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LPV design of reconfigurable and integrated control for road vehicles

Péter Gáspár, Zoltán Szabó and József Bokor

***Abstract*— The aim of the paper is to present a distributed supervisory architecture for the design and development of reconfigurable and integrated control systems in road vehicles. The performance specifications are guaranteed by the local controllers, while the coordination of these components is provided by the supervisor. Monitoring components provide the supervisor with information needed to make decisions about the necessary interventions into the vehicle motion and guarantee the robust operation of the vehicle. In the proposed architecture the supervisor and the components communicate through a well-defined interface. This interface uses the monitoring signals as additional scheduling variables of the individual LPV (Linear Parameter Varying) controllers introduced to distinguish the performances that correspond to different operational modes. The advantage of this architecture is that local LPV controllers are designed independently provided that the monitoring signals are taken into consideration in the formalization of their performance specifications.**

I. INTRODUCTION AND MOTIVATION

An integrated control system is designed in such a way that the effects of a control system on other vehicle functions are taken into consideration in the design process by selecting the various performance specifications. Redundancy on sensor and actuator levels makes it possible to realize the same functionality using different sensor and actuator configurations. Thus integrated design is also motivated by the needs of reconfigurable and reliable control, [1], [2].

A possible solution to an integrated control could be to set the design problem for the whole vehicle and include all the performance demands in a single specification. Besides the complexity of the resulting problem the formulation of a suitable performance specification is the main obstacle for this direct global approach. In the framework of available design techniques the formulation and successful solution of complex multi-objective control tasks are highly nontrivial, see, e.g., [3], [4].

Another solution to the integrated control is a decentralized control structure where the components are designed independently, see e.g., [5], [6]. In the paper the decentralized control system is augmented with a supervisor as illustrated in Figure 1. The role of the supervisor is to meet performance specifications and prevent the interference and conflict between components. The supervisor has information about the current operational mode of the vehicle, i.e., the various vehicle maneuvers or the different fault operations. The supervisor is able to make decisions about the necessary interventions into the vehicle components and guarantee the reconfigurable and fault-tolerant operation of the vehicle. These decisions are propagated to the lower layers through predefined interfaces encoded as suitable scheduling signals.

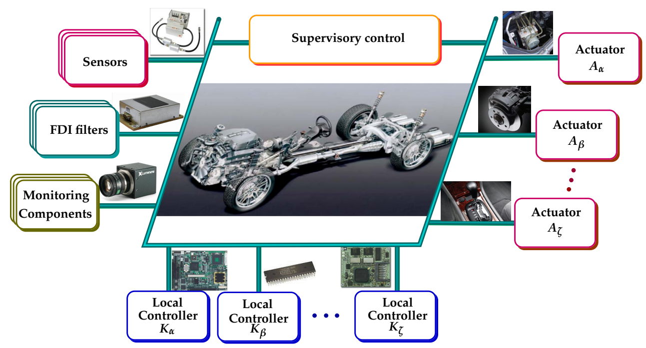

Fig. 1. The supervisory decentralized architecture of integrated control

In the proposed solution the design of local control components is based on LPV methods. The LPV approaches allow us to take into consideration the highly nonlinear effects in the state space description, [7], [8]. Moreover, in the LPV method both performance specifications and model uncertainties are taken into consideration. The main point of the proposed approach is that in the control design of the local components scheduling variables received from the supervisor are used as a key of the integration.

The structure of the paper is as follows. In Section II the architecture of the supervisory integrated control is presented. In Section III, as an illustration, the control-oriented LPV modeling is described. In this section the weighting strategy in the closed-loop interconnection structure is also illustrated. In Section IV the selection of the sensors and monitored components is presented. In Section V the integration of the actuators based on the operation modes is shown. In Section VI the global performances based on the supervisory activity are analyzed. In Section VII the integrated control mechanism is presented through a simulation example. Finally, Section VIII contains concluding remarks.

II. ARCHITECTURE OF INTEGRATED CONTROL

The term configuration refers to a well-defined sensor and actuator set that is associated with a given functionality. Control reconfiguration is triggered by the following

The authors are with Systems and Control Laboratory, Computer and Automation Research Institute, Hungarian Academy of Sciences, Hungary, Kende u. 13-17, H-1111 Budapest, Hungary; Fax: +36-1-4667503; Phone: +36-1-2796171; E-mail: gaspar@sztaki.hu
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requirements: the achieved control performance in certain scenarios must be improved and an increased reliability in the presence of sensor or actuator faults must be achieved. The term event refers to the occurrence of such requirements. A finite set of events $\mathcal{E}$ are assumed. On a higher level an event is handled based on a given functionality thus one can associate a certain event $e \in \mathcal{E}$ with a set of configurations $\mathcal{C}_e$. Reconfigurable control strategies define a policy to select a specific configuration $K \in \mathcal{C}_e$ when an event e occurs. In a normal situation a configuration is formed by a single local component, e.g., steering, otherwise it is composed of several local components that can fulfill the same functional behavior, e.g., steering and brake for generating yaw moment. The event set $\mathcal{E}$ and the corresponding class of the configuration sets $\mathcal{C}_e$ are determined in the preliminary step of the design. This may be a highly nontrivial task.

