Integrating Smart Cars in a Smart World: A Particle Swarm Problem

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RiSA²S — Risk and Safety Assessment of Autonomous Systems Lab

Highlights

GOAL: Explore rules for controlling lateral and longitudinal movement of families of Autonomous Vehicles and generalize the functionality of automatic cruise control to include multiple masters

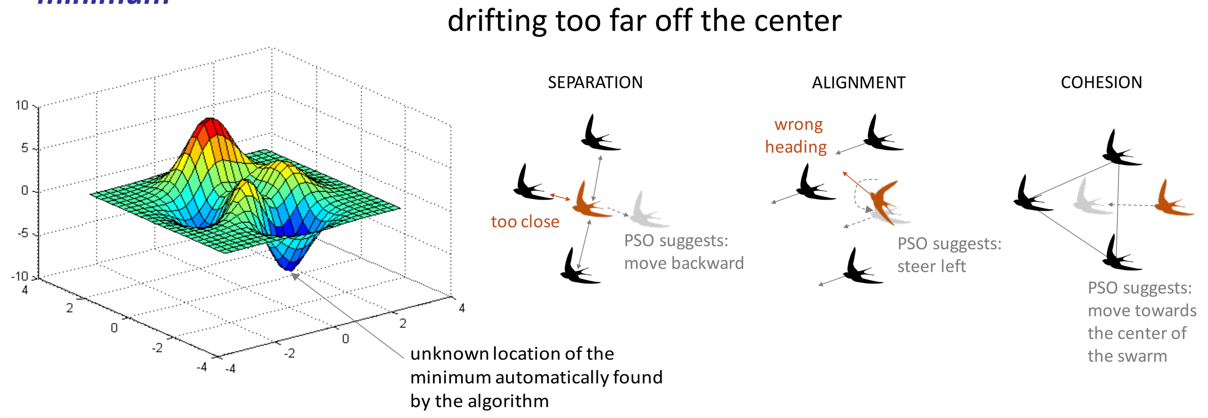
- **Leverage** an analogy with the physical behavior of flocks and shoals
- **Adapt** the physical rules of particle swarms to families of AVs
- **Monitor** safety thresholds to ensure separation using hazard indices
- **Employ** information from hazard indices as safety trigger to execute changes in steering and throttle/braking inputs

Particle Swarm Optimization

Meta-heuristic method based on an analogy with swarm movement. Generates particles to sample a non-linear function and find location of the minimum

The algorithm is based on three rules:

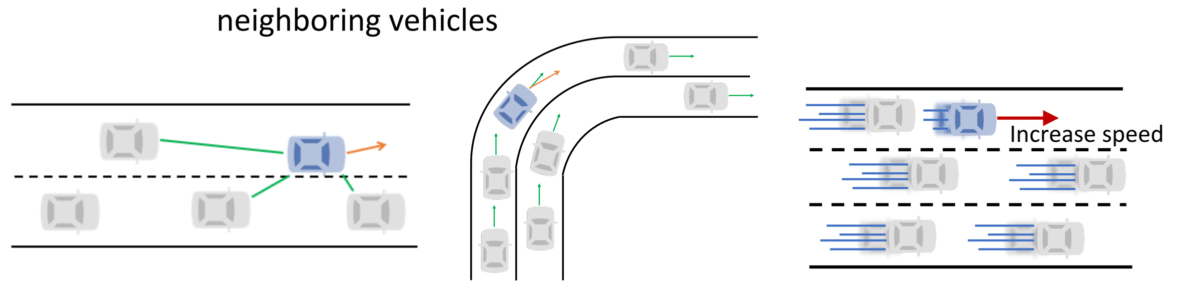
1. Maintaining **separation**: each particle moves to avoid collisions with other particles in the swarm;
2. Maintaining **alignment**: each particle steers in the average direction which the swarm (or a neighboring sub-set of it) is pointing towards;
3. Maintaining **cohesion**: each particle moves towards the average location of the entire swarm without drifting too far off the center



Adaptation to Families of AVs

Adaptation of PSO rules to families of AVs:

1. **Collision avoidance** – Maintaining separation to avoid collision with the nearby vehicles
2. **Heading selection** - Maintaining the weighted average heading to neighboring vehicles
3. **Velocity matching** – Match the average velocity of the neighboring vehicles

