

Hybrid Systems in Human-Centered Automation

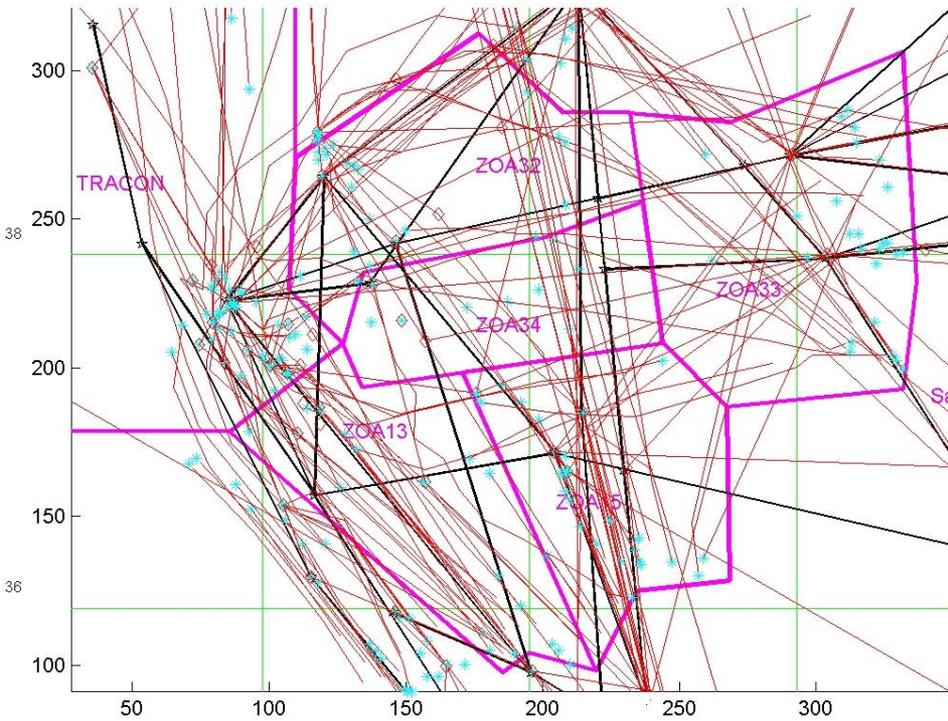
Claire Tomlin



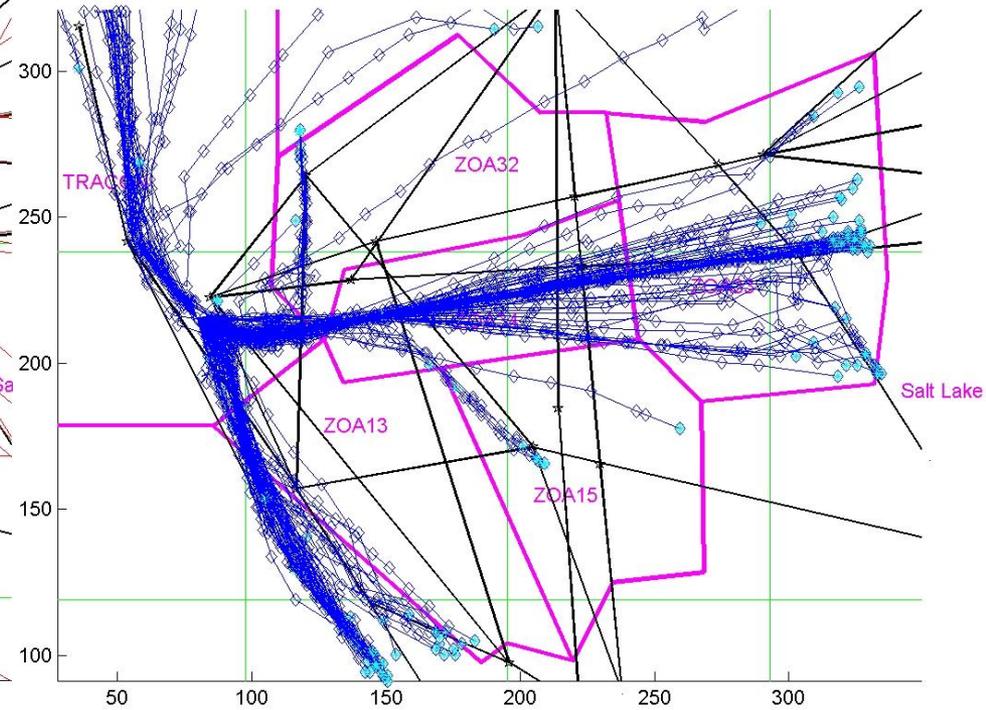
Department of Electrical Engineering and Computer Sciences
University of California at Berkeley

March 11 2015

Air traffic in Oakland Center



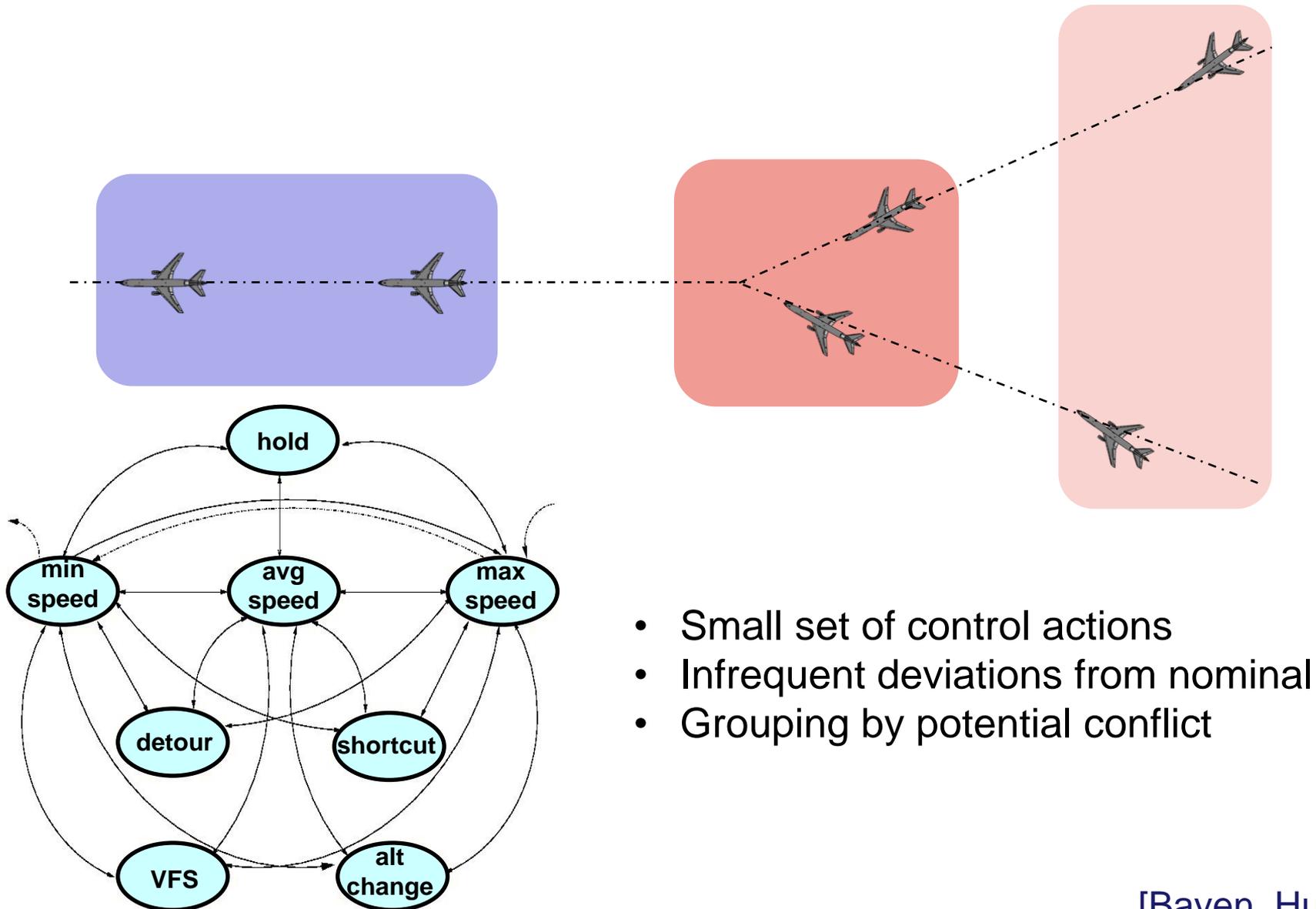
cross traffic



merging traffic

- Safety critical
- Standard corridors of well-travelled routes

Controller must keep aircraft separated



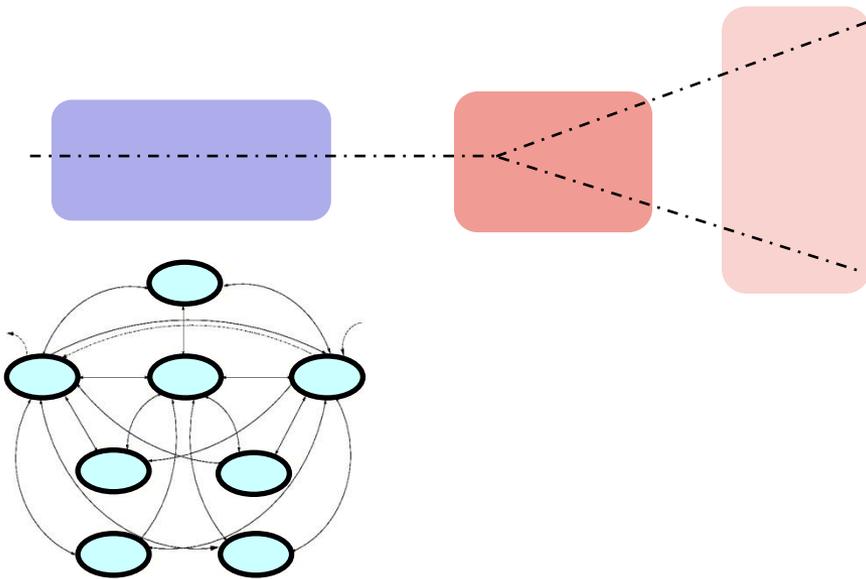
Growing numbers of UAV applications



[Amazon]



[Google]

