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Safe Platooning of Unmanned Aerial Vehicles via Reachability

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Swarm Lab Winter Retreat

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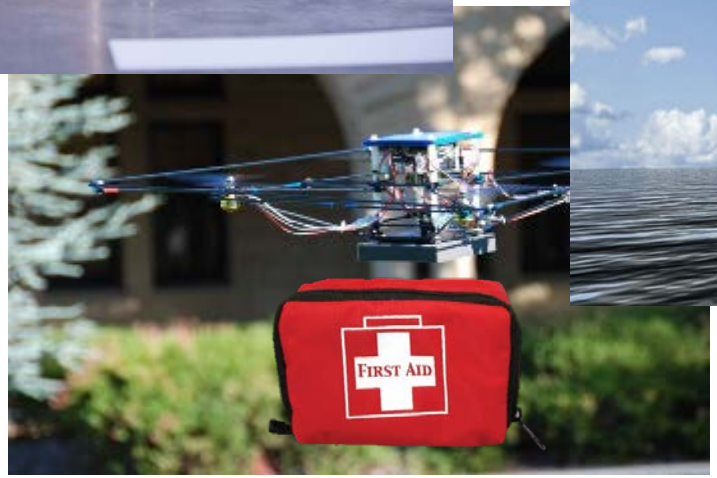
Motivation

Google Project Wing

Aerial surveillance

Amazon Prime Air

Search and rescue



Emergency
Supply
Delivery

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Motivation

- Many UAVs
  - City with 2 million people
  - Each person requests drone delivery every 2 months
  - ~35000 deliveries per day
  - 30 minutes from warehouse to customer
  - Thousands of drones in the air simultaneously
- Large joint state space
- Even pairwise interactions are numerous
- Air highways and platoons provide additional structure to facilitate scalable analysis and intuitive monitoring

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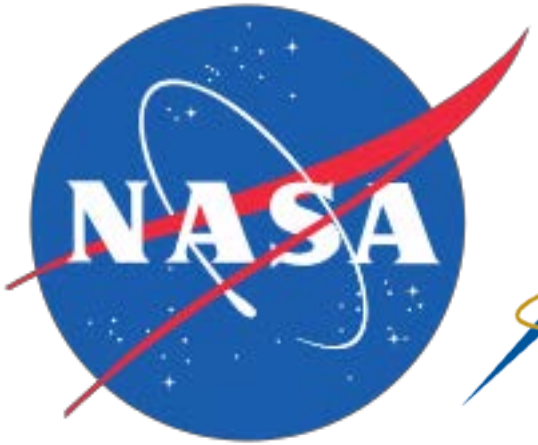
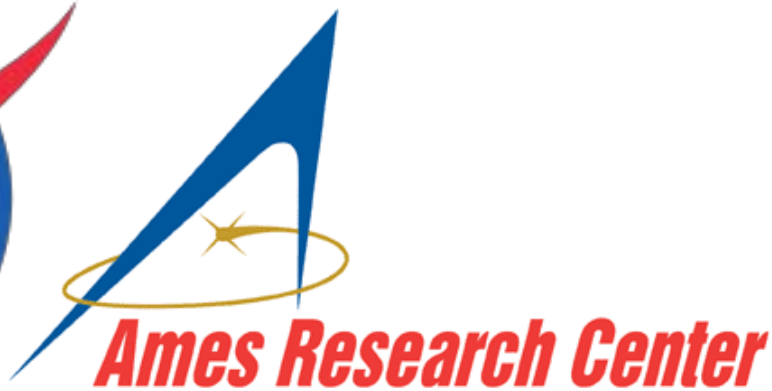
Motivation

- Important and urgent problem for government agencies

- Working with NASA Ames to address the UAV traffic management (UTM) problem





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Goals

- Air highways
- Platooning
  - Vehicles and platoons as hybrid systems
- Reachability analysis
  - Hamilton-Jacobi formulation
  - Liveness controllers
  - Safety controllers
- Simulations

