Observer-Based Multi-Actuator Vehicle Chassis Control In Critical Situations

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• Abstract

- Observer-based control of the vehicle dynamics
- Using four-wheel active steering and active suspension system
- Force the vehicle dynamics to track reference trajectories in critical situations
- TS Fuzzy model of the vehicle dynamics to take into account the cornering forces saturations
- Carsim Validations
Observer-based controller structure

- Driver steering
- Front steering
- Rear steering
- Active roll torque
- Reference model
- Control strategy
- TS observer
• Which control variables?
• Which sensors?

- Yaw rate sensor
- Roll rate sensor
- Steering sensors

The sideslip and roll angles will be estimated (Needed sensor not available)
• Which actuators?

   - Rear active steering
   - Front active steering
   - Active suspension
Vehicle model description
• Lateral and Roll vehicle dynamics

\[
\begin{align*}
    m_s a_{ys} + m_u a_{yu} &= 2F_{yf} + 2F_{yr} \\
    I_z \ddot{\psi} &= 2F_{yf} l_f - 2F_{yrl} \\
    I_x \dddot{\phi}_v &= m_s g h \phi_v + m_s a_{ys} h - k_\phi \phi_v - C_\phi \dot{\phi}_v + M_x
\end{align*}
\]
• Lateral and Roll vehicle dynamics

- Cornering forces modelisation

If $|\alpha_f|$ is $M_{f1}$ then $F_{yf} = C_{f1}\alpha_f$
If $|\alpha_f|$ is $M_{f2}$ then $F_{yf} = C_{f2}\alpha_f$
If $|\alpha_r|$ is $M_{r1}$ then $F_{yr} = C_{r1}\alpha_f$
If $|\alpha_r|$ is $M_{r2}$ then $F_{yr} = C_{r2}\alpha_f$

\[
\begin{align*}
F_{yf} &= \mu_{f1}(\alpha_f)C_{f1}\alpha_f + \mu_{f2}(\alpha_f)C_{f2}\alpha_f \\
F_{yr} &= \mu_{r1}(\alpha_r)C_{r1}\alpha_r + \mu_{r2}(\alpha_r)C_{r2}\alpha_r
\end{align*}
\]
• Lateral and Roll vehicle dynamics

➢ Cornering forces modelisation
• State model of the vehicle dynamics

\[
x(t) = \sum_{i=1}^{4} h_i(\alpha) \left[ A_i x(t) + B_{fi} \delta_f + B_{ri} \delta_r \right] + B_m M_x
\]

\[
x(t) = \begin{bmatrix} \beta & \psi & \phi_v & \phi_v \end{bmatrix}^T
\]

\[
\begin{align*}
A_i &= \begin{bmatrix}
-\frac{\sigma_i l x_1}{m l x_2 v} & \frac{\rho_i l x_1}{m l x_2 v^2} - 1 & -\frac{m_s h C_\phi}{m l x_2 v} & \frac{m_s h (m_s g h - k_\phi)}{m l x_2 v} \\
\frac{p_i}{l z} & -\frac{\sigma_i}{l z v} & 0 & 0 \\
-\frac{m_s h \sigma_i}{m l x_2} & \frac{m_s h p_i}{m l x_2 v} & -\frac{C_\phi}{l x_2} & \frac{(m_s g h - k_\phi)}{l x_2} \\
0 & 0 & 1 & 0
\end{bmatrix},
\end{align*}
\]

\[
B_{f1}, B_{f2} = \begin{bmatrix}
\frac{2C_1 l x_1}{m l x_2 v} \\
\frac{2C_2 l f}{2 m_s h C f_1} \\
0
\end{bmatrix},
\]

\[
B_{f3}, B_{f4} = \begin{bmatrix}
\frac{2C_1 l x_1}{m l x_2 v} \\
\frac{2C_2 l f}{2 m_s h C f_2} \\
0
\end{bmatrix},
\]

\[
B_{r1}, B_{r3} = \begin{bmatrix}
\frac{2C_1 l x_1}{m l x_2 v} \\
-\frac{2C_1 l f}{m l x_2 v} \\
0
\end{bmatrix},
\]

\[
B_{r2}, B_{r4} = \begin{bmatrix}
\frac{2C_2 l x_1}{m l x_2 v} \\
-\frac{2C_2 l f}{m l x_2 v} \\
0
\end{bmatrix}
\]

\[
h_i(\alpha) = \frac{\omega_i(\alpha)}{\sum_{i=1}^{4} \omega_i(\alpha)}, \quad \text{with} \quad \omega_i(\alpha) = \mu_{fj}(\alpha_j) \mu_{rk}(\alpha_r), \quad i = 1, \ldots, 4, \quad j = 1, 2 \quad \text{and} \quad k = 1, 2
\]
State model of the vehicle dynamics