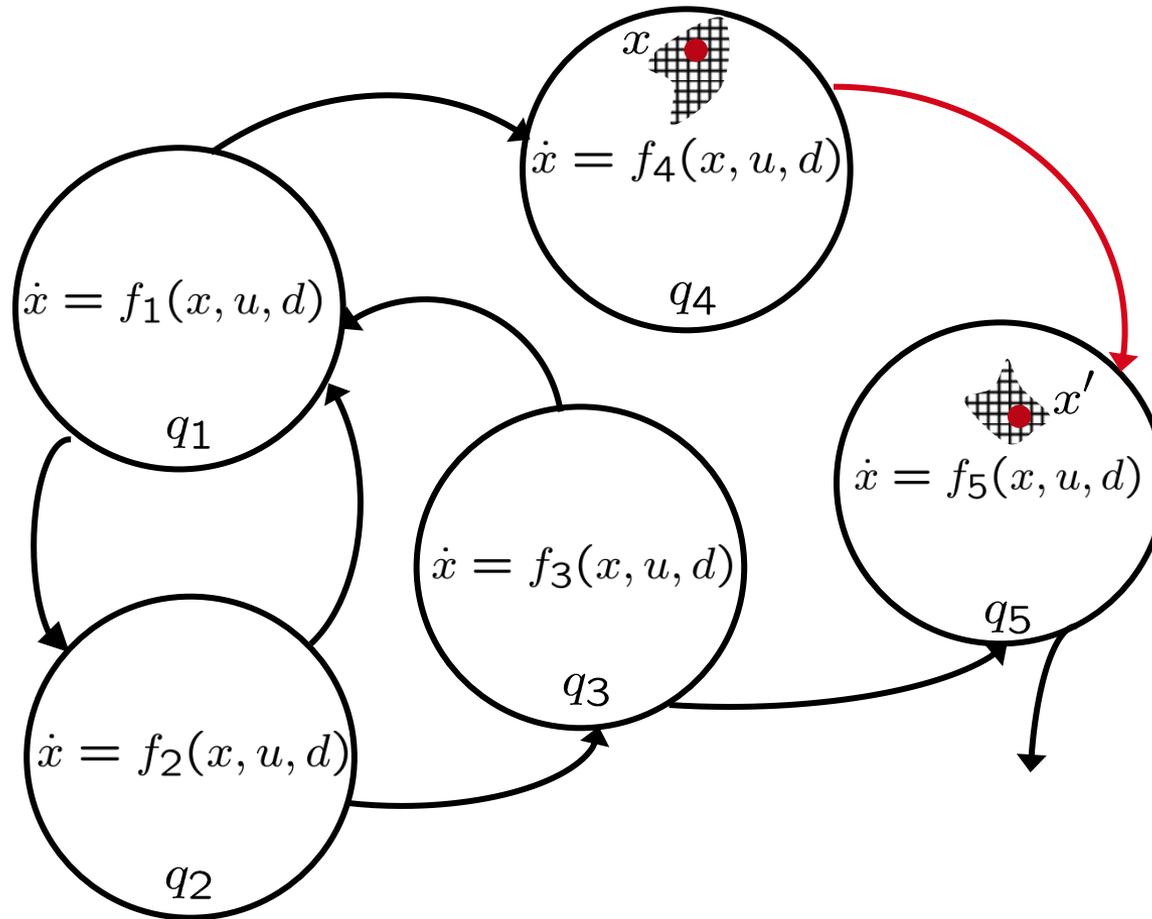


1. Safety
2. Simplicity
3. Ability to adapt to new information

[NASA]

- Collision avoidance system
- Forced landing system

Hybrid System Model

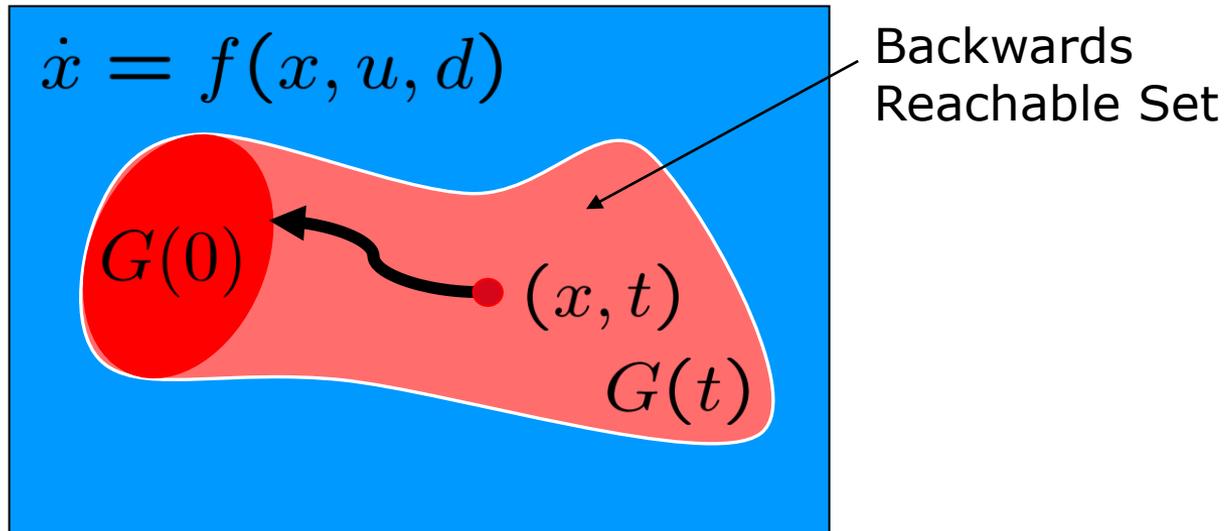


Outline

- Reachable sets for hybrid systems
 - Overview
 - Examples:
 - Collision avoidance
 - Mode sequencing
 - Humans and automation
- Learning dynamic behavior safely
 - Overview
 - Example:
 - Learning to fly

Backwards Reachable Set

All states for which, for all possible **control actions**, there is a **disturbance action** which can drive the system state into a region $G(0)$ in time t



Reachability as **game**: disturbance attempts to force system into unsafe region, control attempts to stay safe

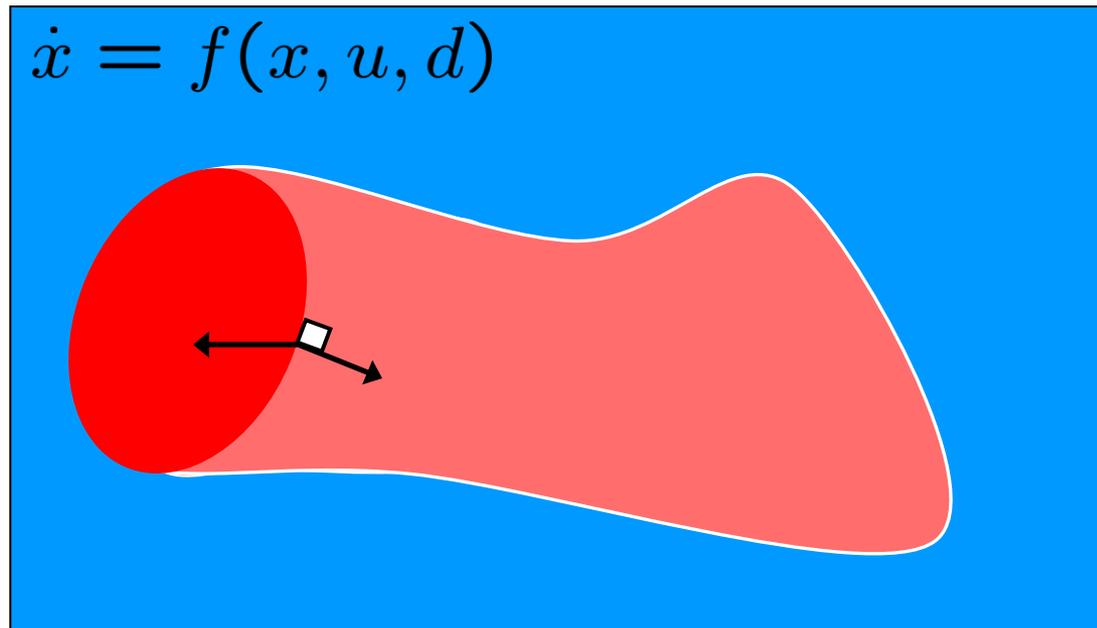
Reachable Set Propagation

Theorem [Computing $G(t)$]:

$$G(t) = \{x : J(x, t) < 0\}$$

where $J(x, t)$ is the unique Crandall-Evans-Lions viscosity solution to:

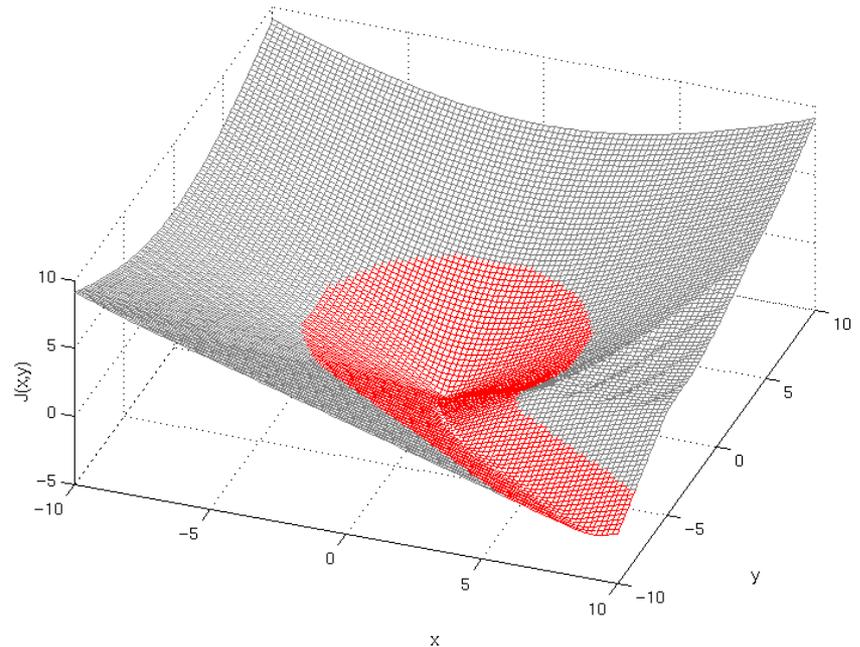
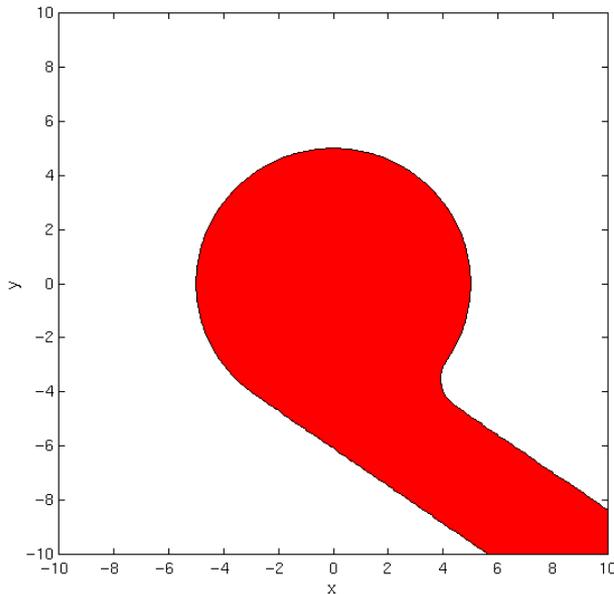
$$-\frac{\partial J(x, t)}{\partial t} = \min\{0, \max_u \min_d \frac{\partial J(x, t)}{\partial x} f(x, u, d)\}$$



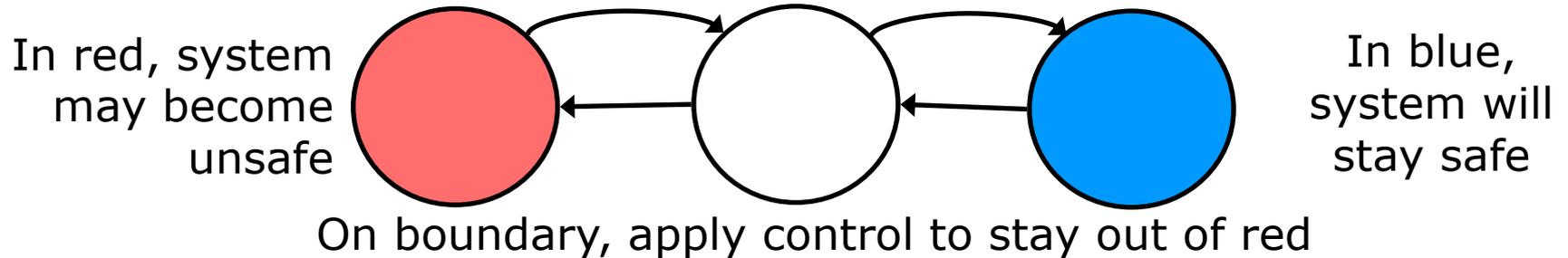
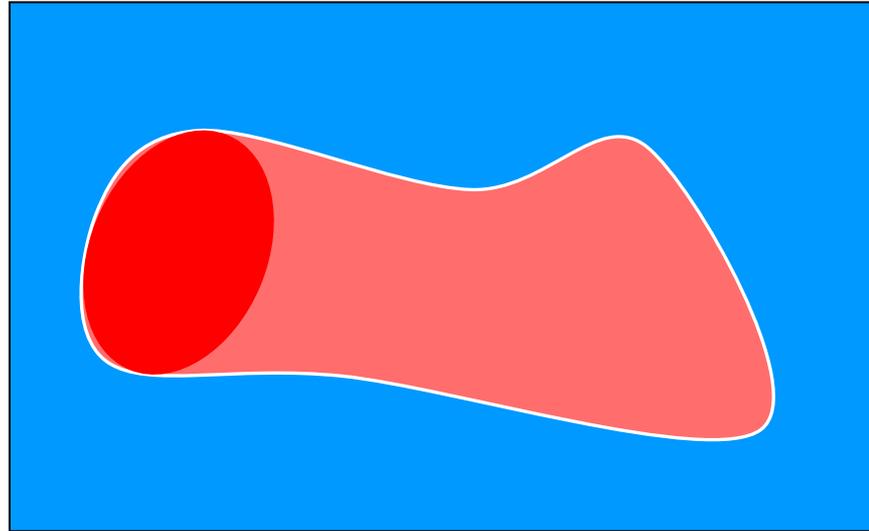
Numerical computation of reachable sets