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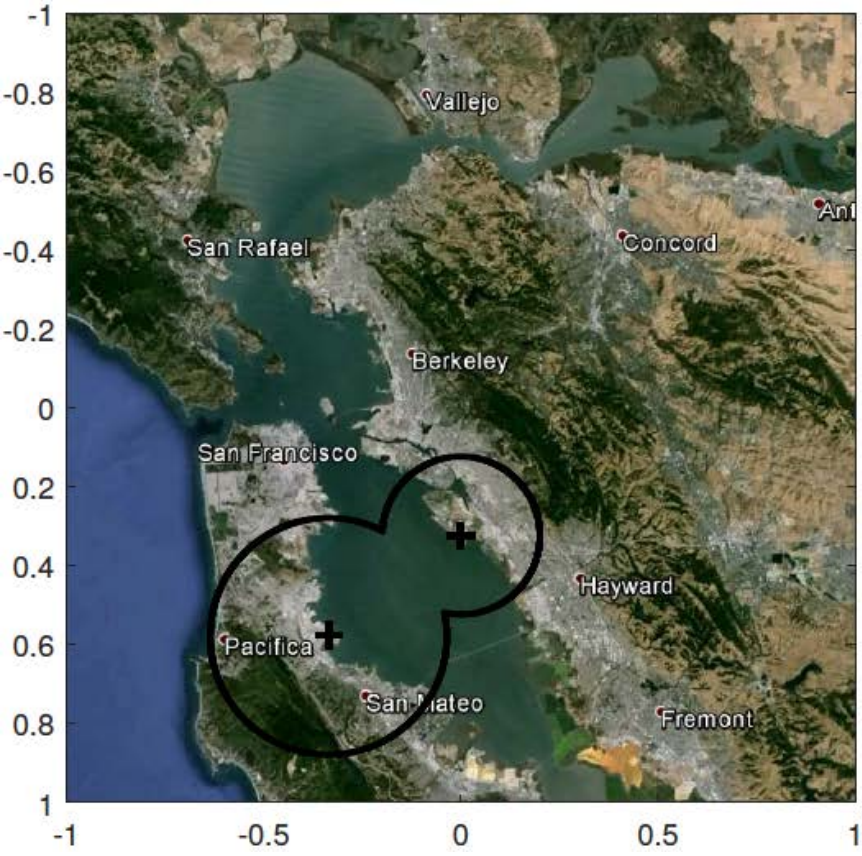
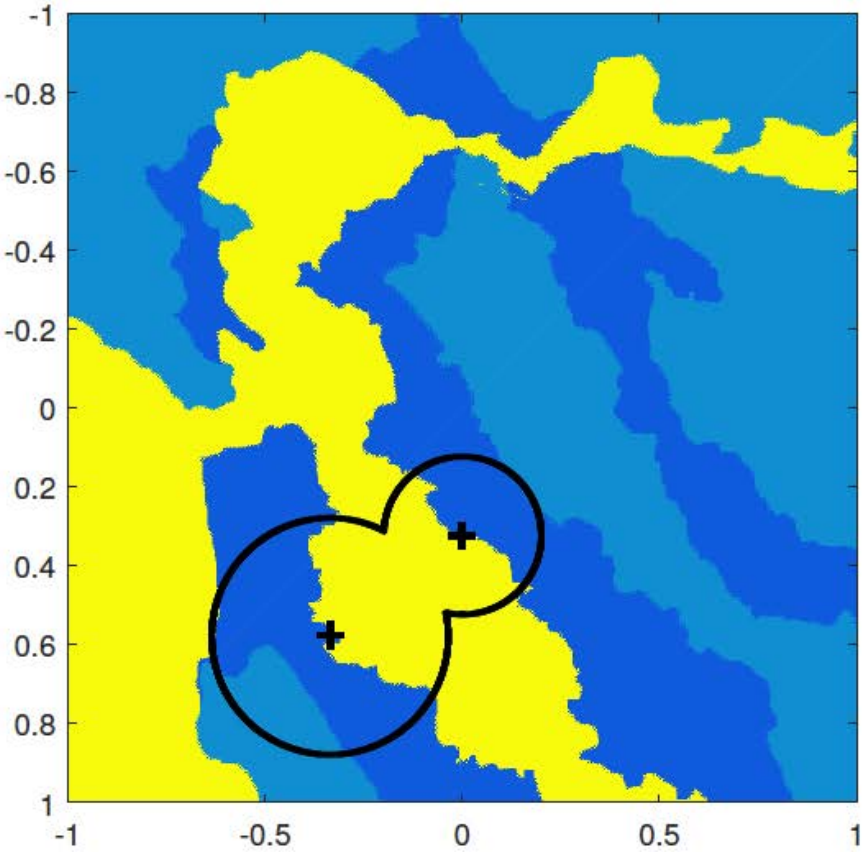
The cost of flying

San Francisco Bay Area



Example cost map



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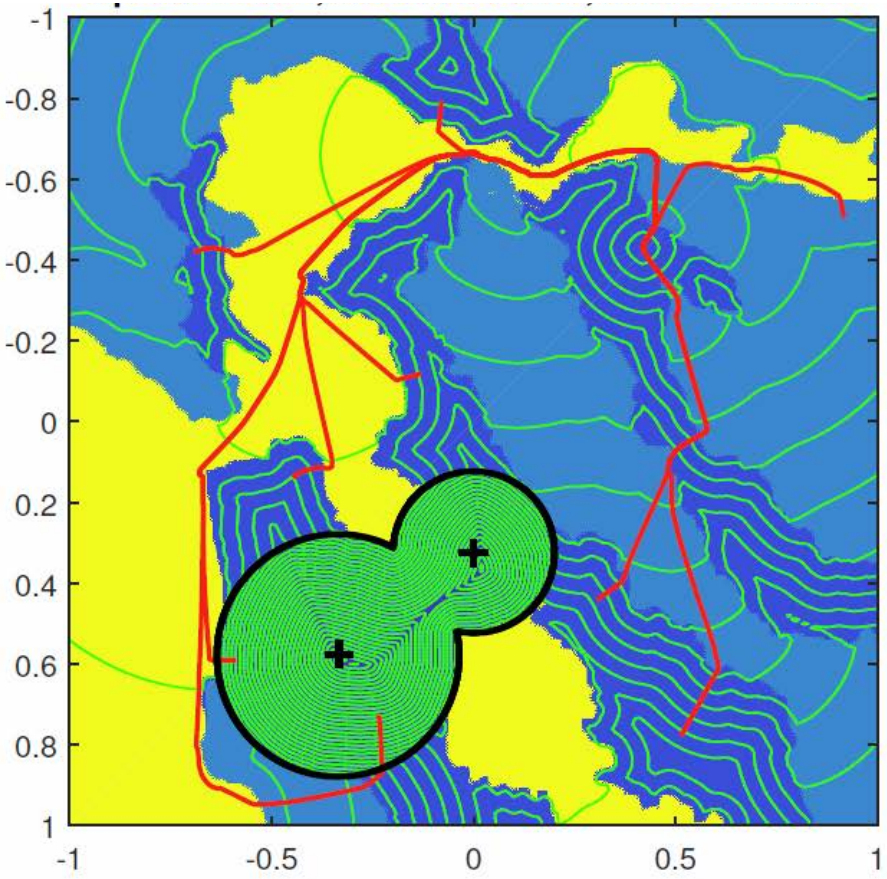
Minimizing cost

- Accidents
- Fuel
- Noise pollution

- Eikonal equation
  - Fast marching method
- "Trunks" and "Branches" in optimal paths