The role of the supervisor is to coordinate the local components and handle the interactions between them. Since the performance specifications of local controllers are often in conflict, the supervisor must also guarantee a balance or trade-off between them. The information provided by the supervisor is composed of messages and signals sent by the monitoring components and fault detection and isolation (FDI) filters. Based on this information the supervisor is able to make decisions about the necessary vehicle maneuvers and guarantee reconfigurable and fault-tolerant operation of the vehicle and send messages to the local controllers. In order to implement a safety feature the operation of a local controller must be modified by a supervisory command. This is realized through appropriately set scheduling variables that are transmitted to the local controllers. At a local level the behaviour of the controller is affected by these scheduling variables through the performance weighting functions. The difficulty in the supervisory control is that global stability and performance are difficult to guarantee.

The design of the supervisor does not involve dynamical systems explicitly. However, due to the time variation of the signals the designer should check the validity of relations between the momentary values of the monitoring signals based on a temporal logic. The difficult part of the design is to ensure the correctness of the specification, see [9], [10]. It must be stressed at this point that the baseline configurations handle only one actuator, which is associated with a given task (functionality). The hierarchy of the configurations and corresponding scheduling variables ensure that the additional actuator(s) considered improve the stability properties of the given functionality.

In contrast to the controller switching strategy the proposed approach uses a performance weighting strategy. On the supervisor level the required configurations are defined uniquely by the specific values of a set of marker signals. These marker signals are used as scheduling variables on the level of local controllers. The task of the supervisor design is to specify these marker signals in such a way that the different combinations of their values define the specific event (functionality) in a unique way. The different combinations of the marker signals encode the designers specification (option) in dealing with multi-objective or conflicting scenarios.

A local component is a well-defined ensemble of a controller, an actuator and a set of related physical or virtual sensors, e.g., units for monitoring components and FDI filters. These elements are able to detect emergency vehicle operations, various fault operations or performance degradations in controllers. They send messages to the supervisor in order to guarantee the safe operation of the vehicle.

Each of the local components is governed by a local controller. A local controller must meet the predefined performance specifications. The signals of monitoring components and those of FDI filters are built in the performance specifications of the controller by using a parameter-dependent form. The performance specifications are formalized in a parameter-dependent way in which the corresponding scheduling variable is given by the supervisor. Thus the controller is able to modify or reconfigure its normal operations in order to focus on other performances instead of the actual performances. It sends messages about the changes to the supervisor and it receives messages from the supervisor about the special requirements.

III. Modeling and control of vehicle systems

The objective of the control design is to track a predefined path, guarantee road holding and increase pitch and roll stability. Five control components are applied in the system: the active brake, steering, anti-roll bars, the suspension system and the driveline system, see Figure 2. The longitudinal force

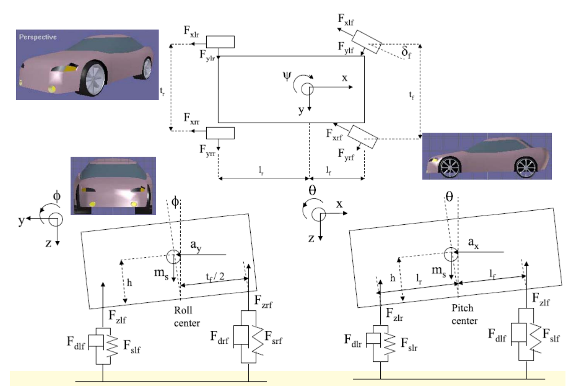


Fig. 2. Vehicle body for yaw, roll and pitch motions

is generated by the driveline and the brake systems. The tracking of the predefined road geometry is performed by the active steering. During maneuvers active anti-roll bars are used to improve roll stability. Road holding and passenger comfort are guaranteed by applying an active suspension system. This system also improves both the roll and the pitch stability. The brake system might also be activated to provide the lateral stability of the vehicle.

The local controllers are designed based on vehicle models with different complexity. Their design is based on state space representation form $\dot{x} = A(\rho)x + B_1(\rho)w + B_2(\rho)u$, where x, w and u are the state, disturbance and input, respectively. Vector ρ includes the scheduling variables. In the first step the state equation is defined and then the performances and measured output are selected considering the control tasks.