Create a level set function $J(x, t)$ such that:

- Boundary of region is defined implicitly by $J(x, t) = 0$
- J is negative inside region and positive outside
- For example, $|J(x, t)|$ could represent the distance to boundary

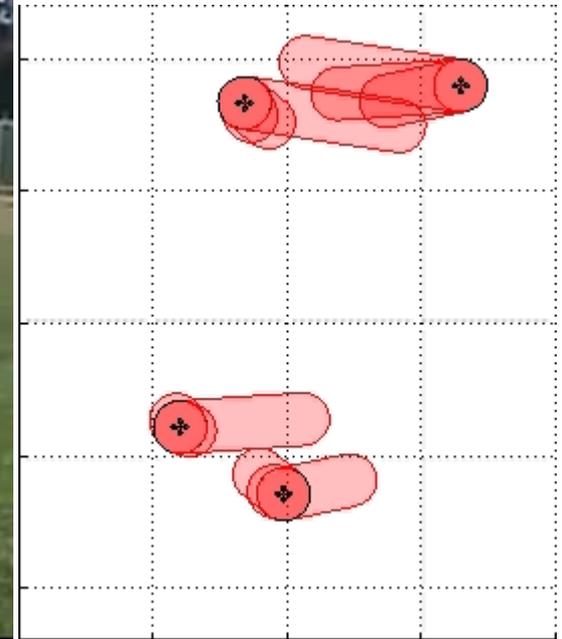


Partitions the state space



Example 1: Collision Avoidance

Pilots instructed to attempt to collide vehicles

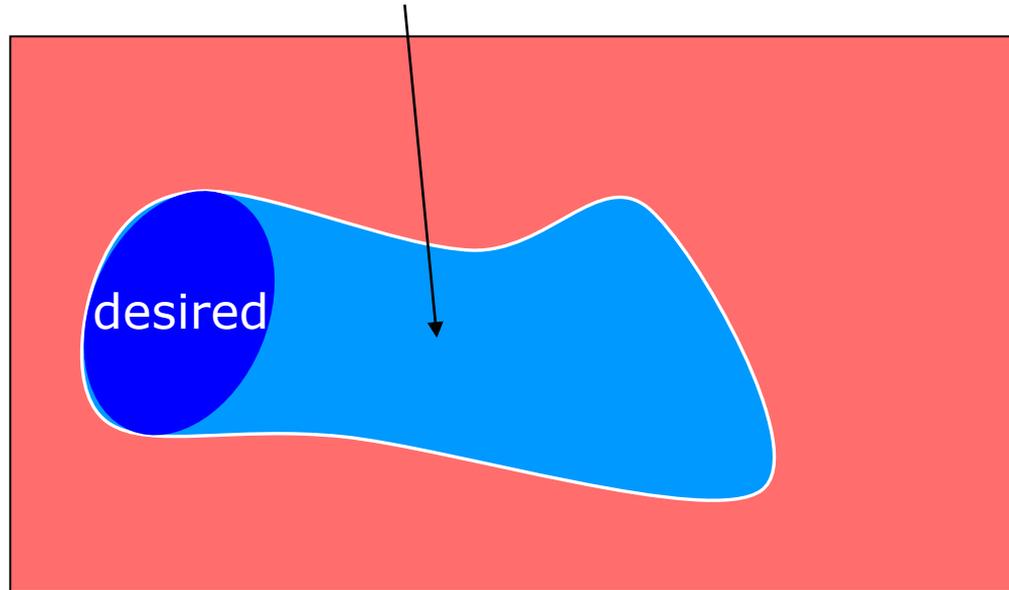


[STARMAC: Stanford Testbed of Autonomous Rotorcraft for MultiAgent Control]

[Hoffmann]

Backwards Reachable Set: Capture

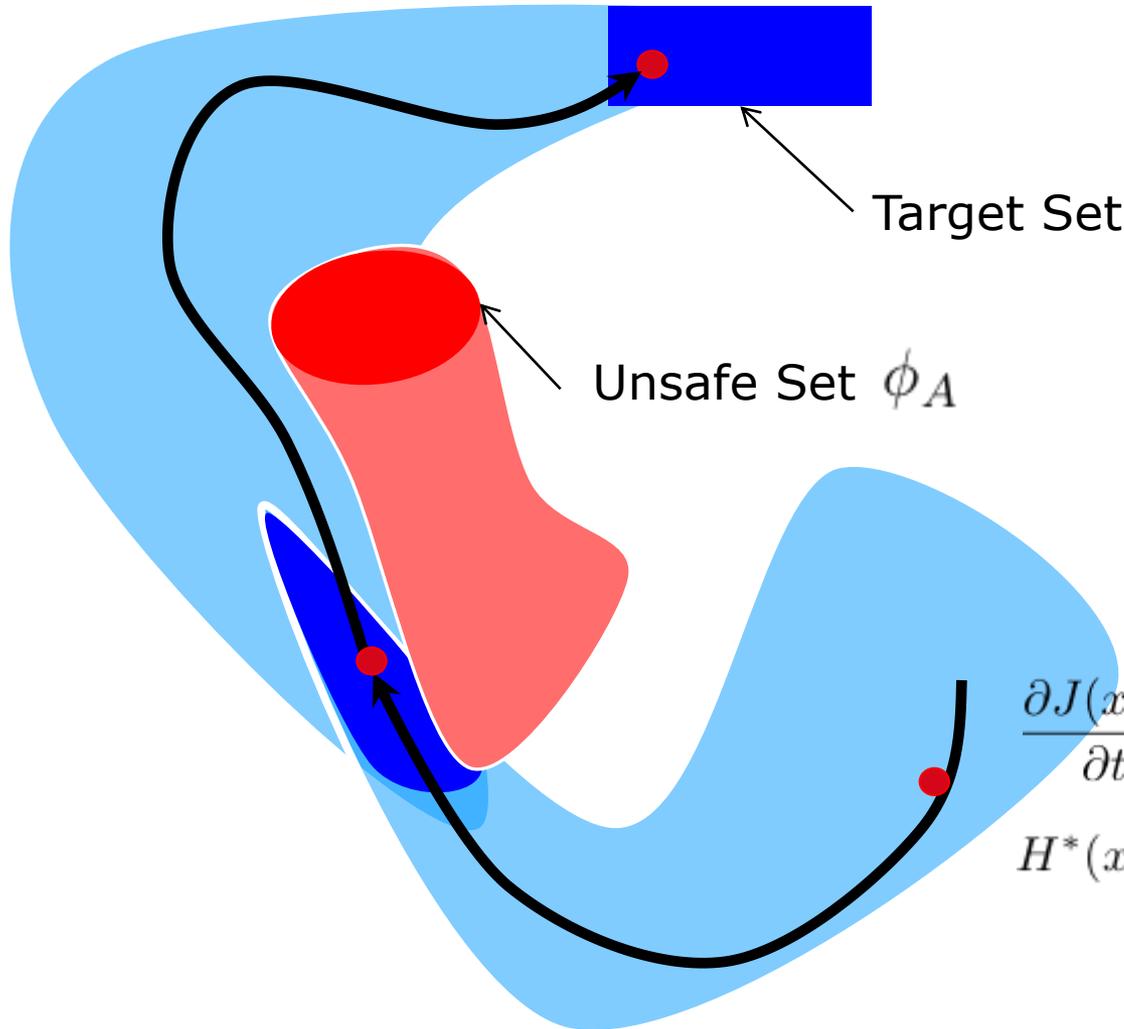
Backwards Reachable Set



Capture property can also be encoded as a condition on the system's reachable set of states

$$-\frac{\partial J(x, t)}{\partial t} = \min\{0, \min_u \max_d \frac{\partial J(x, t)}{\partial x} f(x, u, d)\}$$

Mode sequencing and reach-avoid



String together **capture sets**, starting from the **target set** and working backwards

Avoid sets can be combined with **capture sets** to guarantee safety

$$\frac{\partial J(x, t)}{\partial t} + \min\left[0, H^*\left(x, \frac{\partial J(x, t)}{\partial x}\right)\right] = 0$$

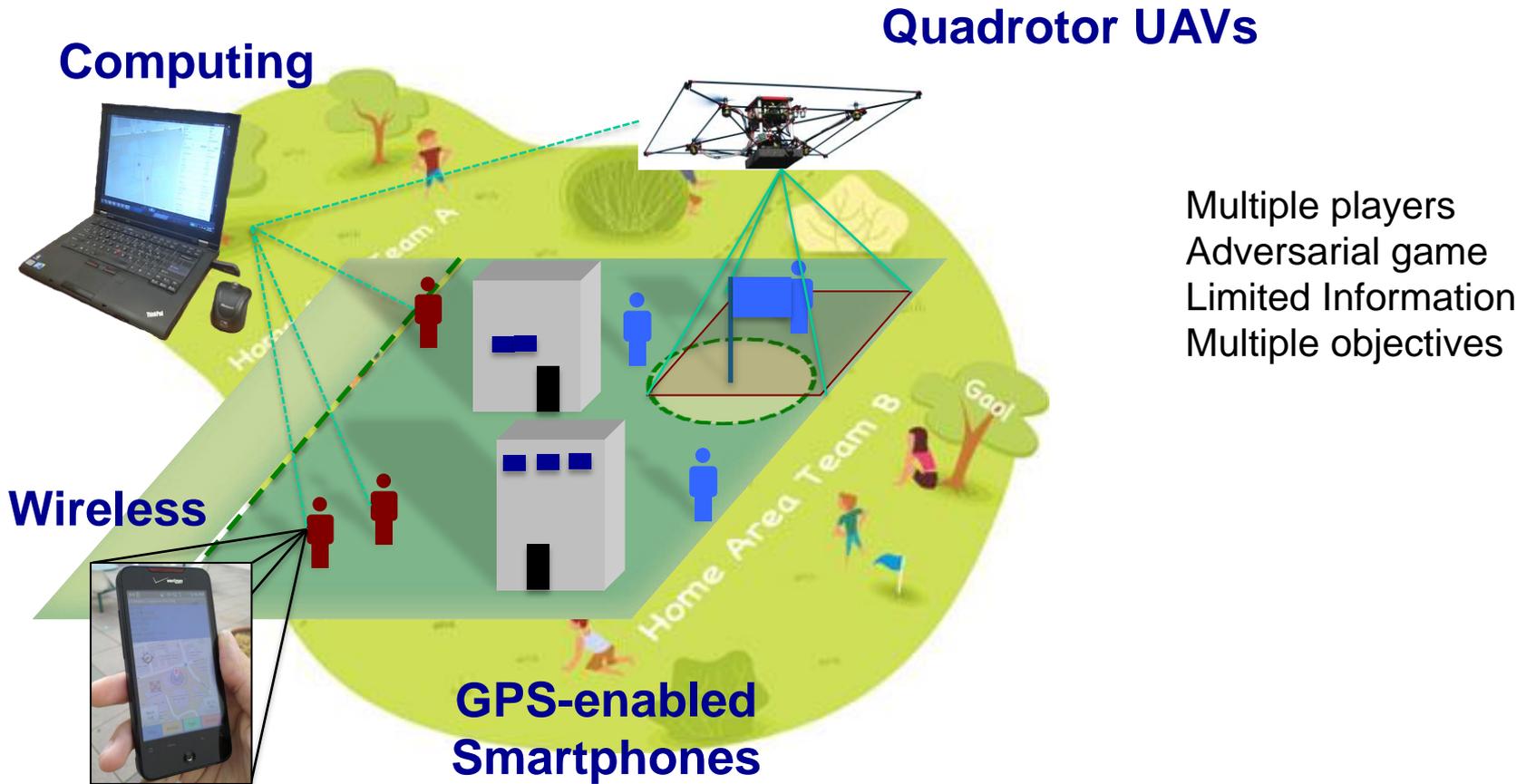
$$H^*\left(x, \frac{\partial J(x, t)}{\partial x}\right) = \min_u \max_d \frac{\partial J(x, t)^T}{\partial x} \cdot f(x, u, d, t)$$

