ME41116
Vehicle Control

Vehicle Stability Control

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Contents

Motivation

- **National Highway Traffic Safety Administration (NHTSA - 2017), in 2015-**
  - **22,441** Passenger Vehicle (PV) occupant fatalities
  - **2,272** fatalities despite use of ESC !!!
    - 1,411 fatalities- Passenger Car
    - 861 fatalities- Light-truck and Van
  - **10.1% of fatalities in PVs equipped with ESC**

Table 1
ESC Lives Saved Estimates, by Year and Vehicle Type, 2011–2015

Year	Passenger Cars With ESC Standard (1)	Light Trucks/Vans With ESC Standard (2)	Passenger Vehicles With ESC Standard Total = (1) + (2)
2015	857	1,091	**1,949**
2014	657	918	**1,575**
2013	551	829	**1,380**
2012	466	759	**1,225**
2011	329	567	**896**
TOTAL	**2,860**	**4,164**	**7,024**

Data Source: NHTSA, NCSA, 2011–2014 FARS Final Files, FARS 2015 Annual Report File and IIHS list of ESC-equipped vehicles.

[1] "DOT HS 812 391 - Estimating Lives Saved by Electronic Stability Control, 2011-2015" March 2017. [Online]. Available: https://crashstats.nhtsa.gov/#/PublicationList/59

Problem Statement

<u>TO INVESTIGATE AND COMPARE THE PERFORMANCE OF AN ESC SYSTEM USING VARIOUS NON-LINEAR CONTROL STRATEGIES</u>

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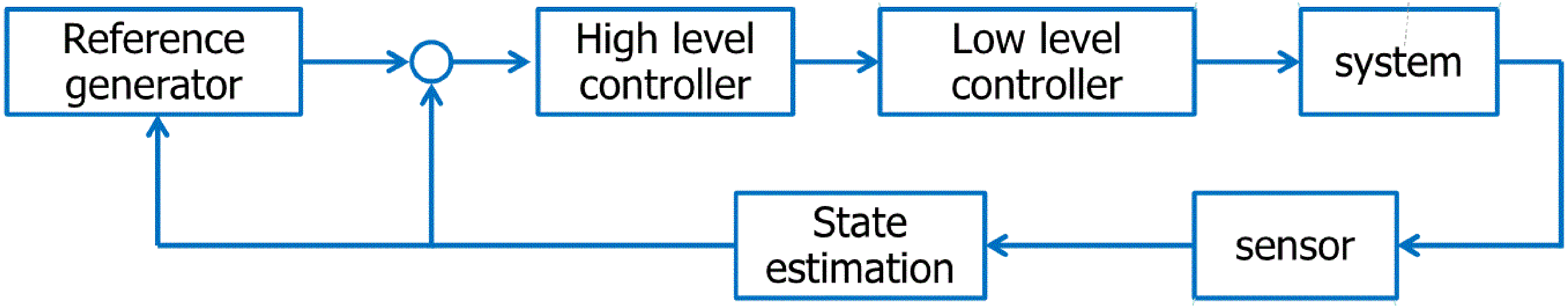
ESC

- **Electronic Stability Control (ESC):**
  - **To improve lateral stability and avoid vehicle skidding using differential braking**



[2] ME41116: Vehicle Dynamics B, TU Delft, Lecture 5, Slide 22

Control Strategies

- **3 strategies have been put to test:**

1. **Non-Linear State Feedback using Lyapunov Stability Method**

   - It is assumed that lateral, longitudinal velocities and accelerations respectively (v_x, v_y, a_x, a_y) and yaw rate (r) are available measurement
   - Model based approach: Non-Linear Bicycle Model

$$\dot{v} = P - ur\,; \qquad P = \frac{1}{M}\{(F_{yfl} + F_{yfr})cos\delta + (F_{yrl} + F_{yrr})\}$$

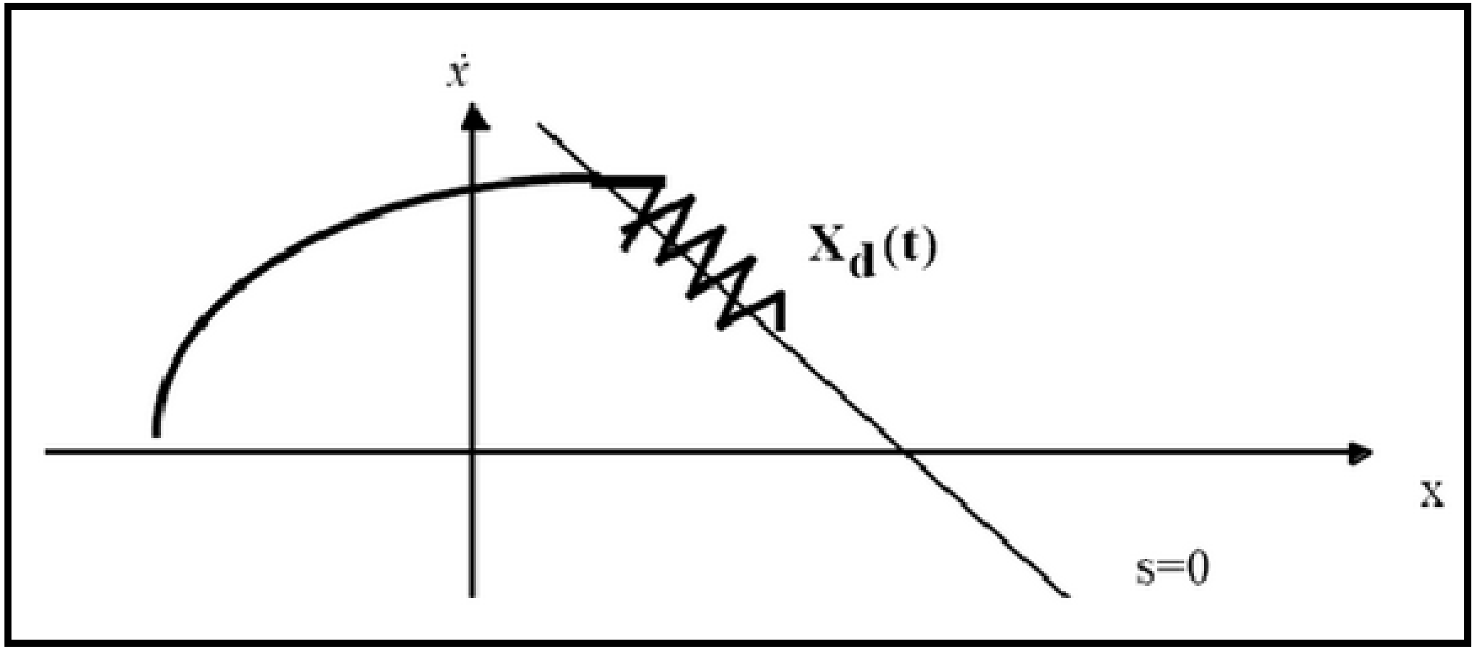
$$\dot{r} = \frac{1}{I_z}(Q + M_z)\,; \qquad Q = a(F_{yfl} + F_{yfr})cos\delta - \mathrm{b}(F_{yrl} + F_{yrr}) + \mathrm{e}(F_{yfl} - F_{yfr})\mathrm{sin}\delta$$