Cost map, value function, and optimal paths

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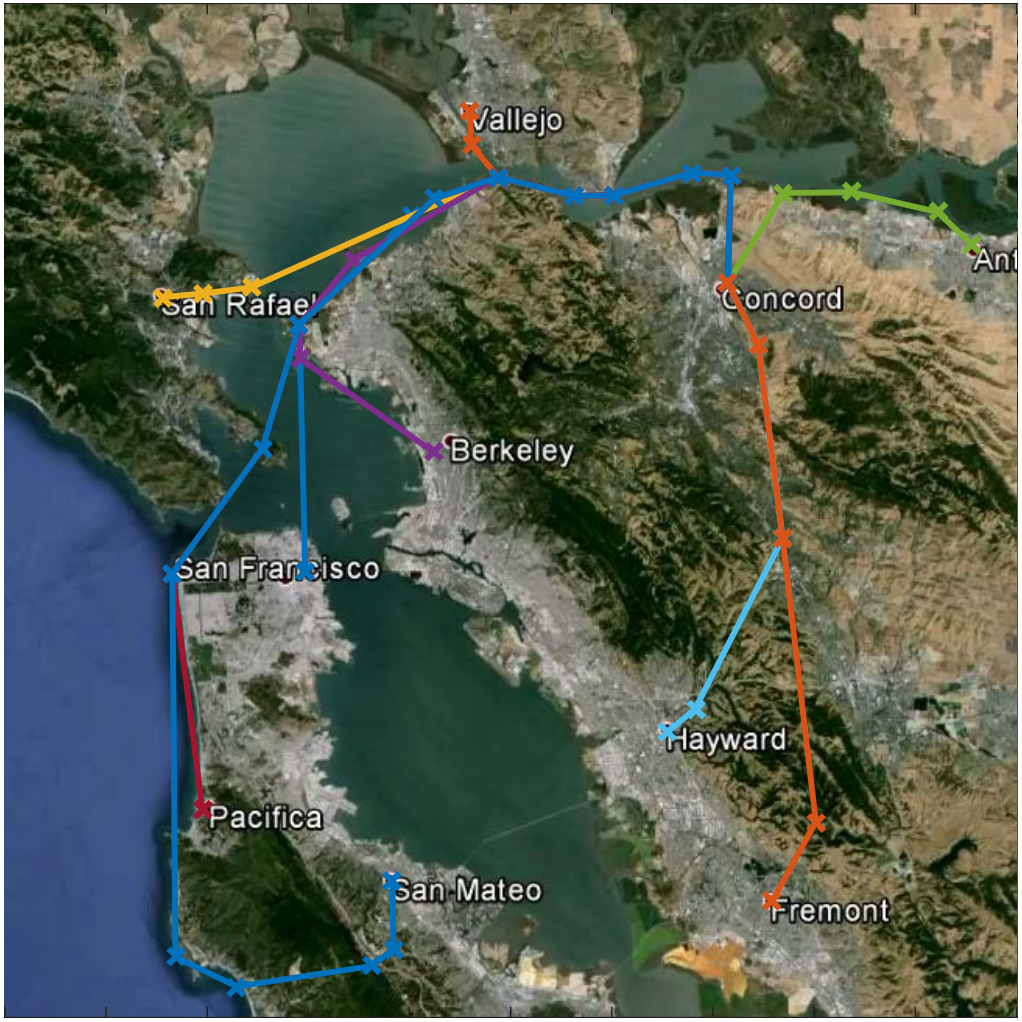
Air Highways



Bay Area map and waypoints

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Air Highways

- Straight-line paths inside a pre-defined altitude range
- Connects destinations and origins
- Platoons travel on air highways

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Platoons

- Vehicles traveling in a single-file formation
- Leader follows the highway
- Followers use simple feedback control to stay in formation
- Simple control laws are used

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Vehicle modes

Free

- Vehicle not in a platoon or on a highway

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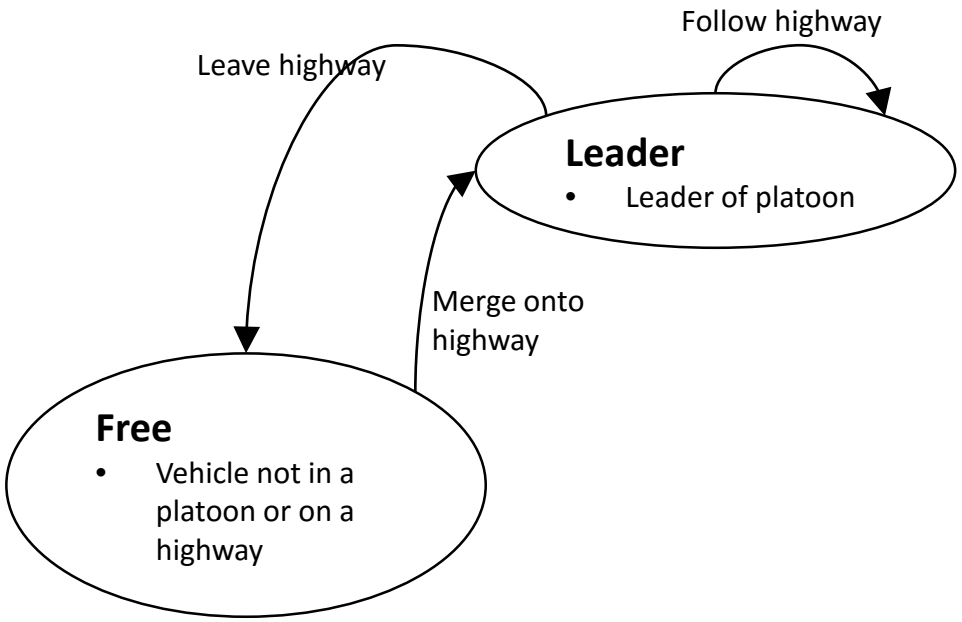
Vehicle modes



