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Input Shaping Control Of A Steer-by-Wire Vehicle For Yaw Stability

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Abstract

There are several ways to incorporate electronic yaw stabilization into the vehicle design. The most popular ones are differential braking or torque distribution, although a better alternative would be the inclusion of a controller into the steering process. However, this is not often pursued, since in a steering system that has a physical coupling between the steering wheel and the vehicle’s wheel, the controller could actually start working against the driver resulting in challenges to safety. This problem can be solved by the incorporation of a steer-by-wire system in the vehicle, which is starting to gain traction due to the rapid development in autonomous and semi-autonomous vehicles. There are many steering assistance systems already available, but most of them focus on either adaptive steering control (adaptive power steering and gear ratios) or total steering control in autopilot functions (lane keeping control). Active safety systems can also be deployed using a steering controller, where in based on the potential advantages of steer-by-wire, the vehicle can have an improved driving performance and maneuverability. In this paper, we introduce a new pure feedforward (open loop) controller for the steer-by-wire system based on the concept of input shaping which aims to reduce the vibration/oscillation caused in vehicles during fast maneuvers.

INTRODUCTION

Vehicle yaw and rollover stability during safety-critical maneuvers when the driver is out of the loop has been a topic of interest for quite some time owing to recent advancements in advanced driver assistance systems (ADAS), semi-autonomous and autonomous vehicle systems [1],[2]. Traditionally, vehicle yaw stability has been achieved using differential braking or torque distribution whereas steering control has been used only for assistive systems such as lane keep systems.

In modern vehicles, steering control is essential for several of the active safety systems such as Lane keep system, Emergency braking system, Active rollover safety system, Electronic stability control, etc. In a mechanical steering system, variable time delays exist between the driver’s inputs and the responses of the vehicle dynamic states during a critical steering course. And due to the non-uniform delay of active brake actuators, a sideslip or a rollover may occur even to a vehicle with a traditional stability control system. This is one of the main reasons why drive-by-wire is a key enabling technology for autonomous vehicle development because safety can be improved by providing computer-controlled intervention of vehicle controls as the steering wheel can be simply bypassed as an input device [3]. Additionally, the fast response time and increased accuracy contributes to improved maneuverability that requires small maneuvering angles.

There has been a growing trend in SbW vehicles in recent times. For example, Infiniti Q50 started incorporating steer-by-wire systems into their vehicles since 2014. Although it faced initial negative reviews, the new revamped version released in 2017 has been widely appreciated [4].

This provides several new opportunities for steering controller development for vehicle safety systems. Although there are several open-ended research areas to be addressed in the steer by wire system’s development space [5], we have chosen to focus only on developing a new steering controller that is effective for ADAS, semi-autonomous and/or autonomous vehicles.

As the responsibility of driving moves further and further away from the driver, the complexity of the algorithms increased multifold. These complexities need a high amount of computation to execute successfully in real-time which is an important factor for consideration while developing control algorithms. One such algorithm is the Input Shaper, a technique where the input to the system is shaped for the control of residual vibration. The algorithm has been explored before in applications relating to crane systems [6][7] but has never been applied to vehicles. The vehicle yaw stability controlled by steering input is also often susceptible to resulting in residual oscillations during safety critical maneuvers (high speed lane change, double lane change, etc.) due to the inertia in the system. Precise position control and rapid (low maneuver time)

rest-to-rest motion is critical during such maneuvers. This requires reducing the inertia of the structure which then results in low frequency dynamics. If the vibration caused in a vehicle is considered in the control model, then timely commands that ideally results in zero residual vibration can be generated to filter out unwanted excitations that could result from the human/planner-generated command signal.

In order to establish metrics for our controller’s performance, we refer to a well-established low computational steer-by-wire (SbW) feedback control algorithm described in a further section.

The mathematical equations of motion used for developing the controller model and the plant model also are presented below in considerable detail. All simulations were performed using Matlab/Simulink [8].

Vehicle DYNAMICS MODELs

The vehicle dynamics model used for our controller design combines the chassis model and the tire-force (Pacejka) model [9]. We use two chassis models in this paper:

*Four-Wheel vehicle model:* The more complex model is the planar 4-wheel vehicle model with yaw, roll and pitch dynamics along with longitudinal and lateral load transfer. This model is used as our plant for controller validation.

*Non-linear bicycle model:* This model combines the left and right wheel on each axle from the Four-wheel model together. Further, the roll and pitch dynamics are neglected resulting only in yaw dynamics. Thus, the model has two translational and one rotational degrees of freedom. This model is used as primary model for control development.

The model equations used in this paper are presented here. For further details on the models please refer the respective papers cited which is where the equations are derived and presented in detail.

Nomenclature

Non-Linear bicycle model

The non-linear bicycle model has 2 translational and 1 rotational degrees of freedom. The derivation and free body diagram (FBD) can be found detailed in [10].

*Equations of Motion for the Chassis*

, and

The normal forces at front and rear are given by and , where

*Equations of Motion for the Wheels and Tires*

The slip angles, slip ratios and wheel speeds are given by

Where and

The nominal tire forces according to the Magic formula [7] are given by:

The lateral combined forces are given by the friction ellipse described by the ellipse equation

The longitudinal combined forces are given by and

The rotated lateral combined forces are given by and

FOUR-Wheel VEHICLE model

The Four-wheel vehicle model equations of motion are presented here. For derivations. FBD and details refer [11].

