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Original Research Article

Autonomous vehicle: A control action performance comparison

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Abstract

An autonomous vehicle is capable of maneuvering itself with little or no driver's effort. In this paper, The Adaptive Cruise Control of the longitudinal section of an autonomous vehicle is considered. The control action is evaluated by studying the tracking performance of a Linear Varying Parameter (LPV) and a Model Predictive Control (MPC) controller. The synthesized controllers were evaluated and a comparison was made between them based on robustness and performance of the controllers.

Keywords: Autonomous vehicle, LPV, MPC, control, model

1. INTRODUCTION

The advent of autonomous vehicle and its usage give rise a to new phase of technological innovation round the globe through the introduction of intelligent systems especially in the area of land transportation (Gonzalez, D., Perez, J., Malanes, V., & Nashashibi, F. 2016). Broadly speaking, autonomous vehicles are classified in to six; Level 0 refers to as "full driver" with no any form of automation, Level 1; refer to as "driver assistance" fully controlled by driver with little assistance such as electronic stability control, Level 2; refer to as "partial automation" in which the driver is complimented especially in the an area of hazard minimization, Level 3; refer to as "conditional automation" though fully autonomous but the presence of driver is necessary under certain condition, Level 4; refer to as "high automation" whereby the vehicle is fully in self-control but a manual mode is also available if the driver want to take control and finally, Level 5; refer to as "full automation" in which no human input is required (Amodio, A. 2018).

Several assistant feature advanced driver systems (ADS) are provided to achieve the control actions which are classified into two; passive and active (Amodio, A. 2018). Passive ADS function in sending signals basically as a warning in case any malfunction is detected or danger due to road condition, lane deviation etc. while in the case of active ADS is has the ability to perform some control actions such as manipulating engine power, break actuators etc.

Another important factor in handling autonomous vehicles is planning that has captured the interest of control and robotics fields of research, planning is also categorized into two; path planning which is expressed as a space function configuration of the vehicle and trajectory planning that handles mostly the dynamic problems (Paden, B., Cáp, M., Yong, S. Z., Yershov, D., & Frazoli, E. 2016),(Gerdes, C., & Rossetter, E. J. 2001).

The vehicle dynamics control is divided into lateral and longitudinal controls, in (Guo, J., Hu, P., & Wang, R. 2011) the strong nonlinearities of the longitudinal and lateral dynamics are tackled using a coordinated control of the steering and braking based on nonlinear backstepping control theory and adaptive fuzzy sliding- mode control technique, the control action was evaluated based on the tracking performance. A shared steering control using the steer-by-wire technology with safe envelopes to improve obstacle avoidance and overall vehicle stability was proposed in (Stephen, M., Susumu, F., & Christian G, J. 2016). The control action used the Model Predictive Control (MPC) scheme where the controller only intervenes when the driver trajectory is not within the designed safe envelopes (Stephen, M., Susumu, F., & Christian G, J. 2016).

Linear Parameter Varying (LPV) control approach was studied in (Gáspár, Z., Szabó,, J., Bokor, C., Poussot-Vassal, O., Sename, & Dugard, L. 2007). Based on H-infinity optimization that utilizes the steering and braking control strategy. The Linear Time Invariant (LTI) control algorithm and LPV controller were simulated. The obtained results show that the LPV control out-performed the later. In this paper, the control approach is evaluated on an MPC controller in comparison to LPV controller; the synthesized controllers are then tested on Fishhook Maneuver under different scenarios corresponding to different road conditions and wind effects. A conclusion is drawn based on the tracking ability of the controllers taking into consideration the non-linearities and other external disturbances such as noise and wind flow.

2. Vehicle Model Dynamics

The model of the vehicle based on (Gáspár, Z., Szabó,, J., Bokor, C., Poussot-Vassal, O., Sename, & Dugard, L. 2007) Was adopted to derived the non-linear LPV model. The main interest in adding the full vehicle model to the bicycle is to capture the nonlinear dynamics entering in the tire force description, global chassis dynamics and effect of dynamic parameter variation. Figure 2 shows the full vehicle model is described with the longitudinal axis (xs), lateral axis (ys), vertical axis (zs), roll (θ), pitch (φ) and yaw (ψ) dynamics of the chassis. The sideslip angle (β) dynamics as a function of the tires.