   - Candidate Lyapunov Function: $V = \frac{1}{2}\left[A(v - v_{ref})^2 + BI_z(r - r_{ref})^2\right] > 0$
   - The time derivative is ensured to be negative semidefinite. Stability can be proved via LaSalle's Invariance Principle. Based on these ideas, the corrective yaw moment is:
   - $M_z = -\frac{Av(P-ur)}{B(r-r_{ref}+\epsilon)} - Q - K(r - r_{ref})$ $\quad$ *where*, A, B, ϵ *and* K *are positive valued tuning parameters*
   - $\dot{V} = -BK(r - r_{ref})^2 < 0$

Control Strategies

- **Sliding Mode Control (SMC)**

<u>CHATTERING</u>



[4] https://www.researchgate.net/figure/Chattering-as-a-result-of-imperfect-control-switching-1_fig1_263967628

Control Strategies

- **3 strategies have been put to test:**

2. **Second Order Sliding Model Control (SMC) with Super-Twisting Algorithm**

- Assumptions: Measurements available- $v_x, v_y, r, and\ a_y$
- $\sigma = r - r_{ref}$ is the sliding surface
- $\dot{\sigma} = \frac{1}{I_z}\left(l_f(F_{y,fl} + F_{y,fr}) - l_r(F_{y,rl} + F_{y,rr}) + M_z\right) - \dot{r}_{ref}$
- $\ddot{\sigma} = \left(-\ddot{r}_{ref} + \frac{1}{I_z}\left(l_f(\dot{F}_{y,fl} + \dot{F}_{y,fr}) - l_r(\dot{F}_{y,rl} + \dot{F}_{y,rr})\right)\right) + \frac{1}{I_z}\dot{M}_z$
- $\dot{u} = \dot{M}_z$
- $u_{ST}(t) = u_1(t) + u_2(t)$
- $\dot{u}_1 = \begin{cases} -u, & |u| > 0 \\ -W sign(\sigma), & |u| \leq 0 \end{cases}$
- $u_2 = \begin{cases} -\eta|\sigma_0|^{\rho} sign(\sigma), & |\sigma| > \sigma_0 \\ -\eta|\sigma|^{\rho} sign(\sigma), & |\sigma| \leq \sigma_0 \end{cases}$
- $M_z = -l_f\left(F_{y,fl} + F_{y,fr}\right) + l_r\left(F_{y,rl} + F_{y,rr}\right) + I_{zz}\dot{r}_{ref} + u_{ST}$

- Control action is a function of Lateral Force which therefore required reconstruction using ‘dteval_light’.

[5] “Vehicle Stability Enhancement Based on Second Order Sliding Mode Control” Norhazimi Hamzah, Yahaya Md Sam, Hazlina Selamat, M Khairi Aripin, Muhamad Fahezal Ismail

Control Strategies

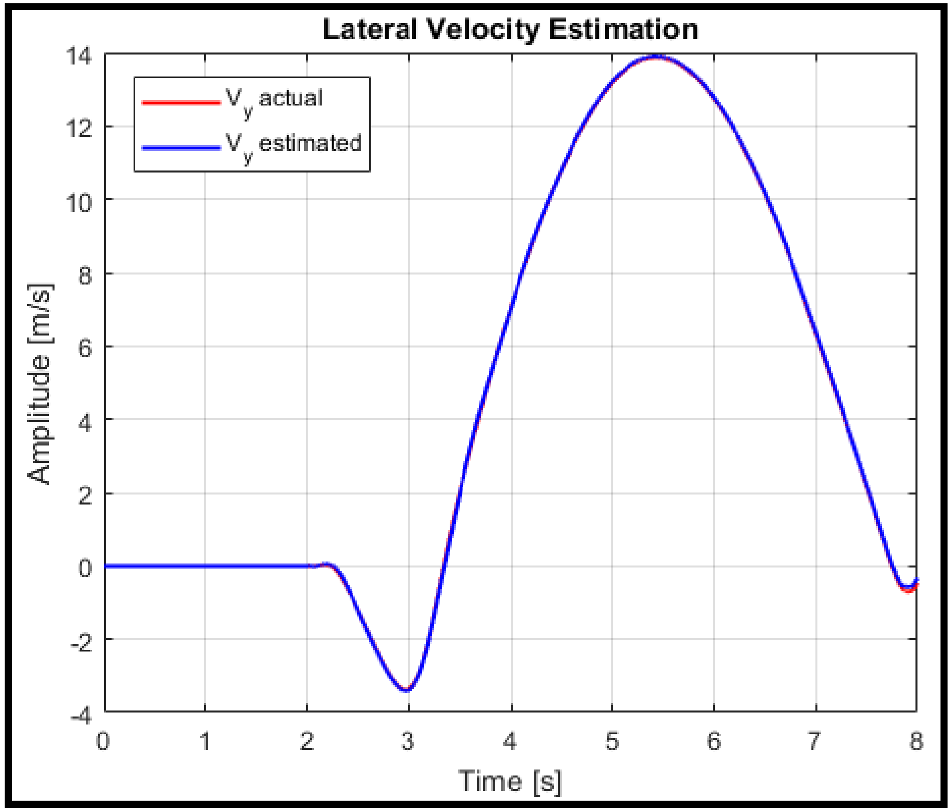
- **3 strategies have been put to test:**

3. **Higher Order Sliding Mode Observer with Adaptive Super-Twisting Controller Design**

- Assumptions: Measurements available- $v_x, r, a_x \text{ and } a_y$
- States to be estimated by Observer- v_y
- $\dot{\hat{v}}_x = \hat{v}_y r + a_x - \frac{m_s}{m} h r \dot{\hat{\theta}} + v_1$
- $\dot{\hat{v}}_y = -v_x r + \frac{J_x}{J_{x,e}} a_y - \frac{k_{x,e}}{J_{x,s}} \hat{\theta} - \frac{b_x}{J_{x,s}} \dot{\hat{\theta}} + v_2$
- $\ddot{\hat{\theta}} = -\frac{k_{x,e}}{J_{x,e}} \hat{\theta} - \frac{b_x}{J_{x,e}} \dot{\hat{\theta}} + \frac{m_S}{J_{x,e}} h a_y$
- $v_1 = k_1 |\tilde{v}_x|^{\frac{1}{2}} sign(\tilde{v}_x)$
- $v_2 = k_2 sign(\tilde{v}_x) sign(r)$
- $\tilde{v}_x = v_x - \hat{v}_x$

$$\beta = tan^{-1}\left(\frac{v_y}{v_x}\right)$$

$$\beta \approx \frac{v_y}{v_x}$$



[6] "Robust observer-based sliding mode controller for vehicles with roll dynamics" Juan J. Ley-Rosas, Luis Enrique Gonzalez-Jimenez, Alexander G. Loukianov and Jorge E. Ruiz-Duarte

