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INTEGRATED ROBUST CONTROL DESIGN FOR IN-WHEEL-MOTOR VEHICLES

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ABSTRACT

The paper proposes a multi-layer supervisory architecture for integrated control systems in road vehicles. The role of the supervisor is to coordinate active control components and provide priority among them. The supervisor has information about the current operational mode of the vehicle and it is able to make decisions about the necessary interventions into the vehicle components and guarantee the reconfigurable operation of the vehicle. The decisions of the supervisor are propagated to the lower layers through predefined interfaces encoded as suitable scheduling signals. The contribution of the paper is the application of the LPV methodology in a design case study in which an integrated control of four wheel independently-actuated electric vehicle with active steering system is developed.

1. INTRODUCTION AND MOTIVATION

In line with the requirements of road vehicles several performance specifications are in the focus of the research: improve road holding, passenger comfort, roll and pitch stability, reduce fuel consumption and emission. The difficulty of the conventional design strategy is that the performance demands, which are met by independent controllers, are often in interaction or even conflict with each other in terms of the full vehicle. The purpose of the integrated vehicle control strategy is to combine and supervise all control components affecting vehicle dynamics responses, see, e.g., [3]. An integrated control system is designed in such a way that the effects of a control subsystem on other vehicle functions are taken into consideration in the design process by selecting among the various performance specifications. The paper proposes a multi-layer supervisory architecture that can be used for integrated control systems in road vehicles.

In the paper the decentralized control system is augmented with a supervisor as illustrated in Figure 1. The role of the supervisor is to coordinate the different active control components and provide a well definedpriority among them. The supervisor has information about the current operational mode of the vehicle and it is able to make decisions about the necessary interventions into the control of the different vehicle components and guarantee the reconfigurable operation of the vehicle. These decisions are propagated to the lower layers through predefined interfaces encoded as suitable defined scheduling signals. More details, see [2].

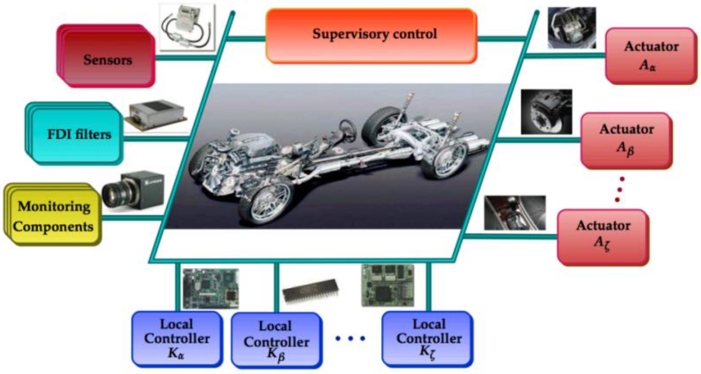


Figure 1: The supervisory decentralized architecture of integrated control

As an example, in a global chassis control system three control components operate simultaneously in a coordinated way. The steering system generates steering angle, the braking system generates braking yaw torque, while the suspension system generates vertical forces. The brake torque is generated by unilateral brake pressures based on a wheel force distribution. The supervisor monitors the vehicle dynamics in order to guarantee its main tasks. Although the selection of the actuator is usually performed by using practical considerations, in the presentation a theory-based method is developed. There are three main factors to consider in the actuator selection procedure: construction limits, energy requirements, and dynamics of the actuators.

On the level of the individual vehicle components the control problem is formulated and solved by a unified modelling and design method provided by the linear parameter varying (LPV) framework. The LPV framework allows us to take into consideration the nonlinear effects in the state space description while maintaining much of the possibilities of the robust linear design. The requested global behaviour is achieved by a judicious interplay between the individual components guaranteed by an integrated control mechanism. Finally, the integrated control problem is also formalized and solved in the LPV framework.