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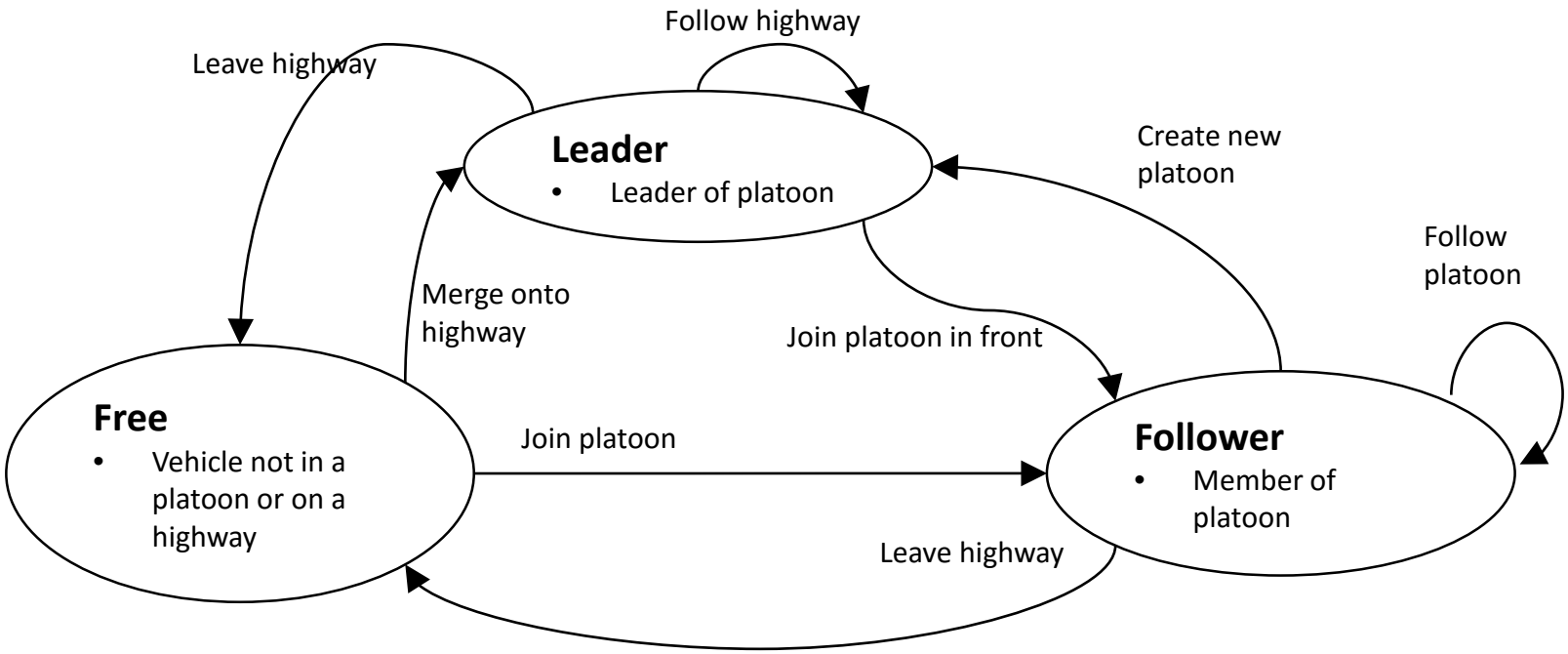
Vehicle modes