Control Strategies

3. Higher Order Sliding Mode Observer with Adaptive Super-Twisting Controller Design

- **Corrective action is $\boldsymbol{\delta_c}$ − active steering correction and $\mathbf{M_z}$ − corrective moment action**

  - $\Delta F_{y,f} = F_{y,f} - F_{y,f,d}$
  - $\Delta F_{y,f} = \frac{J_{x,e}}{J_x}\frac{m}{\mu_y}\left(\lambda_{11}|s_1|^{\frac{1}{2}}sign(s_1) + \sigma_1 - v_2\right)$
  - $M_z = J_z(-\lambda_{21}|s_2|^{\frac{1}{2}}sign(s_2) + \sigma_2)$
  - $\delta_c = \Delta F_{y,f}^{-1}$
  - $\Delta F_{y,f}^{-1} = \frac{1}{B_{y,f}}tan\left[\left(\frac{1}{C_{y_f}}\right)arcsin\left(\frac{\Delta F_{y,f}}{D_{y_f}}\right)\right]$
  - $s_1 = \hat{v}_y - v_{y,ref}$
  - $s_2 = r - r_{ref}$ where,

  s_1 *and* s_2 *are the 2 sliding surfaces*

  - $\dot{s}_1 = -\lambda_{11}|s_1|^{\frac{1}{2}}sign(s_1) + \sigma_1 + \rho_1$
  - $\dot{\sigma}_1 = -\lambda_{12}sign(s_1)$
  - $\dot{s}_2 = -\lambda_{21}|s_2|^{\frac{1}{2}}\mathrm{sign}(s_2) + \sigma_2 + \rho_2$
  - $\dot{\sigma}_2 = -\lambda_{22}\mathrm{sign}(s_2)$
  - $\dot{\lambda}_{11} = \begin{cases} \omega_1\sqrt{\frac{\gamma_1}{2}}, & if\ \ s_1 \neq 0 \\ 0 & \end{cases}$
  - $\lambda_{12} = 2\epsilon_1\lambda_{11} + \eta_1 + 4\epsilon_1^2$
  - $\dot{\lambda}_{21} = \begin{cases} \omega_2\sqrt{\frac{\gamma_2}{2}}, & if\ \ s_2 \neq 0 \\ 0 & \end{cases}$
  - $\lambda_{22} = 2\epsilon_2\lambda_{21} + \eta_2 + 4\epsilon_2^2$

[7] "Robust observer-based sliding mode controller for vehicles with roll dynamics" Juan J. Ley-Rosas, Luis Enrique Gonzalez-Jimenez, Alexander G. Loukianov and Jorge E. Ruiz-Duarte

Vehicle Validation Model

Vehicle data

Symbol	Description	Value	Unit
M	total vehicle mass	1,900	$[kg]$
I_{xx}	Inertia along x-axis	700	$[kgm^2]$
I_{yy}	Inertia along y - axis	3,200	$[kgm^2]$
I_{zz}	Inertia along z-axis	3,500	$[kgm^2]$
r_{eff}	Effective Wheel Radius	0.3035	$[m]$
$r_{w,l}$	Wheel Loaded Radius	0.2866	$[m]$
m_{rim}	Rim mass	0.15	$[kg]$
m_{tire}	Tire mass	9.8	$[kg]$
$I_{xx,tire}$	Rim Inertia along x - axis	1	$[kgm^2]$
$I_{yy,tire}$	Rim Inertia along y - axis	1	$[kgm^2]$
l_f	Front Wheelbase	1.48	$[m]$
l_r	Rear Wheelbase	1.41	$[m]$
h_{Bf}	Half of Front Trackwidth	0.5*1.56	$[m]$
h_{Br}	Half of Rear Trackwidth	0.5*1.58	$[m]$
h_{cg}	Height of CoG	0.54	$[m]$
h_r	Height of Rear Roll Center	0	$[m]$
h_f	Height of Front Roll Center	0	$[m]$
$m_{us,f}$	Front Axle mass	120	$[kg]$
$m_{us,r}$	Rear Axle mass	90	$[kg]$

Vehicle Model

- **Meant for all controllers to be tested and tuned**
- **Multibody nonlinear vehicle model created using SimMechanics**

Assumption

- **No throttle input considered to be imparted to the vehicle**
- **No heave motion has been considered**
- **Flat Road profile**

Vehicle data

Symbol	Description	Value	Unit
Kz_f	Front Vertical Stiffness	52,000	$[N/m]$
Kz_r	Rear Vertical Stiffness	40,000	$[N/m]$
Dz_f	Front Vertical Damping Coefficient	3,000	$[Ns/m]$
Dz_r	Rear Vertical Damping Coefficient	3,000	$[Ns/m]$
$Kroll_f$	Front Roll Stiffness	130,000	$[N/rad]$
$Kroll_r$	Rear Roll Stiffness	40,000	$[N/rad]$
$Droll_f$	Front Roll Damping Coefficient	2,000	$[Ns/rad]$
$Droll_r$	Rear Roll Damping Coefficient	2,000	$[Ns/rad]$
i_s	Natural Steering Ratio	15.4	$[-]$