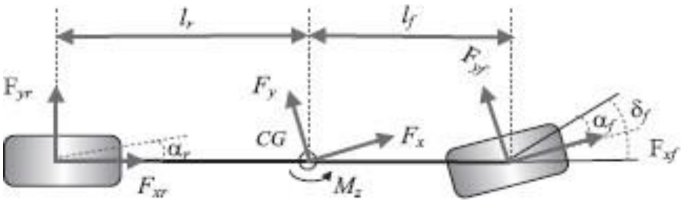

Figure: Suspension of forces

The parameters are defined as;

- m is Vehicle mass,
- I_z is vehicle yaw inertia,
- C_f linear lateral tire front cornering stiffness,
- C_r linear lateral tire rear cornering stiffness,
- I_f distance COG – front axle,
- I_r distance COG – rear axle,
- t_r rear axle length,
- R tire radius,
- T_b Change braking torque,
- g gravitational constant,
- μ − tire/road contact friction and
- δ Steering angle.

The model is derived under the following assumptions for simplicity:

1. Vertical, roll, and pitch motion are ignored
2. The braking and steering dynamics are approximated as linear first-order systems
3. The effect of suspension on the tire axels is neglected.

The dynamic model is derived using physical concepts, side slip β and the yaw rate ψ dynamics will be considered from now on. Applying Newton's law to the vehicle's longitudinal and lateral, yield (Gáspár, Z., Szabó,, J., Bokor, C., Poussot-Vassal, O., Sename, & Dugard, L. 2007):

$$mv\dot{\beta} = Fyf + Fyr + mv\dot{\psi} \quad (1)$$
$$Iz\ddot{\psi} = lf\,(-Fxf \sin(\delta) + Fyf \cos(\delta)) - IrFyr - \Delta Fxr \quad (2)$$

Where,

$$\beta = \frac{\dot{y}s}{\dot{x}s} \qquad v = \sqrt{\dot{x}s + y\dot{s}},$$

$$\Delta Fxr = Fxrl - Fxrr = \frac{uRmrg}{2}(Tbrl - Tbrr)$$

By substituting ΔFxr in equation

Yields;

$Iz\ddot{\psi} = lf\,(-Fxf \sin(\delta) + Fyf \cos(\delta)) - IrFyr - uRmr\,2\,g\,(Tbrl - Tbrr)\,tr + Mdz$ (3)

Fyf and Fyr can be modelled using Pacejka's tire model [9] as follows:

$Fyf = Cf\,(\delta - \beta - \frac{\text{If}\dot{\psi}}{\beta v})$ and $Fyr = Cf\,(-\beta - \frac{\text{Ir}\dot{\psi}}{\beta v})$

The evolution of side slip and yaw rate can be expressed in state space representation as follows:

$$\begin{bmatrix}\dot{\beta}\\ \ddot{\psi}\end{bmatrix} = \begin{bmatrix} -\mu\frac{C_f+C_r}{mv} & 1+\mu\frac{-I_fC_f+I_rC_r}{mv^2} \\ \mu\frac{-I_fC_f\cos\delta+I_rC_r}{I_z} & \mu\frac{-I_f{}^2C_f\cos\delta-I_r{}^2C_r}{I_zv}\end{bmatrix}\begin{bmatrix}\beta\\ \dot{\psi}\end{bmatrix} + \begin{bmatrix}\frac{C_f}{mv} & 0 & 0 \\ \frac{I_fC_f\cos\delta}{I_z} & \frac{1}{I_z} & \frac{-\mu RM_rt_rg}{2I_z}\end{bmatrix}\begin{bmatrix}\delta \\ M_{dz} \\ \Delta T_b\end{bmatrix}$$

For the purpose LPV control synthesis, (t) and $\delta(t)$ are considered as time varying parameters. A linear version of this model can be derived around the following equilibrium point to ensure a stable model. It was therefore assumed that Steering angle $\delta = 0$, Low steering angle $\cos(\delta) = 1$, velocity ratio as well as slip angle are both low. The linear version of the model used for design and simulation of Linear MPC is as shown below.

