 4

Project Overview

Pursuit Evasion

- A class of problems in which one agent (pursuer) attempts to locate and then intercept another agent (evader)
- Active areas of research within this field:
  - Mapping and localization
  - Detection and tracking of the pursuer or evader
  - Path planning and trajectory optimization
  - Safety and obstacle avoidance
  - Real world implementation



LAGEPP

Lyon 1

Project Focus

- **Identify state of the art approach**, focusing on:
  - **Safe autonomous navigation** in environments containing **dynamic obstacles**
  - Guaranteed **collision avoidance** while preserving navigation performance
- **Develop proposed approach:**
  - **Implement** safety-critical navigation in **simulation**
  - **Validate** on **TurtleBot 4** mobile robot research platform
  - Establish **foundation for further research** within this lab

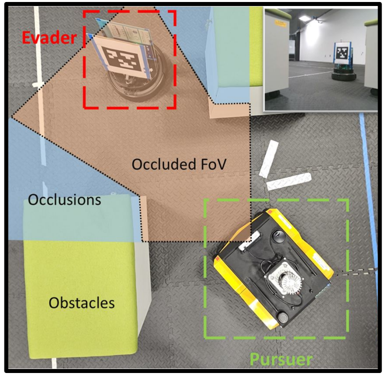
Literature Review

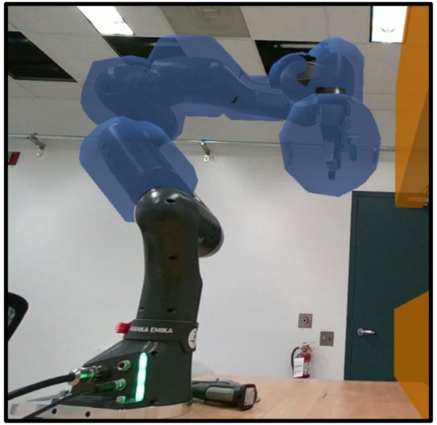
Literature Review

❖ **Control Strategies for Pursuit-Evasion Under Occlusion Using Visibility and Safety Barrier Functions** *(Zhou et al., 2024)*

➢ Proposes Safety Barrier Functions to ensure line-of-sight to address detection challenge

➢ Does not include methods for guaranteeing safe navigation around obstacles





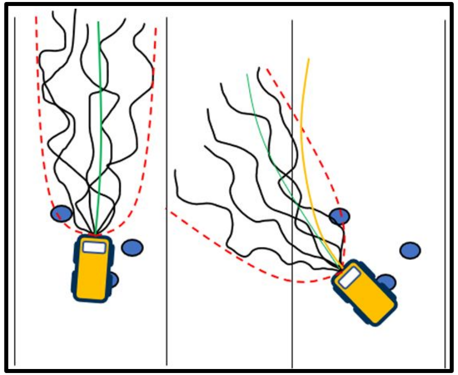
❖ **Safe Navigation and Obstacle Avoidance Using Differentiable Optimization Based Control Barrier Functions** *(Dai et al., 2024)*

➢ Key contribution is Differentiable Barrier Functions based on a scale factor rather than distance, which improves optimization

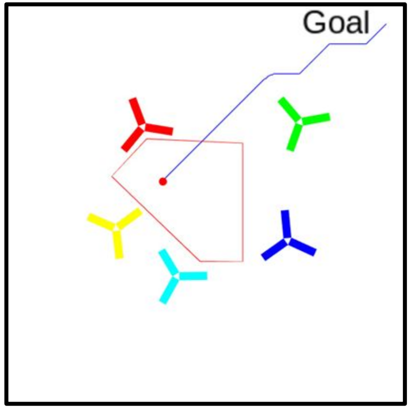
➢ Does not specifically address the challenges of dynamic obstacle avoidance for mobile robots

Literature Review

❖ **Shield Model Predictive Path Integral: A Computationally Efficient Robust MPC Approach Using Control Barrier Functions** *(Yin et al., 2023)*