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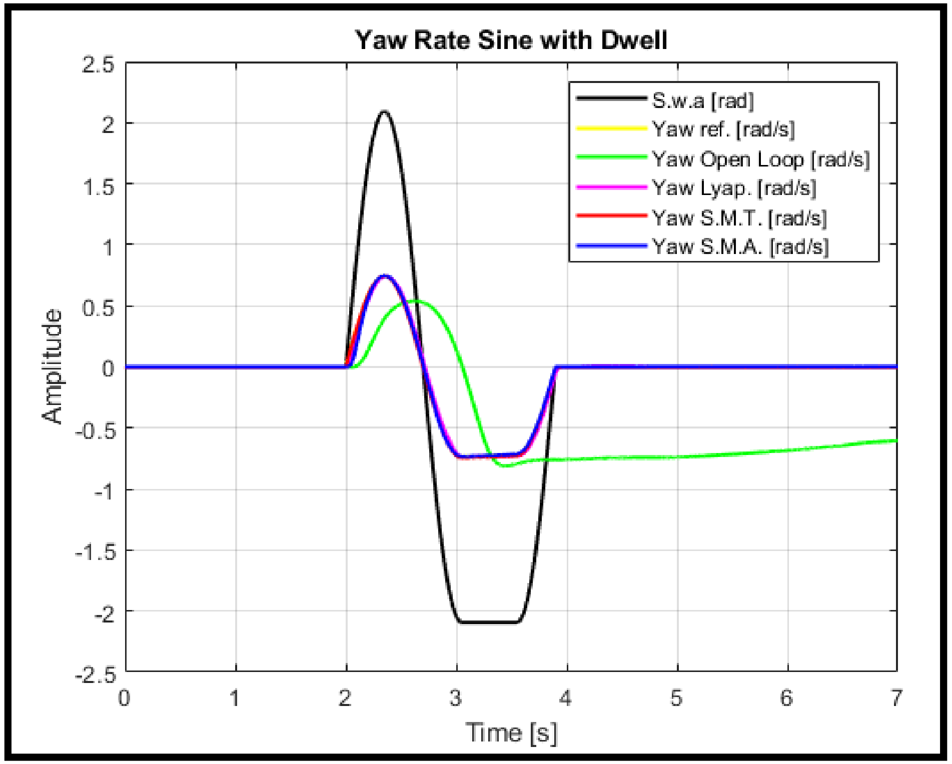
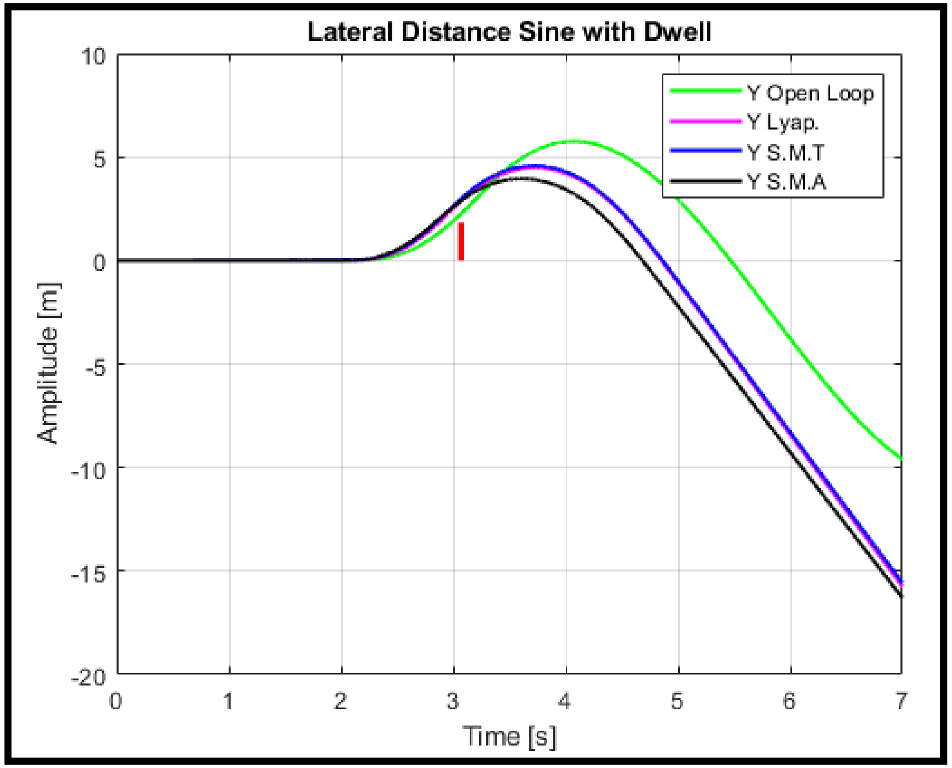
Simulation and Results

❑ Sine with Dwell

- Testing and tuning of controllers
- Initial longitudinal speed: 25m/s
- Time Response- **yaw rate and lateral distance**





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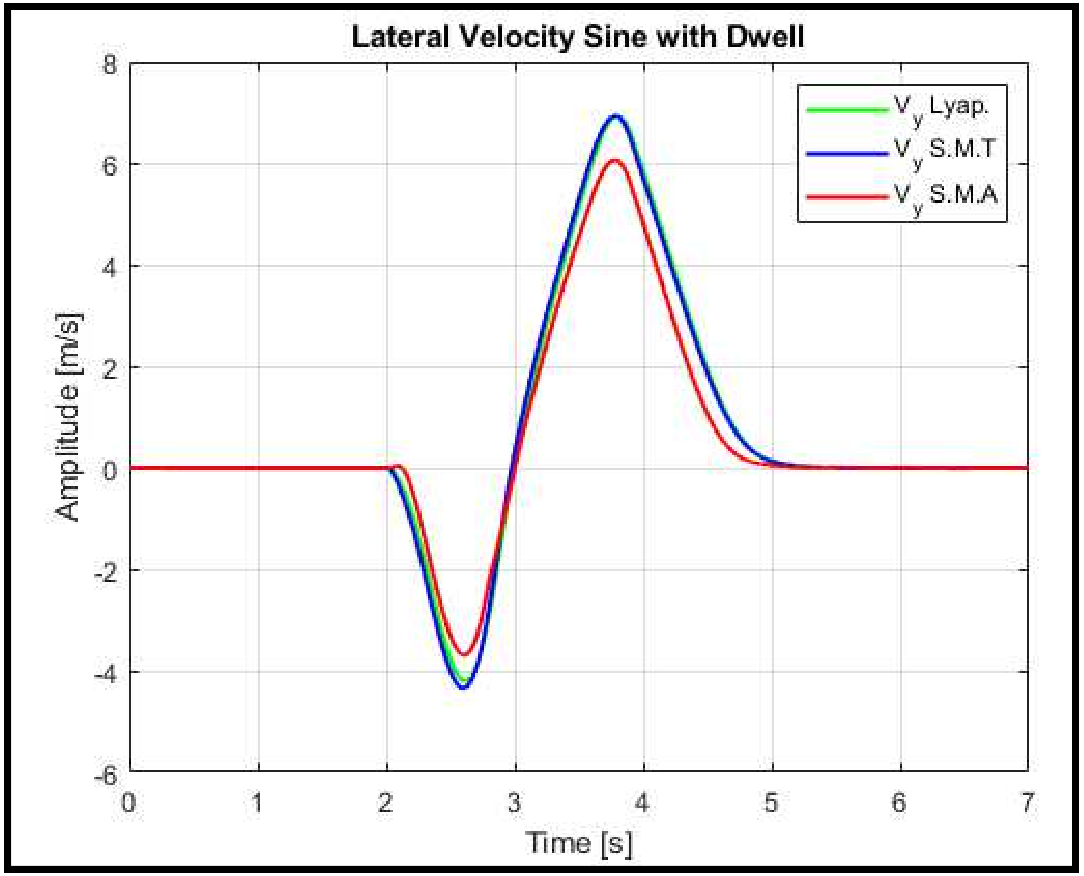
Simulation and Results