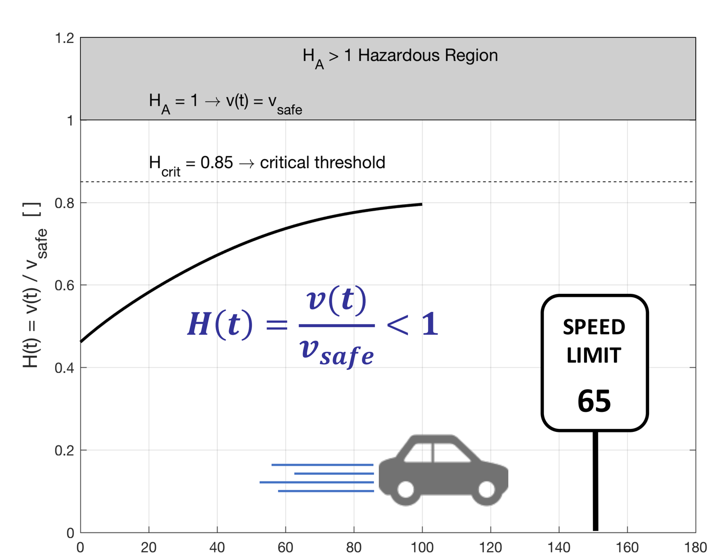


Schematic representation of the three rules concepts

The implementation of the three rules leverages the notion of **Hazard Level** or Index

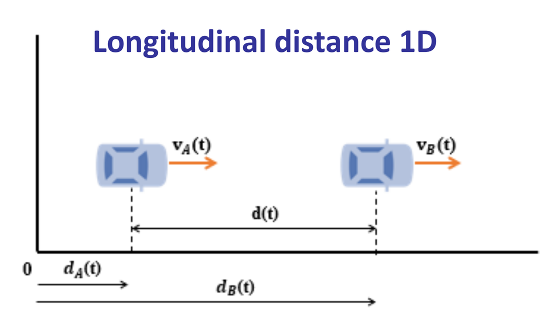
Intuition: non-dimensional quantity that measures the closeness to an accident/pre-identified adverse outcome

H(t) at every instant of time provides an index to quantify "how dangerous" the current system state is.

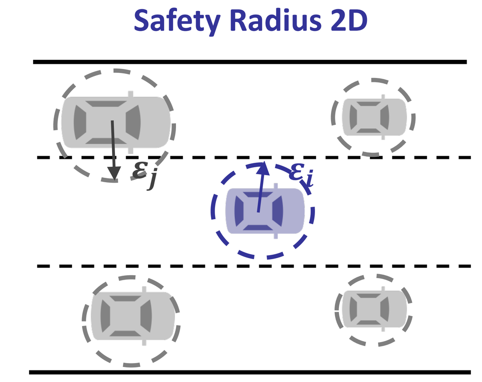


Hazard Level and Safety Thresholds for Particle Swarm

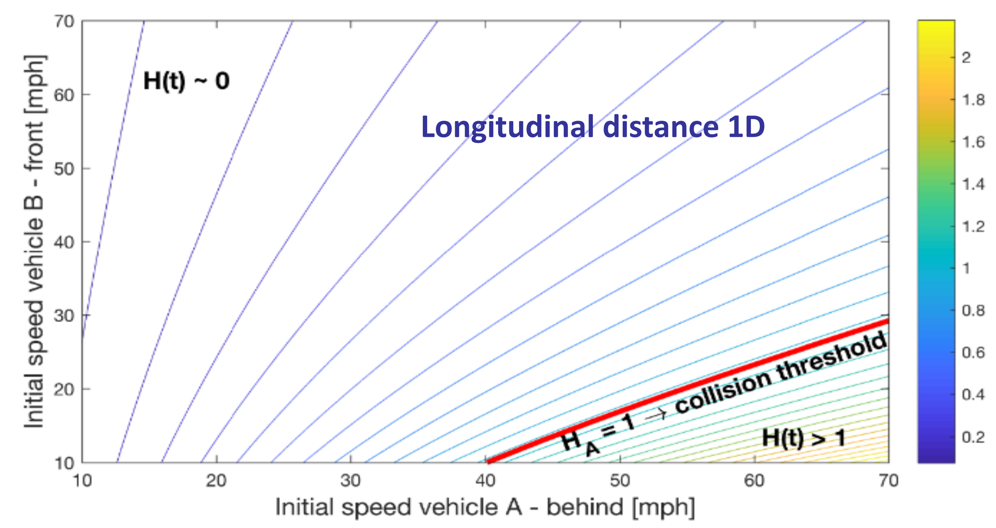
Rule #1 : Collision Avoidance → Need to ensure separation and that if a vehicle starts an emergency braking it won't collide with who is in the front (rear-ends remain the most common type of accidents among AVs)