Vehicle state model with active steering and active roll moment

\[ \dot{x}(t) = \sum_{i=1}^{4} h_i(\alpha) \left[ A_i x(t) + B_{fi} (\dot{\delta}_d + \dot{\delta}_c) + B_{ri} \delta_r + B_m M_x \right] \]

\[ \dot{x}(t) = \sum_{i=1}^{4} h_i(\alpha) \left[ A_i x(t) + B_i u(t) + B_{fi} \dot{\delta}_d(t) \right] \]

\[ u(t) = \begin{bmatrix} \dot{\delta}_c(t) \\ \delta_r(t) \\ M_x(t) \end{bmatrix}, \quad B_i = \begin{bmatrix} B_{fi} & B_{ri} & B_m \end{bmatrix} \]

\( \delta_a(t) \) is the front wheel steering angle due to the driver action, \( \delta_c(t) \) and \( \delta_r(t) \) are respectively the front and rear active steering and \( M_x \) is the active roll moment.
Observer based controller design
• Observer based controller

TS Observer design

\[
\begin{align*}
\dot{x} &= \sum_{i=1}^{4} h_i(\hat{\alpha}) \left[ A_i \dot{x} + B_i u + B_{fi} \delta_d + L_i (y - \hat{y}) \right] \\
y &= Cx, \quad \hat{y} = C\hat{x} \\
z &= C_z x, \quad \hat{z} = C_z \hat{x}
\end{align*}
\]

\[
C = \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0
\end{bmatrix}, \quad C_z = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 2/mg & 2/mg \\
0 & 0 & C_\phi & k_\phi
\end{bmatrix}
\]

where \( y = [\psi \quad \phi_v]^T \) is the measured output, \( z = [\beta \quad \psi \quad LTR]^T \) is the controlled output and matrices \( L_i \) are observer gains to be determined.
Observer based controller

Control law:

\[
u(t) = - \sum_{j=1}^{4} h_j(\hat{\alpha}) \left[ K_P j \hat{x} + K_I j \int_0^t (\hat{z}(\tau) - z_{ref}(\tau)) \, d\tau \right] \]

Let us denote the tracking error: \( \dot{e}_c = \hat{z} - z_{ref} \)

and denote the estimation error: \( e_o = x - \hat{x} \)
• Observed based controller

Augmented system

\[
\dot{\tilde{x}}(t) = \sum_{i=1}^{4} \sum_{j=1}^{4} h_i(\hat{\alpha}) h_j(\hat{\alpha}) \left[ \tilde{A}_{ij} \tilde{x}(t) + \tilde{B}_{wi} W(t) \right]
\]

\[
\tilde{x}(t) = \begin{bmatrix} x & e_c & e_o \end{bmatrix}^T
\]

with

\[
\tilde{A}_{ij} = \begin{bmatrix} A_i - B_i K_{Pj} & -B_i K_{ij} & B_i K_{Pj} \\ C_z & 0 & -C_z \\ 0 & 0 & A_i - L_i C \end{bmatrix}, \quad \tilde{B}_{wi} = \begin{bmatrix} B_{fi} & 0 & I \\ 0 & -I & 0 \\ 0 & 0 & I \end{bmatrix}, \quad W(t) = \begin{bmatrix} \delta_d(t) \\ z_{ref}(t) \\ \nu(t) \end{bmatrix}
\]
Observer based controller

Augmented system

\[
\dot{\tilde{x}}(t) = \sum_{i=1}^{4} \sum_{j=1}^{4} h_i(\hat{\alpha})h_j(\hat{\alpha}) \left[ \tilde{A}_{ij}\tilde{x}(t) + \tilde{B}_{wi}W(t) \right]
\]

\[
\tilde{x}(t) = \begin{bmatrix} x & e_c & e_o \end{bmatrix}^T
\]

