

Development of Decentralized Integrated Chassis Control for Vehicle Stability in Limit Handling

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ABSTRACT

As we move towards the world of autonomous vehicles it becomes increasingly important to integrate several chassis control systems to provide the desired vehicle stability without mutual interference. The principles for integration proposed in existing technical literature are majorly centralized which are not only computationally expensive but does not fit the current supplier based OEM business model. An Automotive OEM brings multiple suppliers on-board for developing the Active Safety systems considering several factors such as cost, quality, time, ease of business etc. When these systems are put together in the vehicle they may interfere with each other's function. Decoupling their function results in a need of heavy calibration causing performance trade-offs and loss in development time. This puts forward a need for an algorithm which integrates individual control systems supplied by different vendors and enable them to function simultaneously to meet the vehicle dynamics performance criteria. To recreate the above scenario, individual control systems viz. Electronic Stability Control (ESC), Active Front Steer (AFS) and Active Suspensions have been developed and validated independent of each other using Matlab Simulink and CarSim. Further, two integrated chassis control approaches have been proposed. The first approach involves fractionating the output signals of individual control systems based on a vehicle velocity based 'Relative Gain Array' approach. The second approach demonstrates a friction circle monitoring approach to operate the tire within friction limits. This paper will present control algorithms of the above proposed approaches. Finally, the proposed approaches are evaluated for their performance and robustness to variations.

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INTRODUCTION

The importance of ride, handling, comfort and stability of the vehicle has grown largely in recent years. To meet the expectations of the customer and tight safety regulations, Automotive OEMs are providing several actively controlled systems which can accommodate and improvise on limitations of mechanical components to deliver the required specifications. In today's typical vehicle, there are currently over 40 active control systems operating together [1]. In such scenario, the precise integration of these systems becomes vital such that they work in harmony instead of interfering with each other's function to deteriorate the performance of the vehicle. Researchers and the automotive industry are working on developing different algorithms to achieve this.

The technical literature on the Integrated Chassis Control is majorly divided in two categories. The first category of algorithm proposes a master controller which calculates the demand based on vehicle states and then allocates the control input to different sub-control systems. This approach is referred to as the Centralized approach. Wang and Longoria propose an algorithm for yaw stability during limit handling where a Sliding mode controller calculates the desired stabilizing yaw moment (the demand), and then commands ABS and steer by wire to develop necessary tire slip ratio and slip angle respectively [4]. Another approach proposed by Hou and Zhang, describes an

Adaptive fuzzy logic controller and fractional PID controller which distribute the desired yaw moment to Vehicle Dynamics Control (VDC) and Active Front steer (AFS) [7]. Other algorithms include a supervisory control which allocates control input based on optimization [5] and based on the vehicle response [10]. The above mentioned approaches have superior performance however are costly and computationally expensive. Importantly, they often do not fit into the supplier OEM model of existing product development process. For e.g. an Automotive OEM may have one supplier for brake controls and a different one for steering controls. Each supplier develops its own control system and delivers finished control module to the OEM. Each control module has its own supervisory and lower level controller. Therefore, the idea of Centralized control of having just one master controller would require a single supplier to develop all subsystem controls which is practically not feasible.

The second category of algorithms propose a decentralized approach where control inputs generated by individual control systems (based on references and vehicle states) are coordinated before they are sent to actuators. The decentralized approach treats each control system as a black box with only inputs and outputs known. This approach is implementable in OEMs. The simplest idea of decentralized controller would be decoupling of control inputs. However, this

approach requires rigorous calibration for robustness as observed in current industry practices. [3] and [12] propose rule based and fuzzy logic algorithms for decoupling control systems.

This puts forwards a need for developing a controller which coordinates the control inputs of individual systems based on a model based approach to account for change in references and disturbances. Youseok Kou proposes an offline Model Predictive control to reduce computations and online fixed point allocation for coordinating control commands [2].

This paper attempts to develop a decentralized approach which requires a negligible increase of the computational power compared to the decoupling approach, but which delivers superior performance and is robust to variations. A gap analysis in Figure (1) elaborates this on a complexity vs performance scale.