In the in-wheel motor system electric motors are built into the hub of the wheels and they are driven directly. An appropriately balanced in-wheel system is able to improve the yaw dynamics of the vehicle by adapting road conditions. The comfort usually deteriorates as a consequence of an increase in the weights of the wheels. By using integrated vehicle control the operations of the in-wheel motors can be designed. Some examples have already been published, see e.g., [1,4,5,6].

The structure of the paper is the following. In Section 2 the structure of the integrated vehicle system is presented. In Section 3 the hierarchical structure of the in-wheel vehicle system is developed. In Section 4 the operation of the in-wheel vehicle is illustrated through a simulation example. Finally, Section 5 formulates some concluding remarks.

2. HIERARCHICAL CONTROL STRUCTURE OF THE IN-WHEEL VEHICLE SYSTEM

In the control design, it is necessary to consider the longitudinal and lateral dynamics of the vehicle. For this purpose, the linearized two wheeled bicycle model is considered, where the notations $\alpha_1 = (\delta - \beta - \dot{\psi} l_1 / \dot{\xi})$ and $\alpha_2 = (-\beta + \dot{\psi} l_2 / \dot{\xi})$ are introduced, see Figure 2. Then thevehicle motion is described by the following force and moment equations:

$$J\ddot{\psi} = c_1 l_1 \alpha_1 - c_2 l_2 \alpha_2 + M_{br} \quad (1)$$

$$m\dot{\xi}(\dot{\psi} + \dot{\beta}) = c_1 \alpha_1 + c_2 \alpha_2 \quad (2)$$

$$m\ddot{x} = F_l - F_d \quad (3)$$

where m is the mass, J is the yaw-inertia of the vehicle, l_1 and l_2 are the length of the front and rear axles distance from the center of gravity, c_1 and c_2 are cornering stiffness of the front and rear tires. The yaw and side-slip angle is denoted with ψ and β, while ξ is the longitudinal displacement of the vehicle. The air resistance, road resistance etc. are disturbance forces denoted with F_d .The inputs of the system are the steering angle (δ) of the front wheel, the brake yaw torque (M_{br}), and the longitudinal force (F_l) delivered by the in-wheel motors.

The control task is to minimize the tracking error between the actual yaw rate and its reference value:

$$\mathrm{Min}(\dot{\psi} - \dot{\psi}_{ref})^2 \quad (4)$$

During the controller design all thedisturbances, sensor noises and the actuator bandwidth must be also taken into consideration.

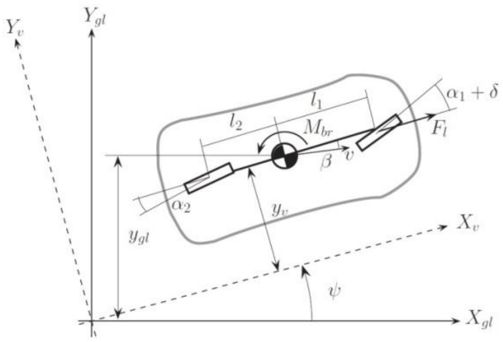


Figure 2: Bicycle model in the horizontal dynamics of the vehicle

Finally, the motion equation of the vehicle is transformed into an LPV state-space representation form:

$$\dot{x} = A(\rho)x + B_1 w + B_2(\rho)u \quad (5)$$

$$z = C_1 x + D_1 w \quad (6)$$

$$y = C_2 x + D_2 w \quad (7)$$

The state vector of the system, i.e., $x = [\dot{\xi} \;\; \xi \;\; \dot{\psi} \;\; \beta]^T$ contains the signals corresponding to the longitudinal velocity, the longitudinal displacement of the vehicle, the yaw-rate and the side-slip angle.
The control inputs of the system are the longitudinal force, the front steering angle and the brake yaw-moment: $u = [F_l \;\; \delta \;\; M_{br}]^T$

