A Framework for Multi-Vehicle Navigation using Feedback-Based Motion Primitives

Marijan Vukosavljev, Zachary Kroeze, Mireille E. Broucke,

and Angela P. Schoellig

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Institute for Aerospace Studies
UNIVERSITY OF TORONTO

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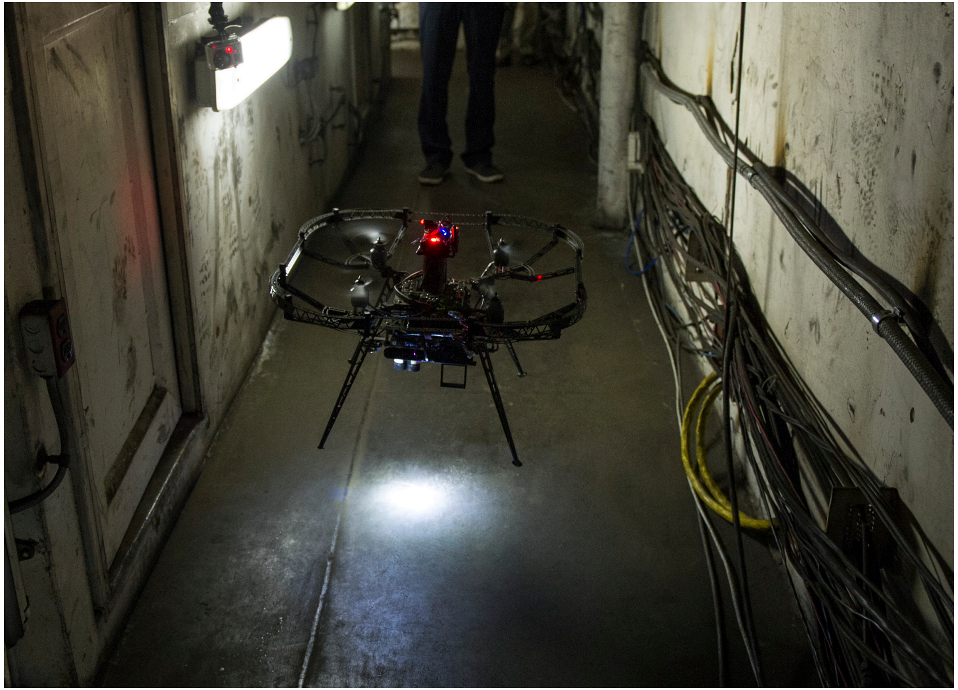
Motivation



Motivation

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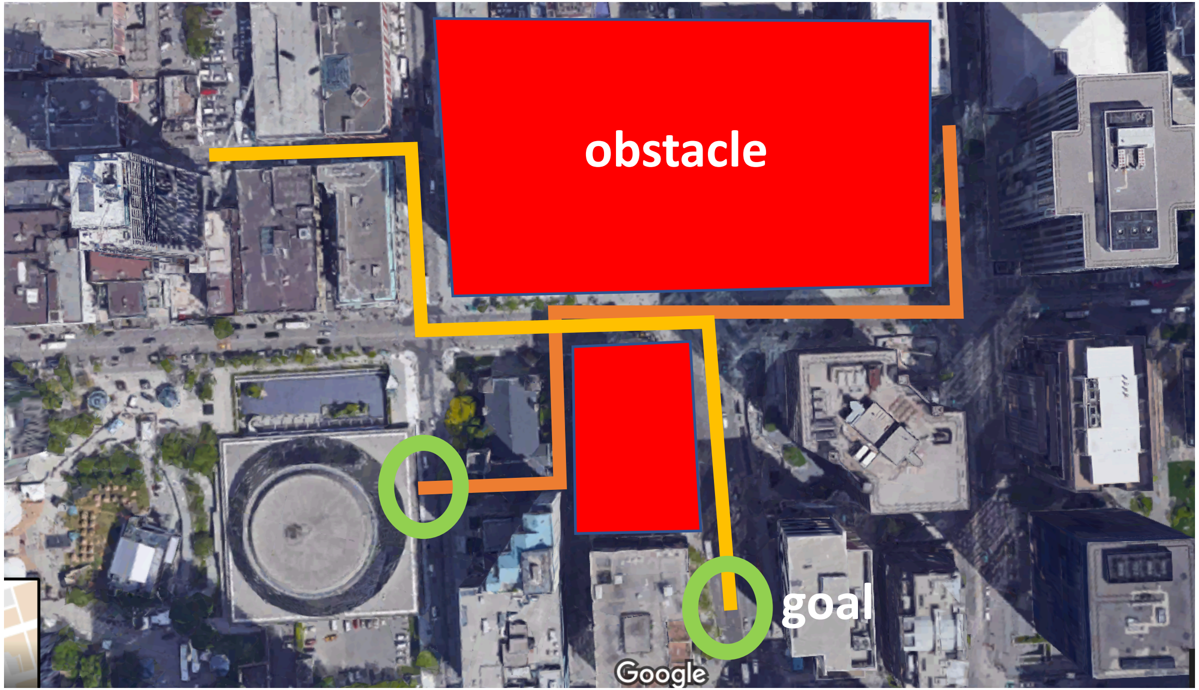
Path planning and control in known environments