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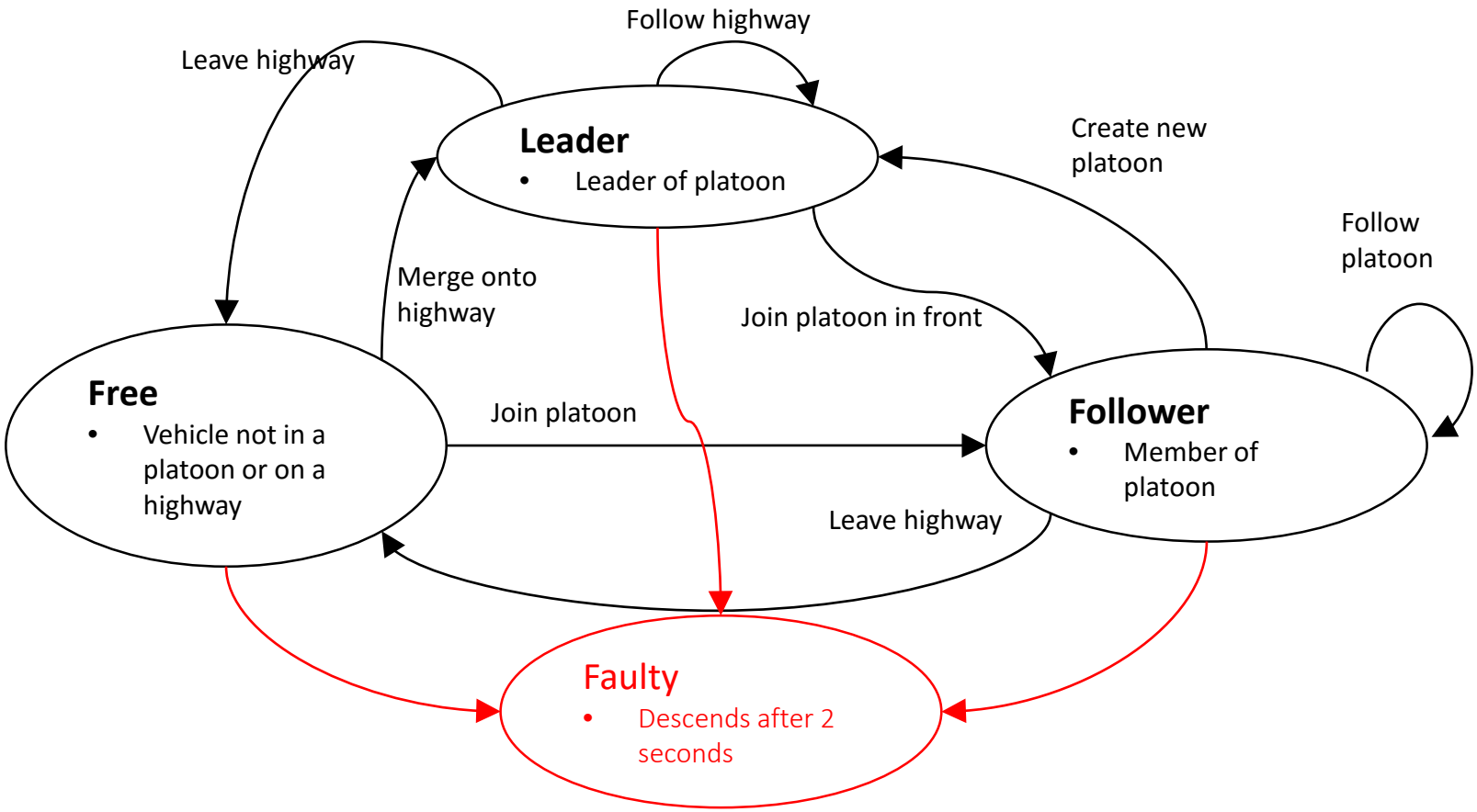
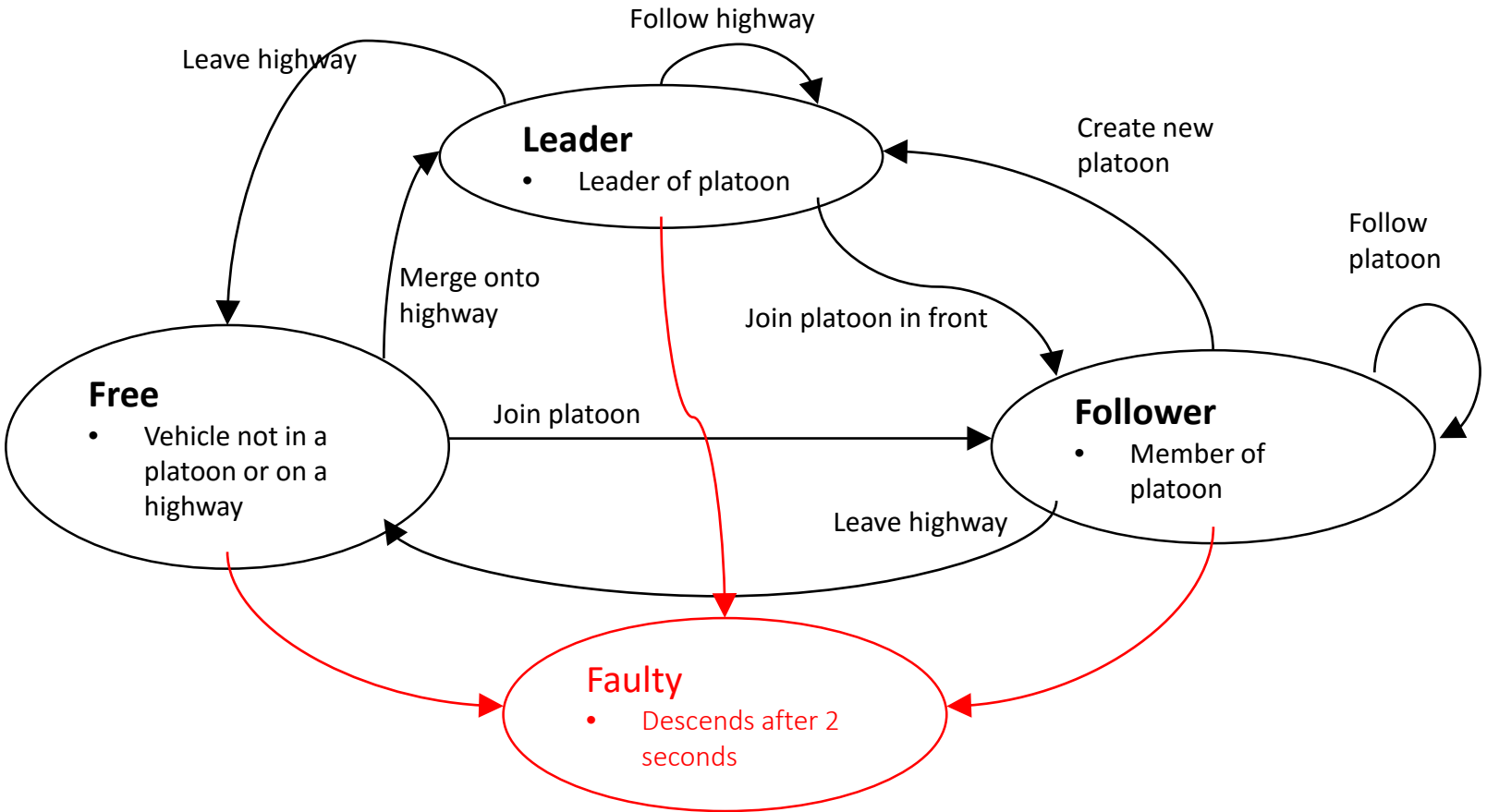
Vehicle modes



Vehicle modes

- How do we guarantee safe and successful transition between these modes



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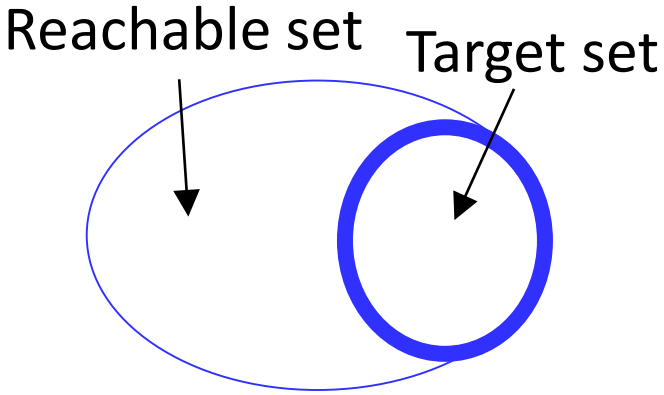
Goals

- Air highway placement
- Platooning
  - Vehicles and platoons as hybrid systems
- **Reachability analysis**
  - **Hamilton-Jacobi formulation**
  - **Liveness controllers**
  - **Safety controllers**
- Simulations

Reachability Analysis

For a dynamical system with given

- Dynamics $\dot{x} = f(x, u, d), x \in \mathbb{R}^n$
- Target states $\mathcal{T}$



