Optimal Control of An On-Demand All Wheel Drive System (ODAWD) for Vehicle Traction Enhancement

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• Optimal control

• On-demand All Wheel Drive – ODAWD

• Traction enhancement
Contents

• Introduction
• Vehicle Modeling
• Controller for Hydraulic System
• Controller for Hybrid System
• Q&A
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An AWD users survey

- Traction for driving through deep snow or sand without being stuck
- Start-off traction on icy or snowy roads
State of the Art

- Manually operated AWD systems
- Fixed-ratio torque split.
- On-demand control and optimal control of slip.
Objectives

- Traction enhancement
- Slip optimization
- Optimal Torque transmission
Lon’l Friction Coef vs. Lon’l Slip

![Graph showing the relationship between adhesion coefficient and slip for different surfaces: road, dry; cobblestones, dry; concrete, dry; road, wet; cobblestones, wet; snow; and ice. The graph plots the adhesion coefficient on the y-axis and slip on the x-axis.]
Lat’l Friction Coef vs. Lon’l Slip
Basic Structure

- Control law
- Plant dynamics (Vehicle & Wheel)
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Vehicle Dynamics

\[ F_{fric,w} - F_{wind} - F_R - m_{COG} \cdot g \cdot \sin(\chi_{road}) = m_{COG} \cdot \dot{V}_{COG} \]
Wheel Dynamics

\[ J_{wi} \cdot \dot{\omega}_i = \sum T_{yi} = T_{di} - F_{xi} \cdot R - F_{rrri} \cdot R \]
A Validated Vehicle Model
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Lon’l Friction Coef vs. Lon’l Slip

![Graph showing the relationship between adhesion coefficient and slip for different surfaces: road, dry; concrete, dry; cobblestones, dry; road, wet; cobblestones, wet; snow; ice. The graph indicates the variation of adhesion coefficient with slip for each condition.]
Further Focus and Simplification

• Focused on longitudinal traction enhancement.

• Single-track model
Objective function

\[ J = (S_{\text{des},f} - S_f)^2 + (S_{\text{des},r} - S_r)^2 \]
Performance Index Minimization

• The FONC (First Order Necessary Condition) in optimal control theory states that

\[
\frac{dJ}{dr} = 0
\]

would give an optimal solution.
Dynamics equations

\[ \dot{V}_x = \frac{F_x}{M} = \frac{\mu(S_f) \cdot F_{zf} + \mu(S_r) \cdot F_{zr}}{M} \]

\[ \dot{\omega}_r = \frac{r \cdot T_{total} - \mu(S_r) \cdot F_{zr} \cdot R}{J_{wr}} \]

\[ \dot{\omega}_f = \frac{(1-r) \cdot T_{total} - \mu(S_f) \cdot F_{zf} \cdot R}{J_{wf}} \]
Control law

\[ \mathbf{r} = \left\{ \left\{ \frac{V_x}{R^2} \cdot \left( \frac{1}{\omega_f^2} + \frac{1}{\omega_r^2} \right) + \frac{C}{R} \cdot \left( \frac{1}{\omega_f} + \frac{1}{\omega_r} \right) \right\} \cdot \frac{\mu(S_f) \cdot F_{zf} + \mu(S_r) \cdot F_{zr}}{M} \right\} \]

\[ -\left( \frac{V_x}{\omega_f \cdot R} + C \right) \cdot \frac{T_{\text{total}} \cdot V_x}{\omega_f^2 \cdot R \cdot J_w} + \frac{V_x}{\omega_f^2 \cdot J_w} \cdot \left( \frac{V_x}{\omega_f \cdot R} + C \right) \cdot \mu(S_f) \cdot F_{zf} \]

\[ + \frac{V_x}{\omega_r^2 \cdot J_w} \cdot \left( \frac{V_x}{\omega_r \cdot R} + C \right) \cdot \mu(S_r) \cdot F_{zr} \} \]

\[ / \frac{T_{\text{total}} \cdot V_x}{R \cdot J_w} \cdot \left\{ \frac{1}{\omega_r^2} \left( \frac{V_x}{\omega_r \cdot R} + C \right) - \frac{1}{\omega_f^2} \left( \frac{V_x}{\omega_f \cdot R} + C \right) \right\} \]
Simulink Simulation
Implementation in Hydraulic system