$$\begin{bmatrix}\dot{\beta}\\ \ddot{\psi}\end{bmatrix} = \begin{bmatrix} -\mu\frac{C_f+C_r}{mv} & 1+\mu\frac{-I_fC_f+I_rC_r}{mv^2} \\ \mu\frac{-I_fC_f+I_rC_r}{I_z} & \mu\frac{-I_f{}^2C_f-I_r{}^2C_r}{I_zv}\end{bmatrix}\begin{bmatrix}\beta\\ \dot{\psi}\end{bmatrix} + \begin{bmatrix}\frac{C_f}{mv} & 0 & 0 \\ \frac{I_fC_f}{I_z} & \frac{-\mu RM_rt_rg}{2I_z} & \frac{\mu RM_rt_rg}{2I_z}\end{bmatrix}\begin{bmatrix}\delta \\ T_{brl} \\ T_{brr}\end{bmatrix}$$

Polytopic LPV control

The working principle of polytopic LPV with a given number of parameters dependence ρi is summarized below (Guo, J., Hu, P., & Wang, R. 2011):

With parameter affinity, vector of parameters evolves inside a polytope represented by $Z = 2^N$ vertices ωi, number of vertices of the polytope formed by the extremum values of each varying parameter. Having two varying parameters, Z corresponds to four vertices.

The controller will have a form of: $(\rho) = \sum_{i=1}^{N} \alpha i(\rho) \begin{bmatrix} A\omega i & B\omega i \\ C\omega i & D\omega i\end{bmatrix}$ subjected to convex combination as with $\sum_{i=1}^{2^N} \alpha i(\rho) = 1$ *and* $\alpha i(\rho) > 0$.

$\begin{bmatrix} A\omega i & B\omega i \\ C\omega i & D\omega i\end{bmatrix}$ Are LTI controllers at each vertex schedule with $(\rho) = \frac{\bar{\alpha}-\alpha}{\bar{\alpha}-\bar{\alpha}}$-. To Ensure the stability of the system it was established that $A^T(\rho) + XA(\rho) < 0$.

2.1. Control Structure

In order to perform the controller synthesis a control structure is needed to be define weighting functions and input disturbances. A tracking error (We) and three controls $Wu1$, $Wu2$ and $Wu3$ are considered in the design. The figure below shows the control structure employed for the control synthesis.

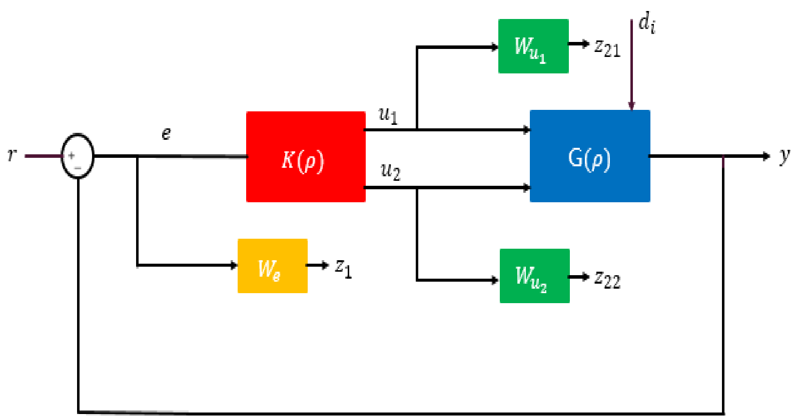

Figure: 2.1 control structure.

$z1$, yaw rate error exogenous output signal, is the output of the tracking error performance weight defined as;

$$We = \frac{1}{2\gamma}\left(\frac{\frac{s\gamma}{2\pi f_1}+1}{\frac{s}{2\pi f_1}+1}\right)$$

Where $f1 = 1Hz$ is the cut-off frequency of the high-pass filter, $\gamma = 0.1$ is the attenuation level for low frequencies yield (static tracking error ≤ 10%).