In order to track the predefined trajectory, the longitudinal and lateral dynamics must be taken into consideration. Thus, the vehicle must track reference signals of velocity and yawrate as well.The velocity tracking is realized by fulfilling the following optimization criterion:

$$z_{\xi} = \left| \dot{\xi}_{ref} - \dot{\xi} \right| \rightarrow 0 \quad (8)$$

Next, the difference between the reference yawrate and the measured actual yawrate of the vehicle must be minimized:

$$z_{\psi} = \left| \dot{\psi}_{ref} - \dot{\psi} \right| \rightarrow 0 \quad (9)$$

These performances are built into a performance vector:

$$z = [z_{\xi} \;\; z_{\psi}]^T \quad (10)$$

At the same time, in order to avoid actuator saturation, the control signals must be limited. The maximal forces of the in-wheel drive system, the brake system are determined by their construction, as well as the maximal steering angle of the steering system. These limitations are also formulated in a performance criteria vector, as follows:

$$z_2 = [\delta \;\; M_{br} \;\; F_l]^T \quad (11)$$

The system of the vehicle depends nonlinearly on the velocity, which is assumed to be measured or estimated. Thus, using the scheduling vector $r = \dot{x}$ the model is transformed into a linear parameter varying (LPV) model. The measured output of the system is the velocity and the yawrate of the vehicle, i.e.,

$$y = [\dot{\xi} \quad \dot{\psi}]^T \quad (12)$$

The control design is based on a weighting strategy formulated through a closed-loop interconnection structure, as it is illustrated in Figure 3.

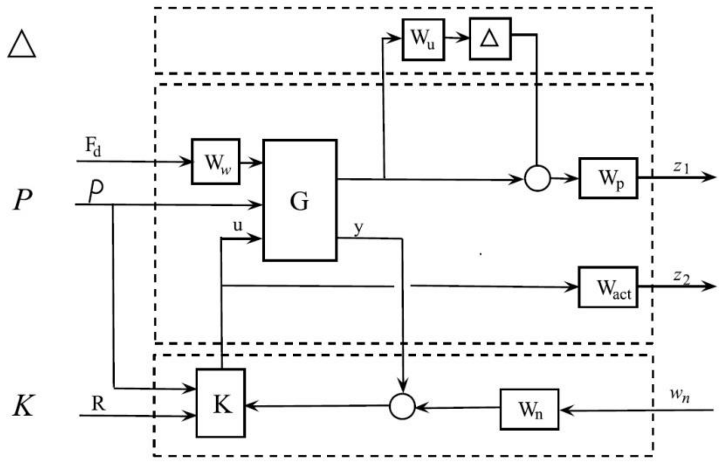


Figure 3: Closed-loop interconnection structure

The weighting functions are selected according to the weight specifications of the disturbance and the inverse of the weight specifications on the outputs. The role of weighting function W_p is to define the performance specifications in such way, that a trade-off is guaranteed between them. These functions can be considered as penalty functions with large values where small signals are desired. Weighting functions W_w and W_n reflect the size of the disturbances and sensornoises. The Δ block contains the uncertainties of the system normalized by the weight W_u. The effect of the actuator interventions are handled by the weighting function W_{act}. The transfer functions of all these weighting functions are selected to have a second-order proportional form:

$$W = \lambda(\alpha_2 s^2 + \alpha_1 s + 1)/(T_1 s^2 + T_2 s + 1) \tag{13}$$

where λ, $\alpha_{1,2}$ and $T_{1,2}$ are design parameters and reflect engineering knowledge.

Setting this model the control of the vehicle is designed based on the LPV framework, using parameter-dependent functions, see [7,8]. The aim of the LPV performance problem is to determine a parameter-varying controller that both stabilizes the closed-loop system and keeps the induced L_2 norm from the disturbance to the performances smaller than the value γ.

3. LOW-LEVEL CONTROL IN THE IN-WHEEL MOTORS

In order to control the in-wheel vehicle, the designed high level control signals must be converted to construct real physical outputs for the vehicle. For this purpose, a multi-layer hierarchical structure is applied, as illustrated in Figure 4.