- Testing and tuning of controllers
- Initial longitudinal speed: 25m/s
- Time Response- **lateral velocity**

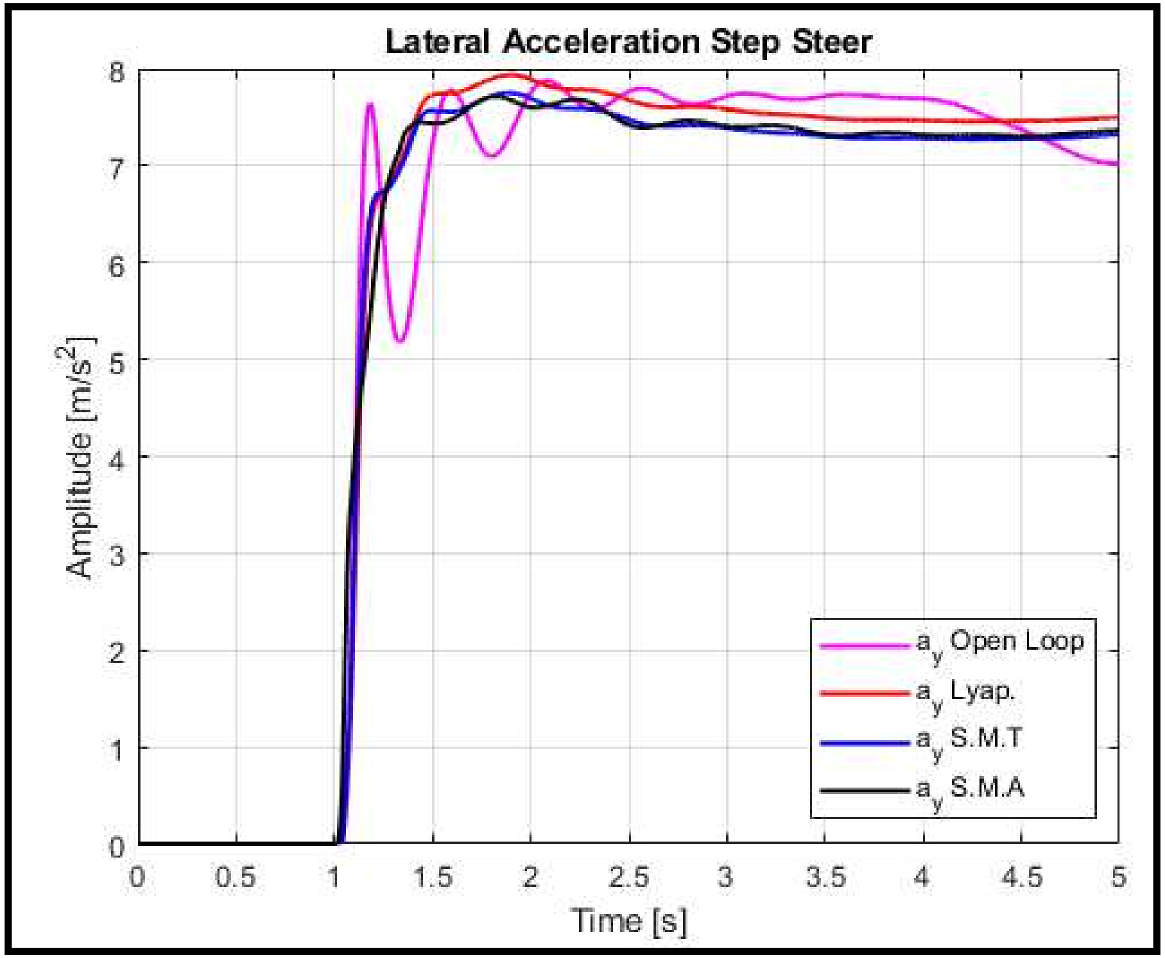
❑ Sine with Dwell



Simulation and Results

❑ **Step Steer**

- Lateral stability performance evaluation
- Steering wheel step input: 90^o
- Initial longitudinal speed: $25\mathrm{m/s}$
- Time Response- **lateral acceleration**



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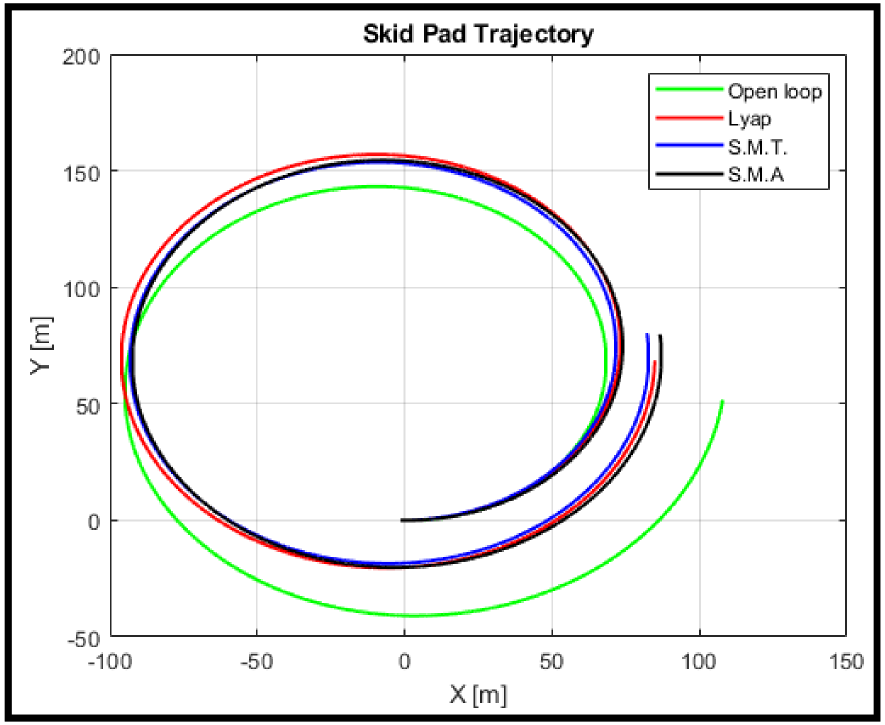
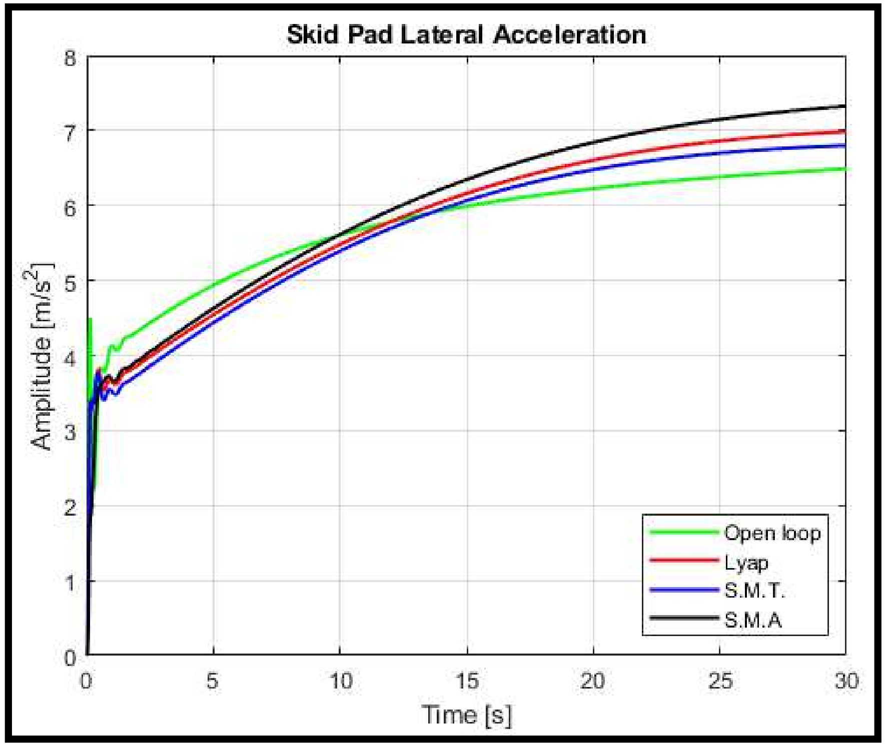
Simulation and Results