$z2$, the exogenous steering control signal attenuation, is the output of the steering control performance weight defined as;

$$w_{u1} = G_\delta\left(\frac{(\frac{s}{2\pi f_2}+1)(\frac{s}{2\pi f_3}+1)}{(\frac{s}{2\alpha\pi f_3}+1)^2}\right)$$

Where $f3 = 10$ Hz is the steering actuator bandwidth and $f2 = 1$Hz is the lower limit of the actuator intervention. This filter is designed in order to allow the steering system to act only in the region of interest $[f2, f3]$, the steering action is allowed and gain amplification bounded by $G\delta = 5 \times 10^{-3}$. The interest of such complex filter is to allow the steering system to act at frequencies the driver is not able to provide, while handling the actuator limitations.

$z3,4$, the exogenous braking control signal attenuation, is the output of the braking control weight defined as;

$$w_{u3,u4} = G_T\left(\frac{(\frac{s}{2\pi f_4}+1)}{(\frac{s}{2\alpha\pi f_4}+1)^2}\right)$$

Where $f4 = 10$ Hz as the braking actuator bandwidth, $\alpha = 100$ as the roll-off parameters (chosen to handle the dynamical braking actuator limitations) and $G = 4 \times 10^{-4}$ is the allowed amplification gain of the control input which given to avoid saturation of control signal.

Generalized Plant

Taking into consideration three varying parameters $\rho 1 = \frac{1}{v}$, $\rho 2 = \frac{1}{v}2$ and $\rho 3 = cos\delta$, oriented control model from equation (1) yield:

$$(\rho): \begin{cases} \dot{x}(t) = A(\rho)x + B(\rho)u(t) \\ y(t) = C(x) \end{cases} \quad (4)$$

As a necessary condition for Polytopic LPV, the input matrix (A) is parameter independent, thus, decouple with a low pass filter. The generalize plant can be represented in state form as follows:

$$\begin{bmatrix} \dot{x} \\ z_1 \\ z_2 \\ y - r \end{bmatrix} = \begin{bmatrix} A_p(\rho) & B_1(\rho) & B_2(\rho) \\ 0 & w_e & -w_e G(\rho) \\ 0 & 0 & w_u \\ 0 & -1 & G(\rho) \end{bmatrix} \begin{bmatrix} x \\ w \\ u \end{bmatrix}$$

3. Results and Analysis

The synthesis controllers were compared between the NMPC and the LPV simulated on the non-linear model. However, the control synthesis for LPV was performed on the linear model. A detailed comparison was made on the performance of robustness of both techniques under different scenarios based on road conditions. The fish hook maneuver scenario was used to evaluate the dynamic rollover stability because it ensures that the vehicle did not rollover in a situation of avoidance maneuver. The fish test maneuver scenario is shown in figure 3.1.

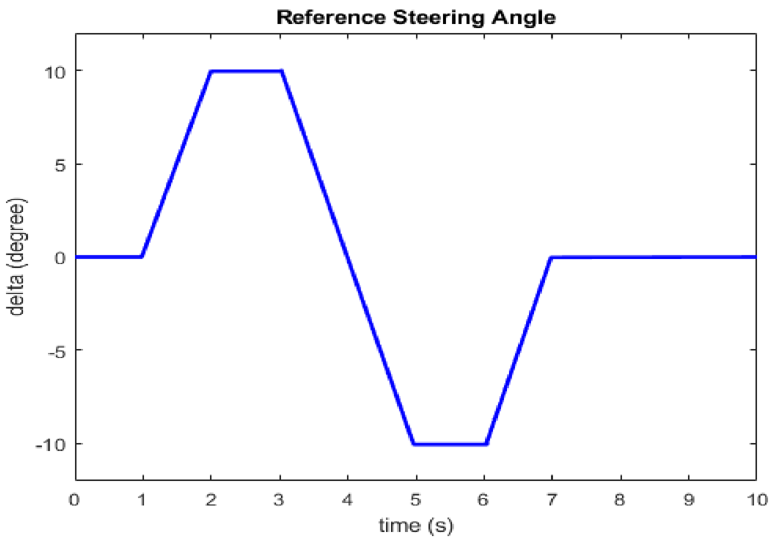

Figure 3.1: Fishhook maneuver

Road Conditions and Wind Effect

The nonlinear model considered for the longitudinal and lateral dynamics of the vehicle takes into account the road conditions (μ) and the wind affecting the vehicle Mdz. The value of μ and Mdz lies in the intervals [0.2, 1] and [0, 1] respectively. The lower value of μ corresponds to wet road conditions while 1 corresponds to dry road conditions. Good tracking performance is among the most important performance indicators for a control system design, Figure 7 and figure 8 shows the tracking performance of LPV and NMPC on fishhook maneuvers under configuration-1 and configuration- 2.