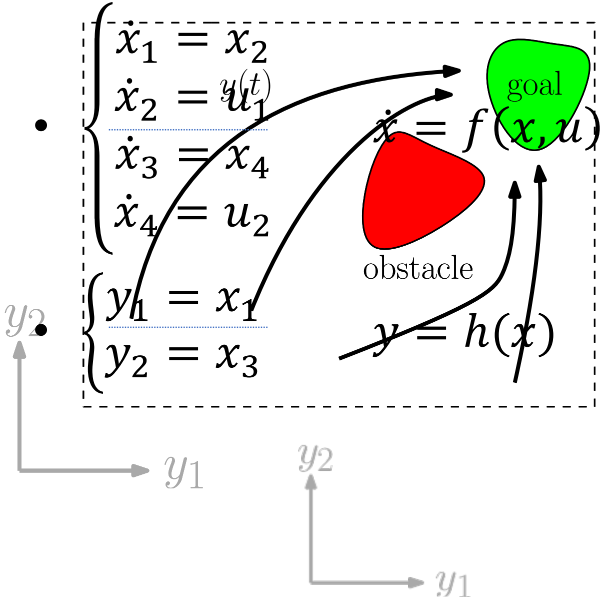
Problem Statement

- **Given**:
  - dynamics $\dot{x} = f(x,u)$, outputs $y = h(x)$, where $x \in \mathbb{R}^n$, $y \in \mathbb{R}^p$
  - goal and obstacle sets in *output space*
- **Find**: feedback controller $u(x)$ and set of initial conditions $X_0 \subset \mathbb{R}^n$ such that $y(t)$ eventually enters the goal set and always avoids the obstacle set
- Can be posed as a reach-avoid problem for a control system

- Example: two double integrators, n = 4, p = 2

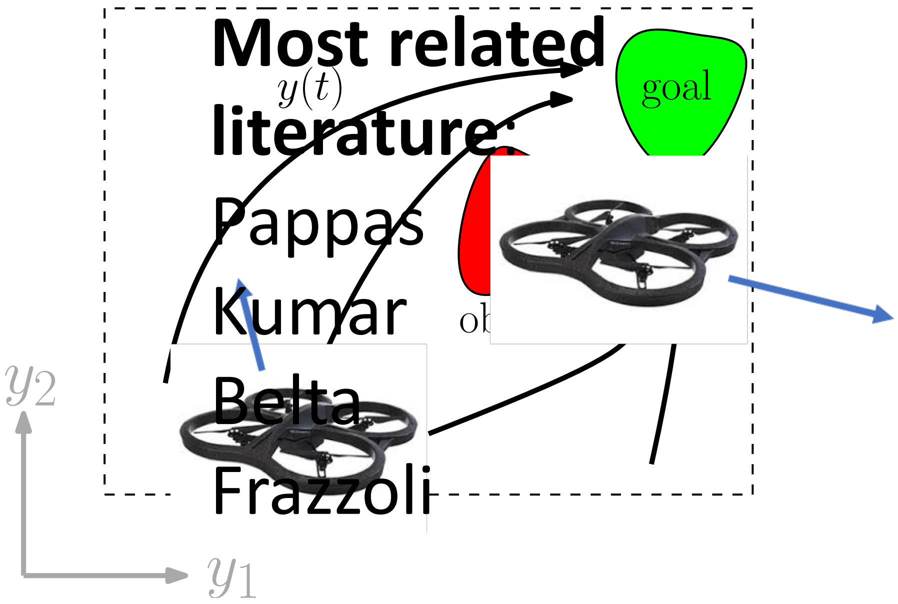
$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u_1 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = u_2 \end{cases}$$