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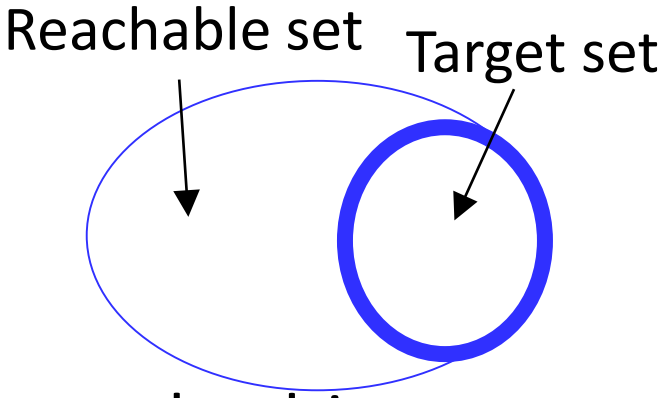


Determines, with guarantees

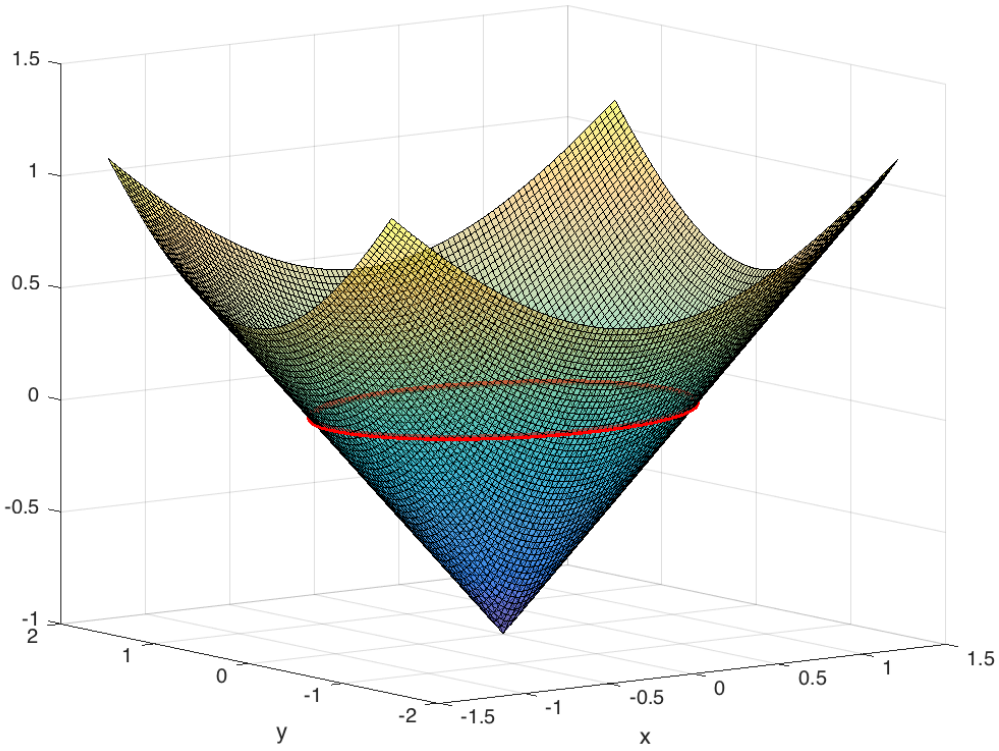
- Set of states from which the system can be driven to the target state

Hamilton-Jacobi Formulation

Implicit surface functions

- Represent a set G using an implicit surface function $\phi_G(x)$:

$$\phi_G(x) \leq 0 \Leftrightarrow x \in G$$

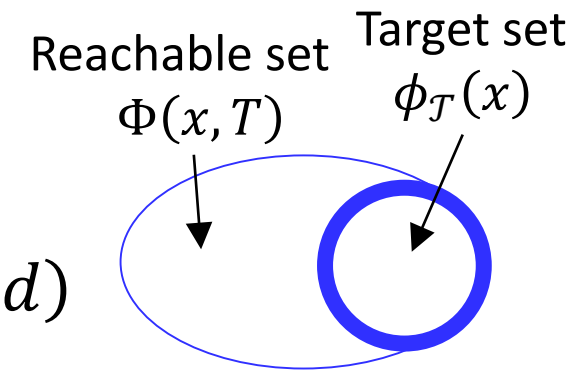


Hamilton-Jacobi Formulation

$\Phi: \mathbb{R}^n \times [-T, 0] \to \mathbb{R}$ is the solution to

$$\frac{\partial \Phi}{\partial t} + \min[0, H(x, \nabla \Phi)] = 0, t \in [-T, 0]$$

