

Chapter 2

State Estimation and Coordinated Control System

Abstract By taking full advantage of distributed electric vehicles in vehicle dynamic control field, optimized design has been made on dynamic control of full vehicle based on state estimation and coordinated control system of distributed electric vehicles. For tackling such problems concerning distributed electric vehicles as imperfect system in state estimation field, insufficient coordination degree in coordinated control field, poor control adaptability and poor disturbance-resistance capability, a system for dynamic state estimation and coordinated control of full vehicle by making full use of property of distributed electric vehicles is set, comprehensively improving precision of state estimation and dynamic performance of vehicles. This chapter studied state estimation and coordinated control system of distributed electric vehicles. Based on the concept of hierarchical design, the integrated system framework was designed, functions of various subsystems were specified, input and output of various subsystems were defined, logical relation of each layer was combed and technological difficulties and key points concerning the system was planned.

2.1 Structural Design of the System

Given the fact that state estimation and coordinated control system of distributed electric vehicles are complicated with multiple input and output being involved and that information and variables of variety are interconnected, centralized control tends to make the controller structure complex, functions ambiguous and development difficult and lead to difficulty in software maintenance and poor expansion performance. However, hierarchical control provides a more satisfactory solution for the above problem with superior expansion performance, making the control structure clear and conducive to development and maintenance. Therefore, hierarchical control structure was adopted in structure design of the control system in this dissertation.

Major functions to be realized: estimation of dynamic state parameter of vehicles according to the current operation information of drivers, feedback information of distributed electric driving wheels, INS information and GPS information; setting of expected longitudinal and lateral control targets by making use of the collected information of vehicle operating state parameters; calculation of allocation value of

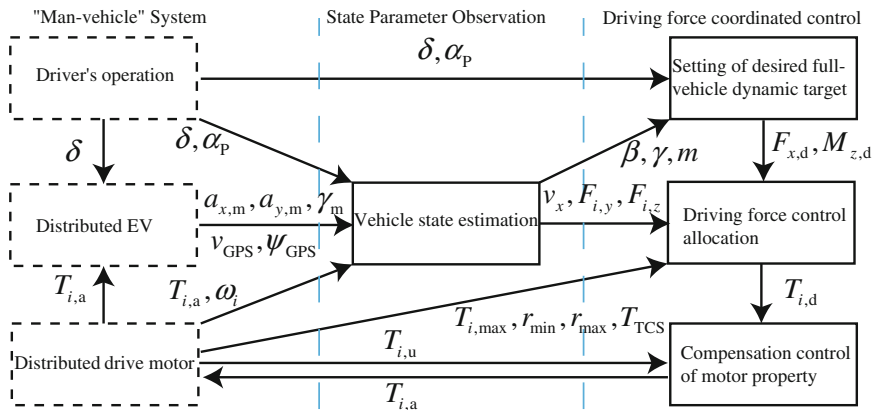


Fig. 2.1 Overall system of state estimation and coordinated control

driving force for each wheel by adopting proper control and allocation method; off-setting motor difference resulting from dynamic response and steady-state response of motor by adopting appropriate motor control method so as to execute the expected driving force allocation value for each wheel and realize longitudinal and lateral control targets by use of the allocation value.

After the above system functions were confirmed, overall structure of state estimation and coordinated control system of distributed electric vehicles was designed. As shown in Fig. 2.1, corresponding hierarchical control module was built in this dissertation based on the designed system function and logical relation of each layer was specified, comprehensively realizing the overall scheme for state estimation and coordinated control.

On the basis of in-vehicle INS information, GPS information, driver's operation information and electric driving wheel information, dynamic estimation system of distributed electric vehicles makes combined estimation on multiple important state variables of vehicles via certain state estimation methods, including longitudinal velocity v_x , side slip angle β , yaw rate γ , lateral force $F_{i,y}$ of tire, vertical force $F_{i,z}$ of tire, mass m and gradient θ of road surface. Acquisition of these state variables provides foundation for coordinated control of distributed electric vehicles. coordinated control system of distributed electric vehicles is of hierarchical structure, including upper layer, medium layer and lower layer. The upper layer control is used to determine dynamic demand of full vehicle and the expected control targets mainly based on driver's operation information and current state of vehicles estimated by vehicle state observer and compare the expected control target and actual control target, then outputting the expected longitudinal driving force $F_{x,d}$, and expected direct yaw moment $M_{z,d}$. Medium control allocates driving force, and its main target is to develop driving moment $T_{i,d}$ allocated by each driving wheel so as to satisfy dynamic demand $F_{x,d}$ and $M_{z,d}$ of full vehicle set by upper layer. In the process of control allocation, motion state of vehicles and running state of motor need to be