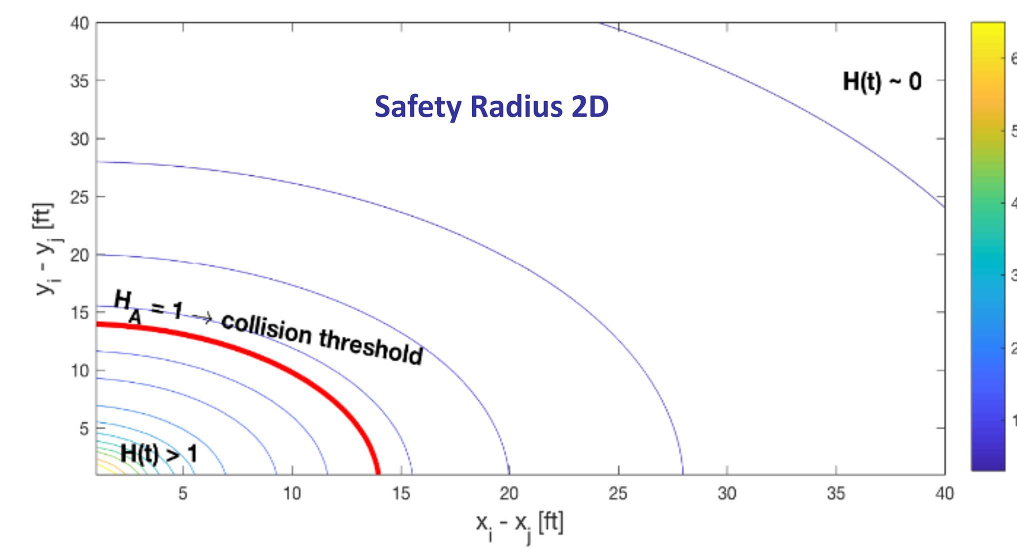


$$H(t) = \frac{d_{stop_A}(t)}{d_B(t) - d_A(t)} = \frac{d_{stop_A}(t)}{d(t)} = \frac{v_{0_A}^2 / 2\mu g}{d_0 + \frac{v_{0_B}^2 + v_{0_A}^2 - v_B^2(t) - v_A^2(t)}{2\mu g}}$$

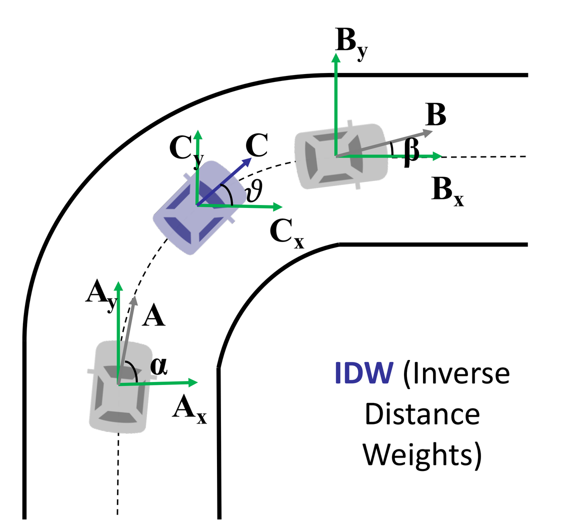


$$H_{i,j}(t) = \frac{\varepsilon_i + \varepsilon_j}{\|\bar{d}_i - \bar{d}_j\|} \quad with \ \bar{d} = \begin{bmatrix} x \\ y \end{bmatrix} \rightarrow \quad H_{i,j}(t) = \frac{\varepsilon_i + \varepsilon_j}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}$$