$$\begin{cases} y_1 = x_1 \\ y_2 = x_3 \end{cases}$$



Framework Features

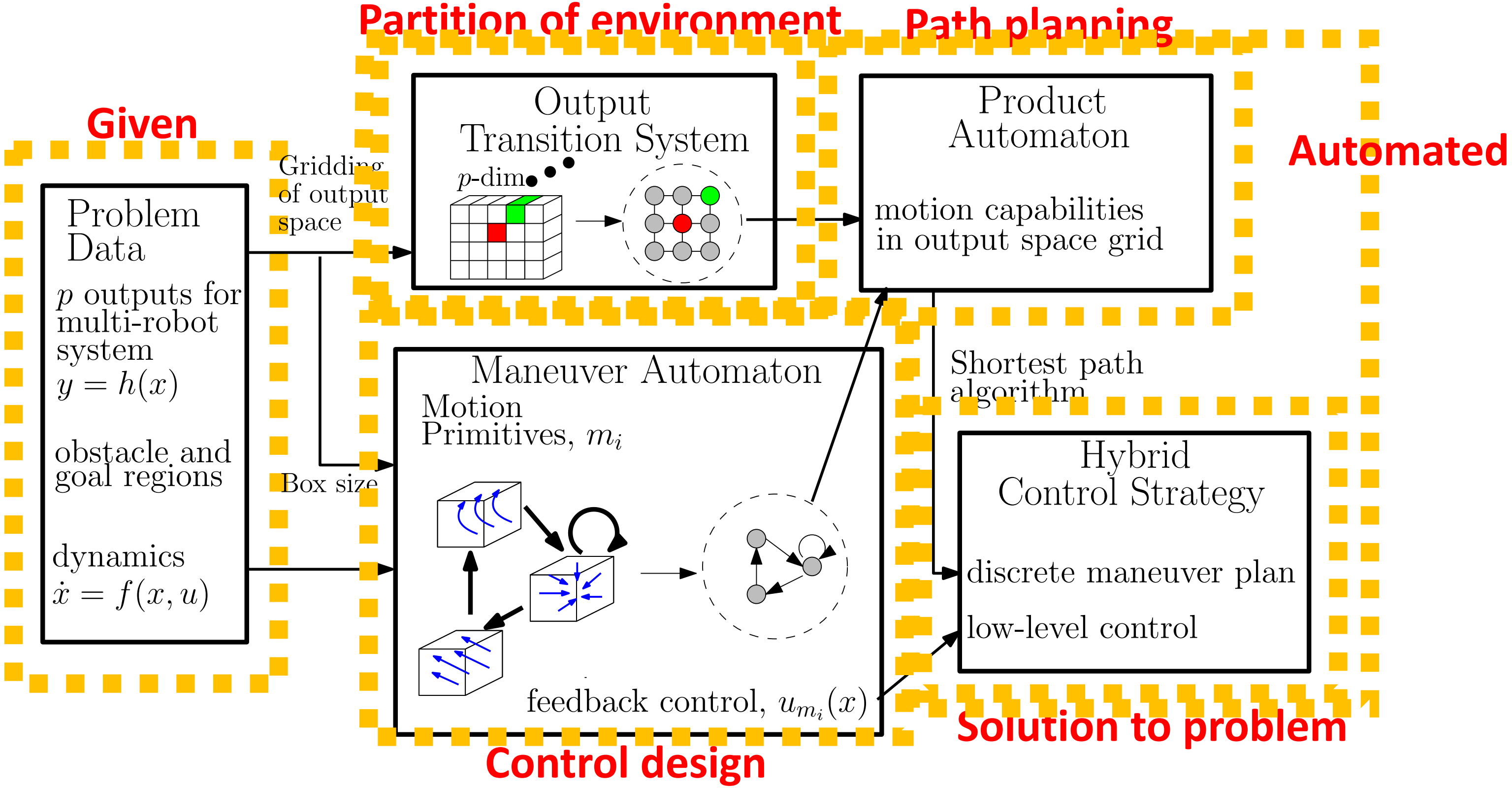
- Feedback control
  - Wide range of initial conditions
  - Robust to disturbances
  - Requires no explicit path
  - Safety guarantees
- Simultaneous motion
- Computational efficiency
  - Symmetry
  - Lower dimensional spaces
  - Modularity



