Vehicle State Estimation Using Steering Torque

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July 1, 2004
Outline

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  – Need for sideslip estimation in vehicle dynamics control
• Vehicle model
• Steering system
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  – Role of aligning moment
  – Steering disturbance and vehicle state observers
• Conclusion and future work
Toward a by-wire future

- Throttle-by-wire and brake-by-wire already available on production cars.

- Steer-by-wire a more significant leap from conventional automotive systems—still several years away.

- Steer-by-wire promises to significantly improve vehicle handling and driving safety.
Example: handling modification demonstrated on experimental steer-by-wire vehicle
Need for sideslip estimation

- Handling modification relies on full vehicle state feedback (yaw rate and sideslip).
- In experiments, estimated from a combination of GPS and INS measurements.
- Drawbacks of GPS: loses signal under adverse conditions, cost.

- Knowledge of sideslip also critical for electronic stability control (ESC) systems.
- Often determined based on integration of lateral acceleration or model.
- Drawbacks: accumulation of error due to sensor drift, model uncertainty.
Steer-by-wire as a sideslip estimator

- Steer-by-wire system is a self-contained sensor for tire forces.
- Tire forces directly influence vehicle dynamics.
- Completely estimate sideslip using only steer-by-wire system and yaw rate sensor.
- Also works with electric power steering systems.
The car as a dynamic system

- Assume constant longitudinal speed, $V$, so only lateral forces.

- Lateral forces generated by tire “slip.”
  \[ F_y = -C_\alpha \alpha \]

- Force and mass balance:
  \[ m \cdot a_y = F_{y,f} \cdot \cos \delta + F_{y,r} \]
  \[ I_z \cdot \dot{r} = a \cdot F_{y,f} \cdot \cos \delta - b \cdot F_{y,r} \]
Linearized vehicle model

- Equations of motion:

\[
\begin{bmatrix}
\dot{\beta} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
\frac{-C_{\alpha,f} - C_{\alpha,r}}{mV} \\
\frac{C_{\alpha,r} b - C_{\alpha,f} a}{I_z}
\end{bmatrix} - 1 + \left(\frac{C_{\alpha,r} b - C_{\alpha,f} a}{mV^2}\right) \begin{bmatrix}
\beta \\
r
\end{bmatrix} + \begin{bmatrix}
\frac{C_{\alpha,f}}{mV} \\
\frac{C_{\alpha,f} a}{I_z}
\end{bmatrix} \delta
\]

- Yaw rate, \( r \), and sideslip angle, \( \beta \), completely describe vehicle motion in plane.

- Steering angle, \( \delta \), is the input.
Conventional steering system

- steering column
- intermediate shaft
- power assist unit
- gear assembly
- pinion
- rack
- universal joints
- handwheel

[Image of a conventional steering system diagram]
Conversion to steer-by-wire

- steering column
- handwheel
- power assist unit
- gear assembly
- pinion
- rack
Steer-by-wire actuator
Steer-by-wire sensors

- Handwheel angle sensor
- Steering actuator
- Pinion angle sensor
Force feedback system

- belt drive
- handwheel feedback motor
- handwheel angle sensor
- steering actuator
- pinion angle sensor
Aligning moment due to pneumatic trail

- Part of aligning moment comes from tire deformation during cornering.
- Point of application of resultant force occurs behind center of contact patch.
- Pneumatic trail generates moment about steer axis (usually against direction of steering).
Aligning moment due to pneumatic trail

- Becomes nonlinear at larger slip angles.
- In conventional steering system, change in steering feel alerts driver that vehicle is approaching limits of handling.
Aligning moment due to mechanical trail

- Other part from the wheel caster angle.
- Offset between intersection of steering axis with ground and center of tire contact patch.
- Lateral force acting on contact patch also contributes to moment about steer axis (against direction of steering).
Steering system dynamics

\[ J_w \ddot{\delta} + b_w \dot{\delta} + F_w + \tau_a = r_s \tau_M \]
\[ \tau_M = k_M i_M \]