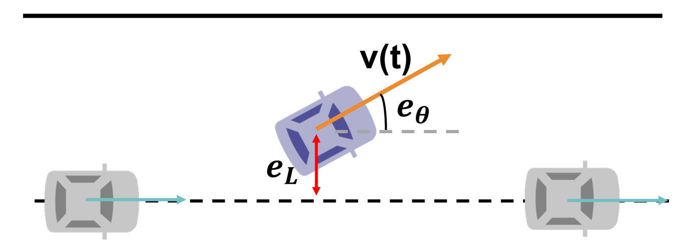


Rule #2 : Weighted Heading Selection → The heading of the controlled vehicle is computed using a weighted average of the surrounding vehicles, using inverse distance weights (heading of vehicles that are closer are weighted more than those far away)



IDW (Inverse Distance Weights)

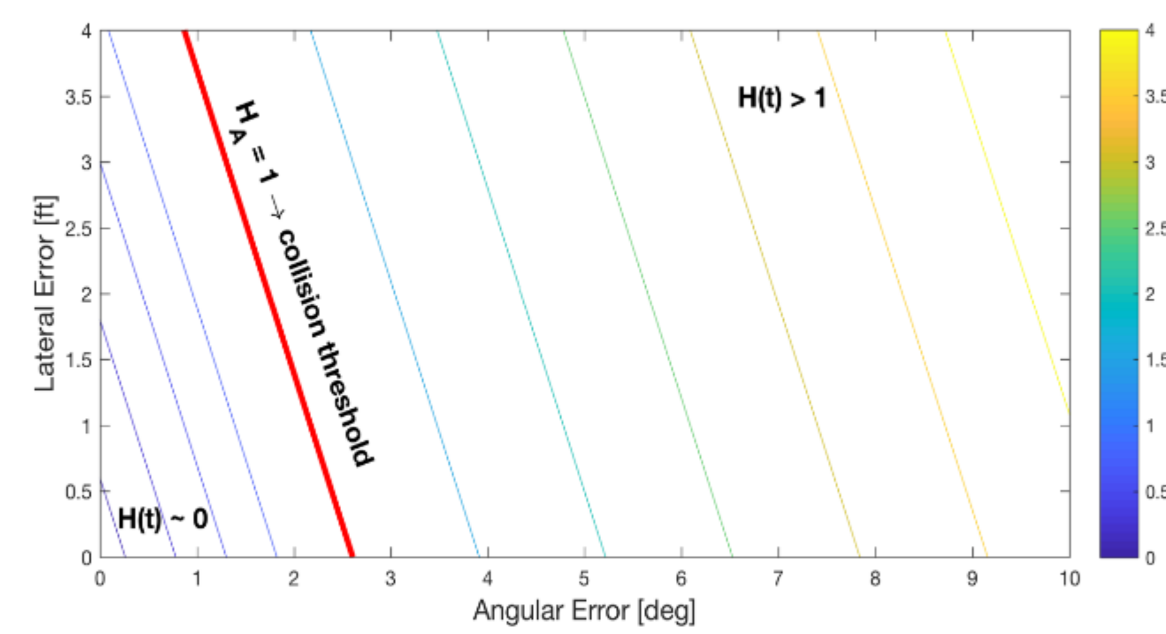
$$\vartheta = tan^{-1}\left(\frac{\sin\alpha(d_2) + \sin\beta(d_1)}{\cos\alpha(d_2) + \cos\beta(d_1)}\right)$$



Hazard monitoring based on Angular and Lateral Error

We want to ensure: $e_L + v(t)t\sin e_\theta < \frac{w}{2}$

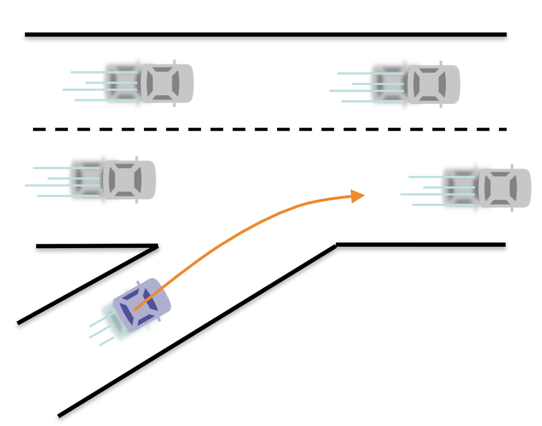
$$H(t) = \frac{e_L + v(t)t\sin e_\theta}{w/2}$$