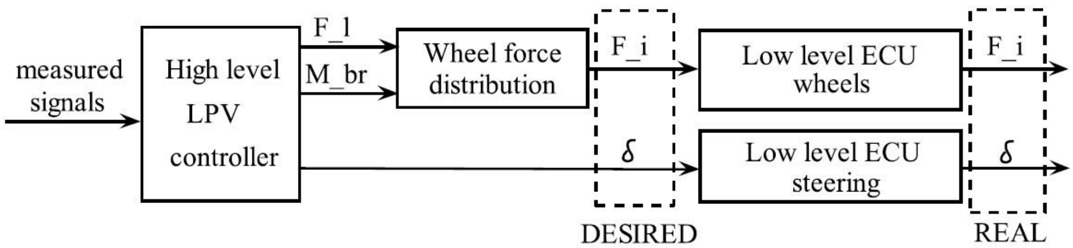


Figure 4: Architecture of control system

In the first layer the control inputs are calculated by the LPV controller, i.e., the longitudinal force, steering angle and brake yaw moment are to be determined.

Next, the second layer divides the signals of the high level controller based on considerations of vehicle dynamics.Note, that the steering angle calculated by the high level controller is not present in the wheel force distribution, thus only its construction limits are taken into consideration, i.e.,$\delta_{min} \leq \delta \leq \delta_{max}$.

The function of the third layer is to convert the signal values of the second layer into real physical parameters of the actuators. This task is managed by thelow-level controllers of the steering system, the hydraulic brake system and the in-wheel motors as well.

In the design of the low-level controllers the specific nonlinear properties of the actuator must be taken into consideration. In the steering system, the electric servomotor moving the rack is most commonly operated with Pulse Width Modulated (PWM) signal. Depending on the construction of the in-wheel hub, the electric engine can be controlled with PWM signals. Note that in some constructions of in-wheel motors the steering and braking actuators are all integrated in the wheel as well, and controlled by the drive-by-wire system.

The task of the wheel force distribution in the second layer is to define the longitudinal driveor brake forces of the wheel. It is important to separate braking and acceleration mode of the vehicle motion, since the weight load of the front and rear axle is different in both cases.

When accelerating, the longitudinal force is distributed equally between all four in-wheel motors in a straight line. In case of the vehicle traveling along a curve, steering and differential braking is applied as well.Note, that in order to maintain constant velocity set by the driver or the cruise control system, the negative force applied by differential braking must be transferred to the front wheels with positive sign, as illustrated in Figure 5/(a).

During the braking phase of the vehicle, the wheel force distribution strategy is basically different, because of the pitch dynamics, see Figure 5/(b). The braking force of the front wheels should be bigger than that of the rear. For the calculation of the optimal brakeforce distribution, the following formula is used, see [9]:

$$F_r = -F_f - (mgl_2)/(2h) + \sqrt{(F_f(l_1 + l_2)mg/h) + (mgl_2/2h)^2} \tag{14}$$

where F_r and F_f are the wheel forces at the rear and at the front, h is the height of the central of gravity of the vehicle, respectively.