$$\Phi(x, 0) = \phi_{\mathcal{T}}(x)$$

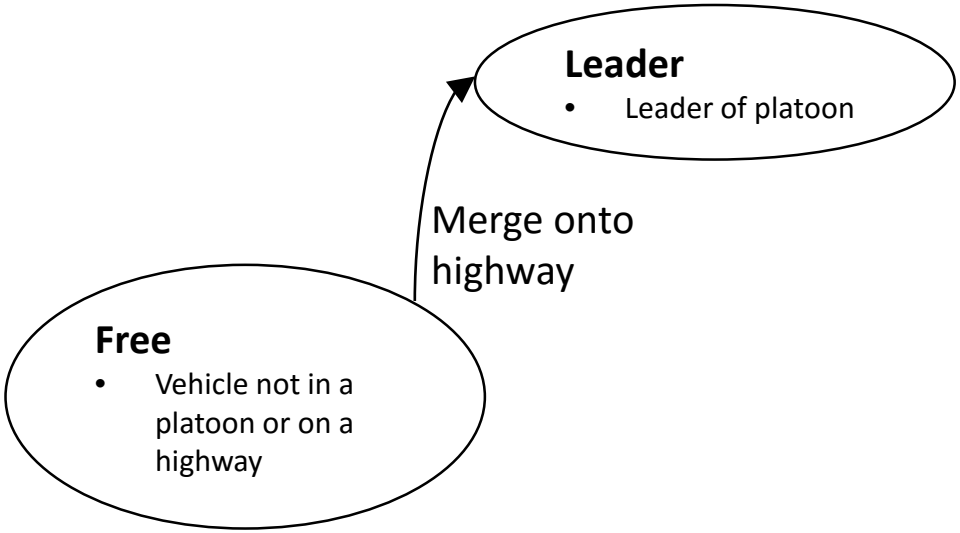


where the Hamiltonian is given by

$$H(x, p) = \min_u \max_d p^T f(x, u, d)$$

Liveness controllers from reachable sets

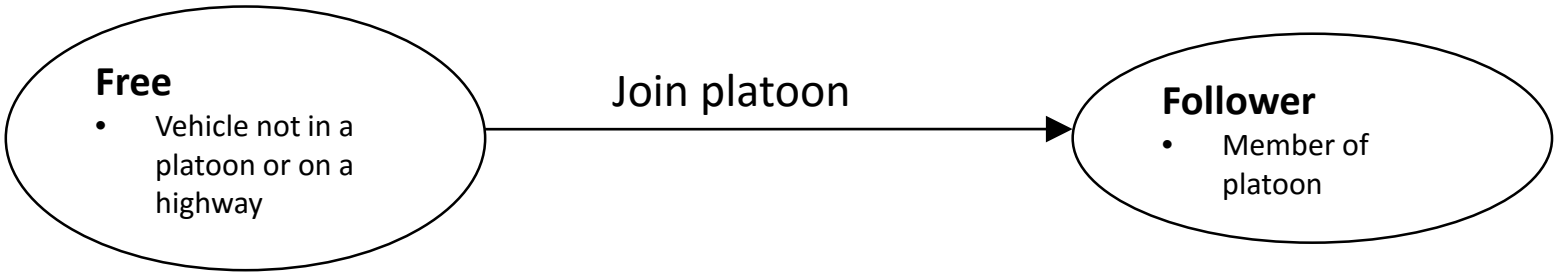
- Merging onto a highway
  - Target set: desired merging point and relative velocity
  - Reachable set: set of states that can reach target set



Liveness controllers from reachable sets

- Merging onto a highway
  - Target set: desired merging point and relative velocity
  - Reachable set: set of states that can reach target set

- Joining platoon on highway
  - Target set: desired merging point in terms of relative coordinates
  - Reachable set: set of states in relative coordinates that can reach target set



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Safety controllers

- Collision avoidance
  - Target set: collision box in relative states plus (union) velocity limits
  - Reachable set: set of states in relative coordinates that will hit target set assuming worst case disturbance

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Safety controllers

- Collision avoidance
  - Target set: collision box in relative states plus (union) velocity limits
  - Reachable set: set of states in relative coordinates that will hit target set assuming worst case disturbance

- Controller
  - Use liveness controller if safe
  - Use safety controller if not safe

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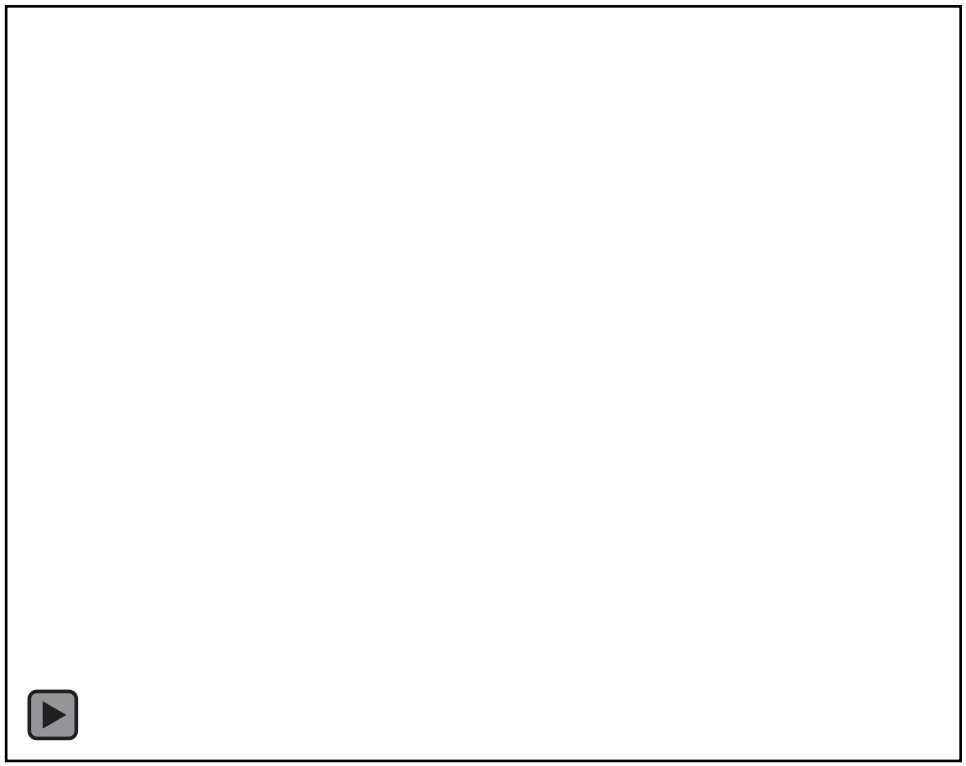
Dynamics

- Single quadrotor dynamics

$$\dot{p}_x = v_x$$
$$\dot{v}_x = u_x$$
$$\dot{p}_y = v_y$$
$$\dot{v}_y = u_y$$
$$u_{\min} \leq |u_x|, |u_y| \leq u_{\max}$$

Liveness and Safety



Safety reachable set:

- dashed boundaries

Liveness reachable set:

- dotted boundaries

Sequence of events:

1. First vehicle merges onto highway
2. Second vehicle joins the platoon created by the first vehicle
3. The rest of the vehicles join the platoon