- ➢ Proposes a MPPI based computationally efficient obstacle avoidance method for mobile robots
- ➢ Uses a stochastic approach which doesn't provide mathematical guarantees of safety

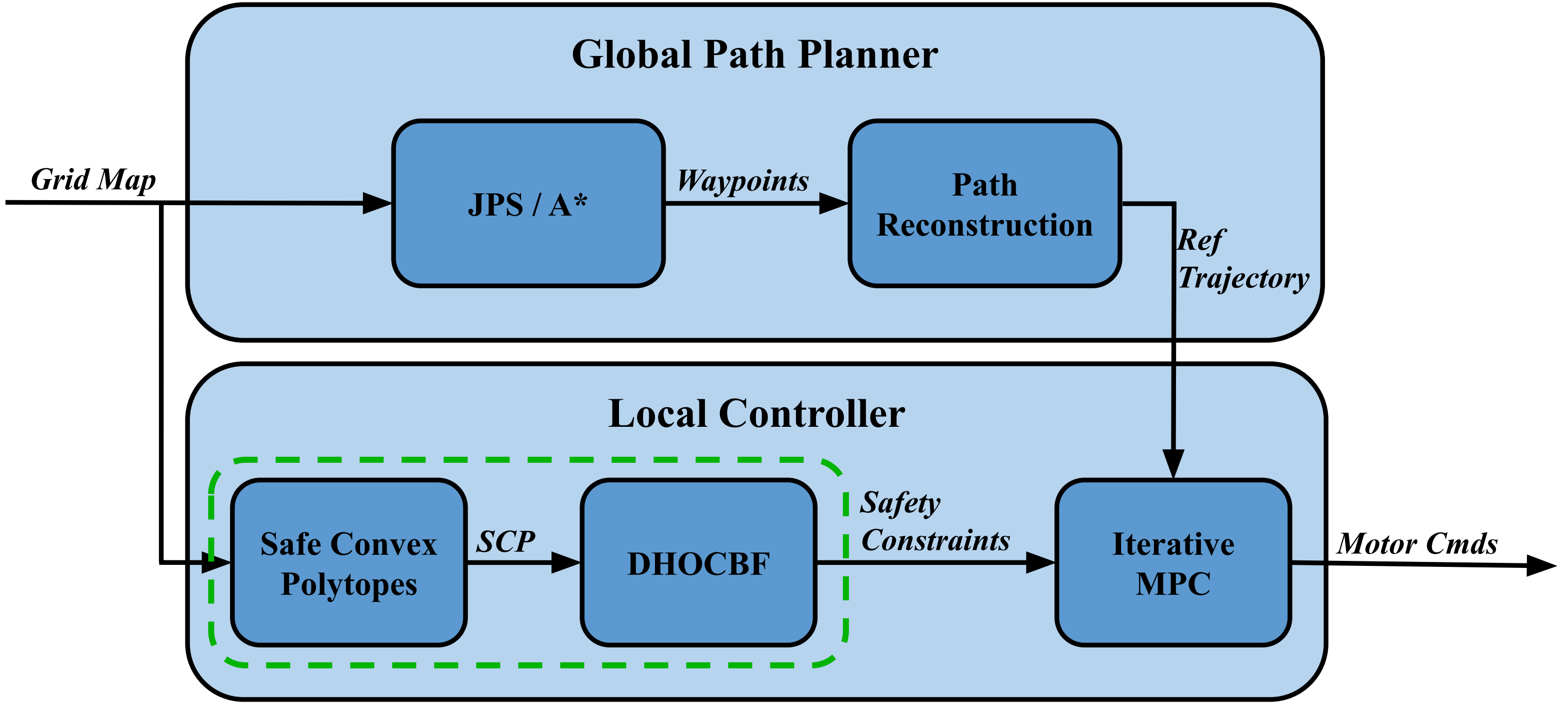


❖ **Safety-Critical Planning and Control for Dynamic Obstacle Avoidance Using Control Barrier Functions** *(Liu et al., 2025)*