Subject to $J(x, t) \geq -\phi_A$

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 - Examples:
 - Learning to fly
 - Reach-avoid games

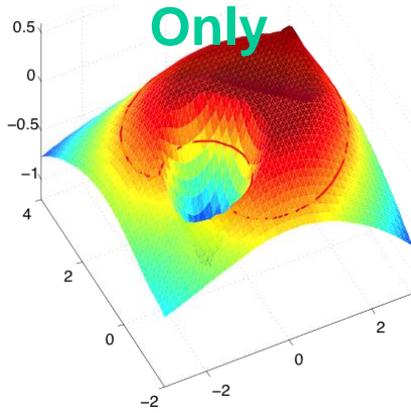
Example 2: Teaming up humans and robots



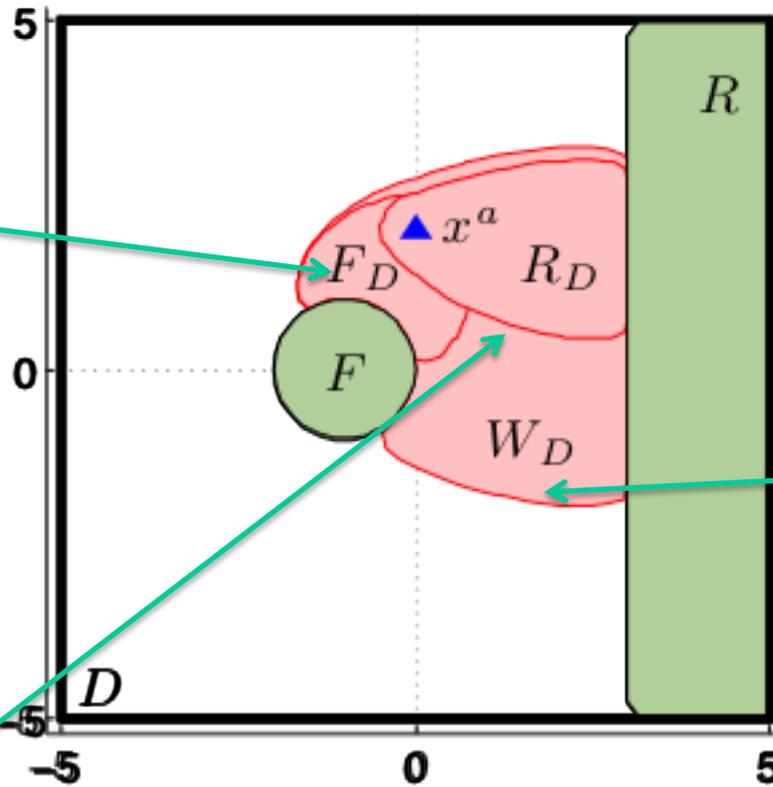
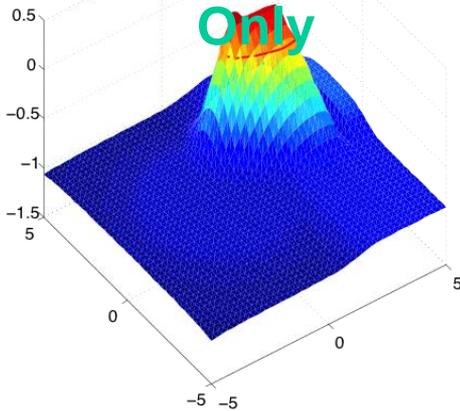
http://www.goforyourlife.vic.gov.au/hav/articles.nsf/pages/Capture_the_Flag

“Capture the Flag”

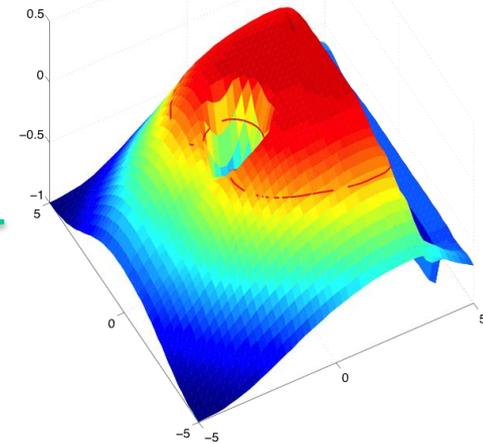
Flag Capture Only



Flag Return Only

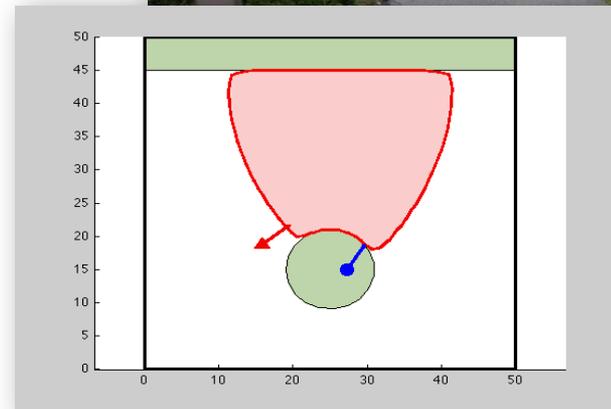
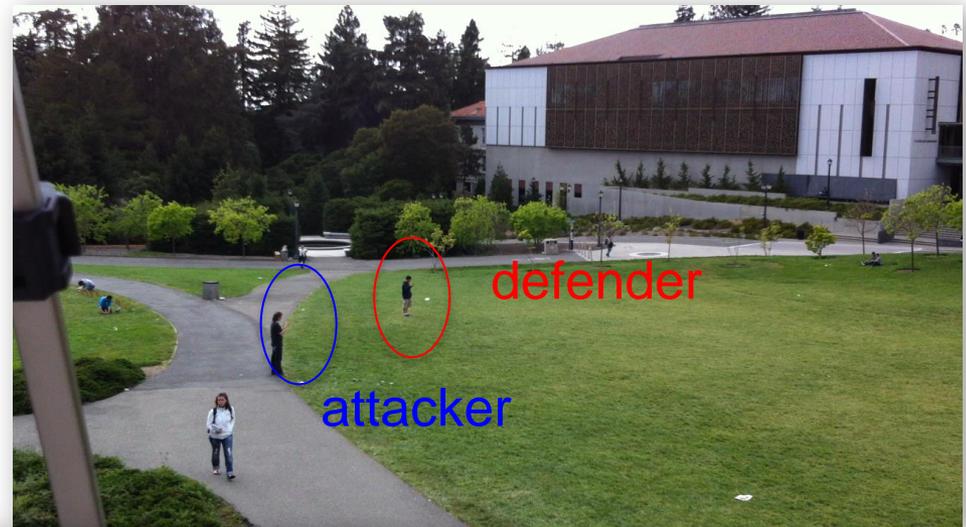
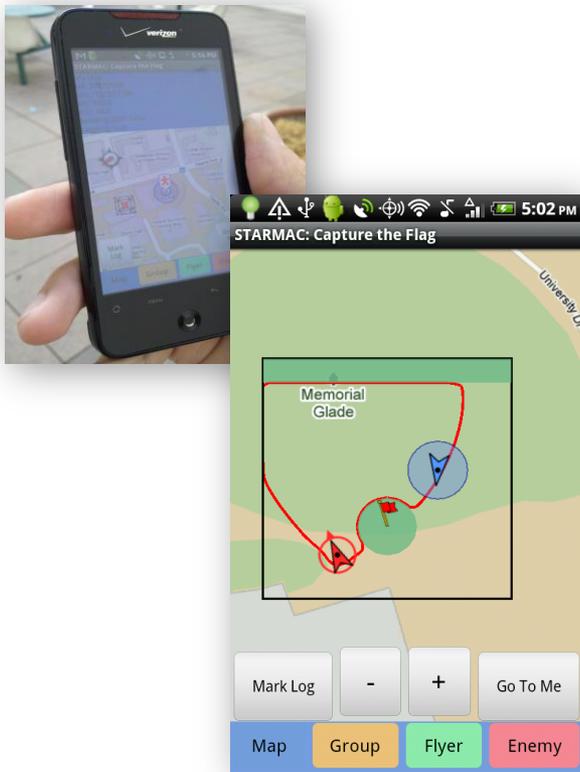


Full Game



Action Support For Human Agents

The computed solution can be used to guide and assist human agents.



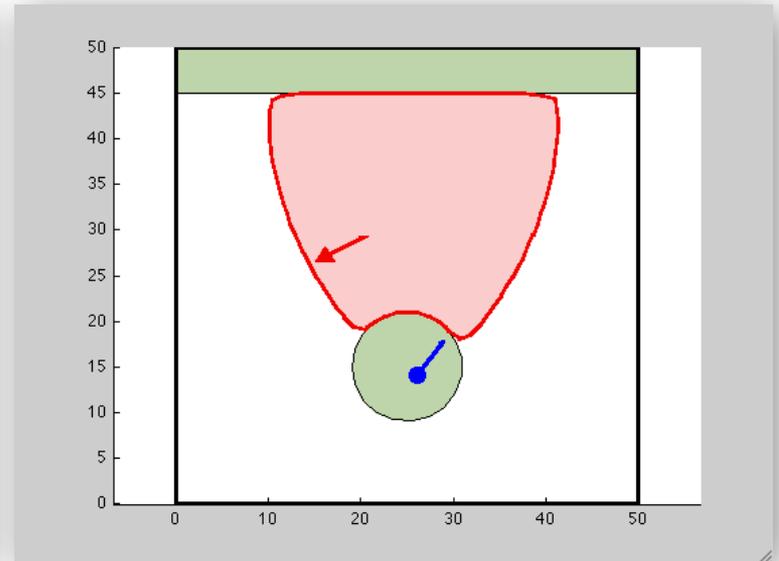
**Undergraduate
Team**

Scott Hoag
Andrew Sy

[Huang]

Supporting Complex Actions

Reachable sets also **assist and enable** more complex actions and strategic decision making.



In this case reachability information helps the attacker mislead the defender to win from a **losing initial configuration**.

