

Obtaining Desired Vehicle Dynamics Characteristics with Independently Controlled In-Wheel Motors: State of Art Review

Husain Kanchwala
 IITK

Pablo Luque Rodriguez and Daniel Alvarez Mantaras
 University of Oviedo

Johan Wideberg
 ETSI

Sagar Bendre
 NATRIP

ABSTRACT

In recent times, electric vehicles (EV) are gaining a lot of attention as they run clean and are environment friendly. Recent advances in the applications of integrating control systems in automotive vehicles have made it practicable to accomplish improvement in vehicle's longitudinal and lateral dynamics. This paper deals with a brief overview of current state of art vehicle technologies like direct yaw moment control, traction control and side slip control of EV. There are various controller algorithms available in literature with different torque vectoring strategies. As EV can be precisely controlled because of quick in hub wheel motor response times, therefore various torque vectoring strategies can be comfortably used for enhancing vehicle dynamics. Moreover, by using four independent in-wheel motors, several types of motion controls can be performed. These motion controls are intensively researched by a comprehensive literature review with an aim to obtain desired vehicle handling characteristics.

The motivation behind doing this study is to obtain a guideline for systematic development of control strategy. The control law development is discussed in three subsequent stages, namely, Supervisory control, Upper level control and Lower level control. The controller is to be designed and implemented for the torque management of the four independent electric traction motors of a FOX racing electric car.

CITATION: Kanchwala, H., Rodriguez, P., Mantaras, D., Wideberg, J. et al., "Obtaining Desired Vehicle Dynamics Characteristics with Independently Controlled In-Wheel Motors: State of Art Review," *SAE Int. J. Passeng. Cars - Mech. Syst.* 10(2):2017, doi:10.4271/2017-01-9680.

1. INTRODUCTION

Decreasing oil resources and increasing environmental problems have stimulated the need for research in alternative energy sources for automobiles. Electric vehicles have come up as a strong contender among all other alternate vehicles (Rüther, et al., 2015). They run on renewable energy source and are tail-pipe emission free. With ever increasing fuel prices and health impacts of internal combustion engines there is a demand for the eco-friendly means of transportation (Ji, et al., 2012; Rezvani, et al., 2015; Wideberg, et al., 2014). Unlike conventional vehicles, which were driven by an engine connected to a powertrain, the EVs are generally driven by individual wheel motors. The advantage of individual motor control is enhanced safety, comfort and improved handling dynamics.

There have been various vehicle dynamics control and torque vectoring algorithms available in literature. We analysed most relevant research that underwent in this area in order to develop a

guideline to be followed while designing such a control system. As the torques can be controlled independently, direct yaw moment control and side slip control has come out as one of the most widely used technology for pro-actively preventing accidents.

In 1996, the world's first vehicle with a right-and-left torque vectoring type direct yaw moment control system was developed (Sawase & Sano., 1999). The focus is to develop a controller which can control Couple traction/braking (T_i ; $i = FL/FR/RL/RR$) of the four in-wheel motors, from basic driving slogans, that are, steering angle, position of the accelerator and brake pedal as shown in Figure 1. Generally, all vehicle dynamics control (VDC) algorithms are based on a hierarchical structure, where, from the slogan of driving and vehicle information the vehicle's response (FOX vehicle in our case) is identified. This structure arises in several levels as shown in Figure 2



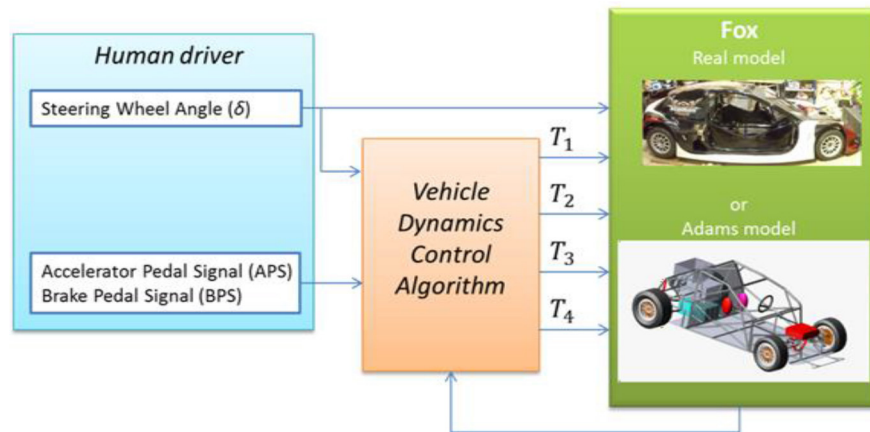


Figure 1. Vehicle Dynamics Control structure. Image source: (Kanchwala, et al., 2015)