❑ Skid Pad

- Performance evaluation
- Steady state manoeuvre with constant steering wheel angle: $\mathbf{45^o}$
- Initial longitudinal speed: $\mathbf{15m/s}$ which is increasing as the manoeuvre progresses
- Time Response- **vehicle trajectory and lateral acceleration**



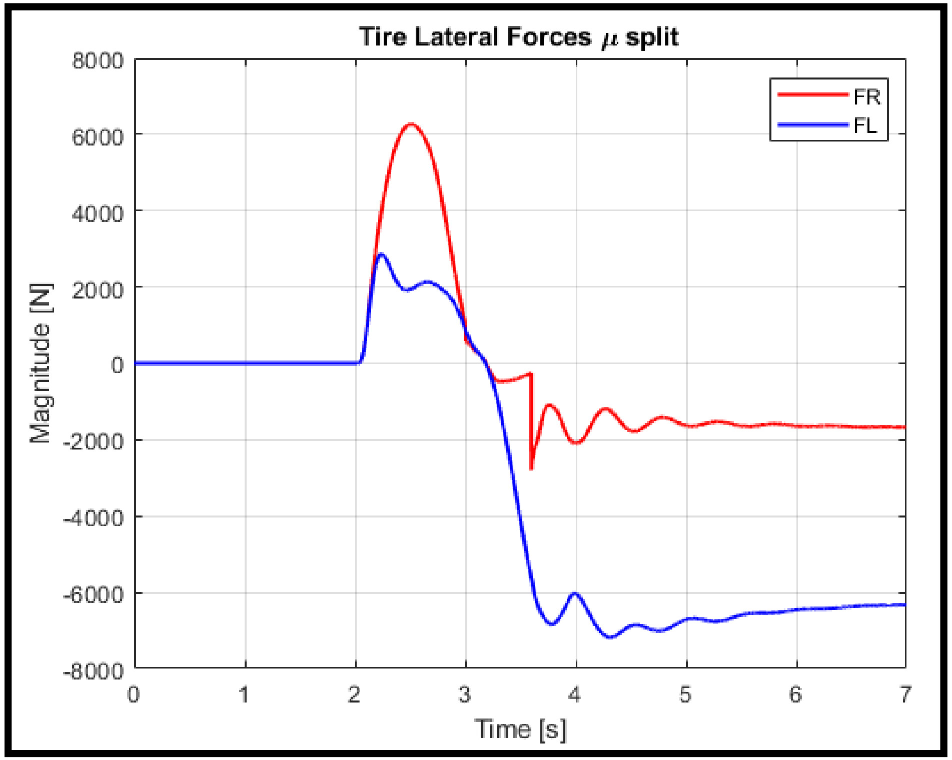


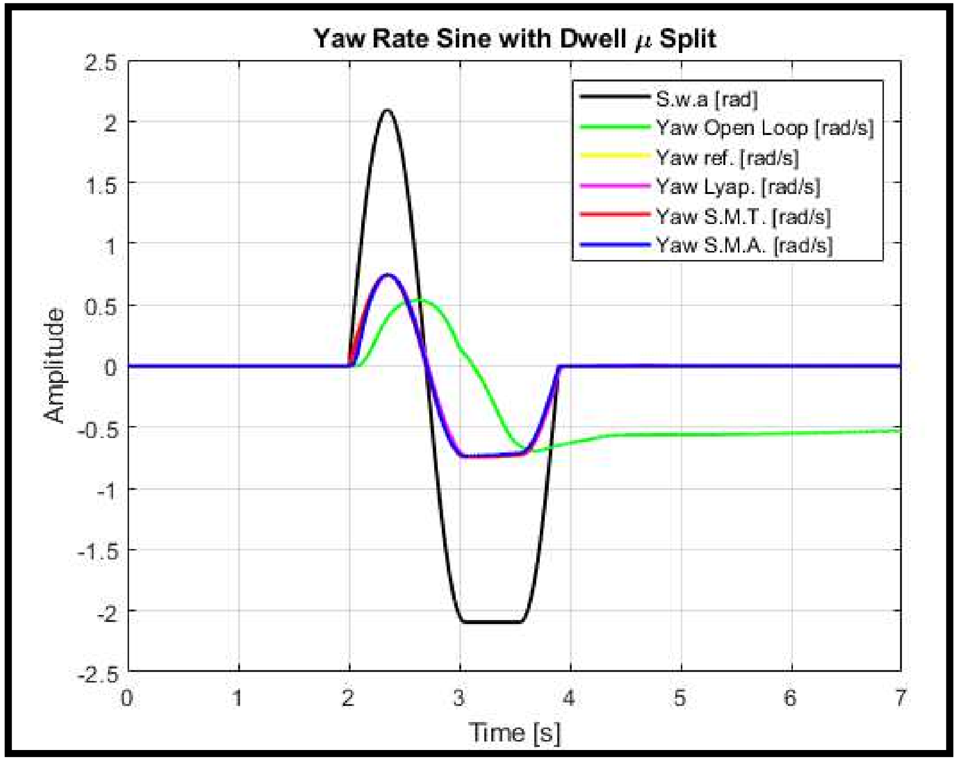
[8] "ISO 4138 Passenger cars – Steady-state circular driving behavior – Open-loop test methods"