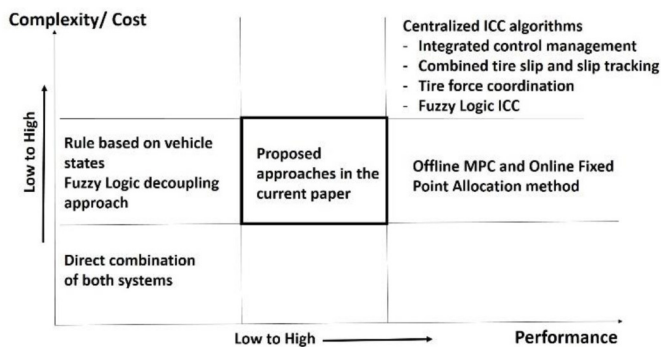


Figure 1. Gap analysis showing different ICC approaches placed on a complexity vs performance scale. The comparison is relative to one another.

The first section of the paper deals with the development and validation of individual control systems viz. Electronic Stability Control (ESC), Active Front Steer (AFS) and Semi-Active suspensions. These individual systems are modelled in Matlab/ Simulink and validated by a software-in-loop simulation using CarSim on standard test tracks. The second section of the paper deals with the development of the integration methodologies for these individual control systems. Two decentralized approaches were developed. The first approach involves fractionating the output signals of individual control systems based on a vehicle velocity based 'Relative Gain Array' approach. The second approach demonstrates a friction circle monitoring approach to operate the tire within friction limits.

The last section of the paper compares performance of the decentralized control with individual control systems. It also demonstrates robustness of these algorithms for variations in road surface conditions and vehicle loading conditions.

INDIVIDUAL CONTROL SYSTEMS

The typical approach followed to design a control system is to first assume a simplified yet realistic vehicle model (Plant). The control algorithm is designed for this plant with vehicle states as the input to the controller. Gains of the controller should be such that they should be able to track the reference, reject disturbances and accommodate differences in the actual non-linear vehicle model and the simplified

model. Similar approach is followed to design individual control systems viz. Electronic Stability Control (ESC), Active Front Steer (AFS) and Semi-Active suspensions.

To recreate the business model of multiple suppliers and one OEM, the above control systems are designed independent of each other using different vehicle models. They are also validated independent of each other on different vehicles and test procedure in CarSim.

Electronic Stability Control (ESC)

A 3-DOF yaw plane model shown in Figure (2) is considered for developing the control algorithm for ESC. This model is a bicycle model together with longitudinal dynamics that is used to include the effects of speed and yaw motion change resulted from differential braking. The wheel rotational dynamics is captured using the model also shown in Figure (2).

Model assumptions are listed below.

1. Roll Dynamics is neglected.
2. Linear tire model for lateral forces at smaller angle.
3. Rolling resistance is neglected.

The yaw motion of the vehicle can be described by equation (1).

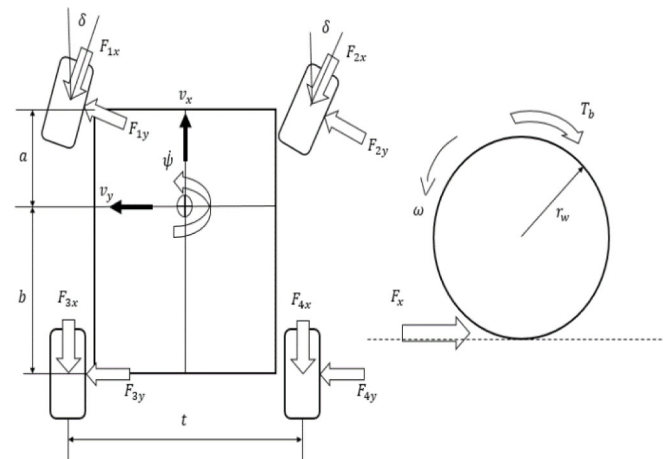


Figure 2. 3 DOF vehicle model (left); Wheel rotational dynamics (right)

$$I_{zz}\ddot{\psi} = \left[a(F_{1y} + F_{2y}) \cos \delta - b(F_{3y} + F_{4y}) + (\cos \delta + \rho) \left(M_{\psi b} + \frac{t}{2}(F_{2x} - F_{1x}) \right) \right] \quad (1)$$

Where, $M_{\psi b}$ is the yaw torque from differential braking. ρ is the front to rear brake bias.

Further the dynamics of the wheel can be represented by equation (2).

$$I_w \dot{\omega} = F_x r_w - T_b \quad (2)$$

Where, T_b is the braking torque and is the control input.

A sliding mode control methodology is chosen to develop the control algorithm for ESC as shown in Figure (3) and this approach is chosen because of its effectiveness in handling the approximations vehicle model or reference. [6]

The supervisory ESC controller calculates the desired yaw rate from drivers steering input. Based on the error is actual and desired yaw rate the stabilizing yaw moment is defined. If the conditions for the ESC actuation are satisfied then the stabilizing yaw moment is converted to longitudinal slip for individual wheel and provided to the ABS actuator.