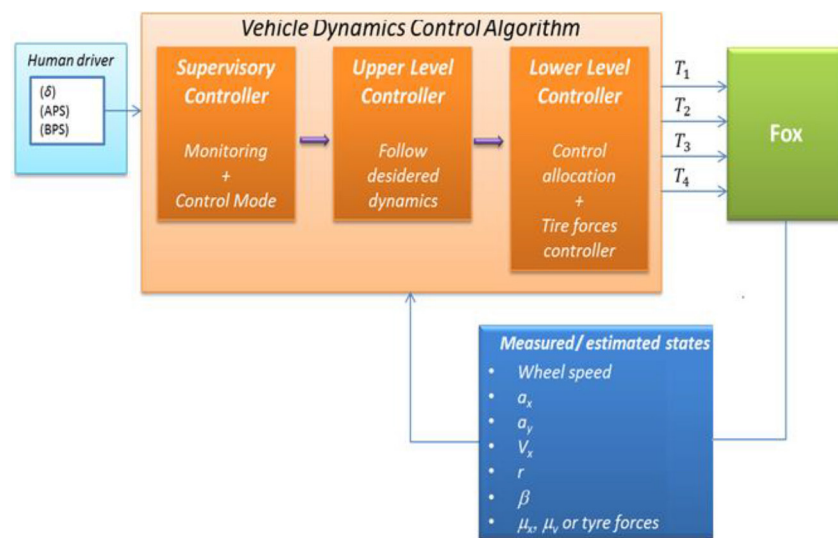


Figure 2. Structure of hierarchically coordinated VDC system

Generally, the variables used by VDC algorithms to monitor the dynamic behavior of vehicle are:

r : –Yaw rate; β : – Slip angle

The system identifies whether the desired dynamics for the driver is within the range of operation of the vehicle. This further determines maximum grip between tires and ground. In case of detecting a discrepancy of the actual dynamics and the desired (and adjusted according to the maximum obtainable performance), a directional control is set to adjust r and β to the desired values.

This directional control of the vehicle involves injection of a moment (M_z) which is generated by traction/braking force difference in left-right wheels. Finally, longitudinal forces on each of the wheels are restricted to the maximum allowable value based on friction limit. There are three main control operation levels, namely,

1. Supervisory Controller
2. Upper-level Controller
3. Lower-level Controller

These control levels described in detail in the adjoining sections.

2. BACKGROUND

2.1. Steps in Developing a Controller

In order to develop an algorithm for torque allocation the following steps are to be carried out.

1. Characterization of the Desired Dynamic Response

This can be done in either two ways.

a. Simulation

This is based on the mathematical model of the vehicle developed in any of the vehicle dynamics simulation interface like, Adams-Car, CarSim, Matlab, etc. The vehicle is tested against a standard handling maneuver (for example: ISO 3888 Double lane change (Kanchwala, et al., 2014)).

b. Field Testing

The vehicle can be tested according to the test criterion of a handling test (National Highway Traffic Safety Administration, Department of Transportation, April 6, 2007) along with a set of sensors mounted in

order to get various response characteristics. The desired dynamics can be presented in several ways. Formulas from a simplified model can be represented as:

$$r_{desired} = f_1(\delta, V_x); \beta_{desired} = f_2(\delta, V_x)$$

2. Deciding the Control Type and Layout

Series of works are needed to be carried out for developing the controller, namely,

a. Control of Yaw Rate and Side Slip Angle

Sliding mode, PID, Optimal LQ control, Fuzzy, etc.

b. Torque Allocation

Torque vectoring and wheel traction limits to be studied.

c. Control of Wheel Dynamics

Controlling the longitudinal slip of different wheels.

d. Characterization of the Electric Motors

This allows for sharing of pairs of traction / braking to optimize both efficiency/consumption and the dynamic response of the vehicle.

2.2. Vehicle Dynamics Control - VDC

VDC and stability control systems (Wang & Longoria, June, 2006) have attracted considerable attention from both academic and industry researchers. Main objective of VDC is to make the vehicle respond as intended by the driver (especially in adverse conditions) and to alleviate driver workload. This can be achieved by coordinating the actuation resources (tires) to expand the system operational envelope.

While cornering at high lateral acceleration, tire forces approach to or are at the physical limit, i.e. road adhesion. The vehicle side-slip angle grows and the effectiveness of vehicle steering angle in generating yaw moment reduces significantly because of tire force saturation. This fact is first illustrated by the so-called β -method (Shibahata, et al., 1993). The decrease of restoring yaw moment generated by tire lateral force at high side-slip is the main cause of vehicle unstable motion. By the addition of an external yaw moment the vehicle stability can be recovered. Generally, the number of actuation inputs (slip and slip angles of four tires) is more than the number of control variables (longitudinal, lateral velocities and yaw rate). Therefore, a hierarchically coordinated control structure with control allocation provides a suitable approach (Fredriksson, et al., 2004; Wang & Longoria, June, 2006).