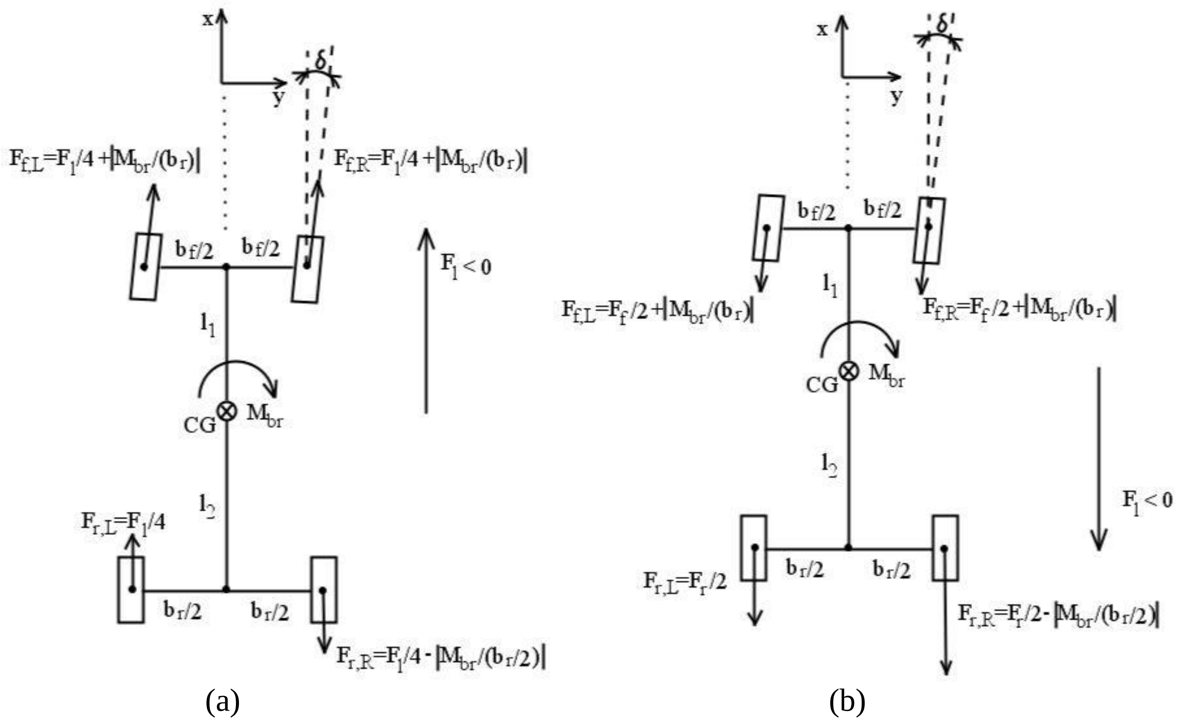


Figure 5: Wheel force distribution during acceleration and braking

4. ANALYSIS OF THE IN-WHEEL VEHICLE SYSTEMS

The in-wheel vehicle system is able to change its normal operation and adapt to new conditions or fault situations, e.g., the fault-tolerant reconfigurable solutions focuses on new, achievable, performances instead of the current performances, see e.g., Wang. To provide a fault-tolerant control, i.e., to guaranteea requested performance level, the controller requires fault information in order to modify its operation. Thus, FDI (fault detection and isolation) filters are also designed for the operation of the actuators. The actuator reconfiguration is based on the presence of a functional redundancy, i.e., the fact that two actuators are able to influence the same component of the vehicle dynamics. Thus, the fault-free actuator is able to substitute for the operation of another actuator that has been affected by a failure or its performance has degraded. The control design is based on two factors: the failure or performance degradation has already been detected and the fault information and the necessary intervention possibilities have been built into the control strategy. In the LPV design framework adopted in this paper the reconfiguration is triggered by a modification of the performance weights, function to a scheduling variable set by the supervisor, depending on the monitored fault signals.

In order to cope with the different possibilities of the available devices the interface dedicated to an individual component determined for the integrated control should be augmented with additional status signals that instruct the supervisor to reconfigure for the given situation. The integrated control system should produce a guaranteedperformance, thus, for the actuators and sensors the relevant performance requirements should be determined. These requirements are introduced for the uncertainty weights in the robust LPV specification of the individual components.One of the main difficulties of the design is to formulate and analyse these specifications in order to meet the requirements and to choosethe corresponding weights that do not lead to conservativecontrollers.

The specifications of the control solutions create a balance between driving (or road holding) and comfort. This balance often leads to a compromise between vehicle functions, which may not be suitable for all the drivers. Thus, the integrated control should be combined with a driver model in order to the driver behaviours and requirements be considered and incorporated in the design of the control system. Consequently, in the driver assistance system the interaction between the vehicle and driver is taken into consideration. A possible control structure that achieves this goal is illustrated in Figure 6.