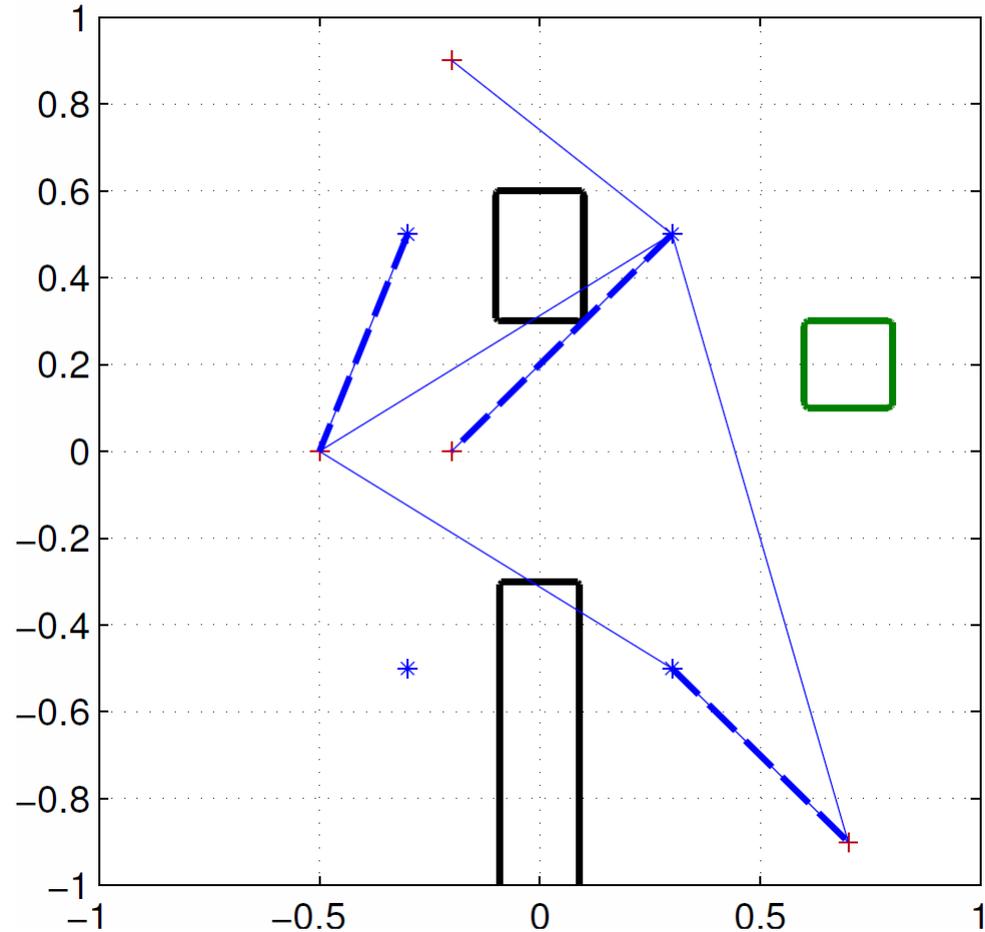
[Huang]

Reachability-Guided UAV Search



Example 3: From Two Player to Multiplayer

- Construct a bipartite graph:
 - 2 sets of nodes:
 $\{D_1, D_2, \dots, D_N\}, \{A_1, A_2, \dots, A_N\}$
 - For each D_i , test if D_i can defend the target for every A_j
 - If yes, draw an edge between D_i and A_j
- Run any matching algorithm to find a maximum matching
 - (Linear program, Hopcroft–Karp algorithm, $O(\sqrt{V}E)$)



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Safety
Simplicity



Ability to
adapt to new
information

Learn models from data...

... but stay safe while learning

- **Safety:**

- A nominal model with error bounds
- Reachable sets computed to ensure safety in worst case

- **Performance:**

- Use online learning to update model
- Cost function used to generate control action within the safe set

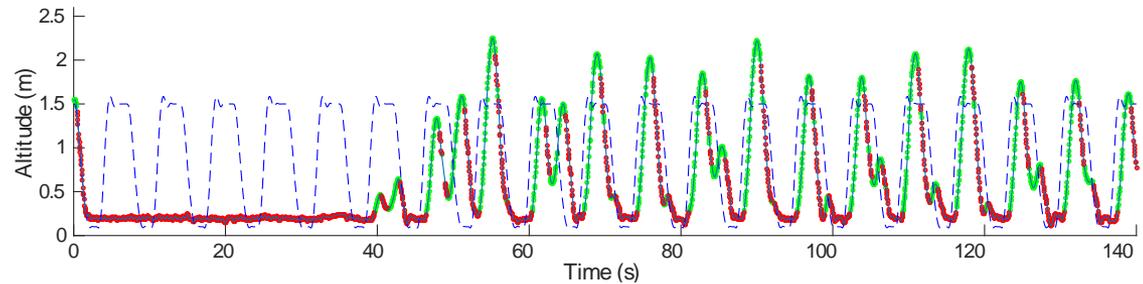
Example 4: Learning to fly from scratch

The quadrotor first:



drops

Learn to fly from scratch?



After about 1 minute,
it can roughly track the trajectory

Soon, it starts experimenting

...but the safe controller steps in

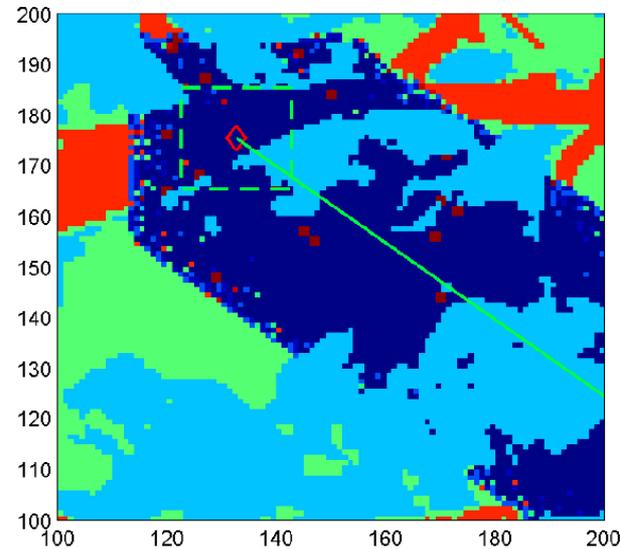
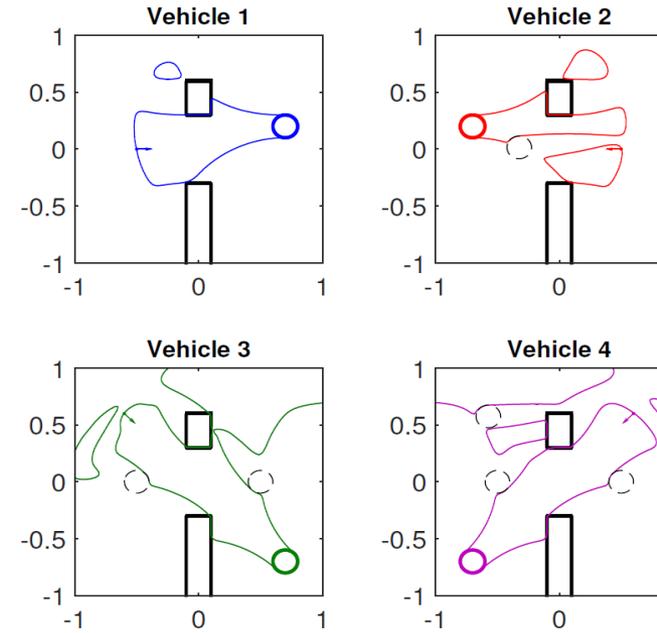
[Akametalu, Fisac]

Conclusions and current work

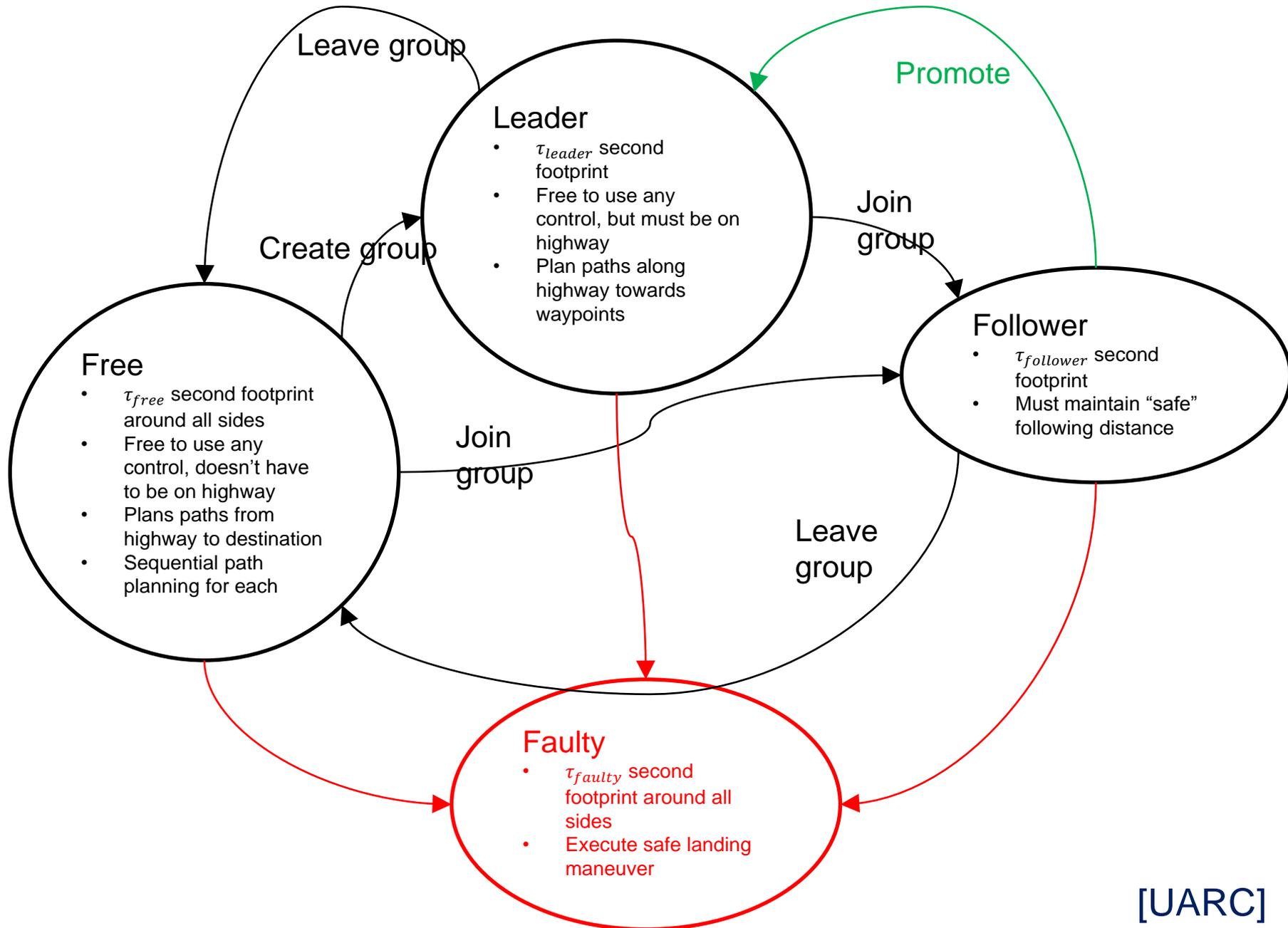
- Analysis and control of hybrid systems
 - Safety, from reachability analysis
 - Simplicity, from hybrid system representation
 - UAV safety from reach-avoid games [NASA]
 - Contrails: ATC game for Android