considered in real time, including maximum in-wheel driving force constraint $T_{i,\max}$, moment slope constraint $r_{\max}$ and $r_{\min}$ and moment command T_{TCS} made by TCS. Lower control is used for motor property compensation and setting moment control command $T_{i,u}$ on the basis of expected driving force $T_{i,d}$ of each wheel and actual motor feedback moment $T_{i,a}$ set according to moment allocation of medium layer, making the actual motor output moment follow the expected moment.

The following section discusses state estimation and coordinated control of distributed electric vehicles.

(1) State estimation system of distributed electric vehicles

State estimation system is the foundation for vehicle dynamic control. Given the properties of distributed electric vehicles, this system observes various states of vehicles in a comprehensive way by making use of in-vehicle common sensor and in combination of feedback of distributed driving wheel, where available sensors include longitudinal acceleration sensor, lateral acceleration sensor, yaw rate sensor, roll rate sensor, steering wheel angle sensor, accelerator pedal sensor and GPS (global positioning system) and available feedback information of electric driving wheel include information of driving moment and rotate velocity of driving wheel. As shown in Fig. 2.2, this subsystem is designed by hierarchical structure. Firstly, various types of information that can be offered by distributed electric vehicles are collected and signals are preprocessed. “INS sensor integration system” can provide longitudinal