Most related literature:

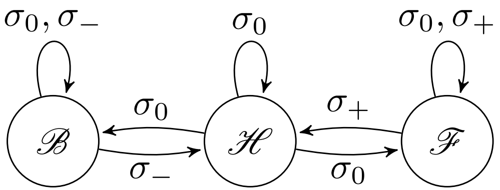
Pappas
Kumar
Belta
Frazzoli

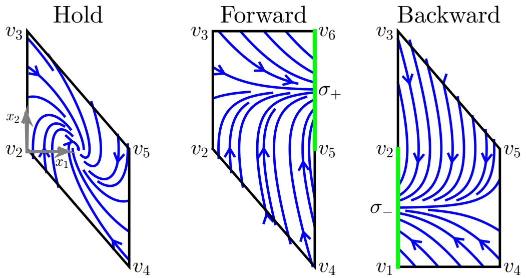
Proposed Framework



Maneuver Automaton

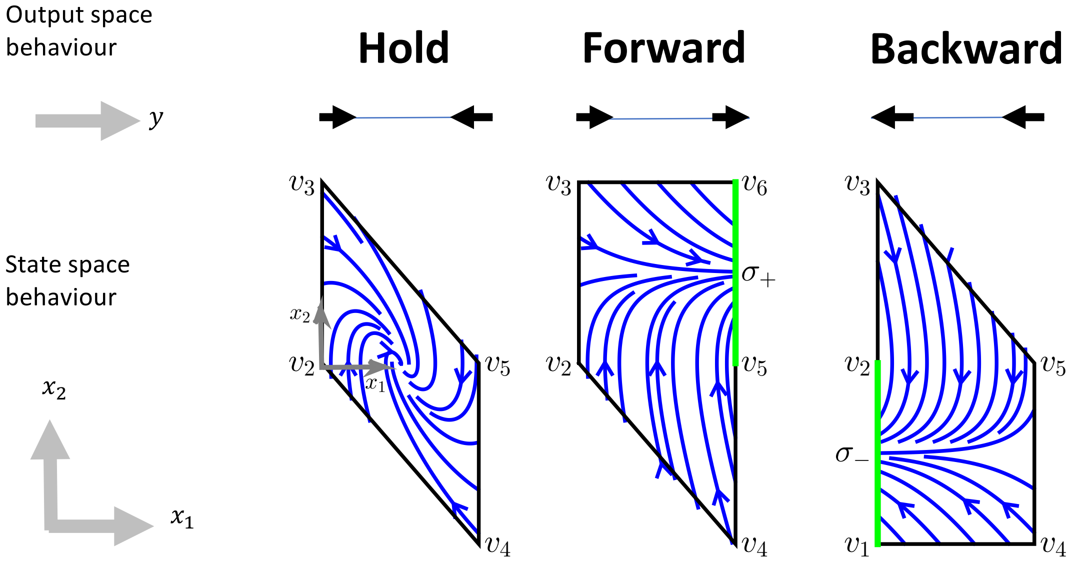
- Formally a hybrid system
- Hybrid state space: motion primitives and continuous state in $\mathbb{R}^n$
- Edges: concatenation constraints between motion primitives
- Each motion primitives is implemented by a feedback controller over a designated subset in $\mathbb{R}^n$