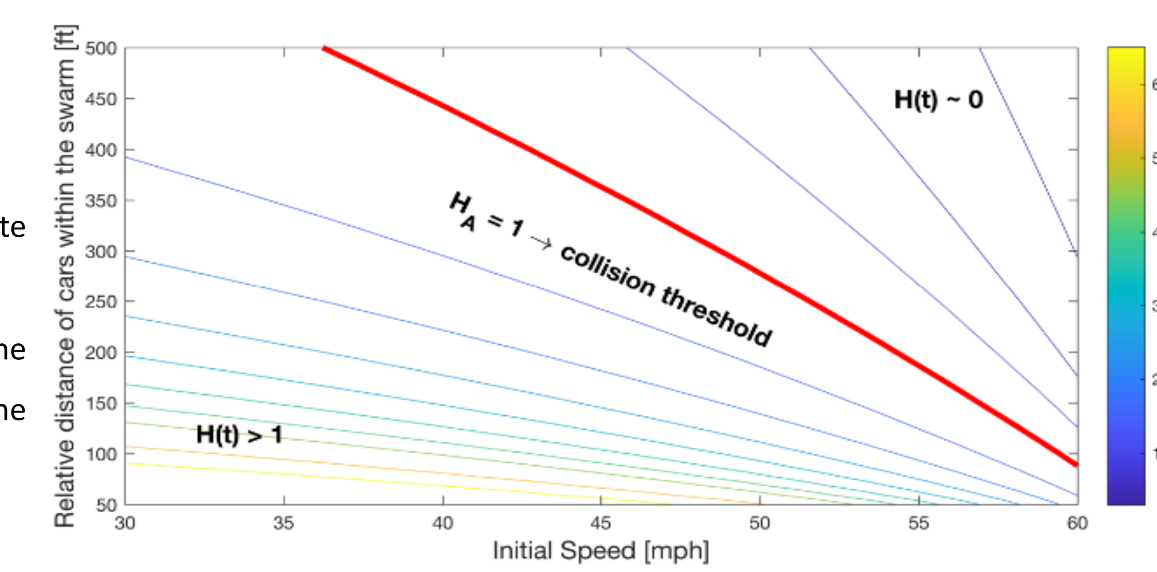
Rule #3 : Velocity Matching → This rule is employed to define the geometry of the swarm in terms of relative distance between the vehicles, target average velocity, and safety margins employed

The problem is adjusting the speed at which the swarm is travelling to accommodate the new vehicle, and selecting the best distance between the vehicles