From vehicle dynamics point of view, yaw rate and side slip angle are closely related with vehicle maneuverability and lateral stability (Cho, et al., 2006). Based on driver steering input, desired yaw rate is determined, and correspondingly the desired yaw moment for this

yaw rate is obtained. In coordinated VDC systems, reference model provides vehicle reference motions based on driver commands. The higher-level controller produces the generalized control efforts such as imposed forces and moments required to meet desired vehicle states. Control allocation optimally distributes the slip ratio and slip angle of each tire to simultaneously induce desired longitudinal and lateral forces (Li, et al., 2008; Li, et al., 2009). The task of a combined tire slip and slip angle tracking (*Tire forces controller*) controller is to manipulate driving/braking torque and steering angle of all wheels, independent of vehicle state. Corresponding vehicle states are fed back to higher level controller to close the loop. External yaw moment, independent of lateral forces and steering angle, is generated by the transverse distribution of vehicle braking force between left and right wheels. It is known as differential braking and is achieved using the main parts of anti-lock braking system (Van Zanten, et al., 1998). Longitudinal (braking and driving) forces for implementing VDC systems gives quick control action and is possible to integrate relevant hardware with existing anti-lock/spin systems (Van Zanten, 2000).

2.3. State of Art: Control Law and Strategies

The key point in the strategy of yaw stability control law is to find required corrective yaw moment. Control laws, defined by the researchers in previous research, have the likeness of using yaw rate and vehicle slip angle as control variables. They differ in control strategies, which are addressed below.

A fuzzy logic based direct yaw control for all wheel drive (AWD) EV is proposed in (Tahami, et al., 2003) which is taken as Case 1 (Figure 3) for discussion. A novel strategy is adopted where yaw rate and wheel slip ratio is controlled in the control loop. Separate fuzzy logic based controllers for yaw rate and wheels' slip ratio are used, where the yaw rate controller is determining the required torque. Corrective torque from yaw controller can saturate the tire force, to avoid this a slip controller is used to keep the slip ratio within the stable region. In yaw rate controller, reference yaw rate is generated by neural-network. It generates the reference yaw based on the vehicle speed and steering.

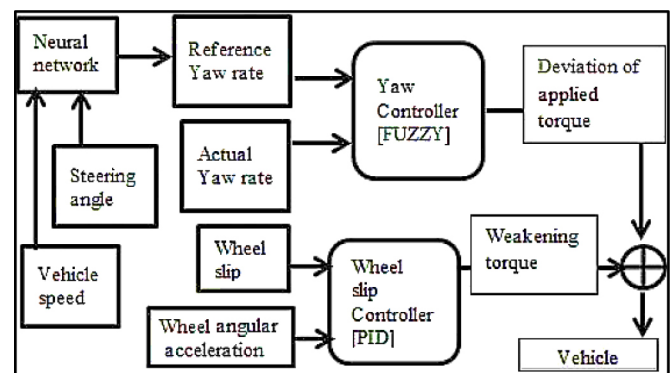


Figure 3. Control Structure of Case 1 (Tahami, et al., 2003)

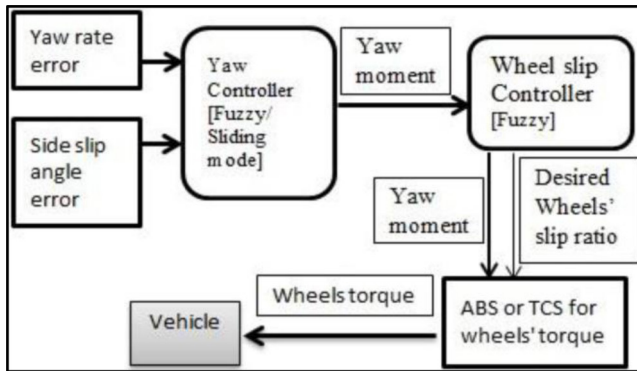


Figure 4. Control Structure of Case 2 (Tahami, et al., 2003)

In case 2, (Figure 4), controller is designed to calculate the desired yaw moment from yaw rate error and vehicle slip angle error (Li, et al., 2008). Desired wheels' slip ratios are calculated based on desired yaw moment using fuzzy logic. It is assumed that ABS/TCS is available to manipulate braking or wheel traction. The key points in this paper realized are, the controller has used yaw rate and slip angle to find yaw moment and it is responsible for controlling the individual wheel sleep.

In Case 3, (Figure 5), for more robustness an active front steering controller is used. This controller is based on sliding mode control which provides the corrective steering angle (Zhao, et al., 2009). Rest of control architecture is same as Case 2. Use of steering control along with fuzzy controller is a novel strategy.