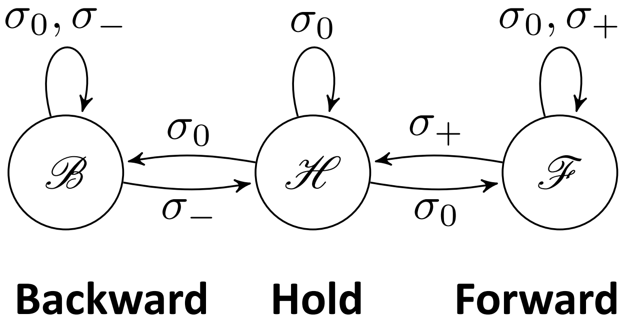




Maneuver Automaton - Design

- First focus on double integrator: $\dot{x}_1 = x_2, \dot{x}_2 = u$, with $y = x_1$





Reach control
B. Roszak and M. E. Broucke, “Necessary and sufficient conditons for reachability on a simplex,” 2006.

Maneuver Automaton - Application

- Quadrocopter model reduces to double integrator in each positional direction
- For the multi-quadrocopter model, stack all the double integrators
- Choose Hold, Forward, and Backward in each output component
- For example, one quadrocopter with planar motion:

$$\begin{matrix} y_1 \\ y_2 \end{matrix} \quad \begin{pmatrix} \mathscr{H} \\ \mathscr{H} \end{pmatrix} \quad \begin{pmatrix} \mathscr{F} \\ \mathscr{H} \end{pmatrix} \quad \begin{pmatrix} \mathscr{H} \\ \mathscr{F} \end{pmatrix} \quad \begin{pmatrix} \mathscr{F} \\ \mathscr{F} \end{pmatrix} \quad \begin{pmatrix} \mathscr{B} \\ \mathscr{H} \end{pmatrix} \quad \cdots$$