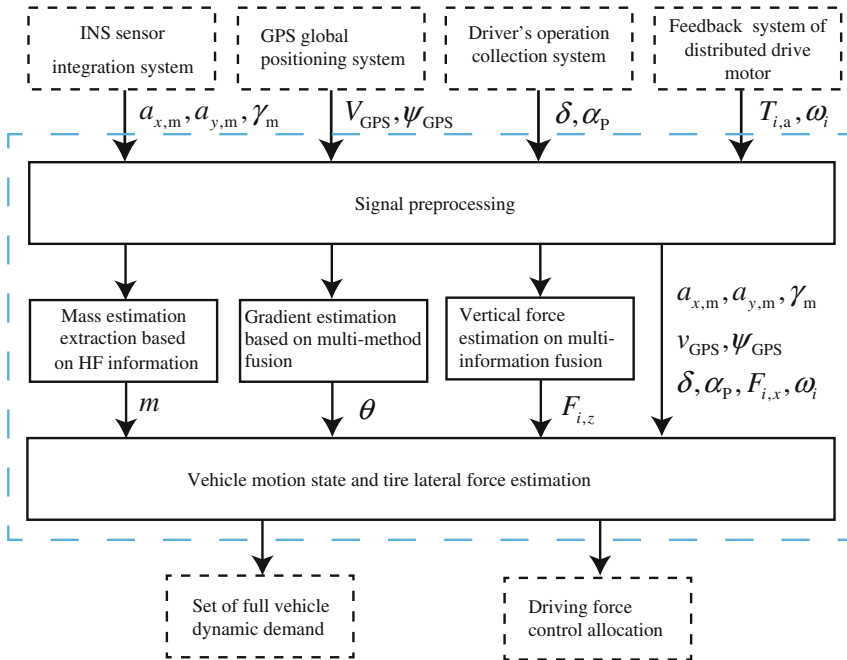


Fig. 2.2 Design flow of state estimation subsystem

acceleration $a_{x,m}$, lateral acceleration $a_{y,m}$ and yaw rate γ_m , while “GPS” can provide absolute velocity V_{GPS} and heading angle ψ_{GPS} of vehicles and “driver’s operation information collection system” can steering angle δ of front wheel and accelerator pedal aperture α_P and “feedback information system of distributed drive motor” is able to offer actual moment $T_{i,a}$ and rotate velocity ω_i of vehicles. Secondly, multiple parameters are estimated. By “mass estimation extraction based on high frequency information”; mass m of full vehicle can be obtained; gradient θ of road surface can be acquired according to “gradient estimation based on multi-method fusion”; vertical force $F_{i,z}$ of each wheel can be acquired by “vertical force estimation based on multi-information fusion”. Ultimately, “vehicle motion state and tire lateral force estimation” is made by integrating information of multiple sensors and information of mass, gradient and vertical force acquired by estimation. By “vehicle motion state and tire lateral force estimation”, longitudinal velocity v_x , side slip angle β , yaw rate γ and lateral force $F_{i,y}$ of each wheel of full vehicle can be estimated.

(2) Coordinated control system of distributed electric vehicles

Coordinated Control system of distributed electric vehicles is composed of the following three subsystems, including “determination of full vehicle dynamic demand”, “driving force control allocation” and “compensation control of motor property”.

1. Setting of desired dynamic target of full vehicle

Major function of “setting of desired dynamic target of full vehicle” subsystem is to calculate the desired longitudinal driving force $F_{x,d}$ and direct yaw moment $M_{z,d}$ of full vehicle according to driver’s operation and running state of vehicles. Given that setting of longitudinal desired driving force has impact on dynamic performance of vehicles, the system makes open-loop control over the expected longitudinal driving force by making use of driver’s operation information. Given that direct yaw moment has direct impact on stability of vehicles, this dissertation calculates the direct yaw moment of vehicles by utilizing the structure jointly controlled by feedforward and feedback where the feedforward develops the direct yaw moment M_{ff} of feedforward on the basis of expected targets and driver’s operation information. Moreover, since vehicles are affected by a series of uncertain factors to different degrees in running process, feedback control is required to ensure lateral stability of vehicles and convergence of control targets. When actual targets deviate from the expected one, the feedback develops direct yaw moment M_{fb} and regulates the desired direct yaw moment and controls lateral motion state of full vehicle, guaranteeing stability of vehicles. Flow to develop desired dynamic target of full vehicle is as shown in Fig. 2.3.

2. Driving force control allocation

Major function of “driving force control allocation” is to allocate desired longitudinal driving force $F_{x,d}$ and direct yaw moment $M_{z,d}$ of full vehicle in “setting of desired dynamic target of full vehicle” subsystem among each driving wheel. Main purpose of control allocation is to satisfy longitudinal dynamic demand and lateral stability demand of full vehicle and takes full advantage of redundancy configuration structure of distributed electric vehicles, so as to optimize design of driving force

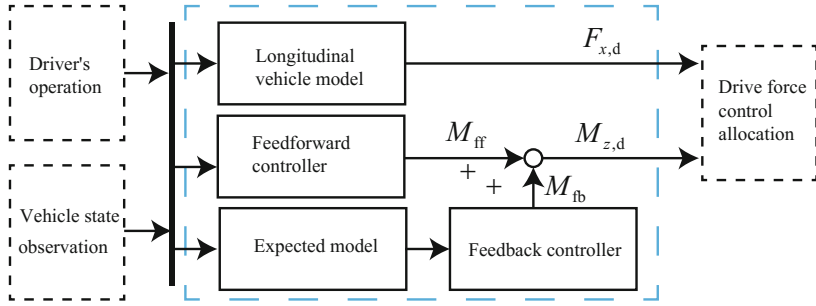


Fig. 2.3 Flow for setting of desired dynamic target of full vehicle

control allocation of full vehicle. Moment constraint of electric driving wheel needs to be taken into consideration for driving force control allocation, including execution capacity constraint of motor system, trackslip constraint, failure of driving wheel, etc. In addition, corresponding constraint functions are designed, including maximum in-wheel driving force constraint $T_{i,max}$, moment slope constraint r_{max} and r_{min} and moment command T_{TCS} made by TCS. By such a way, upper limit $\bar{x}$ and lower limit $\underline{x}$ of driving force at the current moment can be acquired. Meanwhile, if desired longitudinal dynamic contracts to desired lateral stability, corresponding longitudinal and lateral regulation weighting function H_F and H_M is set to satisfy the current major desired targets of full vehicle, so as to realize self-adaptive control. Optimized design aims at controlling the usage rate of various motors and avoiding overuse of partial vehicle wheels. On such a basis, optimized target function is designed with constraint and expected driving moment $T_{i,d}$ of each wheel is optimized and solved by non-linear optimization. Flow for driving force control allocation is as shown in Fig. 2.4.