The primary role of the brake is to reduce the forward velocity of the vehicle or stop it. It is also able to generate unilateral brake forces at the front and the rear wheels at either of the two sides $u_b = \Delta F_b$. In the control system the brake is able to modify the yaw angle of the vehicle during a cornering and reduce the effect of lateral acceleration. Thus, the brake is able to substitute for different vehicle components if they are affected by a fault or degradation in terms of performances. The steering is used to follow the desired course. The control input is the steering angle: $u_d = \delta_f$.

Active suspensions are used to provide good handling characteristics and improve ride comfort while harmful vibrations caused by road irregularities act upon the vehicle. The suspension system is also able to improve pitch and roll stability by generating pitch moment during abrupt braking and roll moments during emergency maneuver. The control inputs are generated by the suspension actuators: $u_s = \left[f_{fl}, f_{fr}, f_{rl}, f_{rr}\right]^T$. The role of the active anti-roll bars is to keep roll stability even during vehicle maneuvers such as a sharp cornering, double lane changing or overtaking. The active anti-roll bars operate continuously during travelling and generate stabilizing roll moments between the sprung and unsprung masses to improve roll stability. The control inputs are the roll moments at the front and the rear between the sprung and unsprung masses generated by active anti-roll bars: $u_r = \left[u_{rf}, u_{rr}\right]^T$.

The nonlinear effects of the forward velocity, the adhesion coefficient of the vehicle in the lateral direction or the nonlinear characteristics in the suspension spring and damper components are taken into consideration $\rho = [v, \mu, \rho_{bij}, \rho_{kij}]^T$, where ρ_{kij} and ρ_{bij} are the relative displacement and its velocity. It is assumed that with suitably-selected scheduling variables ρ these nonlinear components can be transformed into affine parameter-dependent forms. Then the nonlinear models are transformed into LPV models in which nonlinear terms are hidden with suitably selected scheduling variables. This transformation requires that the components of vector ρ be measured, see [11], [12].

The design of a local controller is based on the control-oriented LPV model and weighting strategy. The closed-loop system applied in the design of integrated control includes the feedback structure of the model $G(\rho)$, the compensator, and elements associated with the uncertainty models and performance objectives: $z = C(\rho)x + D_1(\rho)w + D_2(\rho)u$, where $w = [d \;\; n]^T$ includes both the external disturbances and the sensor noise. A typical interconnection structure is shown in Figure 3. In this framework performance requirements z are imposed by a suitable choice of the weighting functions W_p. The proposed approach realizes the reconfiguration of the performance objectives by an appropriate scheduling of these weighting functions. Δ_m block contains the uncertainties of

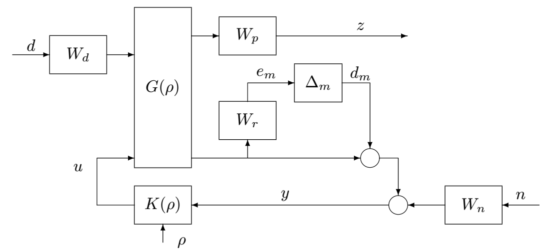


Fig. 3. The closed-loop interconnection structure

the system, such as unmodelled dynamics and parameter uncertainty. In this augmented plant unmodelled dynamics is represented by a weighting function W_r and a block Δ_m. The purpose of the weighting functions W_w and W_n is to reflect the disturbance and sensor noises.

In the design of local controllers the quadratic LPV performance problem is to choose the parameter-varying controller in such a way that the resulting closed-loop system is quadratically stable and the induced $\mathcal{L}_2$ norm from w to z is less than γ. The existence of a controller that solves the quadratic LPV γ-performance problem can be expressed as the feasibility of a set of Linear Matrix Inequalities (LMIs), which can be solved numerically. Stability and performance are guaranteed by the design procedure, see [7], [13].

IV. Sensors and monitored components in the distributed control system

The local components also include units for monitoring vehicle operations and FDI filters. These components are able to detect emergency vehicle operations, various fault operations or performance degradations in controllers. They also send messages to the supervisor. In the reconfigurable and fault-tolerant control of the local controller several signals must be monitored and scheduling variables are added to the scheduling vector in order to improve the safety of the vehicle, e.g., variables are needed to encode the rollover risk, represent the harmful effects of abrupt braking and take a detected failure of an active component into consideration.

The efficient operation of the supervisor and the local controllers require reliable and highly accurate signals from the system. To meet this requirement redundant sensors, diverse calculations and fault detection filters are needed. To achieve the efficient and optimal intervention the detections of faulty sensors are important since they must be substituted for in operations based on these sensors. Low cost solutions are preferred in the vehicle industry, thus simple sensors and software-based redundancy must be applied.

In the following several examples for monitored components related to specific control goals are presented: Yaw stability is achieved by limiting the effects of the lateral load transfers. The purpose of the control design is to minimize the lateral acceleration, which is monitored by a performance signal: $z_a = a_y$. Unilateral braking is one of the solutions, in which brake forces are generated in order to achieve a stabilizing yaw moment. In the second solution additional steering angle is generated in order to reduce the effect of the lateral loads. These solutions, however, require active driver intervention into the motion of the vehicle to keep the vehicle on the road.