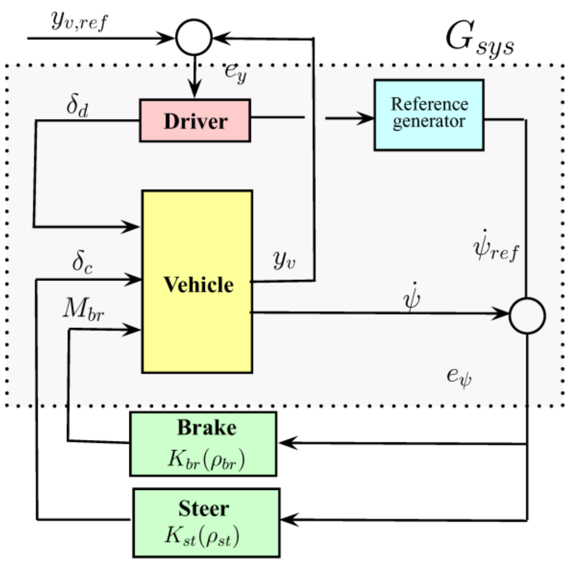


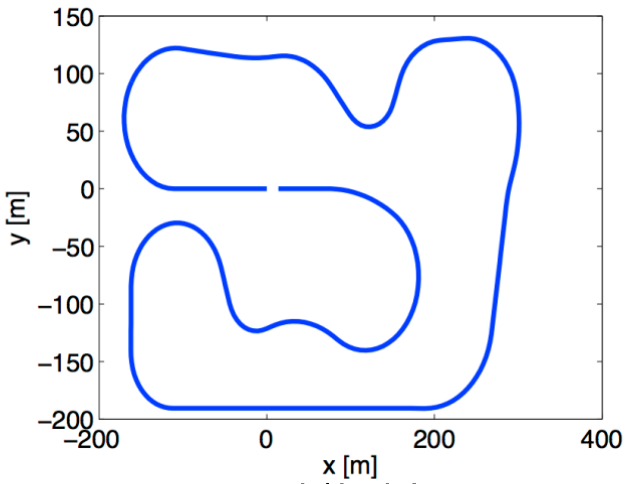
Figure 6: Structure of a driver assistance system

Verification of the specification for the supervisor isa highly nontrivial task. In order to provide a formal verification of the achievedcontrol performance on a global level, the problem must beformulated globally, which might be a highly computation-intensive procedure.Moreover the presence of competing multi-objectivecriteria denies the applicability of this global approach in general.Therefore in practice the formal global verification is oftenomitted and the quality of the overall control scheme isassessed through simulation experiments.

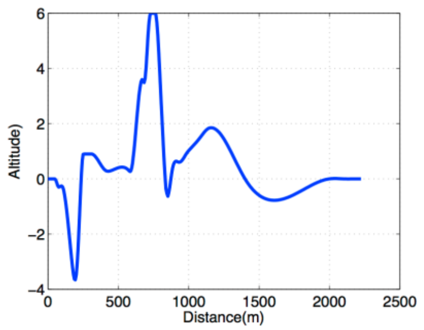
5. SIMULATION EXAMPLES

The simulation vehicle is driven by in-wheel electric motors mounted inside all the four wheels, while both braking and differential braking is performed by a conventional hydraulic brake system.The geometry and terrain characteristics of the racetrack determining the reference path of the vehicleis shown in Figure 7/(a),(b), while the reference velocity is illustrated in Figure 7/(c).

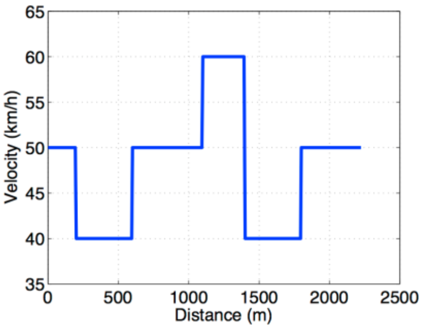
The objective for the in-wheel electric vehicle is to travel along the racetrack with the predefined reference velocity with minimal lateral error, using the in-wheel motors, the steering and the brake system.