3. Compensation control of motor property

Major function of “compensation control of motor property” subsystem is to execute target driving force of each set by control allocation layer in motor system, so as to satisfy the demand of dynamic control. In the process of compensation of motor property, reference model of motor is designed firstly by adopting self-adaptive control, and self-adaptive control law is designed on such a basis. Reference model is mainly used for simulating the expected motor response property. The system integrates target moment $T_{i,d}$ set by control allocation layer of driving force, expected moment $T_{i,m}$ set by reference model and the current actual moment $T_{i,a}$, so as to make real-time dynamic regulation to control law. Self-adaptive controller calculates moment command $T_{i,u}$ of motor in real time by making use of self-adaptive control rate and sends such a command to distributed drive motor ultimately so as to realize property compensation control of the motor, ensure actual moment of the motor following the expected one and meet the dynamic control demand of full vehicle. Flow for compensation control of motor property is as shown in Fig. 2.5.

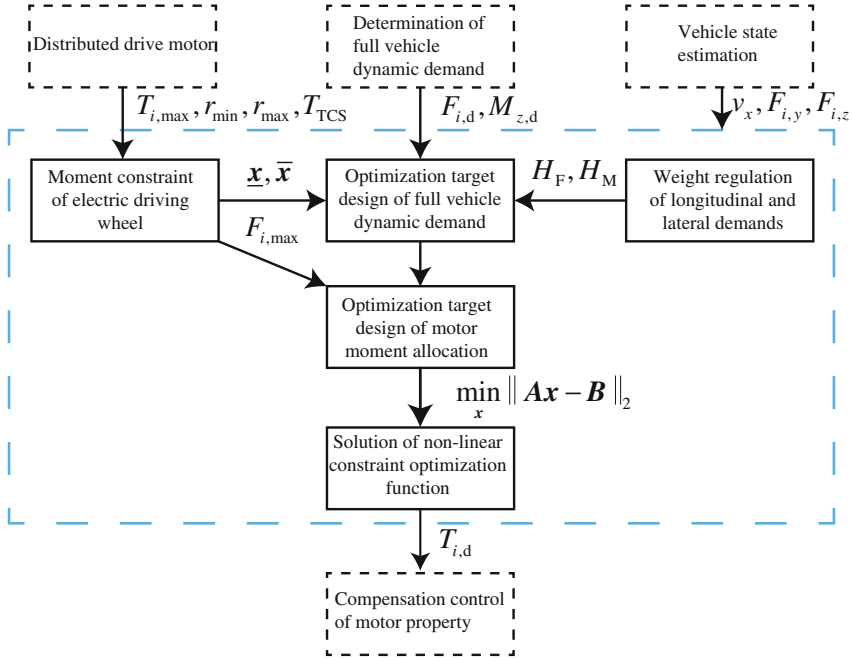


Fig. 2.4 Flow for driving force control allocation

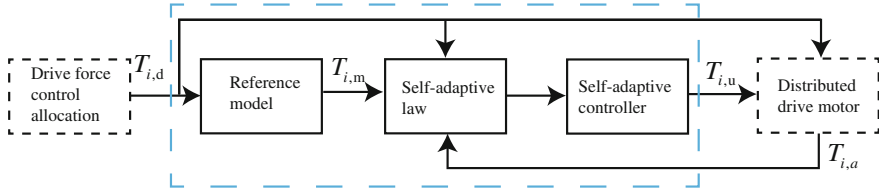


Fig. 2.5 Flow for compensation control of motor property

2.2 Technological Difficulties and Key Points

Technological difficulties and key points related to state estimation and coordinated control system of distributed drive vehicles fall into four parts, including design of state estimation system, design of desired dynamic target of full vehicle, driving force control allocation and compensation control of motor property. The following presents further description for each key technology mentioned.