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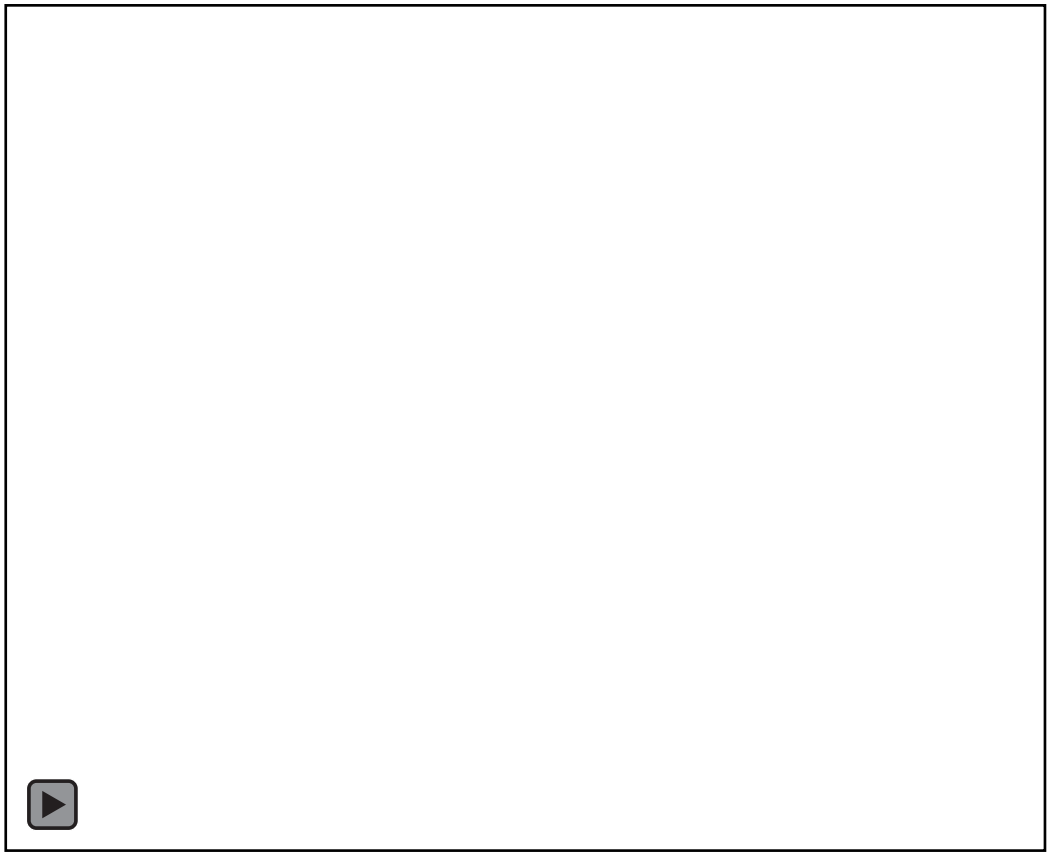
Intruder!



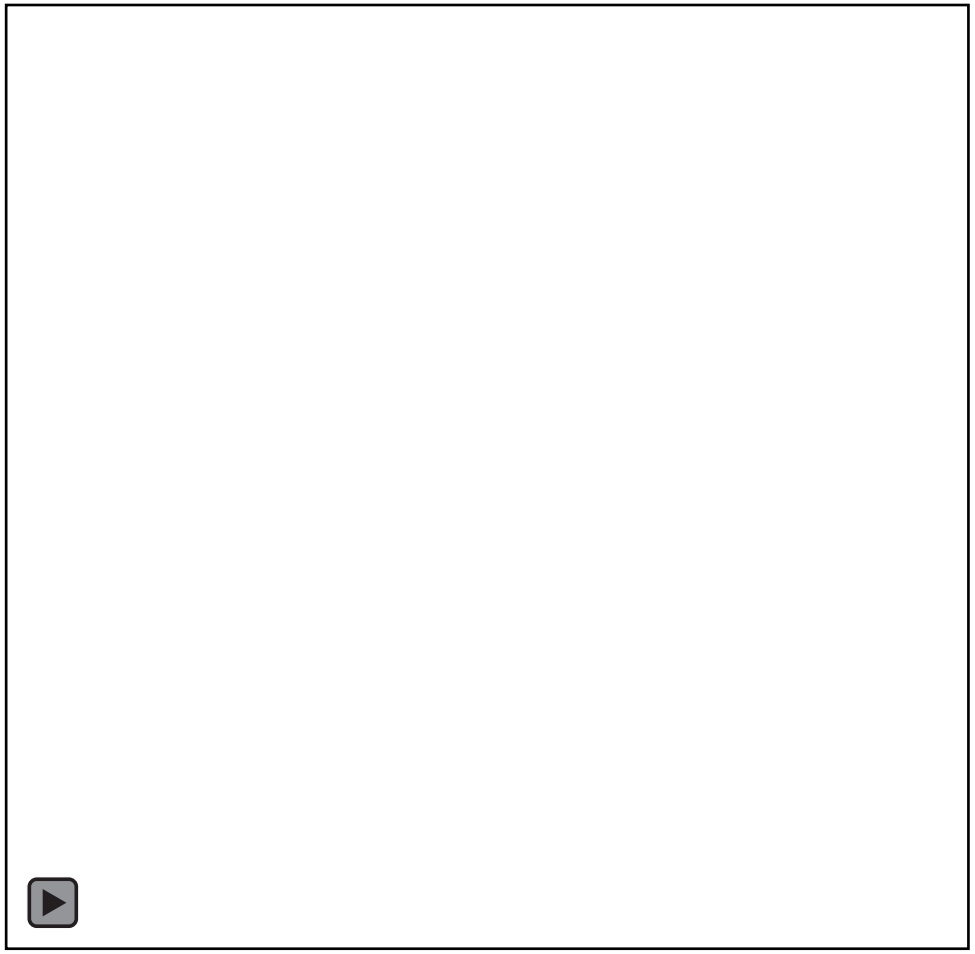
Vehicles automatically perform maneuvers to avoid collision

- Safety is guaranteed by reachable set

Vehicles automatically re-establish formation

- Liveness reachable sets guarantee success

Two highways simulation



Two highways

- One with a 3-vehicle platoon
- The other with a 4-vehicle platoon.

2 vehicles in the 4-vehicle platoon changes highways

The remaining 2 vehicles remain on the same highway.

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Summary

- Air highway placement
- Vehicles modeled as hybrid systems
- Reachability analysis for guaranteeing safety and mode transitions

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Thank you!

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