Control Policy on the Product Automaton

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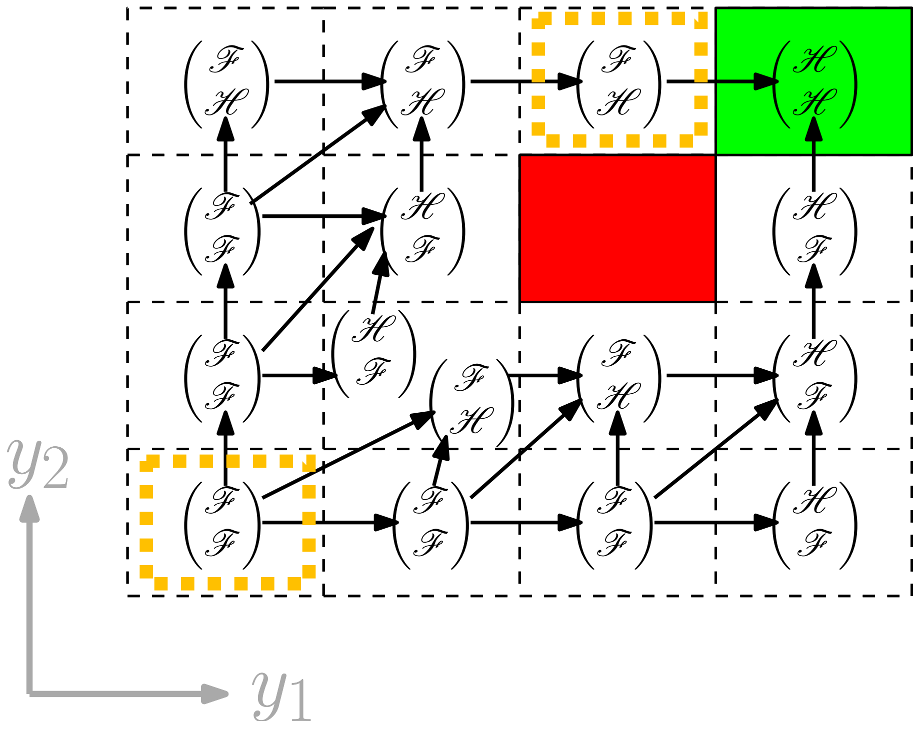
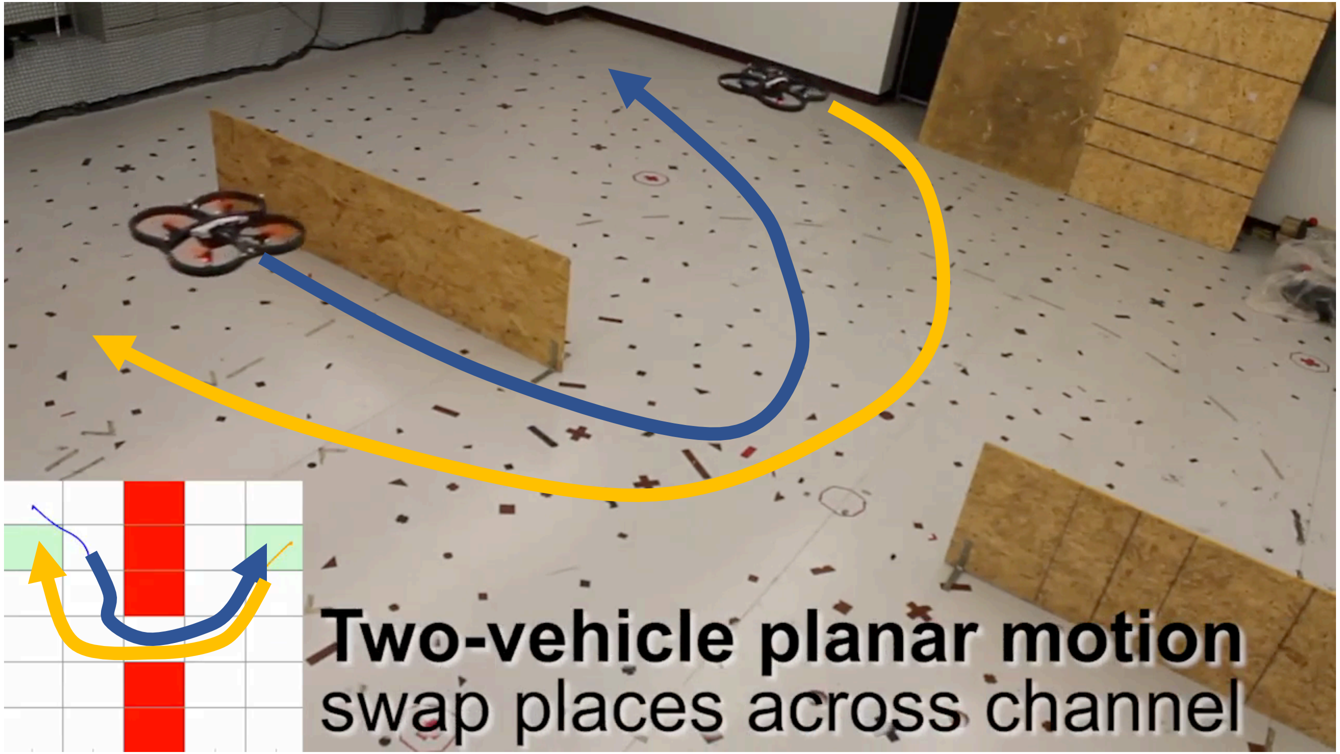
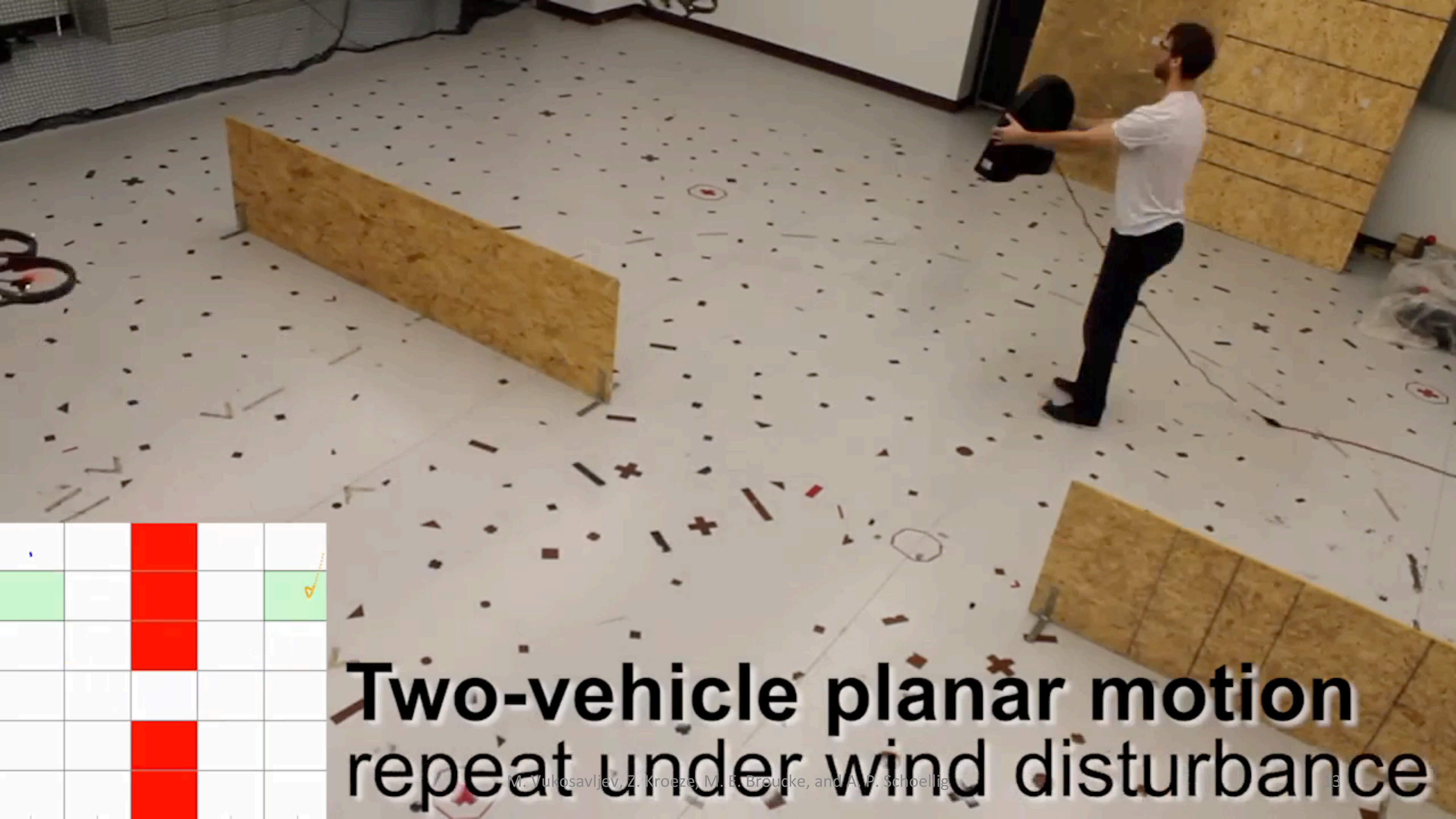


