Automated Vehicles Control
Architecture

Masayoshi Tomizuka
Cheryl and John Neerhout, Jr. Distinguished Professor
Department of Mechanical Engineering
University of California, Berkeley

GCEP Advanced Transportation Workshop
Stanford University
October 10, 2005
Congratulations! Stanford Racing Team

GRAND CHALLENGE WEBCASTS
Webcast Five: 12:15pm, October 9, Five Finishers and a Winner

Audio: 0:41 / 6:57

Click a thumbnail to see a picture:

Stanford’s Stanley, first to cross the finish line and winner of the Grand Challenge
This presentation is based on automated highway systems (AHSs) research conducted at the California PATH (Partners for Advanced Transit and Highways) Program by faculty members, graduate students and PATH staffs.

AHS is a mode of intelligent transportation systems (ITS)

Motivations are ease of traffic congestions, enhanced safety, energy saving, decreased pollution...

Research was initiated in 1986 and continued till the beginning of 2000’s funded by the California Department of Transportation.
Control architectures are useful not only to AHS but for other ITS systems.

- Bus rapid transit (BRT)
- Intelligent cruise control
- Other driving assistance devices
Hierarchical System Architecture

Layer 4
- Network
  - Link
  - Link
  - Link

Layer 3
- Coordination
  - Coordination
  - Coordination

Layer 2
- Regulation
  - Regulation
  - Regulation

Layer 1
- Physical
  - Physical
  - Physical

Layer 0

Intelligence on road side
Intelligence on vehicle side
Each layer plays important roles for smooth traffic flow with lowered fuel consumption

- **Network layer**: selection of optimal route for each vehicle
- **Link layer**: optimal speed, platoon size, etc in response to traffic condition
- **Coordination layer**: commands for formation of platoons (merge and split) and lane changes after communications among nearby vehicles.
- **Regulation layer**: execution of commands issued by the coordination layer.
Regulation Layer

Needs control laws to achieve following tasks:

- **Follower**: Follower must stay in a platoon, at fixed distance from vehicle in front
- **Leader**: Leader must track a reference velocity at safe distance from platoon in front
- **Join**: Leader must accelerate and join with platoon in front
- **Split**: Follower becomes leader and decelerates from platoon in front
- **Lane keep**: Each vehicle must stay in specified lane.
- **Change lane**: Free agent must steer to space in adjacent lane.
Reduced Fuel Consumption by Automated Driving

- Reduced drag coefficients for shorter headway (spacing).
- Avoid driving at excessively high speeds.
- Less frequent and profiled accelerations and decelerations for energy saving.
- Minimize stop and go.
Longitudinal Control - Platooning
Radar Sensors
Use feedback linearization and model each vehicle as:

\[ v_i = u_i \]

\[ \tau u_i + u_i = u_{i,\text{des}} \]

- Define the spacing error:
  \[ \varepsilon_i = \delta_{i,\text{des}} - \delta_i \]

- String stability:
  \[ |\varepsilon_{i+1}| \leq |\varepsilon_i|, \quad \varepsilon_{i+1}(s) = H(s)\varepsilon_i \]

  String stability conditions obtained by Swaroop and Hedrick, and others.
Parameters: $\tau=0.1$ sec and $K=q_1=q_2=q_3=1.0$

Add communication from the lead vehicle to followers:
- Reference velocity
- Reference position

Transfer Function Comparison (Hedrick, et al., UCB)
### Results without Leader Information

<table>
<thead>
<tr>
<th>Error Amplification</th>
<th>Time (sec)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- \( \gamma_{21} \)
- \( \gamma_{31} \)
- \( \gamma_{41} \)
- \( \gamma_{42} \)
- \( \gamma_{43} \)
- \( \gamma_{44} \)
Results with Leader Information

[Graph showing time (sec) vs. error with labeled curves for different damping values]
Another Study on Platooning (Kanellokopoulos, et al, UCLA)

- Heavy-duty vehicles.
- Instead of communication, string stability may be achieved by using speed-dependent spacing with time gap.
- However, this result in large steady state inter-vehicle spacing, which is a disadvantage, in particular, for heavy vehicles.
- UCLA team’s research was motivated to overcome this problem.