- ➢ Proposes an MPC based control with guarantees for dynamic obstacle avoidance using CBFs specifically for mobile robotic applications
- ➢ This paper addresses all the key areas of our research, and thus serves as the theoretical framework for our project

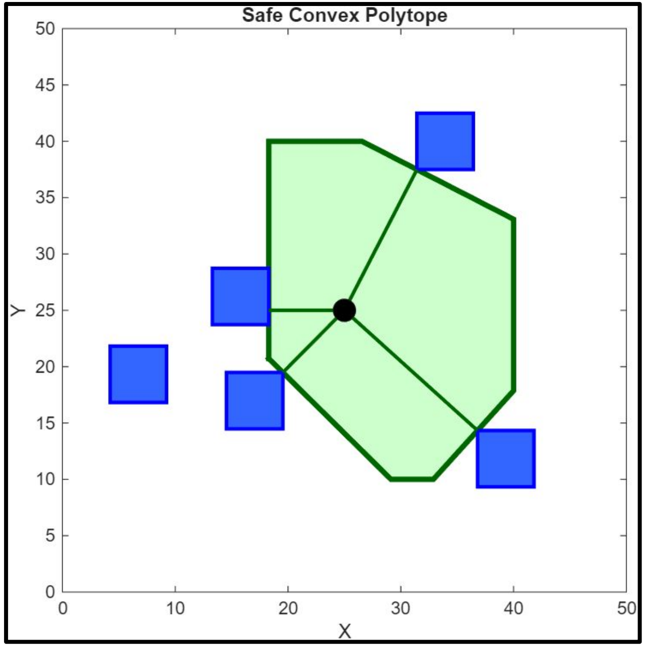
Safe Navigation Control Scheme

Control Scheme



Safe Convex Polytopes (SCPs)

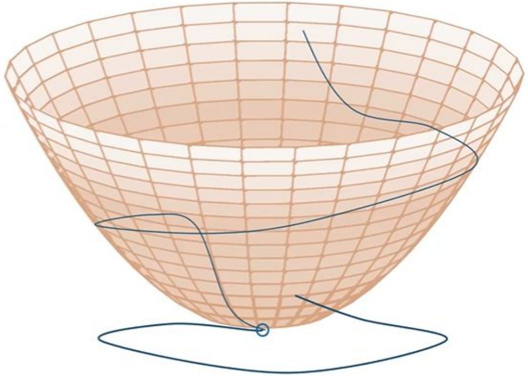
- Instead of relying on hard to obtain obstacle equations, the environment is represented using an **occupancy grid map**, which is used to generate a **safe convex region** around the robot
- This allows the control scheme to handle complex obstacle geometries while simplifying the optimization problem



Control Barrier Functions (CBFs)

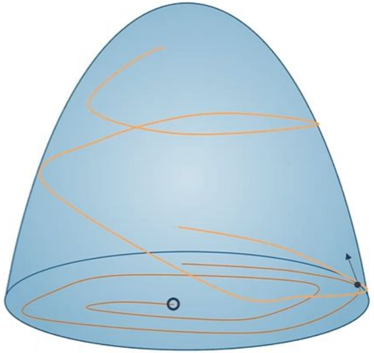
- CBFs provide the mathematical guarantees of safety within our control framework
  - CBFs are mathematically similar to Control Lyapunov Functions (CLF); where CLFs are trying to minimize an *energy-like* function, CBFs are trying to maximize a *safety-like* function

Control Lyapunov Function



$\dot{\boldsymbol{V}}(\boldsymbol{x},\boldsymbol{u}) + \boldsymbol{\lambda V}(\boldsymbol{x}) \leq \boldsymbol{0}$, for $\exists u \in U, \lambda > 0$