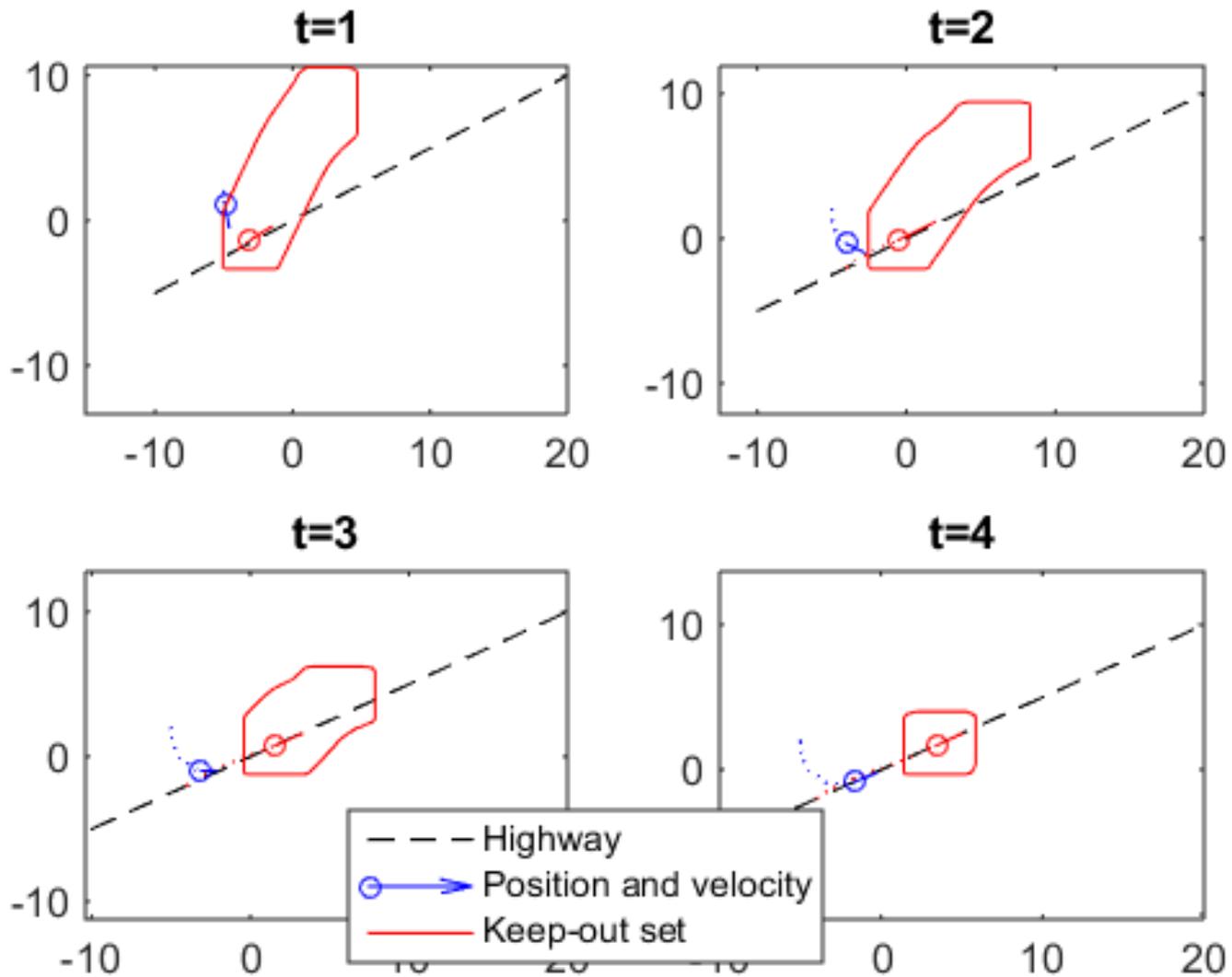
- Ability to learn from new information
 - Safe learning
 - Local updates
 - Forced Landing System [NASA]



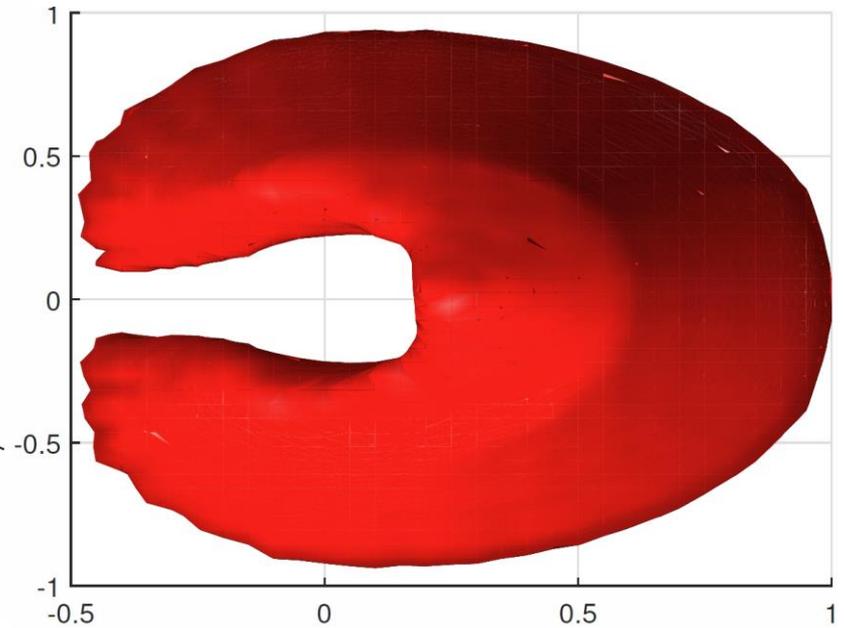
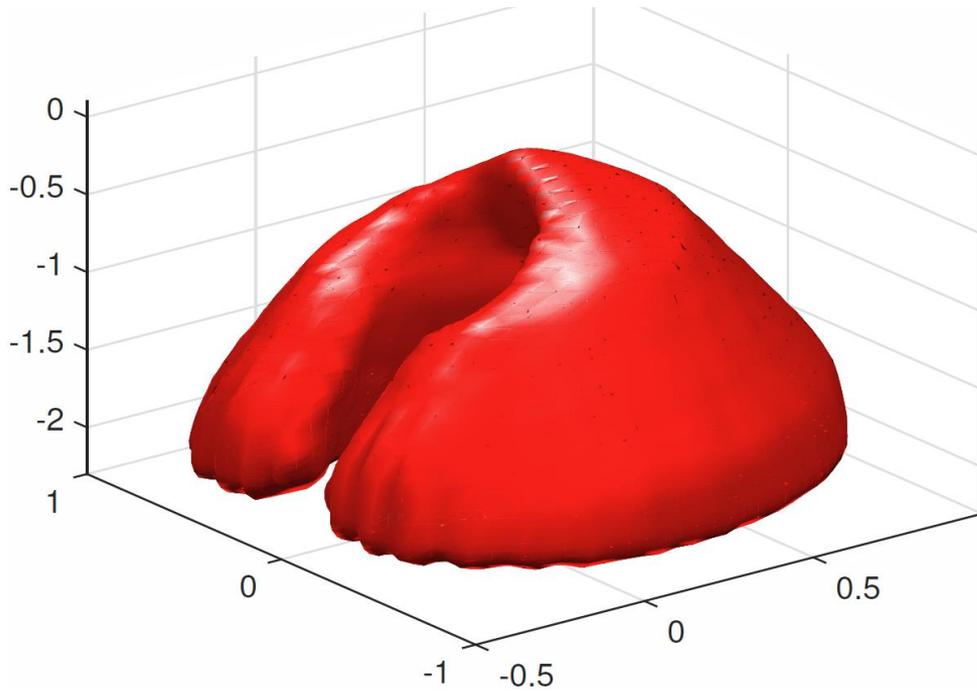
UTM modes



Joining highway



Forced Landing System



[NASA Armstrong]

Thanks

- **Kene Akametalu**
- Anil Aswani (now at IEOR, UC Berkeley)
- **Max Balandat**
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- **Jaime Fisac**
- Jeremy Gillula (now at EFF)
- Gabe Hoffmann (now at Zee.Aero)
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- Haomiao Huang (now at Kuna Systems)
- Soulayman Itani (now at Atheer Labs)
- Maryam Kamgarpour (now at ETHZ)
- Shahab Kaynama (now at ClearPath)
- **Casey Mackin**
- **Frauke Oldewurtel**
- Michael Vitus (now at hiDOF)
- Steve Waslander (now at ME, University of Waterloo)
- **Insoon Yang**
- **Melanie Zeilinger**
- Wei Zhang (now at ECE, Ohio State University)

**NSF
ONR
NASA
AFOSR
NIH**

Call for Papers

Special Issue on Human-Centered Automation

IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING

Topics include, but are not limited to:

- the design and validation of computational models of a system which integrate models of the human with models of autonomous and semi-autonomous systems, such as systems which infer intent of a human operator;
- the design of systems which ease the exchange of information between humans and autonomous systems;
- the analysis and prediction of potential conflicts between the human and the automation;
- the design of autonomy to accommodate varying levels of human experience, training, and acuity;
- the analysis of information asymmetry in collaborative, semi-autonomous systems;
- the design of autonomy for off-nominal conditions, such as multiple sensor failures, human error, or other cascading events;
- the design of autonomy to support systems with multiple humans;
- the design of autonomous systems which are “self-aware”, so that humans are prompted to intervene when required.

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Publication: January 2016

Meeko Oishi, Dawn Tilbury, Claire Tomlin (Guest Editors)

Growing numbers of UAV applications



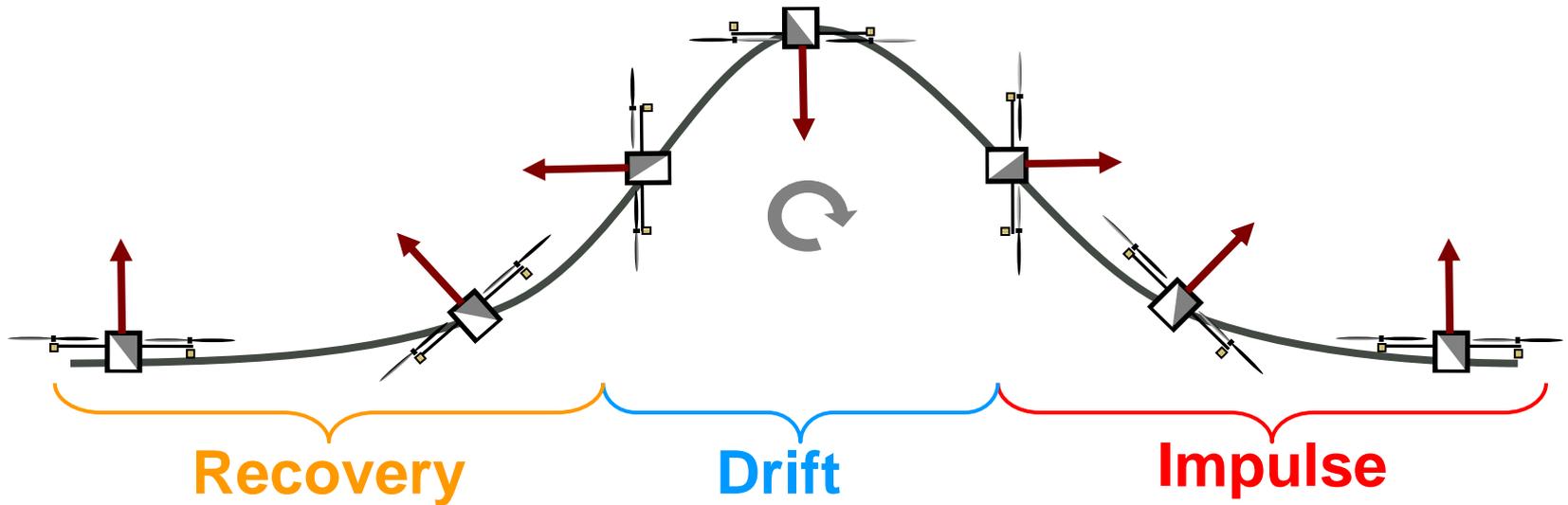
[Amazon]



[Google]

- City with 2M people
- Each person requests drone delivery every 2 months
- 35K deliveries per day
- Delivery takes 30 min
- Up to 1K drones in air simultaneously