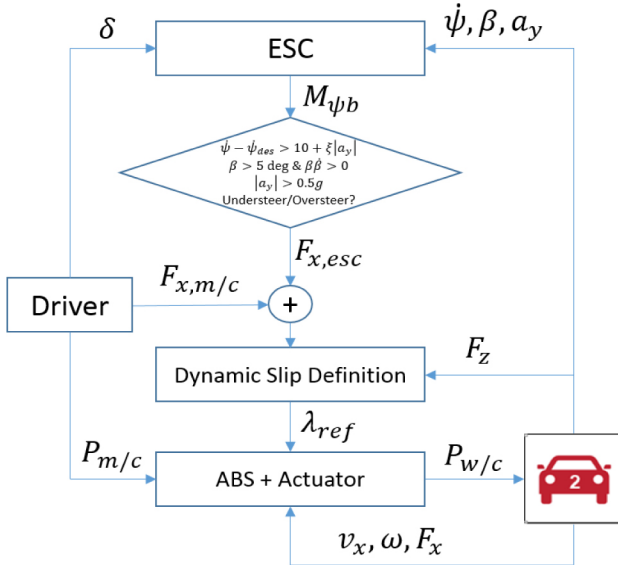


Figure 3. The ESC control algorithm flow chart.

The control input (brake application) is applied to specific wheels based on the Table (1).

Table 1. The ESC wheel select logic based on direction of turn and understeer/oversteer

	Understeer	Oversteer
Left Turn	Rear Left	Front Right
Right Turn	Rear Right	Front Left

Anti-lock Braking System (ABS) controller regulates the wheel cylinder pressure at each wheel to achieve the reference slip defined by the dynamic slip definition thereby generating the desire longitudinal force. This also prevents wheel lock up during ESC operation.

The sliding surfaces for the ESC and ABS controller are given by equations (3) and (4).

$$s_{esc} = \dot{\psi} - \dot{\psi}_d + \xi\beta \quad (3)$$

$$s_{abs} = \lambda - \lambda_d \quad (4)$$

Where, β represents the vehicle side-slip angle, λ is the tire longitudinal slip ratio. The control outputs from above controllers are the stabilizing yaw torque and braking torque respectively and are given by equations (5) and (6). [6][11]

$$M_{\psi b} = \frac{I_{zz}}{(\cos \delta + \rho)} \left[-\frac{a}{I_{zz}} (F_{1y} + F_{2y}) \cos \delta + \frac{b}{I_{zz}} (F_{3y} + F_{4y}) - \eta s + \ddot{\psi}_d - \xi \dot{\beta} \right] \quad (5)$$

$$T_b = F_x r_w - (1 - \lambda) \frac{\dot{w}_x I_w}{r} + \lambda_d \frac{w_x I_w}{r} - K \tanh \frac{s}{\phi} \quad (6)$$

Where $\eta > 0$ and K is derived from the Lyapunov stability condition for sliding mode control $s\dot{s} \geq -\eta s$ and given by equation (7).

$$K \geq \frac{w_x I_x}{r} ((1 - \lambda)g + \eta) \quad (7)$$

This controller essentially calculates the wheel cylinder pressure to achieve the desired control objective.

Active Front Steer (AFS)

A 2-DOF bicycle model with tires is considered for developing the control algorithm for AFS as shown in Figure (4).

Model assumptions are listed below.

1. Tire slip angles are small.
2. Tire contact patch length/2 $\ll a$ and b

A sliding mode control methodology is chosen to develop the control algorithm for AFS.

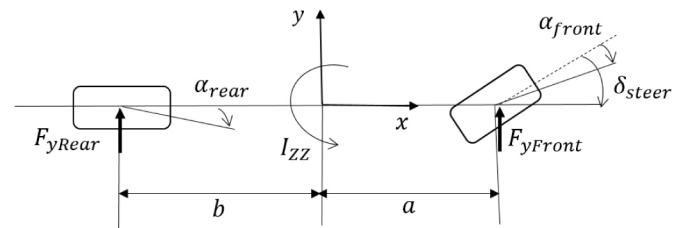


Figure 4. 2 DOF bicycle model of the vehicle

The sliding surfaces are chosen as given in equation (8). [13]

$$s = e_{\psi} + \lambda \int_0^t e_{\psi} dt \quad (8)$$

Where $e_{\psi} = \dot{\psi} - \dot{\psi}_d$ is the error in the yaw rate.

From the linearized bicycle model, the state equation is given by equation (9).