Parameters of a truck platoon

\[ S_0 : \text{minimum distance between vehicles} \]
\[ h : \text{time gap} \]
\[ x_r : \text{vehicle separation} \]
\[ \delta = x_r - (s_0 + hv_f) : \text{separation error} \]
\[ v_l : \text{velocity of leading vehicle} \]
\[ v_f : \text{velocity of following vehicle} \]
\[ v_r = v_l - v_f : \text{relative vehicle velocity} \]
Nonlinear Spacing Policies

Regulation variable: \[ v_r + k \delta; \quad v_r = v_l - v_f, \quad \delta = x_r - (s_0 + h v_f) \]

Variable time gap

Variable spacing error gain

- \[ h = \text{sat}(h_0 - c_h v_r) \]
- \[ k(\delta) = c_k + (1 - c_k) e^{-\sigma \delta^2} \]
Lateral Control: Automated Steering

Vehicle Control System (Lateral Control)

Architecture of Lane Following Control

- Accelerometer
- Yaw rate sensor
- Steering angle sensor
- Control computer
- Steering actuator
- Front wheels
- Tracking error
- Vehicle speed
- Upcoming road curvature
- Vehicle motion direction

Array of magnetometers (Front/rear ends of vehicle)

Processing algorithm

Magnetic markers
Lateral Control Problem: Issues

- Control of an inertia where the control force is generated through tire-road interaction
- Control objectives: tracking accuracy, passenger comfort
- Input-output lateral dynamics indicate that the control problem becomes difficult for higher longitudinal velocities and smaller look-ahead distances
- Control systems must be safe and reliable
Geometric Look-Ahead

\[ Y_{vs} = \frac{(l_r + d_s) y_{fs} + (l_f - d_s) y_{rs}}{l_f + l_r} \]

Vehicle

Road centerline
High Speed Driving Tests (forward/backward)
Failure Management

- Motivation: Improved safety/reliability of operation of automated systems, reduced “down” time.
  - Coordinated response is needed between cars in the event of failure.
  - Components on the cars are not fool-proof under all operating conditions
- The fundamental idea in failure management: **Realizing Redundancy**
Realizing Redundancy

- "Building-in" redundancy: **hardware** (physical) redundancy
  - Installation of multiple sensors and actuators
  - Judicious choice of locations of placement of sensors and actuators
- Exploiting redundancy: **software** (analytical) redundancy
  - Sensor fusion for improved data reliability
  - Fault detection and identification schemes
  - Fault tolerant controller design
  - Degraded mode control strategies
Exploiting Hardware Redundancy for Fault Diagnostics

Example:
1. Steering wheel angle and vehicle wheel angle are both measured.
2. Steering wheel angle, vehicle wheel angle and commanded steering angle are related by 3 independent parity equations.

\( R_{11} \) = commanded steering angle/measured steering angle

\( R_{12} \) = commanded steering angle/measured vehicle wheel angle

\( R_{13} \) = measured steering wheel angle/measured vehicle wheel angle

<table>
<thead>
<tr>
<th>Faulty Component</th>
<th>( R_{11} )</th>
<th>( R_{12} )</th>
<th>( R_{13} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steering actuator</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Steering angle sensor</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Wheel angle sensor</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Tire Blow-Out Effects and Hazard Reduction Control for AHS

Modeling

Tire Burst

Road Interaction  Vehicle Geometry  Operating Condition

Steering Command

Force Generation

Vehicle Dynamics

Output

Tire-burst Controller Structure
Tire burst: Experimental Arrangement
Experiments
Closed-loop Tire Burst Experiment
(Front tire burst; Speed = 20 mph; lateral error)
Concluding Remarks

- Automated driving results in reduced consumption of fuels.
- Fuel saving is achieved primarily from automation in the longitudinal direction.
- Automated driving is not complete without automation in the lateral direction.
- Fault detection and identification, fault tolerant control and emergency handling are important elements of automated driving.