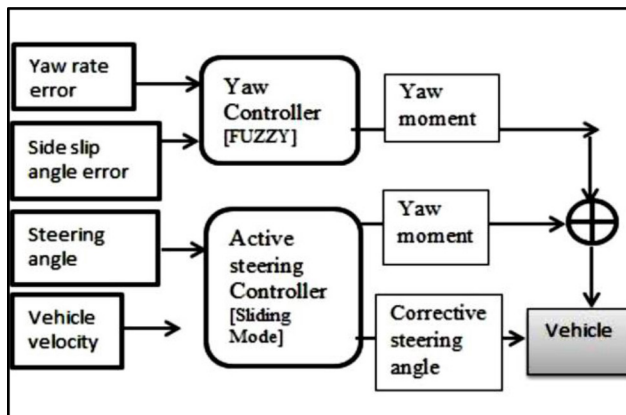


Figure 5. Control Structure of Case 3 (Tahami, et al., 2003)

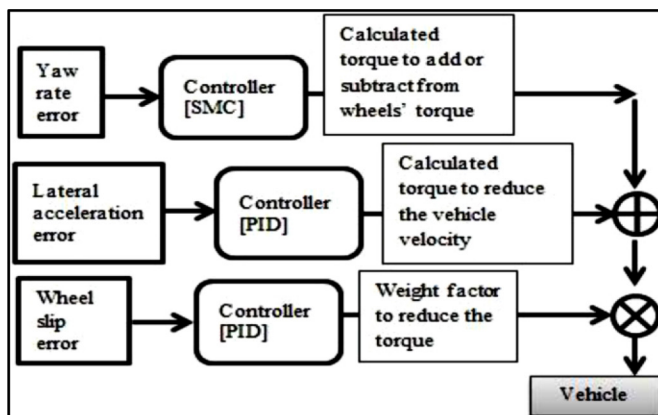


Figure 6. Control Structure of Case 4 (Tahami, et al., 2003)

A PID controller for lateral acceleration error, a sliding mode controller for yaw rate error and another PID controller for wheel sleep error is used by (Kim & Kim, 2006; Kim & Kim, 2007) which is taken as Case 6 (Figure 6). Corrective wheel torques, generated by these three controllers, is then combined and used as total corrective torque to control the yaw rate of the vehicle.

From the above discussion, one can notice different strategies of torque based ESC for EVs. Several controllers like fuzzy, sliding mode control and neural network to control the system.

Direct yaw moment control (DYC) introduced vehicle directional stability control under emergency situations (Mirzaei, 2010). It is shown that DYC is the most effective method of motion control compared with the other conventional control systems such as four wheel steering (4WS) (Abe, 1999; Selby, et al., 2001). The 4WS control, which depends on the relation between tire lateral force and the steer angle as a control command. It is efficient at small values of lateral acceleration, as the steer input has negligible effect on yaw moment when wheel force saturates. Despite the high efficiency of DYC in a wide range of operation, the external yaw moment (control input), should be kept as low as possible because of its some undesirable effects. It slows down the vehicle as corrective yaw moment is applied through the brakes. This effect must be kept to a minimum so that the driver can feel supported rather than overruled. Limiting excessive use of external yaw moment by integrating DYC and 4WS is studied by (Selby, et al., 2001).

Depending on which variable is controlled, different control types of DYC have been proposed. The yaw rate control by DYC has been studied frequently (Esmailzadeh, et al., 2003; Mokhiemar & Abe, 2002; Mokhiemar & Abe, 2006). Some researchers have used the side-slip control type of DYC (Abe, 1999; Abe, et al., 2001). However, both variables have been controlled simultaneously by DYC (Park, et al., 2001; Ghoneim, et al., 2000).

In both side-slip control and yaw rate control by DYC, the desired (reference) models of these variables are established according to driver steering commands. Several researchers have used the steady-state behavior of linear vehicle model during a cornering maneuver as a desired model for the yaw rate with zero side slip (Esmailzadeh, et al., 2003; Geng, et al., 2009).

These models do not include the transient response for vehicle motions and therefore make large tracking errors at the beginning of maneuvers. Some researchers have used linear 2-DOF vehicle plane model (bicycle model) to be followed by the controller (Mokhiemar & Abe, 2006; Kanchwala, et al., 2015). Although the linear bicycle model shows a stable motion, it is unable to predict the tire/road conditions. It is desirable to develop a linear 2-DOF model with tire/road conditions.

There are several control methods to achieve the desired vehicle behavior using DYC in the literature. Ghoneim, et al., 2000 introduced a feedback control using yaw rate with proportional-derivative (PD) structure, while Geng, et al., 2009 used PID structure. Sliding mode control method has been also employed in finding the yaw moment control law (Abe, et al., 2001). Document Sharing Hub