*Equations of Motion for the Chassis*

, and

The normal forces at the wheels are given by solving the set of following 4 equations

*Equations of Motion for the Wheels and Tires*

The slip angles, slip ratios and wheel speeds are given by (i=1,2,3,4):

Where , ,

and

The nominal tire forces according to the Magic formula are given by:

The lateral combined forces are given by the friction ellipse described by the ellipse equation

The rotated combined forces are given by

and

Steer-by-wire Feedback controller

In this feedback based steering control for yaw stability the assumption is of a front wheel drive vehicle. The effective road-wheel steering angle at the front wheels is a sum of driver input/planner input and the controller-decided compensation to enforce stability and safe maneuvering. It compensates for the driver’s understeer or oversteer to prevent skid. The feedback term should not interfere with the vehicle’s desired path and is for stability and safety only. The controller presented here was first proposed in [12] and can be referred to for further details. We used this controller as a comparison for our own controller. The design of the controller is presented below.

According to *Rajamani et al,* the SbW controller’s compensation steering angle rate is given by the control law:

is the vehicle’s actual yaw rate in the current time step.

is the vehicle velocity angle at the front tires which is described by the state equation:

Where is the lateral acceleration at any point P in the vehicle and is given by:

Lastly, is a function chosen based on just the driver input and is considered as the desired yaw rate corresponding to the driver input. Essentially this means that the control law uses the error in the desired yaw rate () as the feedback term in order to calculate the compensation term .

We decided to choose the tuning function to be the desired yaw rate of the driver assuming a neutral steer condition which is the type of maneuver usually achieved by an ADAS or Semi/Fully autonomous vehicle.

Hence the desired yaw rate is given by where R is the road curvature.

Relating to δ, R is given by:

The where is a feedback gain to fine tune the controller performance (ideally it is of value 1).

The control structure/architecture of this SbW controller is presented in Figure 1.

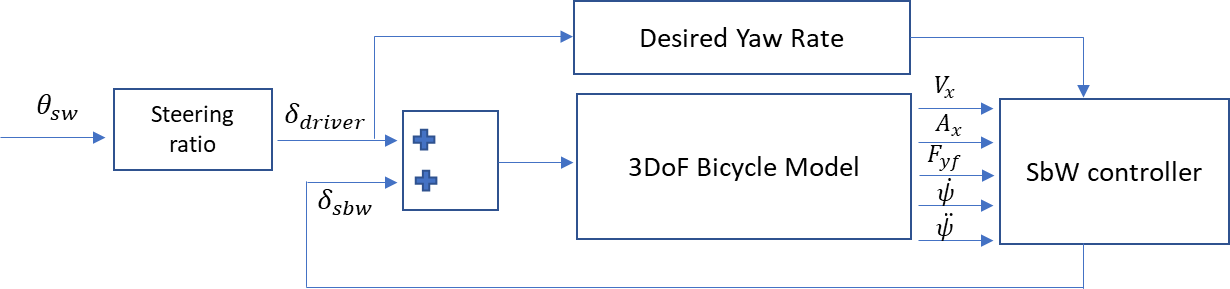


Figure 1: Control structure for the feedback SbW controller.

Steer-by-wire FeedForward controller

The purpose of an input shaper is to control the self-induced vibrations (oscillations) in linear or quasi-linear dynamic systems. A vehicle exhibits oscillatory behavior due to its inertia during high speed maneuvers such as lane change, double lane change, fishhook, etc. These oscillations might be exacerbated by unnecessary inputs from the driver or planner.

This technique is advantageous in terms of computational capacity, design complexity and hardware necessities since it involves a simple convolution of the driver inputs with a series of designed impulses. It is also a feedforward/open-loop control technique where there is no necessity for measurements.

In this paper we attempt to design this controller based on the parameters of a bicycle model that has been linearized around small steering angles and constant velocity. The equations presented here are an adaptation from [13] and has been redesigned specifically for the vehicle stability scenario.

In order to curb oscillations, the first step is to ensure zero vibration in the system while it is moving. This can be done by introducing a second impulse to counteract the first impulse caused by the input. Given a system’s approximate natural frequency () and damping ratio (ζ), the vibration caused by a sequence of impulses can be calculated as:

(1)

Where,

(2)

(3)

and are the amplitudes and time locations of the impulses and n is the total number of impulses. Additionally, is the damped natural frequency of the system.

Now by setting , we can solve for the amplitudes and placement time of those amplitudes. This when given in sequence will cause zero vibration in the system. Now since, we don’t want the solutions to converge to zero or infinity, we need to place certain constraints on the amplitudes of these impulses which are:

We are implementing a two-impulse controller (n=2) for the SbW controller. Assuming the first impulse’s time location to be at t=0, for . Hence, we must now solve for , and .

For (1) to be 0, (2) and (3) each must equal to 0. Hence,

The final solution is given below, but the complete derivation can be found in [13].

where i=1,2 and

is the damped period of vibration

Now we calculate the required parameters based on a linearized bicycle model, where the A matrix is given by

The natural frequency of the system (), damping ratio (), damped natural frequency () and the damped time period () are given by:

.

is the tangential velocity of the vehicle with respect to the road curvature and is given by . Lastly, and are the cornering stiffnesses at the front and rear tires. Here it is approximated to be 16.5% of tire load per radian of slip angle [14]. This implies:

where are front and rear load distribution ratio for the vehicle (). Now we have all the parameters necessary to design a two impulse input shaper.

Results

For the controller to be verified, we put the vehicles through the fishhook maneuver test and the double lane change maneuver test.

1. Fishhook maneuver test: The vehicle drives at 50 miles per hour. The steering wheel is turned left and then right and is held at the right turn for half a second before straightening out. The maneuver is performed with more severe steering angles. [15]
2. Double Lane Change maneuver test: It is representative of an emergency maneuver case where the vehicle must be steered to the adjacent lane and back. [16]

The below plots describe the performance of the uncontrolled vehicle, Feedback controlled vehicle and the feedforward-controlled vehicle.

References

Put references here.