$$H(t) = \frac{SM_{time} + t_{acceleration}}{t_{passby}}$$

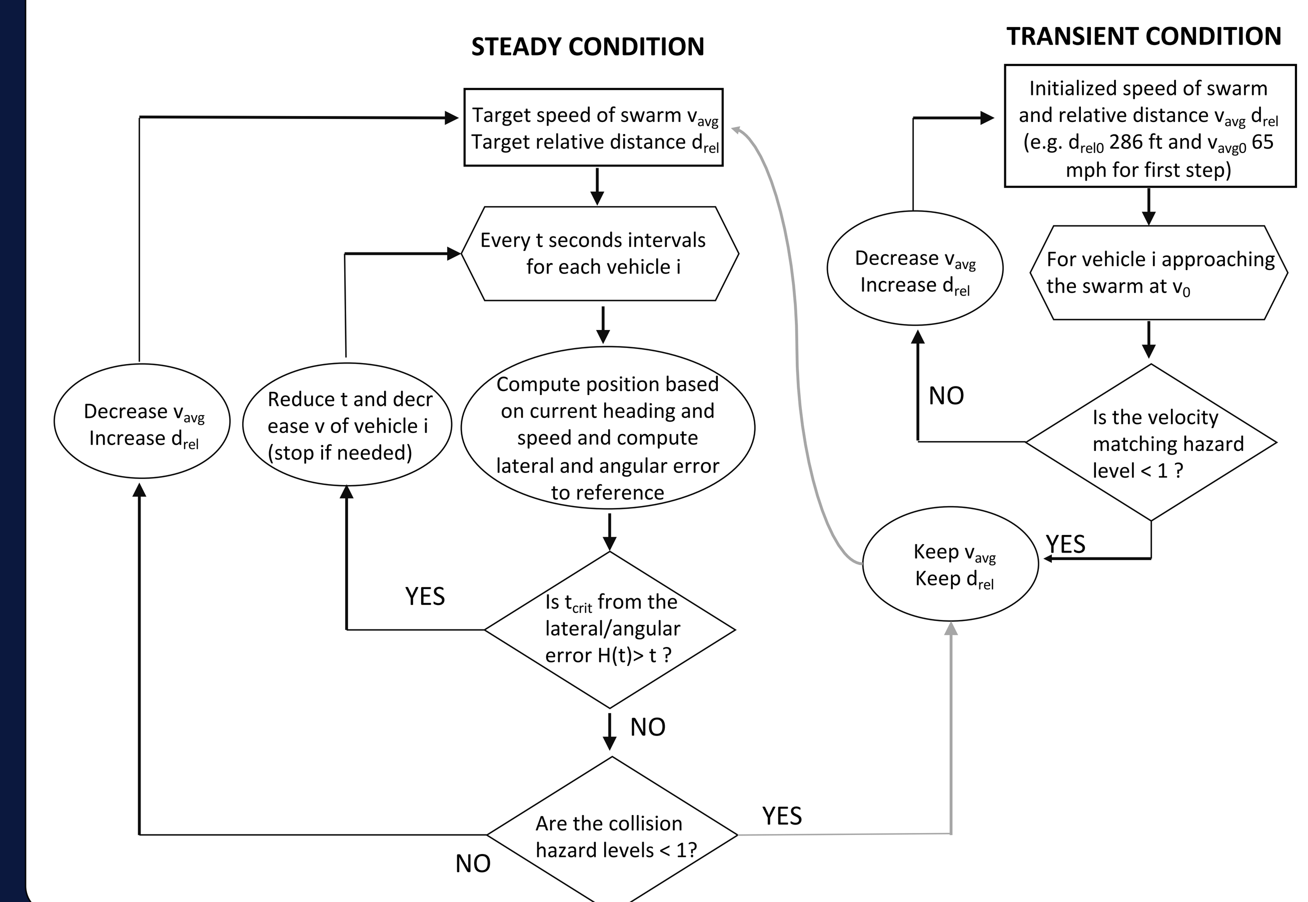


- $t_{acceleration}$: time for controlled vehicle to accelerate from initial speed to average speed of the swarm
- t_{passby}: average interval elapsed between the instants at which two consecutive vehicles in the swarm pass by the same point
- SM_{time}: a safety margin expressed in seconds



Implementation Chart

Implementation considers breakdown into two phases of creation of the swarm: an initialization/transient stage and a steady constant state with fixed number of vehicles



Summary of Contribution

Creation of ad-hoc rules for lateral and longitudinal control of families of AVs and device of four hazard indices for monitoring safety thresholds related to separation and collision avoidance, heading selection, and velocity matching

Function	Notes	Uses
$H(t) = \frac{d_{stop_A}(t)}{d_B(t) - d_A(t)}$	1D stopping distance along the longitudinal axis to ensure sufficient separation	Reset of swarm target velocity (module/value only) and relative distance 1D steady condition
$H_{ij}(t) = \frac{\varepsilon_i + \varepsilon_j}{\|\bar{d}_i - \bar{d}_j\|}$	2D collision avoidance through spheres of influence to ensure separation and cohesion	Reset of swarm target velocity and relative distance 2D steady condition
$H(t) = \frac{e_L + v(t)t\sin e_\theta}{\frac{w}{2}}$	Angular and Lateral error function to avoid lane departure/collision with dividers	Computation of maximum time of refresh for re-computation of steering and acceleration/braking inputs
$H(t) = \frac{SM_{time} + t_{acceleration}}{t_{passby}}$	Comparison of time for incoming vehicle to match velocity of the swarm while avoiding collision with safety margin	Transitory situation of vehicle entering the swarm – reset of target velocity and relative distance in transient condition

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