Configuration	Parameters	LPV Yaw Error ($L2$-Norm)	MPC Yaw Error ($L2$-Norm)
C-1	Mdz = 0.2, Ur = 0.5, v= 8 m/s	1.1450	1.2841
C-2	Mdz = 0.2, Ur = 1, v= 8 m/s	1.0904	0.6695

Table 3.1 parameter configuration table

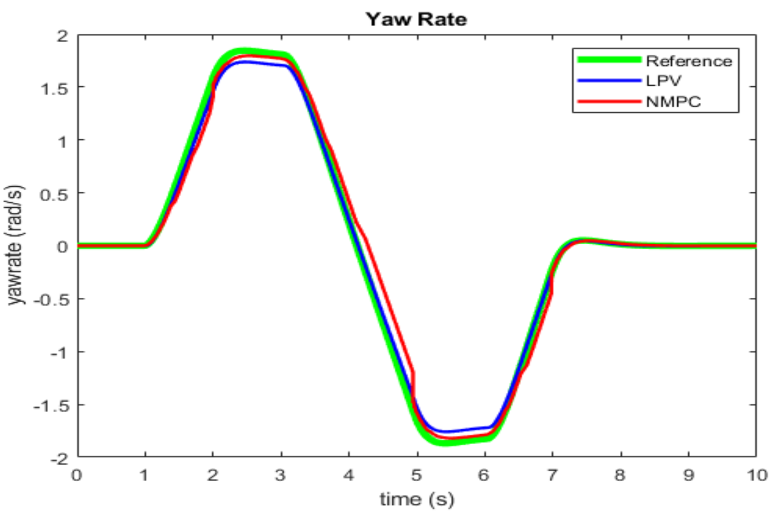

Figure 3.2: Tracking performance of MPC and LPV for Fishhook maneuver under C-1

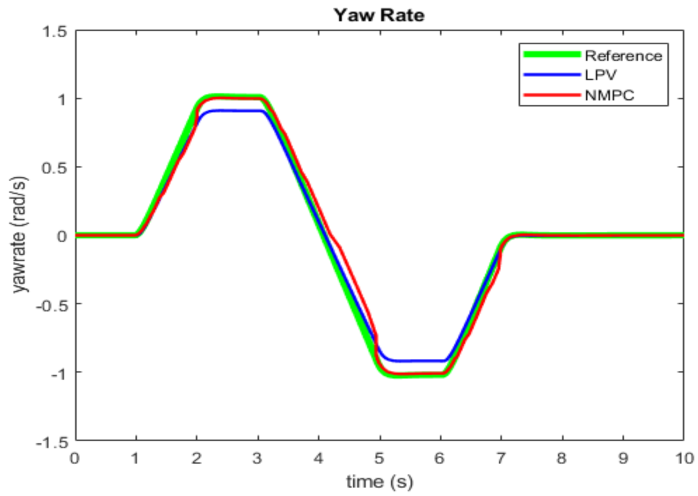

Figure 3.2: Tracking performance of MPC and LPV for Fishhook maneuver under C-2

Figure 7 and figure 8 shows the tracking performance of LPV and NMPC control design strategies at different values of μ and Mdz which corresponds to different scenarios. From figure 7, the tracking performance of LPV is better as compared to NMPC in the first scenario whereas NMPC performs better as compared to LPV in the second scenario.

4. CONCLUSION

In this paper, the control design of lateral and longitudinal dynamics of autonomous vehicle using state of the art techniques including linear parameter varying (LPV) and model predictive control (MPC) was developed. The synthesized controllers are then tested on Fishhook maneuver under different scenarios corresponding to different road conditions and wind effects. A comparison was made based on the tracking performance and robustness of LPV and MPC. From the comparative studies, we can conclude that, the overall tracking and robustness characteristics of LPV controller are slightly better as compared to the NMPC controller.

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