Safe Platooning of Unmanned Aerial Vehicles via Reachability

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Goals

- Tractable analysis of N quadrotors by restricting them into a single-file platoon

- HJ reachability
  - Liveness controllers
  - Safety controllers

- Simulations

HJ Reachability

- Define target set
  - Models either desired or undesired states, depending on application
  - Corresponding implicit surface function:

- Compute reachable set
  - Set of states that can reach within time horizon
  - Assumes worst case disturbance if there is disturbance
  - Corresponding implicit surface function:

   - Obtained by solving HJ PDE

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

- Controller
  - Take straight line towards target until vehicle is inside reachable set
 - Use optimal control from reachable set once vehicle is inside reachable set

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
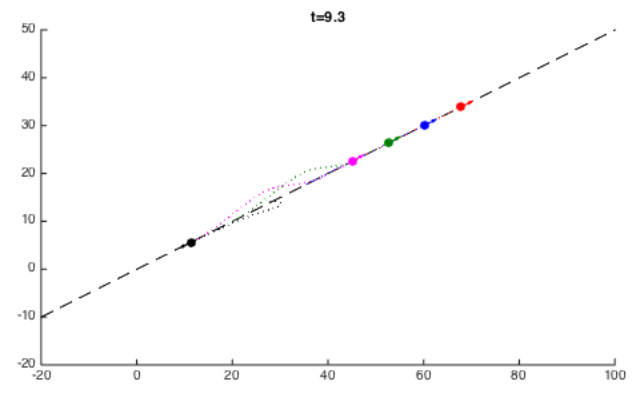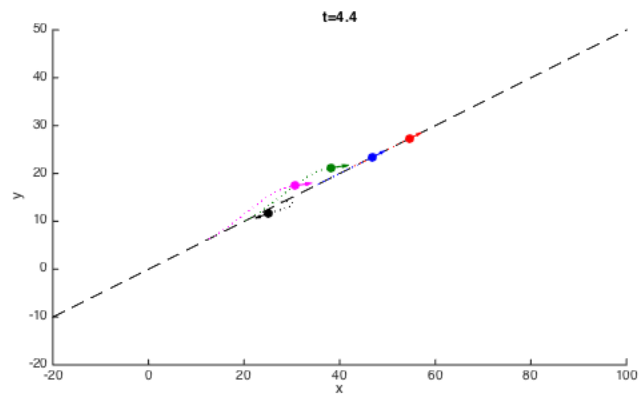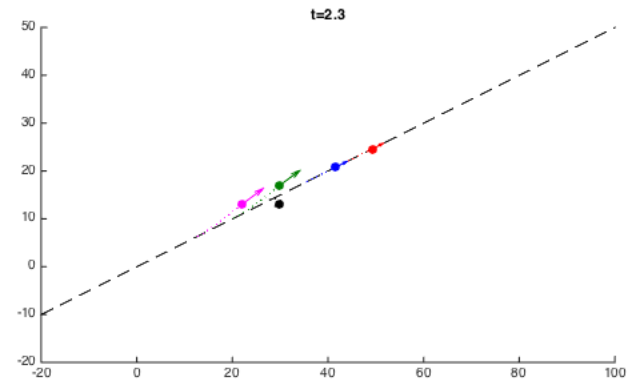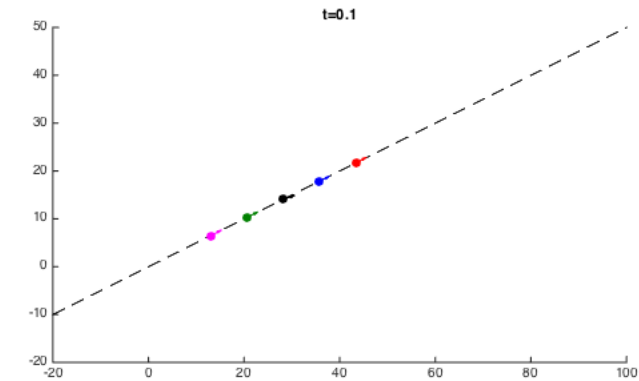 - Use safety controller if not safe
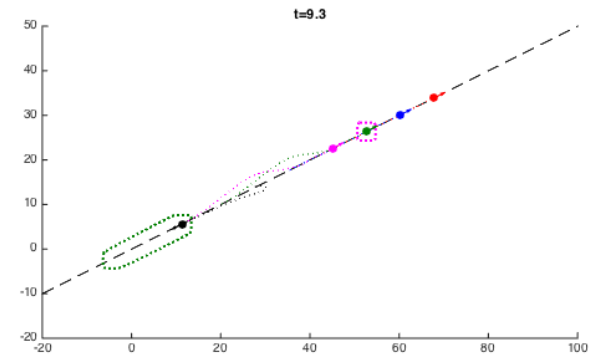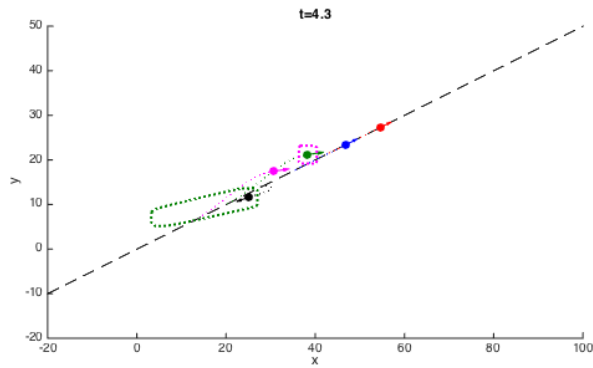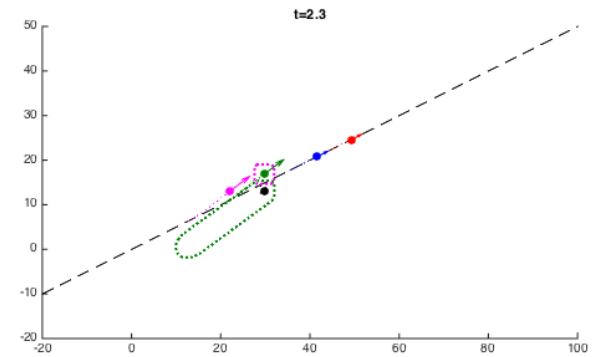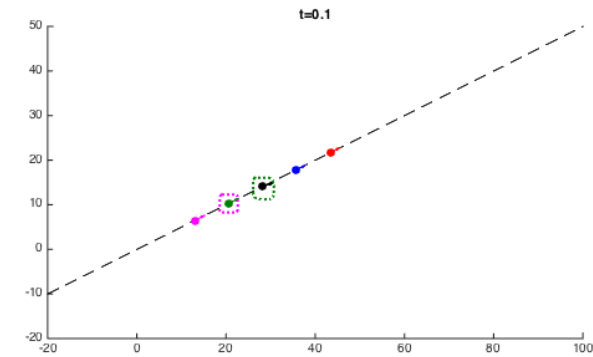
Merging onto highway
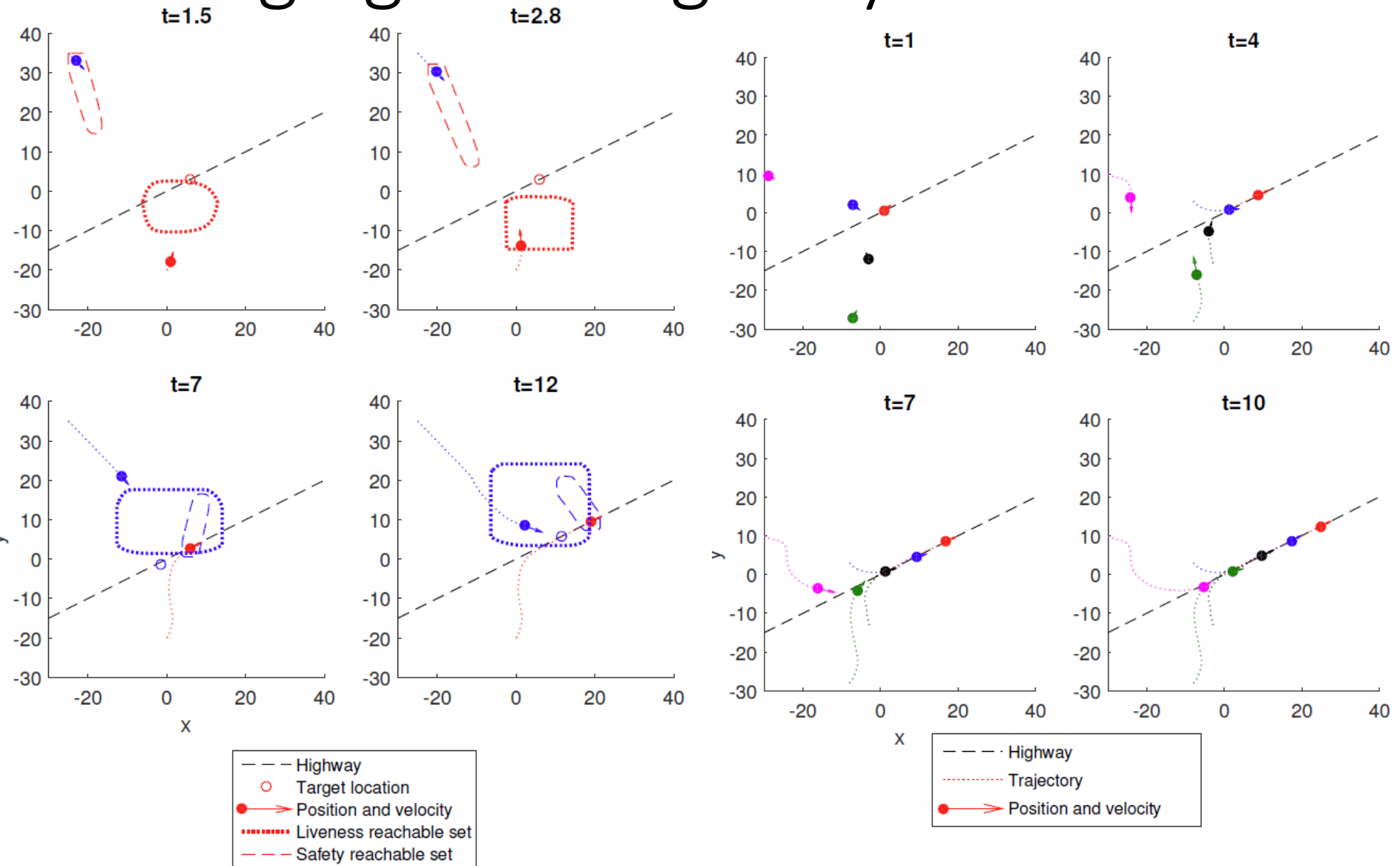
Responding to intruder
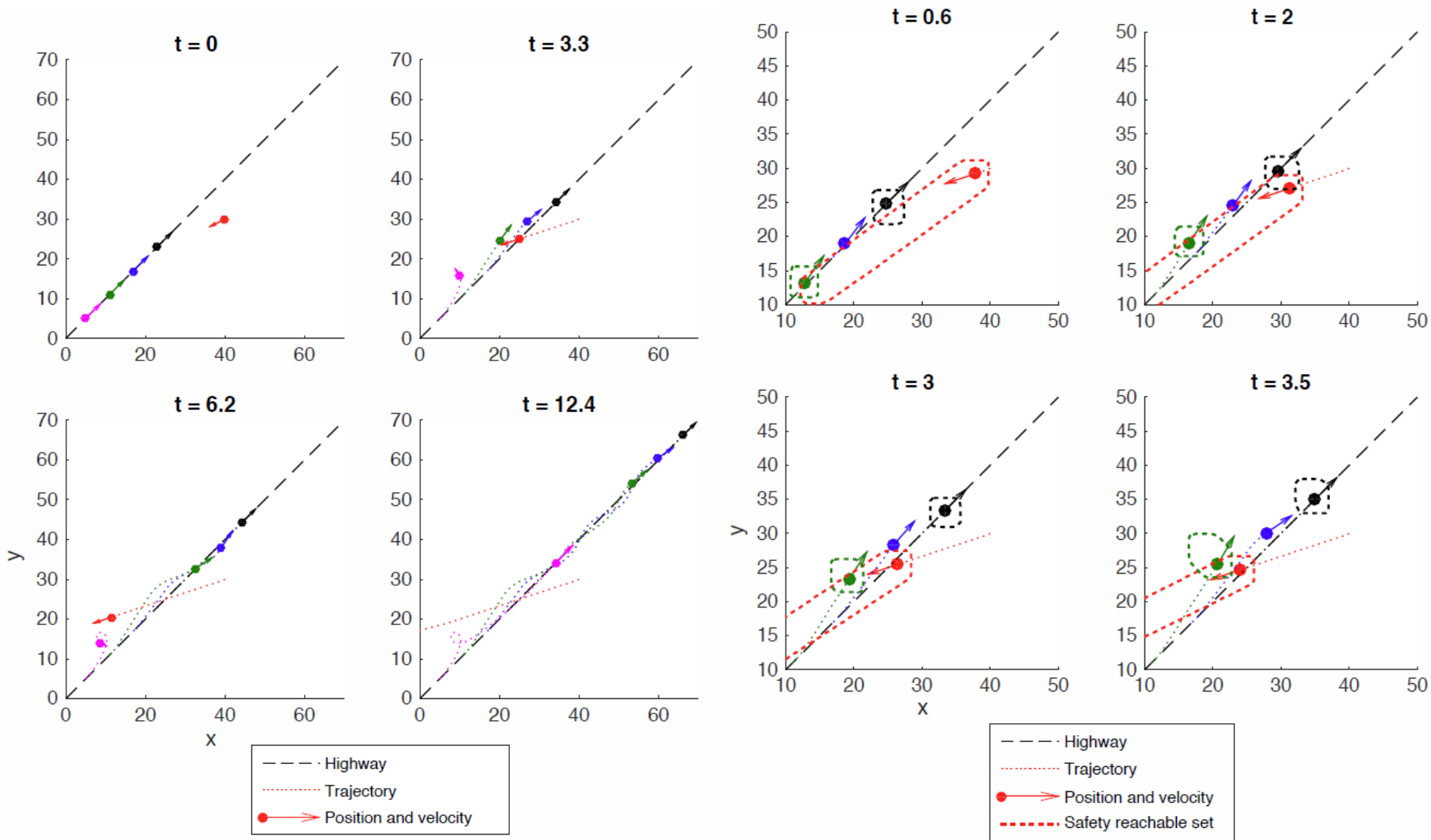
Faulty quad-rotor in platoon

