Motivation

Every day in the US, 10 teenagers are killed in teen-driven vehicles in crashes. Loss of control accounts for 30% of these deaths. Inexperienced drivers make more driving errors, exceed speed limits & run off roads at higher rates.

In 2003, motor vehicle traffic crashes were the leading cause of death for ages 5-33.

To prevent loss of control, we need to understand what determines vehicle motion.

Motion of a Vehicle

- Motion of a vehicle is governed by tire forces.
- Tire forces result from deformation in contact patch.
- Lateral tire force is a function of tire slip.

Tire Curve

- Maximum tire grip.
- Linear, Nonlinear, Loss of control.
Previous work with GPS

Global Positioning System (GPS)

- With Inertial Navigation System (INS), have tire slip angle estimates (Ryu 2002)
- Cornering stiffness in the linear region of handling (Bevly 2001)
- Coefficient of friction estimated in real-time (Hahn 2002 & Hsu 2006)

Need an online estimation process for friction and slip angle without GPS

Features of the Observer

- Uses measurements readily available on production vehicles
  - Gyroscopes, accelerometers, steering encoder, steering torque (thru EPS or SBW)
- Takes advantage of total aligning torque
  - Key piece of information for $\mu$, $\alpha$ estimation
- Accuracy of $\mu$, $\alpha$ estimates are comparable to GPS measurements up to limits of handling
Roadmap

- Derive overall observer scheme
  1. Steering system model
  2. Linear disturbance observer
  3. Nonlinear $\mu, \alpha$-observer

Experimental Results

- Ability to estimate $\mu$ and $\alpha$ up to the limits of handling

Observer Scheme

\[ \tau_d = \tau_a + \tau_j \]

\[ \tau_a \]

\[ \hat{\alpha}_f \]

\[ \hat{\alpha}_r \]

\[ \hat{\mu} \]
1. Form Steering System Model

Steering System Model

We model the torque contributions around the steer axis:
Generated by steer-by-wire motor
1. Motor torque actuator torque $\tau_{act}(i)$
Generated by tire forces
2. Vertical forces jacking torque $\tau_j(\delta)$
3. Lateral forces total aligning torque $\tau_a$
Total Aligning Torque

Results from lateral tire forces acting at a distance known as total trail

\[ \tau_a = -(m + p)F_{yf} \]

- Varies with steer angle \( \delta \)
  - Known from ADAMS
- Varies with slip angle \( \alpha \) and friction coefficient \( \mu \)
- Also varies with slip angle \( \alpha \) and friction coefficient \( \mu \)
Simple $\tau_a$ model

$$\tau_a = -(t_m + t_p) F_y f$$

(Plot shown with $t_m = 0$)

Complete Steering Model

To form complete steering model
- Combine torque contributions ($\tau_a, \tau_j, \tau_{act}$)
- Include effective steering system inertia and damping:

$$J_{eff} \ddot{\delta} + b_{eff} \dot{\delta} = \tau_a(C_\alpha, \alpha, \mu, \delta) + \tau_j(\delta) + \tau_{act}(i, \delta)$$

Total aligning moment Jacking torque Actuator torque
2: Describe Disturbance Observer

Disturbance Observer

\[ J_{ef} f \ddot{\delta} + b_{ef} f \dot{\delta} = \tau_a (C_{\alpha, \mu}, \alpha, \delta) + \tau_j (\delta) + \tau_{act} (i, \delta) \]

- Objective is to estimate total aligning torque \( \tau_a \) from available measurements
- Construct Luenberger observer
  - Inputs: motor current \( i \) and steer angle \( \delta \)
  - Outputs: total aligning moment \( \tau_a \)
3: Form Nonlinear $\mu, \alpha$-Observer

A combination of total aligning torque with lateral force can be used to decode friction and slip angle information.

Extracting $(\mu, \alpha)$ from $\tau_a$ & $F_{yf}$
Nonlinear $\mu,\alpha$-Observer

Update Laws for $\hat{\alpha}_f$, $\hat{\mu}$

$$\dot{\hat{\alpha}}_f = \left( \frac{1}{mV} + \frac{a^2}{I_zV} \right) \hat{F}_{yf} + \left( \frac{1}{mV} - \frac{ab}{I_zV} \right) \hat{F}_{yr} - r - \delta$$

$$\dot{\hat{\mu}} = 0$$

$$\dot{\hat{\alpha}}_r = \hat{\alpha}_f + \delta - \left( a + b \right) \frac{r}{V}$$

Observer Summary

- Derived steering system dynamics ($\tau_\alpha, \tau_j, \tau_{\text{act}}$)
- From these dynamics, formed linear disturbance observer
  - Inputs motor current and steer angle
  - Outputs total aligning moment measurements
- Based on simple models, we derived nonlinear $\mu,\alpha$-observer
  - Uses disturbance observer’s $\tau_\alpha$ measurements to update $\mu,\alpha$ estimates
  - Nonlinear gains based on current $\mu,\alpha$ estimates
Experimental Results

- Apply overall observer to experimental maneuver on P1
Ramp: Friction Estimates

- $\mu_o = 0.6$
- Relatively steady around $\mu = 1$ (agrees with skidpad)

Ramp: Slip Angle Estimates

- Linear
- Nonlinear
- Saturation
Observer Performance

- Observer’s slip angle estimates match well with GPS-based measurements
  - Up to handling limits (peak $F_{yf}$)
- Friction estimates converge once observer has enough lateral dynamic information
  - On dry pavement, $\sim 0.5$ g
  - Expected to converge faster on low-$\mu$ surfaces

Applications

- Observer uses measurements available in production vehicles
  - can be integrated with GPS-based observers
  - used during periods of GPS signal loss
- Provides two quantities ($\mu$, $\alpha$) very useful in vehicle dynamics control systems
  - Enhance active safety systems
Current Work

- Experimentally validate observer on high-μ surfaces
- Prove stability of nonlinear observer
- Integrate observer with control system that stabilizes vehicle at limits of handling