In order to simplify the stability conditions of the closed loop system, matrices \(\tilde{A}_{ij}\) and \(\tilde{B}_{wi}\) can be rewritten as follows:

\[
\tilde{A}_{ij} = \begin{bmatrix} A_i - B_iK_j & S + R_iK_{Pj} \\ 0 & A_i - L_iC \end{bmatrix}, \quad \tilde{B}_{wi} = \begin{bmatrix} B_{1wi} \\ B_{2w} \end{bmatrix}
\]

where: 
\[
\begin{align*}
\bar{A}_i &= \begin{bmatrix} A_i & 0 \\ C_i & 0 \end{bmatrix}, \\
\bar{B}_i &= \begin{bmatrix} B_i \\ 0 \end{bmatrix}, \\
S &= \begin{bmatrix} 0 \\ -C_i \end{bmatrix}, \\
R_i &= \begin{bmatrix} B_i \\ 0 \end{bmatrix}.
\end{align*}
\]

\[
B_{1wi} = \begin{bmatrix} B_{fi} \\ 0 \\ 0 \end{bmatrix}, \quad B_{2w} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad K_j = \begin{bmatrix} K_{Pj} & K_{ij} \end{bmatrix}.
\]
Observer based controller

- H$_{\infty}$ approach

\[
\int_0^\infty \left\{ e_c(t)^T Q_1 e_c(t) + e_o(t)^T Q_2 e_o(t) \right\} dt \leq \rho^2 \int_0^\infty W(t)^T W(t) dt
\]

\[
\int_0^\infty \dot{x}(t)^T \tilde{Q} \dot{x}(t) dt \leq \dot{x}(0)^T \tilde{P} \dot{x}(0) + \rho^2 \int_0^\infty W(t)^T W(t) dt
\]

with \( \tilde{Q} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & Q_1 & 0 \\ 0 & 0 & Q_2 \end{bmatrix} \) and \( \tilde{P} \) is a symmetric positive definite matrix.
• Observer based controller

**Corollary 1:** Given symmetric positive definite matrices $Q_1$ and $Q_2$, if there exist common symmetric positive definite matrices $X$, $P_2$, matrices $V_j$, $W_i$, $K_i$ and scalars $\rho > 0$, solution of the following inequalities:

$$
\begin{bmatrix}
\Gamma_{ij} & S + R_iK_P j & B_1w_i \\
* & \Theta_{ij} & P_2B_2w_i \\
* & * & -\rho^2I
\end{bmatrix} < 0, \quad i, j = 1, 4 \quad (17)
$$

where

- $\Gamma_{ij} = A_iX - B_iV_j + XA_i^T - V_j^TB_i^T + XC_i^TQ_1C_1X$
- $\Theta_{ij} = P_2A_i - W_iC + A_i^TP_2 - C_i^TW_i^T + Q_2$
- $V_j = K_jX$, $W_i = P_2L_i$
- $C_1 = \begin{bmatrix} 0 & 0 \\ 0 & I \end{bmatrix}$, and $\bar{Q}_1 = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_2 \end{bmatrix}$

Then the fuzzy closed loop system (14) is asymptotically stable and the $H_\infty$ control performance in (15) is guaranteed for a prescribed attenuation level $\rho^2$. 

- 16th International IEEE Conference on Intelligent Transportation Systems - ITSC 2013, October 6-9, 2013, The Netherlands
- IEEE transactions on Control Systems technology
• CarSim simulator validation
• CarSim simulator validation

- Vehicle trajectories
• CarSim simulator validation

➢ Driver steering and control inputs

Steering angles of the driver and the controller in the fishhook test

Active roll torque delivered by the controller
- CarSim simulator validation

Vehicle dynamic estimation
• CarSim simulator validation

➤ Comparison of the controlled and uncontrolled vehicle
• CarSim simulator validation
Conclusions and perspectives

Conclusions

- The work deals with the vehicle dynamic control in critical situation.
- A robust control method operating on the active four wheel steering and active suspension to ensure the vehicle stability.
- Since the sideslip and roll angles sensor are too expensive, we have proposed an observer approach by considering the TS fuzzy vehicle model.
- The proposed controller has been validated using CarSim simulator.

Perspective

- Experimental validation.
- Develop a more complex vehicle dynamics model (longitudinal & lateral).
- Develop controllers for autonomous vehicles.
• Questions...?????