Experimental Results

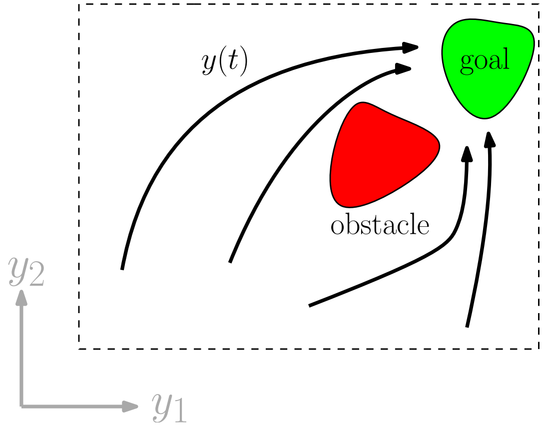



Two-vehicle planar motion
swap places across channel


Two-vehicle planar motion
repeat under wind disturbance

Conclusion

- Addressed a **path planning and control problem** in known environments as a reach-avoid problem
- Employed a modular framework consisting of an output space partition, **low-level feedback** controllers, and a **high-level feedback** for selecting motion primitives
- Highly robust control design that enables **simultaneous motion** in a **computationally feasible** way



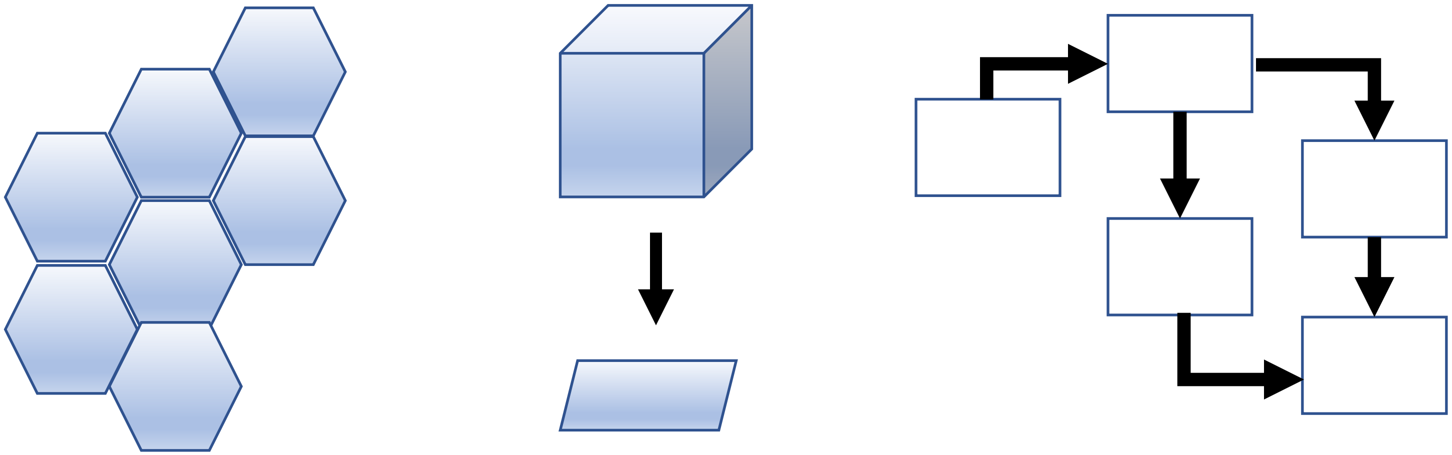
Comparison to Literature

Paper	Feedback control	Simultaneous motion	Computational efficiency
Frazzoli, Dahleh, and Feron; 2005			
Kloetzer and Belta; 2008			
Fainekos, Girard, Kress-Gazit, Pappas; 2009			
Ayanian, Kumar; 2010			
Raman, Kress-Gazit; 2014			
Vukosavljev, Kroeze, Broucke, Schoellig, 2017			

Stack multiple copies

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u_1 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = u_2 \end{cases} \qquad \dot{x} = f(x, u)$$

$$\begin{cases} y_1 = x_1 \\ y_2 = x_3 \end{cases} \qquad y = h(x)$$



Symmetry Lower dimensions Modularity