Intelligent Intersections with Guaranteed Safety  
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Introduction

- Automation of driving tasks is increasingly prominent. E.g. Cruise control, Parking guidance, Lane keeping assistance
- GPS, onboard sensor information along with inter-vehicle communication enable various applications.
- Automated vehicle systems can leverage this information to enhance safety, comfort and efficiency
- Intelligent intersections: where vehicles coordinate their movement through a combination of centralized and distributed real-time decision-making.

Guaranteed safety, higher efficiency - Can replace conventional traffic control devices like traffic lights.

Challenges involved

- Mathematical characterization of perpetual collision avoidance
- Backbone architecture with guaranteed safety, independent of the particular behavior executed
- Apt distribution of functionality between centralized and distributed components
- Information requirements from other cars
- Proof of safety and liveness of a hybrid system
- Guaranteeing safety under random delays, lost packets, noisy information.

Characterization of Perpetual Collision Avoidance

Consider two agents A and B, with states $x_A, x_B$. Let $P_{A}, P_B$ be reachability set mappings for A and B. A is free to move; B makes worst case assumptions on A.

Want to find relations $P_A$ such that

$P_B(x_B) \cap P_A(x_A) \neq \emptyset \ \forall x_A \in X_A$ and $x_B \in P_B(x_B)$

If $C_A$ is the collision relation, we want $P_A(x_A) \subseteq C_A(x_A)$

**Theorem 1:** Such relations $P_A$ can be computed using

$P_{A}(x_A) = \{ x_B \in X_B : x_A \in x_B \}$

$P_{A^+}(x_A) = \{ x_B : P_B(x_B) \cap P_A(x_A) \neq \emptyset \}$

$P_{A^{-}}(x_A) = \{ x_B : P_B(x_B) \cap P_A(x_A) = \emptyset \}$

The resulting $P_A$ is largest perpetually maintainable relation which ensures safety.

Two cars on a lane

Consider two cars A and B with bounded acceleration and non-negative velocity; front car A is free to move.

Suppose $x_A = (x_{A1}, x_{A2})$ and $x_B = (x_{B1}, x_{B2})$; $\dot{x}_A \leq \dot{x}_A \leq \dot{x}_A \leq \dot{x}_A$

**Theorem 2:** Perpetual collision avoidance if and only if

$\int_{x_A}^{x_B} (x_{A2} + \dot{x}_{A2}) dx_{A2} < \int_{x_A}^{x_B} (x_{B2} + \dot{x}_{B2}) dx_{B2}$ \ \ \ $\forall t \geq 0.$

If front car brakes at maximum, rear car should be able to avoid collision by braking at maximum.

We can design piecewise constant acceleration sequences, by numerically computing an input every T seconds using new data.

Cars at a four-road intersection

The above problem extends easily to the multiple car case

Consider four such roads meeting at an intersection

Hybrid architecture for collision avoidance at intersections

Centralized Scheduler at the intersection which interfaces with the distributed intelligence on the cars.

Need to provide a complete specification of car behavior and the scheduling policy, and deduce safety guarantees.

Performance Optimization

Simulated the entire system in MATLAB.

We still have freedom to design the scheduling policy

Want: Intelligent slot assignments to enhance throughput

We propose two methods based on a gradient approach using forward simulation.

- Post-hoc method: Start with an arbitrary slot assignment, and observe final delays. Swap or squeeze slots of adjacent cars; test the new slot assignment. Move to assignments with lower delays until a local minimum is reached.

Drawback: Requires information about future arrivals. Does not consider communication constraints.

- Online method: Communication-aware scheme where each incoming car provides information about its one-hop neighbors.

The scheduler then employs the gradient method for this smaller set of cars, to obtain slot assignments with low delay.

Performance results

The above simulation framework can model stop signs / traffic lights

- Significant improvement in average travel time at low to medium load
- Approaches traffic light behavior at high load
- Results for the online method closely track the results for the post-hoc method.

Concluding Remarks

Main contributions

- We have proposed a candidate hybrid architecture for intelligent intersections with guaranteed safety.
- Clearly specified interfaces and dependencies.
- Precise proof of safety and liveness
- Significant decrease in average travel time at most loads.
- The architecture for safety can accommodate lost packets, communication delays and noisy information. However, a detailed study of the impact on performance using a communication channel model needs to be done.

Future Directions

- Study the general design of safe systems by update of a predictive control sequence using state observations.
- Use the insight gained from this problem to develop a more general theory of safety of complex hybrid systems.