Simulation and Results

❑ Sine with Dwell μ split

- Performance evaluation
- Initial longitudinal speed: **25m/s**
- The μ split is given in the dwell on outer wheels, with a lower friction of **0.1** on outer wheels
- Time Response- **tire lateral forces, yaw rate**





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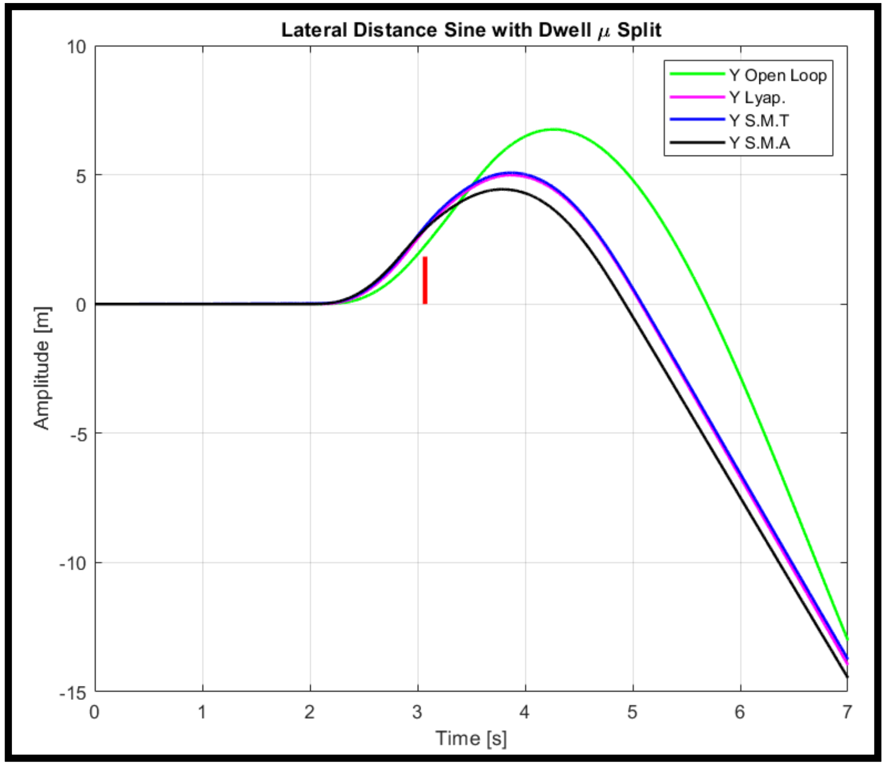
Simulation and Results

❑ Sine with Dwell μ split

- Performance evaluation
- Initial longitudinal speed: **25m/s**
- The μ split is given in the dwell on outer wheels. With a lower friction of **0.1** on outer wheels
- Time Response- **lateral distance**



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Conclusion

- **The controllers successfully track the reference yaw rate even with variations in road friction, as demonstrated in the μ split manoeuvre**
- **The introduction of an Active Front Steering correction is able to reduce the lateral velocity at the benefits of bodyslip angle β**
- **As demonstrated in Step steer, both lateral stability and comfort have been improved by reducing the oscillatory response in the lateral acceleration**
- **The Skid pad manoeuvre demonstrates that in the absence of control, the lateral acceleration exhibits a high initial response. However when steady state condition is achieved, the handling performance is degraded when compared to the closed loop response**
- **The control action ensures that a safe trajectory is achieved as compared to the open loop performance seen with μ split conditions**
- **An integrated control strategy outperformes the other approaches**

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Thank You!!!

Extra slides (1): Tuning Parameters

Controller 1

- A= 1
- B= 1
- K= 250000
- ϵ= 1

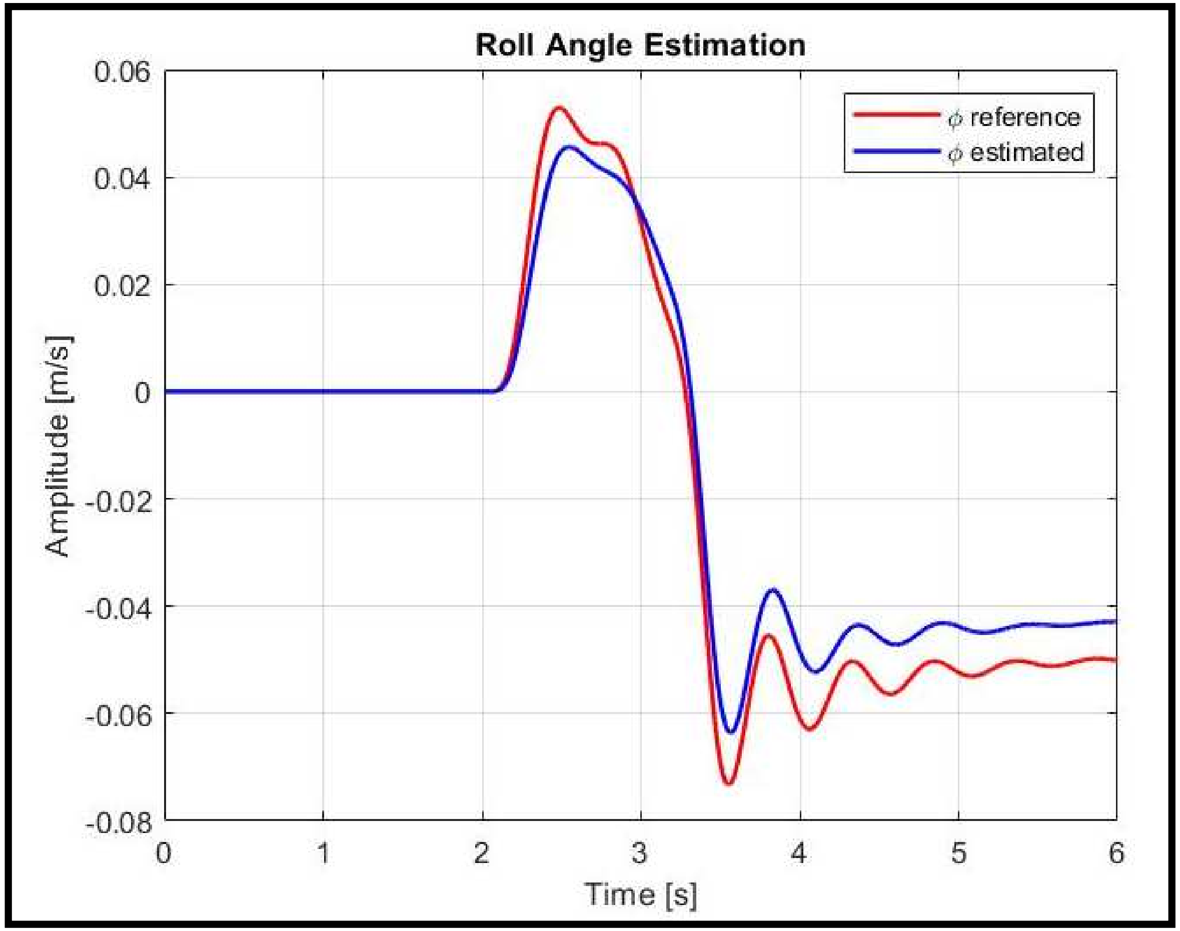
Controller 2

- W= 10^6
- σ_0= 0.1
- ρ = 10^6

Controller 3

- k_1= 20
- k_2= 55
- K= 250000
- ω_1= 3
- ω_2= 60
- η_1= 1
- η_2= 1
- γ_1= 1
- γ_2= 1
- ϵ_1= 0.001
- ϵ_2= 0.01

