Vehicle Active Safety Systems for Preventing Road Departure Accidents

“Keeping Cars on The Road”

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Outline

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• SVRD Active Safety System Overview & Design Tools
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  - Simulation and design tools
• Yaw Rate Estimation
  - One part of the measurement subsystem
• Role of the Driver
  - Driver state and uncertainty modeling
  - Robust steering assist controller
• Concluding Remarks & Acknowledgements
Introduction

Single Vehicle Road Departure Accidents

- On average one person dies every minute somewhere in the world due to a car crash
- Costs of crashes total 3% of world GDP ($31.3 trillion in 2000), and totaled nearly $1 trillion in 2000.

IEEE Spectrum, Jan. 2002

- Single Vehicle Road Departure (SVRD) Accidents account for about 1/4 of all accidents and about 1/3 of all fatalities on U.S. highways.
- Causes of SVRD accidents include driver inattention due to fatigue, drowsiness, driver impairment, distraction, etc.

NHTSA 1998 Data for USA

System Overview

Prototype Vehicle

System Overview

Prototype Vehicle Active Safety System

Helps prevent single-vehicle-road-departure (SVRD) accidents by predicting vehicle path and estimating roadway geometry from computer vision. Issues warning to driver, provides driving steering assist and/or uses differential braking for steering intervention.

- Computer vision system
- Vehicle motion sensors
- Computers for data collection, analysis and control
  - Kalman filters
  - control pressure to wheels for brake-steer
  - Apple Quadra 800, Dell Pentium, I/O rack, etc

Sensors on Prototype Vehicle

Vehicle sensors included:
- wheel speed & yaw rate sensors
- steer angle & steering wheel transducers
- pitch & roll corrections
- several Kalman filters
- control of pressure to individual rear wheels for brake-steer

A high-resolution digital CCD camera, and image processing software, were used to determine the lane geometry. This included the pitch and roll compensation of camera motion.
System Overview

Overall System Structure & Subsystems

**System Overview**

**Time to Lane Crossing (TLC)**

- Time to lane crossing (TLC) based upon lane geometry determination using computer vision, and vehicle path projection using on-board sensors.
- Kalman filtering
- References:
  - Lin & Ulsoy, ITS Journal, 1996
  - Lin, Ulsoy & LeBlanc, JDSMC, March 1999
  - Lin, Ulsoy & LeBlanc, IEEE-TCST, May 2000
System Overview:
Differential Braking

- Path correction by yaw rate control using differential braking
- Can be overridden by driver steering input
- Reference: Pilutti, Ulsoy & Hrovat, JDSMC, Sept. 1998

System Design Tools
CAPC Simulator

A vehicle simulation software tool, CAPC, was developed and used for:
- Subsystem development
- System integration
- Desktop driving simulator
System Design Tools

Ford Driving Simulator

- Standard vehicle buck and controls
- No motion base
- Detailed graphics for trips of up to two hours

Yaw Rate Estimation
Motivation and Background

- Motivation:
  - Yaw rate sensor needed for active safety systems
  - Current yaw rate sensors accurate and expensive.
  - Estimate of yaw rate from accelerometer measurements is desirable both as a primary (near term) as well as back up (future) sensor.

- Background:
  - Kinematic approach [Hitachi 93, Soltis et al 93, Zaremba et al 94]; sensitive to measurement noise.
  - Low cost accelerometers have low frequency drift and high frequency noise [Doeblin 90, Jurgen 94].
Yaw Rate Estimation

Proposed Approach

• Kalman Filter combines a dynamic estimate with a kinematic estimate.
• The KF is gain-scheduled with respect to vehicle forward velocity (u) and the magnitude of the steer angle (d).
• Comparisons and evaluations are made using a linear vehicle simulation model, a nonlinear vehicle simulation model, and experiments.