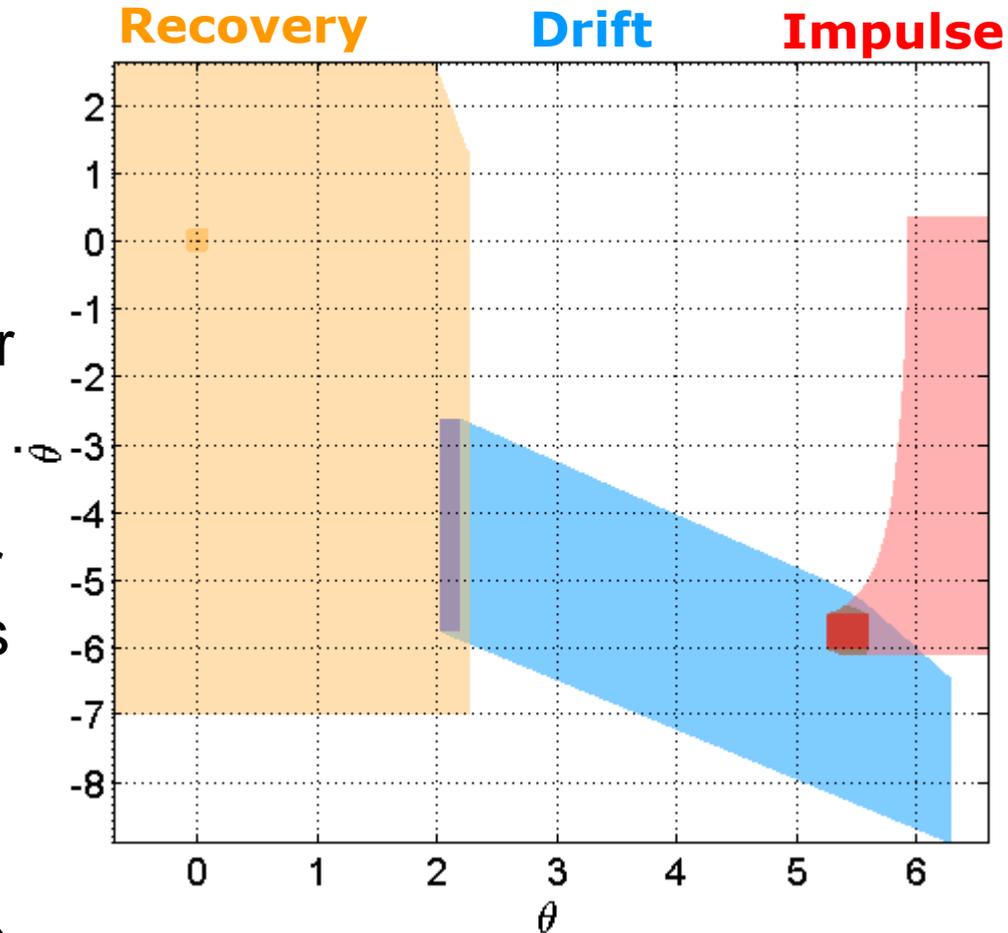
Example 2: Mode sequencing



- Divide flip into three modes
- Difficult problem:
 - Hitting some target sets while avoiding some unsafe sets
- Solution:
 - Analyze rotational dynamics and vertical dynamics separately

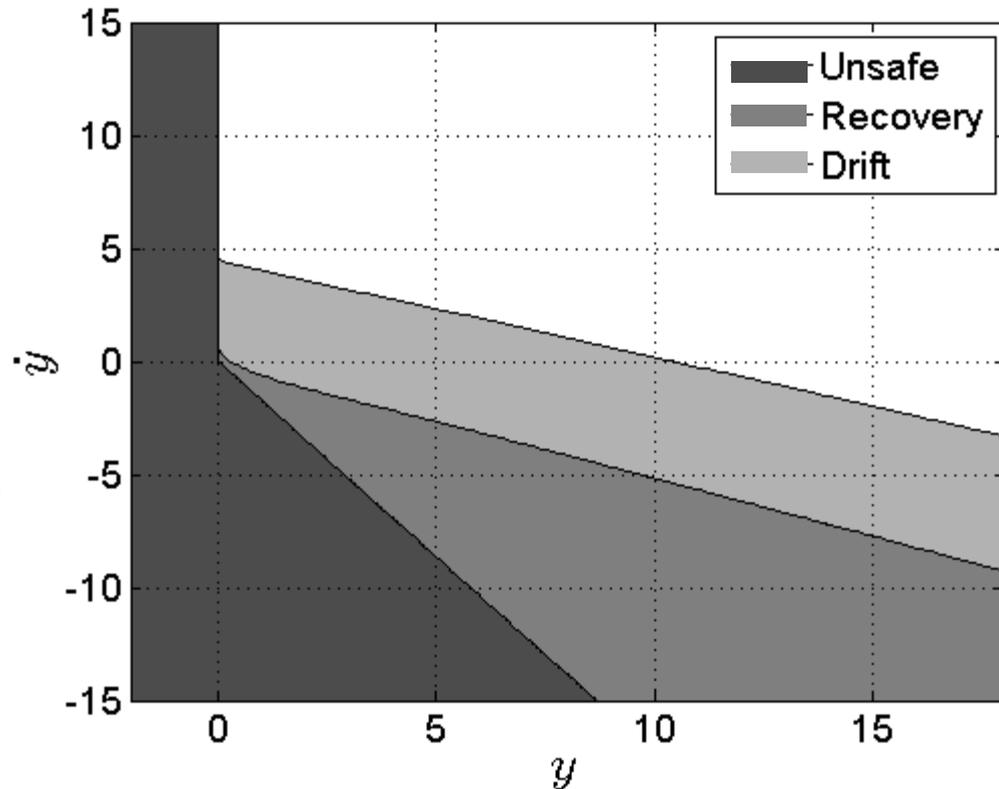
Back-flip: Method (1)

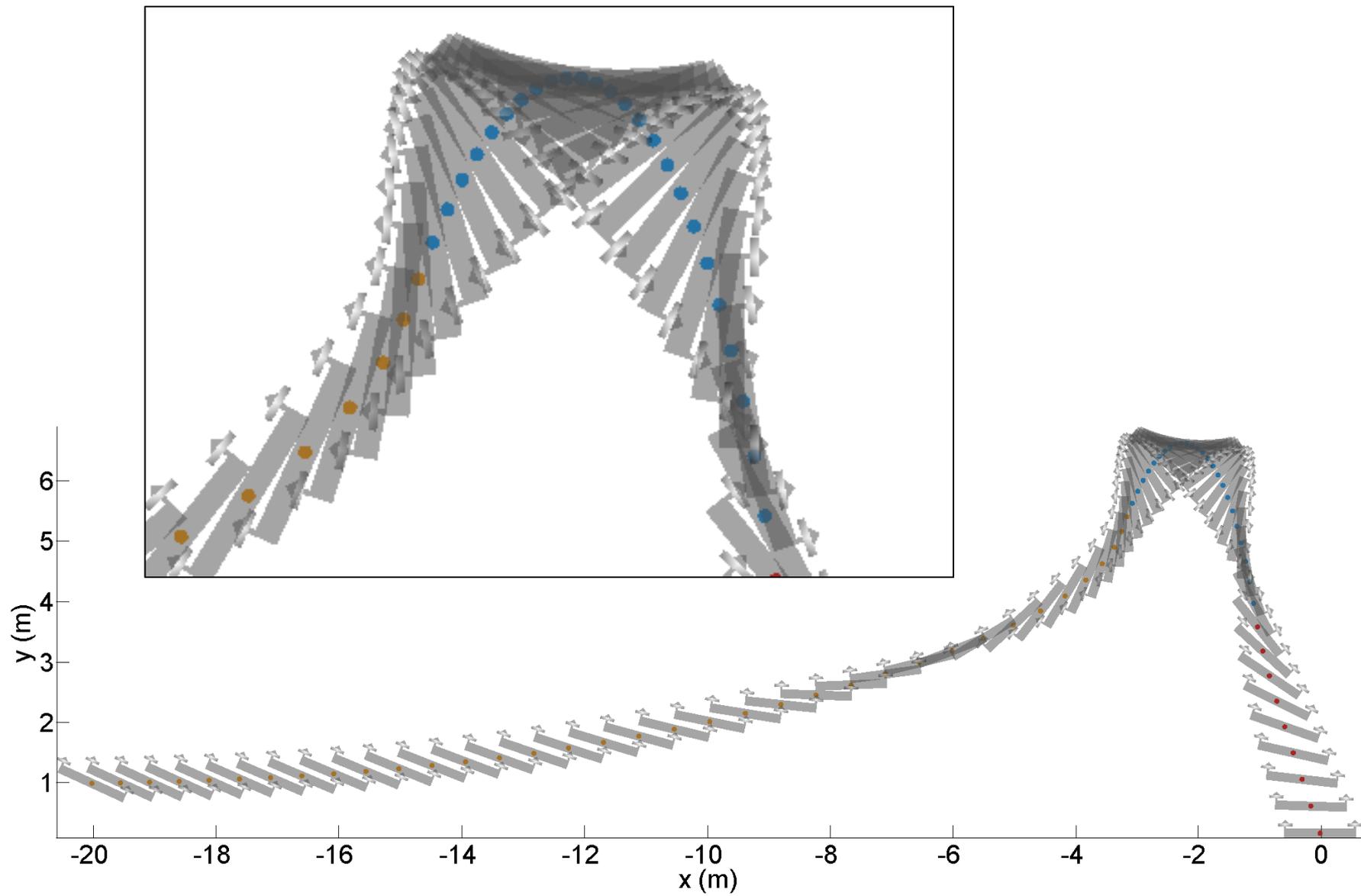
- Identify **target** region in rotational state space for each mode
- Use reachable sets to calculate **capture basin** for each target
 - Dynamic game formulation accounts for worst-case disturbances
- Verify that target of each mode is contained by capture basin of next mode



Back-flip: Method (2)