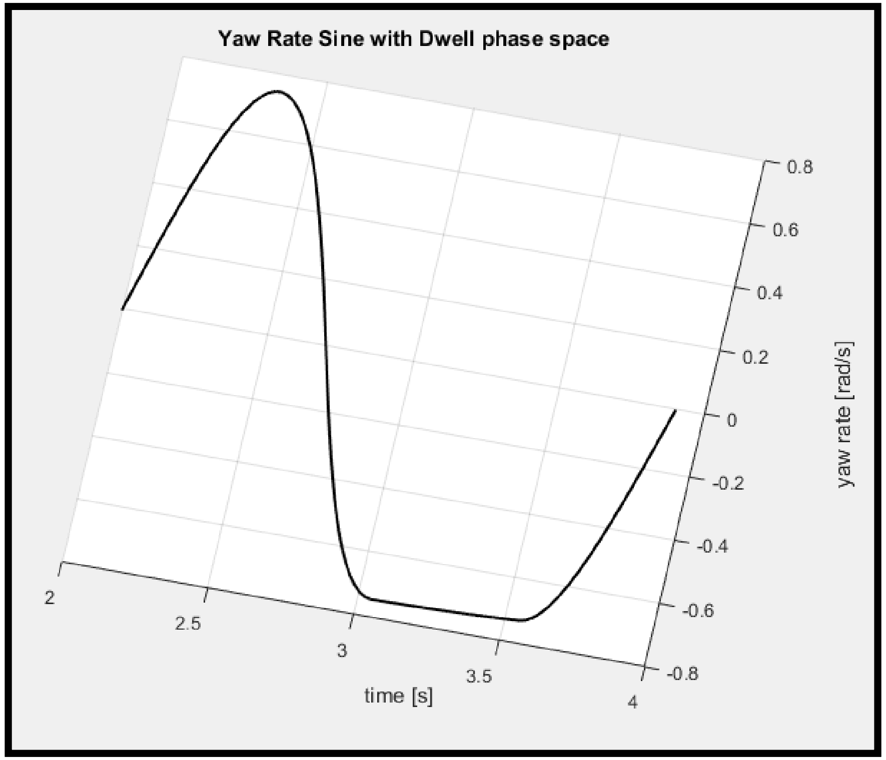
Extra slides (2): PID Controller

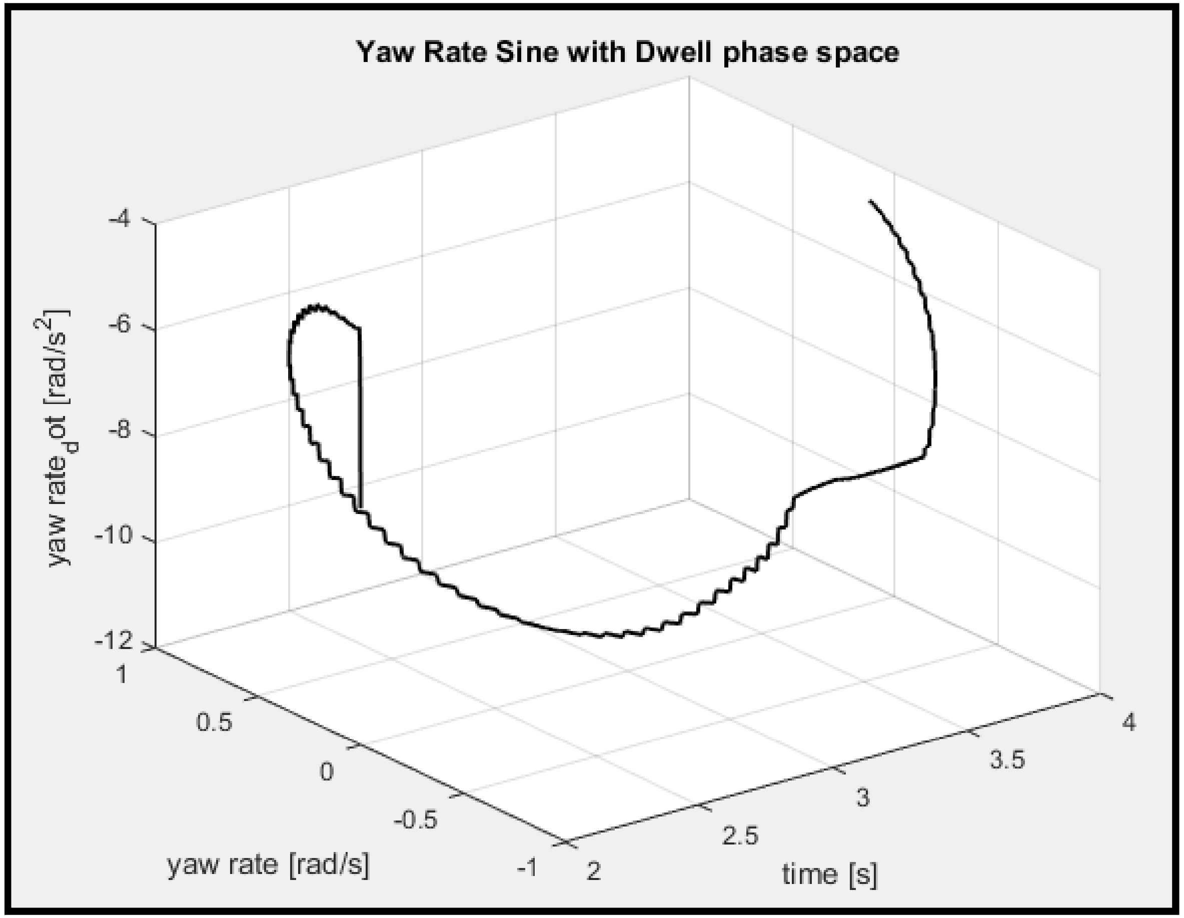


PID:

$$G(s) = 7 \cdot 10^4 \, \frac{(s+10)(s+3)}{(s+1)(s+35)}$$

Extra slides (3): Chattering





Extra slides (4): Transient response