Faulty quad-rotor in platoon w/ RS

Dynamics

- Single quadrotor dynamics

$$\dot{p}_x = v_x, \qquad \dot{p}_y = v_y$$

$$\dot{v}_x = u_x, \qquad \dot{v}_y = u_y$$

$$\underline{u} \leq |u_x|, |u_y| \leq \bar{u}$$

- Relative coordinates

$$p_{x,r} = p_{x,i} - p_{x,j}, \qquad p_{y,r} = p_{y,i} - p_{y,j}$$

$$v_{x,r} = v_{x,i} - v_{x,j}, \qquad v_{y,r} = v_{y,i} - v_{y,j}$$

Dynamics

- Relative dynamics (for collision avoidance)

$$\dot{p}_{x,r} = v_{x,r}, \qquad \dot{p}_{y,r} = v_{y,r}$$

$$\dot{v}_{x,r} = u_{x,i} - u_{x,j}, \quad \dot{v}_{y,r} = u_{y,i} - u_{y,j}$$

- Augmented relative dynamics (for collision avoidance and velocity limit)

$$\dot{p}_{x,r} = v_{x,r}, \qquad \dot{p}_{y,r} = v_{y,r}$$

$$\dot{v}_{x,r} = u_{x,i} - u_{x,j}, \quad \dot{v}_{y,r} = u_{y,i} - u_{y,j}$$

$$\dot{v}_{x,i} = u_{x,i}, \qquad \dot{v}_{y,i} = u_{y,i}$$

HJ Reachability

- HJ PDE for $t \in [-T, 0]$:
$$D_t V(t, x) + \max_u \min_d D_x V(t, x) \cdot f(x, u, d) = 0$$
$$V(0, x) = l(x)$$

- Elimination of complexity issues
  - Decoupled HJ formulation