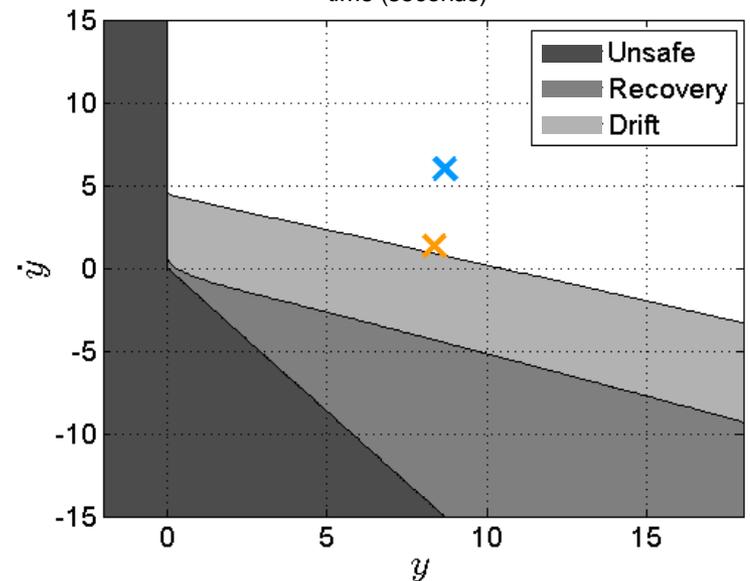
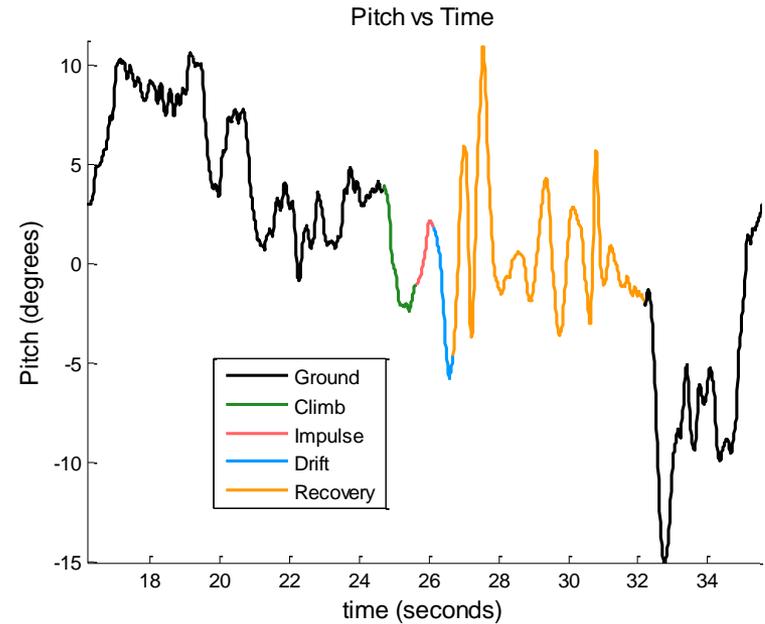
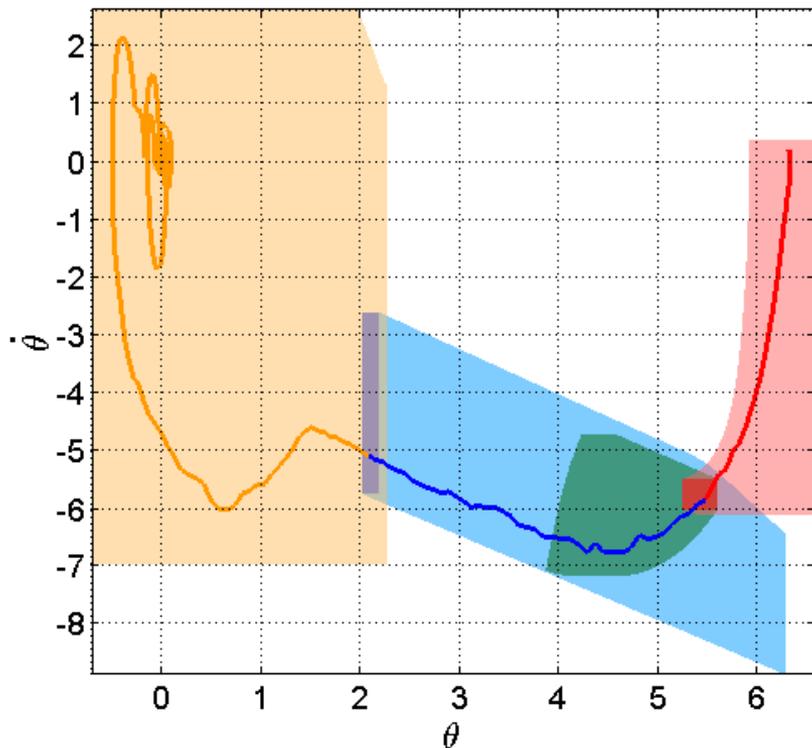
- Identify **unsafe** region in vertical state space for final mode
- Use reachable sets to propagate **unsafe set** for each mode
 - Dynamic game formulation accounts for worst-case disturbances
- Verify that control keeps state out of unsafe set



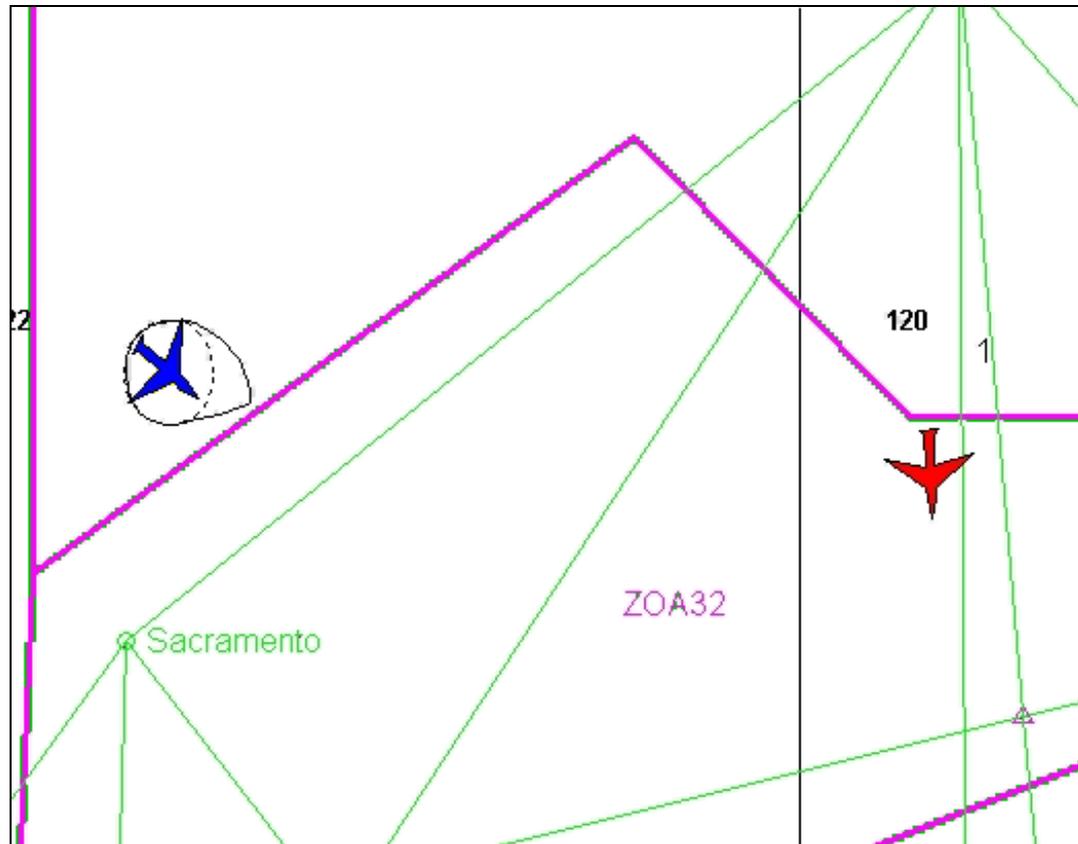


Back-Flip: Results

- Assumptions Validated
- Safety Guaranteed
- Reachability Demonstrated



Reachability in Air Traffic Control



Automation to aid controllers

- Infeasible to get data from real controllers
- Most experiments use retired controllers or student volunteers
- Retired controllers are rare, students get bored, where to get more data?



Contrails: Air traffic control game for Android



Replay Engine on Server

Trajectories,
aircraft
states,
player inputs

A Typical ATC experiment¹

28 participants
168 trials (6 each)

Local US college students

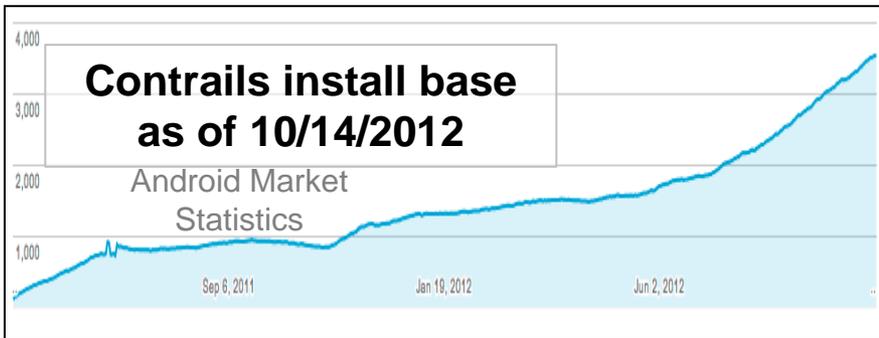
Max individual sample (est): **100**
 planes

Contrails to date

3544 active installs
63,583 games played

10+ countries

Most active user: **9489** planes



Leaderboard

Top controllers from around the world

Sort by? Top:

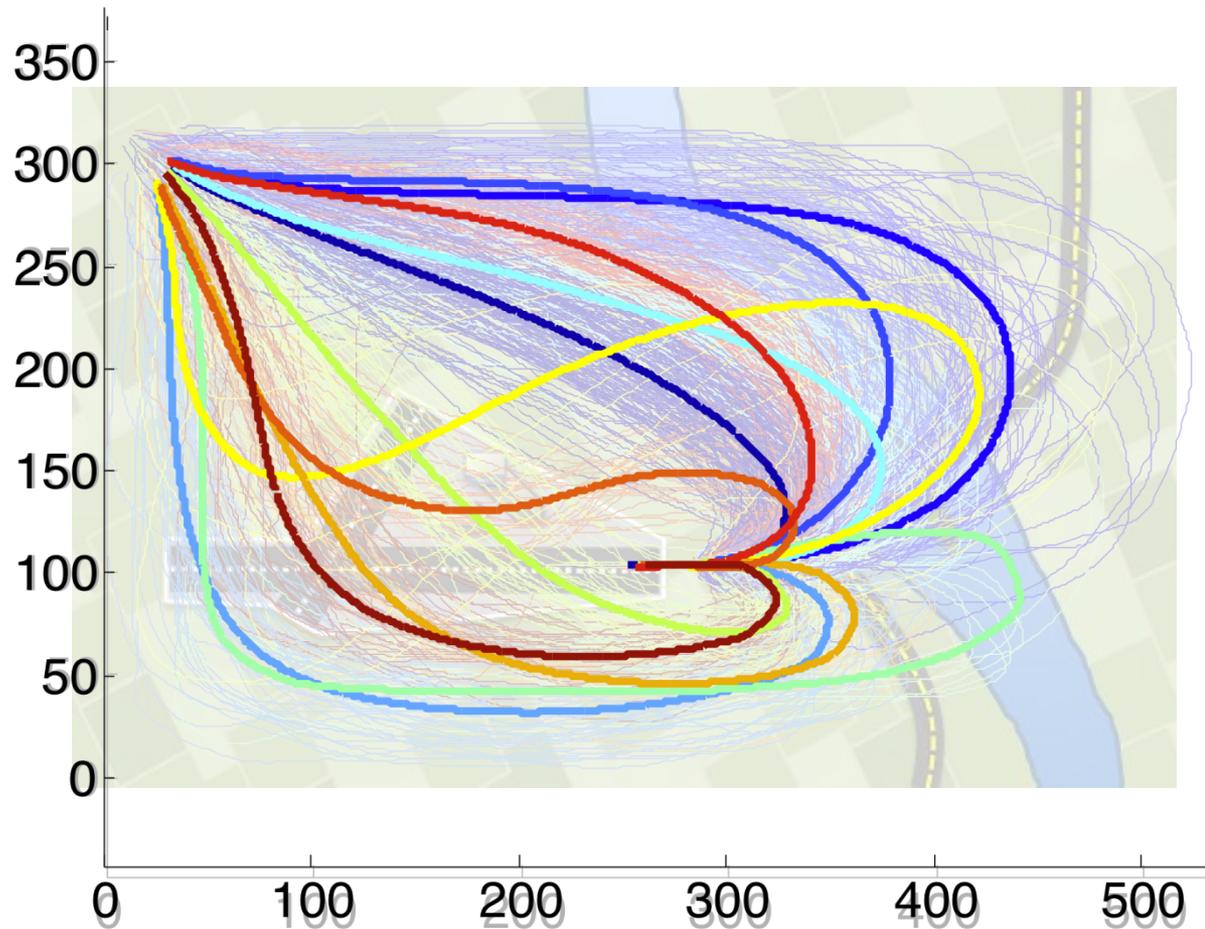
Name	Planes Landed
wizbang_fll	9489
Tobbesuger	8853
7203644221	7761
Rhiannon	6215
lolblock	6210
tony	5963
spa	5651
AK	5073
anek	4808



¹M. Stone et al., "Prospective memory in dynamic environments: Effects of load, delay, and phonological rehearsal." *Memory*, 2001.

Modeling using gathered data

- Hypothesized hybrid model for controlled aircraft
- Data is supportive; clustering suggests discrete set of maneuvers used



Modeling using gathered data

- Predict the maneuver given the airspace
 - Avoidance maneuvers plotted on learned conditional airspace distributions
 - How people sequence moving objects