Control Barrier Function

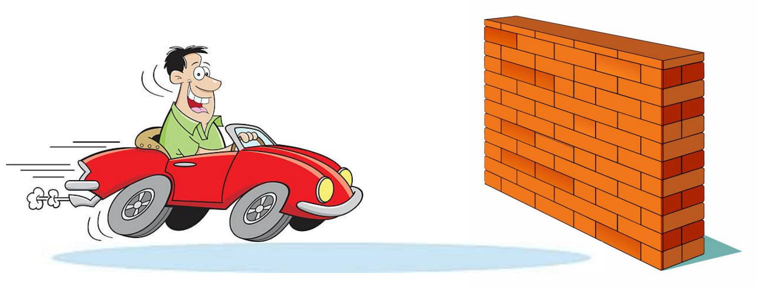


$\dot{\boldsymbol{B}}(\boldsymbol{x},\boldsymbol{u}) + \boldsymbol{\gamma B}(\boldsymbol{x}) \geq \boldsymbol{0}$, for $\exists u \in U,\ \gamma > 0$

Discrete-Time High-Order CBFs (DHOCBFs)

❖ DHOCBFs extend traditional CBFs to account for how control actions indirectly affect subsequent states, allowing safety guarantees to be maintained

Example



1. Control Input is breaking (affects acceleration)
2. This in turn affects velocity
3. Finally affecting position (our safety-critical state)

Definition

Base case defined as standard CBF:

$$\psi_0(x_t) = h(x_t)$$

Recursive definition for higher order CBFs:

$$\psi_i(x_t) = \psi_{i-1}(x_{t+1}) - \psi_{i-1}(x_t) + \gamma_i \psi_{i-1}(x_t)$$

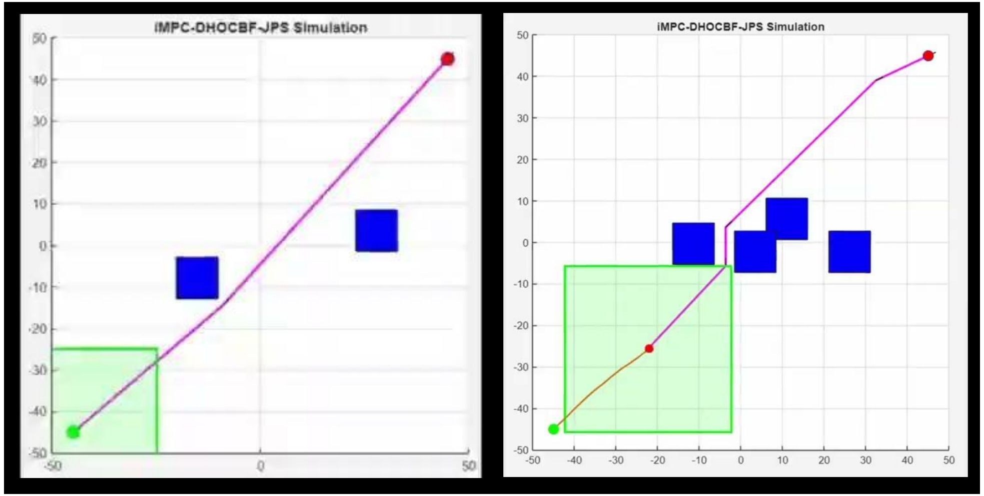
DHOCBF constraint:
(m is the relative degree of the system)

$$\psi_m(x_t) \geq 0$$

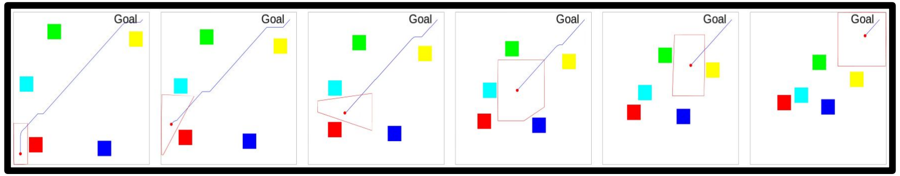
Simulation Results

Simulation Results

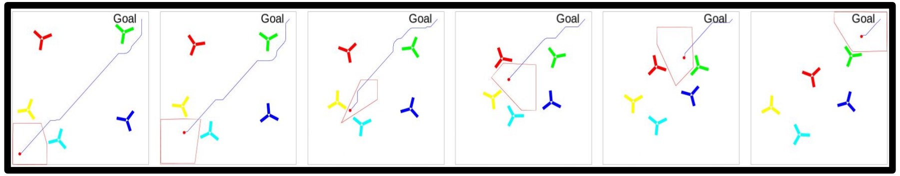
❖ Robot successfully adapts to the dynamic environment while maintaining a collision-free trajectory and reaching the goal