a./ Road of the vehicle



b./ Altitude



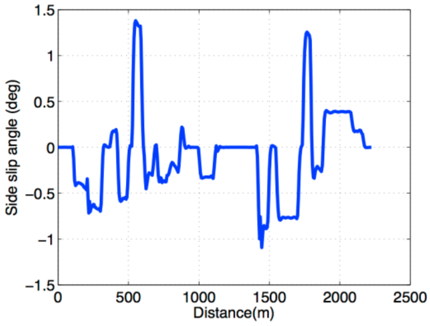
c./ Reference velocity

Figure 7: Reference path and velocity of the racetrack

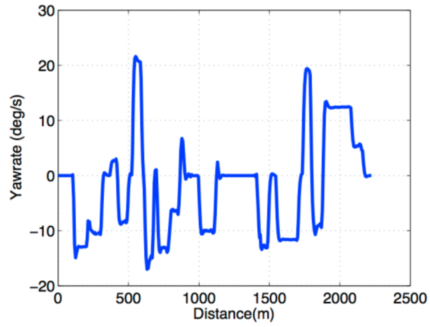
As illustrated in Figure 8 (c) and (d), the value of the vehicle states andβincreases with sharper corners and bigger velocities. The performance of the integrated control system is shown in Figure 8 (a) and (b). The velocity and path tracking ability of the designed control system is acceptable. Note, that the vehicle managed to go around the track without the danger of skidding of the track.

The vehicle motion is influenced by the high level control signals, illustrated in Figure 9. It is well demonstrated in Figure 9 (a) and (b) that the steering and differential braking inputs are both applied during cornering manoeuvres. The longitudinal force shown in Figure 9 (c) affects the longitudinal motion of the vehicle. Heavy acceleration and deceleration corresponding with the changing speed limit can also be observed.

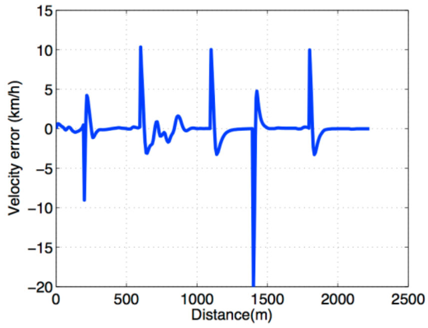
The operation of the in-wheel motors and the steering system is illustrated in Figure 10 (a) and (b).



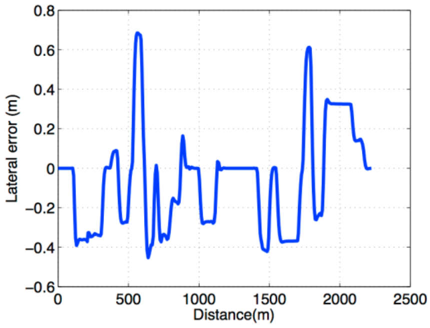
a./ Sideslip angle



b./ Yaw rate

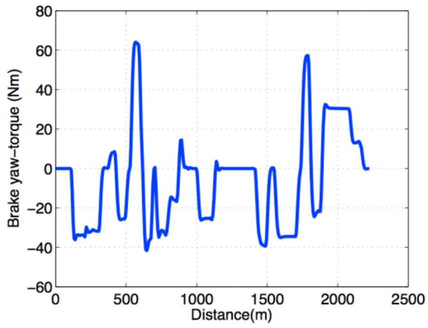


c./ Velocity error

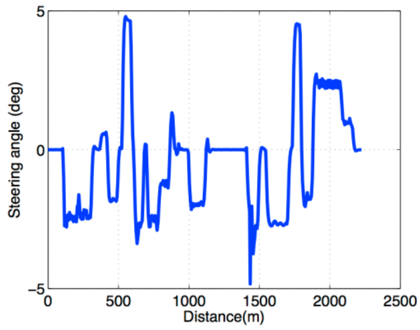


d./ Lateral error

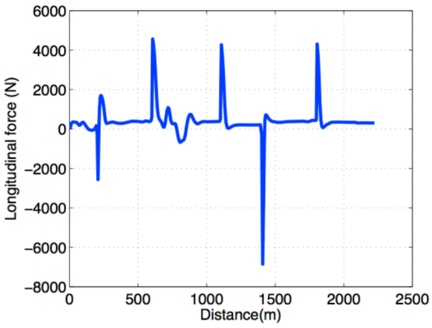
Figure 8: Vehicle states and performances



