Control Design of an Automated Highway System

(Roberto Horowitz and Pravin Varaiya)
Presentation: Erik Wernholt

Contents

- Introduction
  - What is an AHS?
  - Why use an AHS?
- System architecture
  - Layers
  - Models
- On-board vehicle control system
  - Hybrid system
  - Methodology that guarantees safety and efficiency
  - Example: Join maneuver
- Roadside control system
- Questions

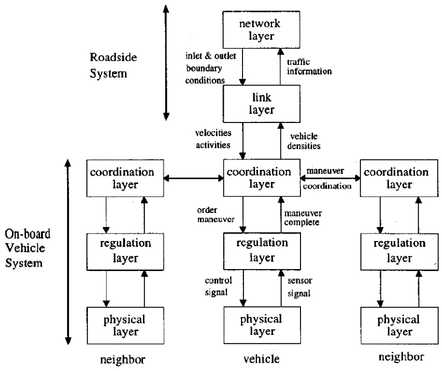
Introduction - what is an AHS?

- “A fully automated control system that leaves few vehicle driving decisions to the driver”
- Scenario:
  - You queue the car at an AHS entrance gate
  - Hardware check and its destination recorded
  - You relinquish control to the AHS
  - The car executes a series of maneuvers, controlled by the AHS
  - As your car approaches its destination, it executes an exit maneuver
  - At the AHS exit gate, your ability to handle your car is checked and control is returned to you.

Introduction - why use an AHS?

- Increase highway capacity while improving safety
  - Capacity of 8000 vehicles per hour and lane (compared with 2000 today)
  - Small relative impact velocity in case of a collision
  - Reduced aerodynamic drag (lower fuel consumption and emissions)
- The vehicles must be fully automated, since people cannot react quickly enough to drive safely with such small distances.

System architecture - layers



System architecture - layers, cont.

- Physical layer
  - All the on-board vehicle controllers of the physical components of a vehicle (e.g. engine, brake, and steering control systems)
  - Main function: to decouple the longitudinal and lateral vehicle guidance control and to approximately linearize the dynamics.
  - The decoupling simplifies the design of the regulation layer.
- Regulation layer:
  - Responsible for lateral and longitudinal guidance of the vehicle, and the execution of the maneuvers ordered by the coordination layer.
  - Is engaged in **one** activity at any time and switches to another activity in response to commands from the coordination layer.

System architecture - layers, cont.

- Coordination layer:
  - Responsible for selecting the activity that the vehicle shall execute, in order to realize its current activity plan
  - Supervises and commands the regulation layer by selecting one activity from a finite set
  - Communicates and coordinates its action with neighboring vehicles
  - Communicates with the link layer roadside control system (e.g. receives an updated activity plan)
  - Stores and updates all relevant information regarding the vehicle's state (identity, current location, activity and assigned activity plan)

System architecture - layers, cont.

- Link layer:
  - Link = a controller for each 0.5-5 km long segment of the highway
  - Control the traffic flow within the link in order to achieve full capacity and minimum vehicle travel time and undesirable transient phenomena
  - Divided into sections, one per lane
  - Receives and discharges traffic flow from neighboring links
  - Broadcasts specific activity plans for each vehicle type and section to the vehicle coordination layer controllers
  - Receives commands from the network layer regarding traffic flow
- Network layer:
  - Control traffic flow within the network of highway links.

System architecture - models

- Physical layer: Detailed differential equations
- Regulation layer: Low order linear systems
- Coordination layer: Finite-state machines (coordination protocol)
- Link layer: Fluid flow models
  - Aggregated space and time vehicle density profiles are used as states.
  - Commands are functions of time and space
  - Dynamics are then described using conservation flow models.
- Network layer: Capacitated graph

2001-05-11 9

On-board vehicle control system - Hybrid system

- The physical and regulation layers are described by a discrete state variable – the current activity – and the continuous state variable of the activity’s differential equation.
- The coordination layer determines the transition from one activity to another. This means that the three lowest layers form a hybrid system.
- Both discrete and continuous state variables are coupled since the coordination layers are communicating and the regulation layers are using measurements of neighboring vehicles’ behavior.

2001-05-11 10

On-board vehicle control system - Methodology for safety and efficiency

- Primary objectives: safely and efficiently control the vehicle while executing the activity plan
- Overall AHS optimality is not monitored or guaranteed at this level
- Necessary to develop a design and verification methodology that guarantees safety and efficiency of the overall on-board vehicle hybrid control system
- This is done in three steps:
  - Active Plan Definition
  - Coordination Layer Design
  - Regulation Layer Design

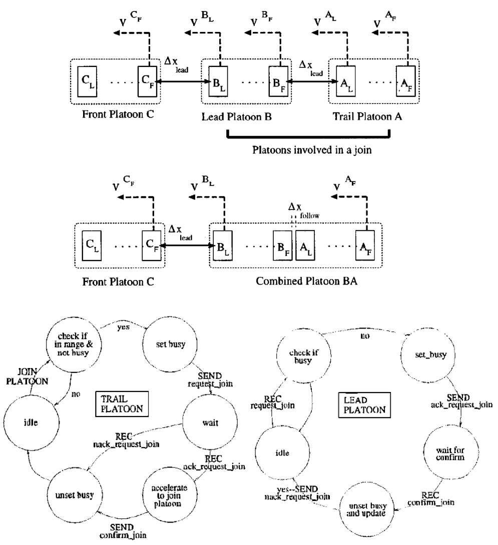
On-board vehicle control system - Methodology for safety and efficiency, cont.