- \( \delta \): road wheel angle
- \( J_w \): moment of inertia
- \( b_w \): damping constant
- \( F_w \): Coulomb friction
- \( \tau_a \): aligning moment
- \( \tau_M \): motor torque
- \( k_M \): motor constant
- \( i_M \): motor current

Introduction
Vehicle model
Steering system
Estimation
Conclusion
Steering system as a disturbance observer

- Express in state space form. Choose steering angle as output (measured state). Motor current is input. Aligning moment is disturbance to be estimated.

\[
\begin{bmatrix}
\dot{\delta} \\
\ddot{\delta} \\
\tau_a
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
0 & -\frac{b_w}{J_w} & -\frac{1}{J_w} \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\delta \\
\dot{\delta} \\
\tau_a
\end{bmatrix} + \begin{bmatrix}
0 \\
\frac{r_s k_M}{J_w} \\
0
\end{bmatrix} i_M
\]

\[
\delta = \begin{bmatrix}
1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{\delta} \\
\ddot{\delta} \\
\tau_a
\end{bmatrix}
\]
Link between aligning moment and sideslip angle

- Aligning moment can be expressed as a function of the vehicle states, $\beta$ and $r$, and the input, $\delta$.

$$\tau_a = (t_p + t_m) F_{y,f} \tag{1}$$

$$= -(t_p + t_m) C_{\alpha f} \alpha_f \tag{2}$$

$$= -(t_p + t_m) C_{\alpha f} \left( \beta + \frac{ar}{V} - \delta \right) \tag{3}$$

$$= -(t_p + t_m) C_{\alpha f} \beta - \frac{a(t_p + t_m) C_{\alpha f}}{V} r + (t_p + t_m) C_{\alpha f} \delta \tag{4}$$
Vehicle state observer

- Express in state space form. Steering angle is input. Yaw rate and aligning moment (from the disturbance observer) are outputs (measurements).

\[
\begin{bmatrix}
\dot{\beta}_{CG} \\
\dot{r}
\end{bmatrix}
= \begin{bmatrix}
\frac{-C_{af} - C_{ar}}{mV} & -1 + \left( \frac{C_{af}b - C_{af}a}{mV^2} \right) \\
\frac{C_{ar}b - C_{af}a}{I_z} & -\frac{C_{af}a^2 - C_{af}b^2}{I_zV}
\end{bmatrix}
\begin{bmatrix}
\beta_{CG} \\
r
\end{bmatrix}
+ \begin{bmatrix}
\frac{C_{af}}{mV} \\
\frac{C_{af}a}{I_z}
\end{bmatrix} \delta
\]

\[
\begin{bmatrix}
\tau_a \\
r
\end{bmatrix}
= \begin{bmatrix}
0 & 1 \\
(t_p + t_m)C_{af} & \frac{a(t_p + t_m)c_{af}}{V}
\end{bmatrix}
\begin{bmatrix}
\beta_{CG} \\
r
\end{bmatrix}
+ \begin{bmatrix}
0 \\
(t_p + t_m)c_{af}
\end{bmatrix} \delta
\]

- Apply standard Luenberger observer.
• Steering angle is measured, so observer should give exact estimate.
• Some error present can be explained by...
• …hysteresis due to power steering dynamics and other unmodeled characteristics of the steering system.
• Sideslip estimate from observer is comparable to estimate from GPS.
Experiment: handling modification to understeering

- Sideslip estimation successfully applied to full state feedback vehicle control.
Experiment: handling modification to understeering

- Steer-by-wire system provides both actuation for control and sensing for sideslip estimation.
Conclusion

• Knowledge of vehicle sideslip is necessary for advanced steering control made possible with steer-by-wire.

• Steer-by-wire system provides convenient way to estimate vehicle sideslip.

• A two-observer structure has been developed linking the steering system dynamics and vehicle dynamics through the tire forces.
Future work

- Apply control and estimation techniques to a dedicated by-wire vehicle.
- Can avoid nonlinear and other undesirable steering system characteristics with a clean sheet design.