a./ Brake yaw torque

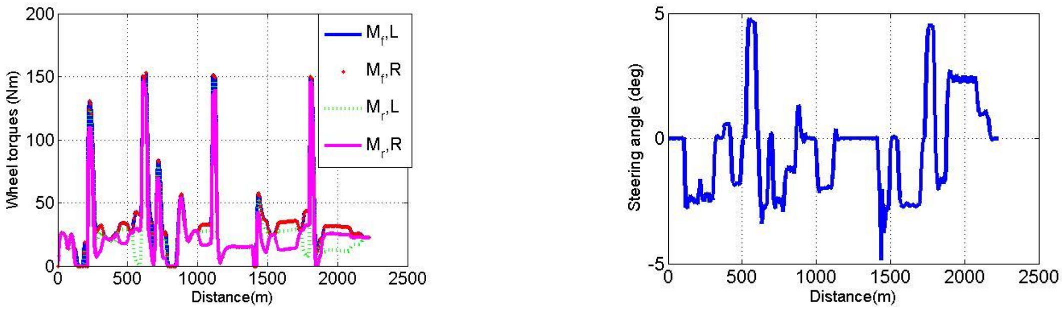


b./ Steering angle



c./ Longitudinal force

Figure 9: High level control signals of the integrated system



a./ Wheel clutch torque b./ Steering angle

Figure 10: Low level control signals of the integrated system

6. CONCLUSIONS

The paper has presented an LPV based method to control in-wheel electric vehicle with the integration of the steering, brake and propulsion system. During the LPV design process, physical construction limits of the vehicle, disturbances, unmodelled dynamics and sensor noises were also considered.The designed hierarchical control system is able to track a predefined road geometry and speed limit with small errors, as it has been proven by the simulations.

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REFERENCES

[1] Fahimi F. Full drive-by-wire dynamic control for four-wheel-steer all-wheel-drive vehicles. Vehicle System Dynamics, 51(3):360-376, 2013.

[2] Gáspár P., Szabó Z. and J. Bokor, LPV design of reconfigurable and integrated control for road vehicles, Proceedings of the Conference on Decision and Control, Orlando, Florida, 2011.

[3] Gordon T., M. Howell, and F. Brandao, Integrated control methodologies for road vehicles, Vehicle System Dynamics, vol. 40, pp. 157–190, 2003.

[4] Hirano Y. Integrated vehicle control of an in-wheel-motor vehicle to optimize vehicle dynamics and energy consumption. Proceedings of the 10th World Congress on Intelligent Control and Automation, 2012.

[5] Osborn R.P. and T. Shim. Independent Control of all-wheel-drive torque distribution. Vehicle System Dynamics, 44(7):529-546, 2006.

[6] Wang R., H. Zhang and J. Wang. Linear parameter-varying controller design for four-wheel independently actuated electric ground vehicles with active steering systems. IEEE Transactions on Control Systems Technology, 2013.

[7] Bokor J. and Balas G. (2005). Linear parameter varying systems: A geometric theory and applications, Proceedings of the 16th IFAC World Congress, Prague, 16(1).

[8] Wu, F., Yang, X. H., Packard, A. and Becker, G. (1996). Induced L2-norm control for LPV systems with bounded parameter variation rates, International Journal of Nonlinear and Robust Control, **3**.

[9] Zomotor, A. (1991). Fahrwerktechnik, Fahrverhalten. Vogel Verlag Und Druck.