\[
\begin{align*}
\dot{x} &= \begin{bmatrix} C_{\alpha f} + C_{\alpha r} \\ a^2 C_{\alpha f} + b^2 C_{\alpha r} \\ a_s \left( C_{\alpha f} + C_{\alpha r} \right) \end{bmatrix} / m u_0 \\
\dot{y} &= c \dot{x} + d \\
A &= \begin{bmatrix} -C_{\alpha f} / m \\ -a^2 C_{\alpha f} / I_s \\ -a_s C_{\alpha f} / m \end{bmatrix} \\
B &= \begin{bmatrix} \frac{a^2 C_{\alpha f} + b^2 C_{\alpha r}}{I_s u_0} \\ \frac{a_s (a C_{\alpha f} - b C_{\alpha r})}{m u_0} \\ \frac{-K_s C_{\alpha f}}{m} \end{bmatrix}
\end{align*}
\]
Yaw Rate Estimation

Simulation Results

![Simulation Results Graphs]

Experimental Results

![Experimental Results Graphs]
Yaw Rate Estimation

Summary and Conclusions

Summary:
- New approach to inexpensive, yet accurate, estimation of vehicle yaw rate combines the advantages of current kinematic estimation methods, with dynamic estimation based upon Kalman filtering.
- Evaluation using linear simulation models, nonlinear simulation models, and actual vehicle experiments.

Conclusions:
- Combines advantages of kinematic estimate (accurate at high yaw rates even with disturbances) with the advantages of dynamic estimate (accurate at low yaw rates despite measurement noise).
- Robust performance is obtained with gain scheduling.
- Promising and inexpensive alternative to solid state yaw rate sensors.

Reference: Sivashankar & Ulsoy, ASME-JDSMC, June 1998
US Patent 5,878,357 issued March 1999
Role of the Driver:
Driver, Vehicle and Active Safety System

Vehicle

Driver

Actuation aid

Perception aid

nominal feedback to driver

VSC
[Van Zanten, 1995]

Vehicle dynamics alteration

normal driver inputs

ABS

warning, night vision
[Pilutti and Ulsoy, 1995]

Role of the Driver:
Steering Assist Controller - Background

* Steering control
  - Vehicle Stability Control, Automated Highway Systems, driver perception enhancement (e.g., warning)
  - Low authority steering assist: parallel copilot [Naab and Reichart, 1994; Hsu et al., 1998]

* Driver model and uncertainty
  - Considerable research on driver steering control models: mostly linear model with delay. (e.g., [Weir and McRuer, 1968; MacAdam, 1981; Kageyama et al., 1991; and Bernard et al., 1998])
  - Driver model from experimental data [Bourassa and Marcos, 1991; Soma and Hiramatsu, 1995; and Pilutti and Ulsoy, 1999].

* Interaction between driver and controller
  - Adjusting the warning based on driver state [Pilutti and Ulsoy 2002; Onken and Feraric, 1997]
  - Relative authority between driver and controller [LeBlanc et al., 1996; Acarman, 2000; Fujieka, 1999]
Role of the Driver:
Robust Steering Assist Controller

Investigate driver model uncertainty and design a robust vehicle steering assist controller with respect to driver model uncertainty.

References:
- Pilutti & Ulsoy, IEEE-TSMC, Sept. 1999: Driver modeling via system ID
- Chen & Ulsoy, JDSMC, Dec. 2001: Driver uncertainty modeling
- Chen & Ulsoy, IJVAS, Jan 2002: Robust steering assist control
- Chen & Ulsoy, ACC, May 2002: Simulator evaluation

Role of the Driver:
Driver Model and Parametric Uncertainty

- Nominal driver model: ARMAX (2,2,1,1) model with one sampling time of delay: 
  \[(1+a_1q^{-1}+a_2q^{-2})d = (b_1q^{-1}+b_2q^{-2})y + (1+c_1q^{-1})\theta\]
- Identification based on 120 segments of 1 minute duration data gives parametric variations within one driver.
- Uncertainty across 12 different drivers also obtained.
- Ref: Chen and Ulsoy, ASME-JDSMC, Dec. 2001
Role of the Driver:
Robust Smith Predictor Control