- PWM
- Solenoid
- Multi-plate Clutch
Transfer Function of Implement

\[ \frac{T_c}{I} = \frac{T_c}{P} \cdot \frac{P}{X} \cdot \frac{X}{I} = \frac{2}{3} \cdot \pi \cdot R^3 \cdot Mu \cdot \]

\[ \frac{K_1}{K_2} \cdot \frac{m_{pc} \cdot s^2 + C_{pc} \cdot s + K_c}{m_{pc} \cdot s^2 + \left(C_{pc} + \frac{A^2 \cdot \rho}{K_2}\right) \cdot s + K_c} \cdot \frac{K_{sl}}{m_s \cdot s^2 + C_a \cdot s + K_s} \]
Hydraulic Front Slip Comparison
Hydraulic Rear Slip Comparison
Hydraulic Velocity Comparison

![Graph showing hydraulic velocity comparison with and without control. The graph plots time on the x-axis and longitudinal velocity on the y-axis, with a blue line indicating 'w/o control' and a red line indicating 'w/ control.' The 'w/o control' line starts higher than the 'w/ control' line and then both lines converge towards the end of the graph.]
Hydraulic Control Variable
Contents

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Two Systems Differences

Mechanical Coupler

Electrical Motor
Two Scenarios of Hybrid System

• Non-engine-intervened control (NEI)

• Engine-intervened control (EI)
Dynamics Equations for NEI

\[ \dot{V}_x = \frac{F_x}{M} = \frac{\mu(S_f) \cdot F_{zf} + \mu(S_r) \cdot F_{zr}}{M} \]

\[ \dot{\omega}_f = \frac{T_e - \mu(S_f) \cdot F_{zf} \cdot R}{J_{wf}} \]

\[ \dot{\omega}_r = \frac{T_m - \mu(S_r) \cdot F_{zr} \cdot R}{J_{wr}} \]
Performance Index Minimization

\[ J = (S_{des,f} - S_f)^2 + (S_{des,r} - S_r)^2 \]

\[ \frac{dJ}{dT_m} = 0 \]
Control law for NEI

\[ T_m = \mu(S_r) \cdot F_{zr} \cdot R + \frac{\omega_r^3 \cdot R^2 \cdot J_w}{M \cdot V_x \cdot (V_x + C \cdot \omega_r \cdot R)}. \]

\[ \left[ \frac{V_x}{R^2} \left( \frac{1}{\omega_f^2} + \frac{1}{\omega_r^2} \right) + \frac{C}{R} \left( \frac{1}{\omega_f} + \frac{1}{\omega_r} \right) \right]. \]

\[ \left[ \mu(S_f) \cdot F_{zf} + \mu(S_r) \cdot F_{zr} \right] \]

\[ - \frac{\omega_r^3 \cdot R}{\omega_f^2 \cdot (V_x + C \cdot \omega_r \cdot R)} \cdot \left( \frac{V_x}{\omega_f \cdot R} + C \right) \cdot (T_{total} - \mu(S_f) \cdot F_{zf} \cdot R) \]
Simulink Simulation
Mechanism of EI

- Engine-intervened control (EI)

- Hydraulic mechanism
Control law of EI

\[ T_e = (1 - r) \times T_{total} \]

\[ T_m = r \times T_{total} \]

- \( r \) is the torque split ratio derived in hydraulic system
Hybrid Front Slip Comparison

![Graph showing Hybrid Front Slip Comparison](image)
Hybrid Rear Slip Comparison

![Graph comparing rear slip without control and with control over time.](image)
Hybrid Velocity Comparison
NEI Control Variable
Conclusion

• On Hydraulic system

• On Hybrid system
Q & A