MATLAB Simulation: Demo of iMPC-DHOCBF algorithm



Paper Simulation Results: Fig. 2 - Convex squares



Paper Simulation Results: Fig. 3 - Nonconvex-shaped fans

Future Work: TurtleBot 4 Implementation

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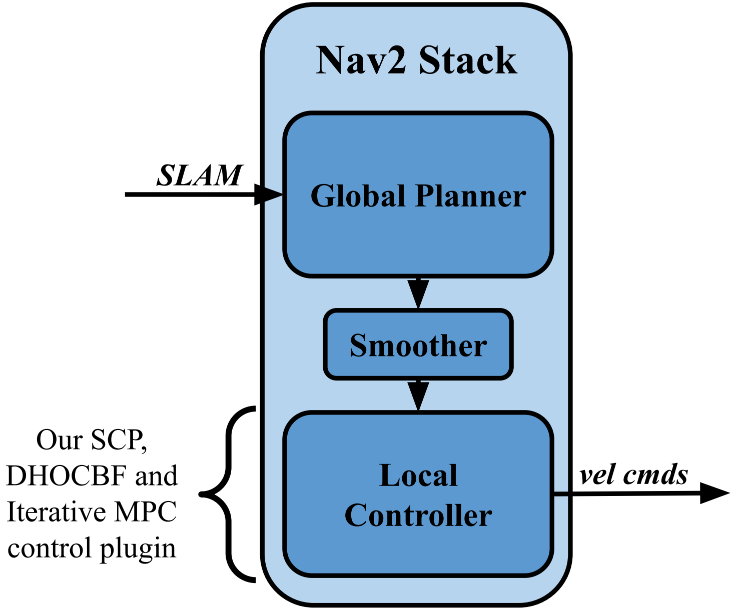
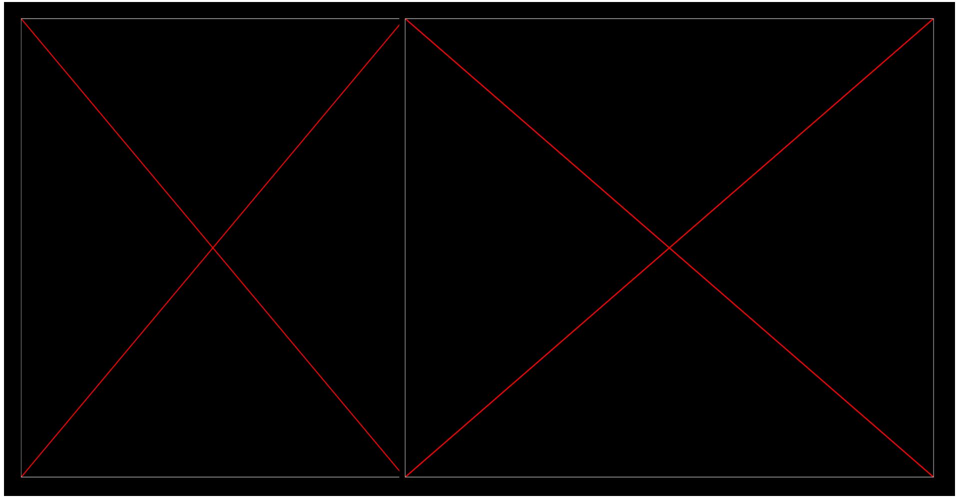
❖ Will evaluate this control framework on TurtleBot 4 to determine whether the safety guarantees demonstrated in simulation can be achieved in real-world environments





Preliminary tests showing autonomous navigation of the TurtleBot 4

Questions?

TurtleBot 4