- Robust Smith predictor based steering assist controller
- $G_d$: Product of driver and vehicle transfer functions without delay
- $C$: QFT and $H_\infty$ robust controllers. Performance specified by stability margins, crossover frequency, and low frequency loop gain.

\[ G_d(s) = \frac{C(s)}{1 + C(s)G_d(s)(1-e^{-Ts})} \]

Role of the Driver:
Adaptive Controller

\[ G_d = k_p \hat{G}_d \]
for nominal driver, $k_p = k_o$

\[
e_r = y_r - y
\]
\[
e = \delta - k_d \hat{G}_d e_r
\]
\[
e_c = k_o - k_c \hat{K}_c
\]
\[
e_c = \int(\gamma_r e + \gamma_r \dot{e} + \gamma_r \ddot{e}) dt
\]
\[
K_c = \int(\gamma_r e + \gamma_r \dot{e} + \gamma_r \ddot{e}) dt
\]
Role of the Driver: Driving Simulator Validation Experiments

- PC-based driving simulator
  - Straight road with wind disturbance scenario
- Short driving experiments:
  - Large steering error initiated artificially.
- Long driving experiments:
  - Fatigue human driver with long driving task (underway)
- Time domain metrics:
  - Standard deviation of lateral position error (STD(y))
  - Time percentage of road departure based on lane crossing (PRD)
- Frequency domain metrics:
  - Phase margin (PM),
  - Gain margin (GM), and
  - Crossover frequency (\( \omega_c \)).

Role of the Driver: Experimental Results – Short Driving

- Repeated 40 times for each driver (with and without controller)
- Improvement observed in both time domain and frequency domain metrics for one driver
- Additional drivers being tested

<table>
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<tr>
<th></th>
<th>Without controller</th>
<th>With controller</th>
<th>Percentage improvement (%)</th>
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<tbody>
<tr>
<td><strong>Short driving</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Average STD(y), (m)</strong></td>
<td>0.766</td>
<td>0.707</td>
<td>7.70</td>
</tr>
<tr>
<td><strong>Average PRD, (%)</strong></td>
<td>16.022</td>
<td>10.698</td>
<td>33.23</td>
</tr>
<tr>
<td><strong>( \sigma ) STD(y), (m)</strong></td>
<td>0.567</td>
<td>0.408</td>
<td>28.04</td>
</tr>
<tr>
<td><strong>( \sigma ) PRD, (%)</strong></td>
<td>15.296</td>
<td>10.392</td>
<td>32.06</td>
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</tbody>
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<table>
<thead>
<tr>
<th><strong>Mean values</strong></th>
<th>Without controller</th>
<th>With controller</th>
<th>Percentage improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PM, (deg)</strong></td>
<td>8.856</td>
<td>9.187</td>
<td>3.74</td>
</tr>
<tr>
<td><strong>GM, (dB)</strong></td>
<td>4.835</td>
<td>5.998</td>
<td>24.05</td>
</tr>
<tr>
<td><strong>( \omega_c ), (rad/sec)</strong></td>
<td>0.987</td>
<td>1.025</td>
<td>3.85</td>
</tr>
</tbody>
</table>
The Role of the Driver

Summary and Conclusions

• Presented driver model uncertainty, robust/adaptive Smith predictor controller design, and driving simulator experiments.

• The system identification approach to compute driver steering model and model uncertainty has been verified. The driver model uncertainty is found to be significant, and can be used to illustrate change in driver steering performance.

• Frequency analysis and computer simulation illustrate that robust stability is achieved with the robust serial steering assist controller.

• Preliminary simulator experiments show promising results of the benefits of the proposed controller. More extensive evaluations are needed.

System Evaluation on Highways: Co-Pilot or Back-Seat Driver?

• SVRD prevention
• Lane geometry
• Path projection
• TLC
• Computer vision
• Motion sensing
• Yaw rate estimation
• Simulation tools
• Warning
• Intervention
• Driver ID
• Robust steering assist controllers
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