- Active Plan Definition
  - Limited set of atomic maneuvers, which simplifies the control design
  - Only leaders can initiate maneuvers
  - Leaders can only execute one maneuver at a given time
  - Maneuvers are coordinated with the relevant leaders of neighboring platoons
  - Only after agreement is reached between these leaders is a maneuver initiated
- Coordination Layer Design
  - Realized as a hierarchy of coupled finite-state machines
  - The coordination of each maneuver is implemented by a protocol between relevant peer leaders involved in the maneuver
  - The protocol specification and overall coordination layer design is formally specified verified using software verification tools (COSPAN)
  - The overall state machine has more than 500 000 states

On-board vehicle control system - Methodology for safety and efficiency, cont.

- Regulation Layer Design
  - Is designed so that the execution of every maneuver initiated by the coordination layer follows the maneuver's state machine protocol =>
  - The hybrid system produces the same sequence of events as that dictated by the coordination layer design, in which the entire continuous time behavior of the vehicle is represented as a single state =>
  - The regulation layer must perform in a manner that is consistent with the coordination layer model.
  - A set of performance parameters is gathered for different maneuvers that will guaranty safety.

On-board vehicle control system - Example: Join maneuver



On-board vehicle control system - Example: Join maneuver, cont.

- Two consecutive platoons, traveling on the same lane, join to form a single platoon.
- The leader of the trail platoon, vehicle A_L has to engage in a join protocol with the leader of the lead platoon, vehicle B_F.
- A sufficient condition for preventing vehicle collision **in a platoon**, is to make the platoon maximum deceleration ratio sufficiently large (defined as the ratio between the maximum allowable decelerations of the last follower and the leader of the platoon)
- A safety set can be defined such that the join maneuver can be completed safely if initiated when the velocities of and distance between A_L and B_F belongs to the set. The set depends on given performance parameters.
- Overall AHS Safety Results: By combining the results in Proposition 1 with the follower law safety results given by (3) and (4), it is possible to derive conditions for overall highway safety.
- By using the results in Proposition 2, it is possible to calculate performance parameters that will yield a provably safe on-board vehicle control system.

Roadside control system

- Primary objective is to optimize the capacity and traffic flow of the overall AHS.
- Control the network and link layers in ways that tend to increase vehicle safety, such as
- Maintaining sufficiently low aggregated vehicle densities and
- Decreasing the inlet traffic flow into links where aggregated traffic density is very large

Questions

Peter Aronsson:

1) The verification, as I understand it, is done individually for each layer. How is the whole system verified?

2) By layering the system, and using different models for different layers, the complete hybrid system is divided into layers, where some layers induvidually are not hybrid. It seems that the major reasons for layering are to handle the complexity of the system, and to apply analysis methods to each layer depending on its model. For instance, analysing the coordinating system with finite state machine analysis techniques. Is layering, with the purpose of extracting the discrete parts of a hybrid system into one layer, a common technique of dealing with hybrid systems?

Patrik Haslum:

1) In what sense is the link stabilizing controller "distributed"?

2) To what extent is the verification described automated? (It seems to be mostly manual, with the exception of some correctness condition on the coordination FSM's, which are discrete only).

3) I ran across some other papers (Russel & co, IJCAI'97, '99) a while ago that were also related to the PATH project: These, aimed to develop a "controller" (in the AI sense) for a single car without relying on any "infrastructure" (i.e. smart roads or communication with surrounding cars). In the end of the present paper, it's mentioned that there are large problems introducing this type of system in reality, because of big costs and the fact that it's got to be done all at once. Given this, doesn't the "smart car on it's own" approach seem like a better idea?

Frida Gunnarsson:

1) The on-board vehicle control system is a hybrid control system. Can the used design method be used on other systems or is there even an underlying method?

2) The authors claim that it is necessary to develop a method to guarantee stability and safety but it seems that they only use very system specific rules, etc. Is it generalizable?

Svante Björklund:

1) Is is possible to control a car enough quickly to mantain a inter-car distance of 1 meter? Is the bandwidth of the car enough high?

2) Why was the NAHSC dissolved in 1998?

3) On page 916 it is told about residual filters generating unique patterns of residuals for each different fault. Is it possible to use the method of algebraic consistency tests in the course Adaptive filtering and change detection?

4) Car that do not have an on-board vehicle control system, how are they handled? Are they not allowed to travel on AHS Highways?

5) Why are so many as 500000 states needed in the coordination layer?

6) Shouldn't it be AMIN <= aPMIN in equation (1)? aPMIN is negative, isn't it?

Jakob Roll:

What strengths and weaknesses can you see with the proposed approach for automated highways (e.g., lumping cars together into "platoons")?

Daniel Karlsson:

1) It says in the article that the three lowest levels in the architecture can be viewed as a hybrid system. Can you elaborate a little on why this is the case?

2) How, approximately, would a hybrid automaton look like or be built from the descriptions given of the individual layers?

David Lindgren:
How would you characterize the AHS-automatas in terms of Hybrid Theory? For instance, are they linear in the (akward) respect we learned at the last seminar, i.e. constant derivatives only, or are they more general?

Dan Lawesson:
The task of the vehicle follower control law is to maintain a constant vehicle spacing between vehicles forming a platoon. Why is a platoon designed to keep constant spacing in distance and not in time (e.g. 80ms instead of 2m) which seems to be a more reasonable measure when maximizing flow under safety constraints? Do platoons always cruise at the same speed? In that case time and space are equivalent measures, I suppose.

Martin Enqvist:
In practice, the actual performance of a vehicle varies over time in an unpredictable way (e.g. due to varying road conditions). Is not this a problem for the safety of an AHS? Would not, for example, the performance of the join maneuver in section III be decreased considerable if worst case accelerations and decelerations have to be considered at all times.