(1) Design of state estimation system

The purpose of state estimation of distributed electric vehicles is to provide support for dynamic control of vehicles. Poor approximation to the true value according to the observation effect of the state estimation system will lower the precision of

parameter utilized by dynamic control of vehicles and have great impact on the control effect. Therefore, one of the keys to realizing dynamic control effect of full vehicle lies in state estimation. Considering controllable single-wheel moment unique to distributed electric vehicles and features of accurate and available rotate velocity, multiple state variables shall be jointly observed in combination of information on electric driving wheel and in-vehicle sensor, so as to meet the demand for dynamic control of full vehicle. State parameters needing to be observed include motion state (including longitudinal vehicle velocity, side slip angle and yaw rate), acting force of vehicle (including lateral force and vertical force of tire), mass of full vehicle and road surface gradient. Accurate estimation of these state parameters will greatly improve the control effect of dynamic control system of full vehicle and the dynamic performance of vehicles. How to integrate multi-source information of distributed electric vehicles to jointly observe various states and comprehensively improve the observation precision of various state variables is one of the difficulties and key points of this dissertation.

(2) Design of vehicle desired dynamic target

In order to guarantee the power performance and stability of vehicles, reasonably desired dynamic target of vehicles shall be designed. Driver's expectation is also reflected by desired dynamic target. Failure to reflect driver's intension by the designed dynamic control target will dampen driving sensitivity and lower lateral stability of vehicles. In the process of developing desired dynamic target of full vehicle, longitudinal dynamic demand and lateral demand of full vehicle shall be determined on the basis of state parameter variables obtained by making use of state estimation system and driver's operation information. In the design of control target, impact of uncertain factors on control shall be taken into full consideration, so as to realize driver's expectation. In combined control over multiple targets, various control targets shall be comprehensively considered and the case that only single target is taken into consideration, which leads to occurrence of vehicle instability, shall be avoided. It is another key point and difficulty of this dissertation to determine reasonable demand target through comprehensive consideration of non-linear dynamic properties, road surface condition, dynamic response and steady-state response of distributed electric vehicles, in order to guarantee utmost safety of vehicles in various limited conditions.

(3) Driving force control allocation

Main purpose of driving force control allocation is to develop target driving moment of each wheel according to dynamic control target of full vehicle. Given the unique structural features of distributed electric vehicles, driving force can be allocated in a flexible way among multiple wheels during control allocation. In the meanwhile of meeting demand of full vehicle, optimized design can be made for some other targets. Various constraints imposed on distributed driving wheel need to be taken into consideration to ensure that all allocated force can be implemented. Constraints to be considered include failure constraint of driving wheel and driving anti-slip control constraint, etc. Due to constraints of driving wheel, driving force control allocation may be unable to meet the dynamic control target of full vehicle set by upper layer

and in such a case multiple dynamic control targets shall be exposed to dynamic weight adjustment based on the current state of vehicles and driver's operation to give top priority of main target. At the same time of optimization target design, minor optimization target shall be designed according to features of distributed electric driving wheel. Ultimately, the main target shall be integrated with the minor target and joint optimization shall be made for main target and minor target by virtue of non-linear optimization method. It is another key point and difficult problem to be solved in this dissertation, to comprehensively consider various constraints of driving force of distributed electric vehicles, and coordinate and optimize main target and minor target to maintain corresponding longitudinal driving force and direct yaw moment to the greatest extent in case of drive trackslip, drive failure and other constraints and guarantee drive capacity and safety of vehicles.

(4) Compensation control of motor property

Major purpose of compensation control of motor property is to control target driving moment made by driving motor following driving force control allocation layer, which is also the basic demand to realize dynamic control of distributed electric vehicles. The system needs to eliminate difference of actuator by rational control method to ensure target driving force to be implemented. In the design of controller, available features of moment of electric driving wheel shall be taken into consideration to design control method with superior robustness. In order to reduce or even eliminate the difference of motor moment, make moment of electric driving wheel stably follow target driving moment and ensure the realization of control intention of full vehicle, which is also one of the key points and difficulties of this dissertation, the designed compensation control method of motor property is required to overcome steady-state error and dynamic error of motor moment.

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