Another control task is to follow the road geometry. The purpose of the control is to minimize the difference between the yaw rate and the reference yaw rate must be minimized: $z_e = |\psi_{act} - \psi_{ref}|$. In practice the calculation of this difference is based on signals of a video camera.

Roll stability is achieved by limiting the lateral load transfers on both axles to below the levels for wheel lift-off during various vehicle maneuvers. The lateral load transfer is $\Delta F_{zi} = k_t \phi_{ti}$, where ϕ_{ti} is the monitored roll angle of the unsprung mass at the front and the rear.The normalized lateral load transfer is introduced: $\rho_R = \Delta F_{zy}/(mg)$. The aim of the control design is to reduce the maximum value of the normalized lateral load transfer if it exceeds a predefined critical value.

Besides the basic control problems these monitoring components require additional sensors. The tracking task requires one or two cameras for reasons of redundancy, the pitch and roll stability require the pitch and roll angle of the sprung mass. In the vehicle industry roll and pitch rates are measured and then the angles are calculated by a numerical procedure.

The fault-tolerant control requires fault information in order to guarantee performances and modify its operation. Thus, FDI filters are also designed for the operation of the actuators. As an example the fault information provided by a fault detection filter is given by $\rho_D = f_{act}/f_{max}$, where f_{act} is an estimation of the failure (output of the FDI filter) and f_{max} is an estimation of the maximum value of the potential failure (fatal error). The value of a possible fault is normalized into the interval $\rho_D = [0, 1]$. The estimated value f_{act} means the rate of the performance degradation of an active component. The actuator reconfiguration is based on the fact that two actuators are able to influence the same vehicle dynamics. The control design is based on two factors: the failure or performance degradation have already been detected and the fault information ρ_D and the necessary intervention possibilities are built into its control design.

V. Actuators and Operation Modes in the Distributed Control System

Steering system: In order to solve the yaw rate tracking problem in the design of the steering system, the command signal must be fed forward to the controller (y_{ref}). The command signal is a pre-defined reference displacement and the performance signal is the tracking error: z_e. The weighting function of the tracking error is selected as:

$$W_{pe} = \kappa_e (T_{d1}s + 1)/(T_{d2}s + 1), \tag{1}$$

where T_{di} are time constants. Here, it is required that the steady state value of the tracking error should be below $1/\kappa_e$ in steady-state.

Brake system: In the design of the brake system the command signal is the difference in brake forces while the performance signal is the lateral acceleration: $z_b = \begin{bmatrix} a_y, u_r \end{bmatrix}^T$. The weighting function of the lateral acceleration is selected as:

$$W_{pa} = \phi_a (T_{b1}s + 1)/(T_{b2}s + 1), \tag{2}$$

where T_{bi} are time constants and

$$\phi_a = \begin{cases} 1 & \text{if} \quad |\rho_R| > R_b \\ \frac{|\rho_R| - R_a}{R_b - R_a} & \text{if} \quad R_a \le |\rho_R| \le R_b \\ 0 & \text{if} \quad |\rho_R| < R_a \end{cases} \tag{3}$$

Here ϕ_a is a gain, which reflects the relative importance of the lateral acceleration and it is chosen to be parameter-dependent, i.e., the function of ρ_R. When ρ_R is small ($|\rho_R| < R_b$), i.e., when the vehicle is not in an emergency, ϕ_a is small, indicating that the LPV control should not focus on minimizing acceleration. On the other hand, when ρ_R approaches the critical value, i.e., when $|\rho_R| \geqq R_b$, ϕ_a is large, it indicates that the control should focus on preventing the rollover.

If a fault is detected in the operation of the anti-roll bars the brake system will be activated at a smaller critical value than in a fault-free case, i.e., when $|\rho_{Da}| > 0$. Consequently, the brake is activated in a modified way and the brake moment is able to assume the role of the anti-roll bars or the suspension actuator in which the fault has occurred. The modified critical value is

$$R_{a,new} = R_a - \alpha \cdot \rho_{Da}, \tag{4}$$

where α is a predefined constant factor. Similarly, if a fault is detected in the steering system ($|\rho_{Ds}| > 0$), the brake must focus on yaw dynamics in order to reduce the tracking error. Thus, in the control design of the brake the performance specification concerning the steering system is also built in.

Suspension system: The performance signals in the suspension design are: $z_s = \begin{bmatrix} a_z & s_d & t_d & u_s \end{bmatrix}^T$. The goals are to keep the heave accelerations $a_z = \ddot{q}$, suspension deflections $s_d = x_{1ij} - x_{2ij}$, wheel travels $t_d = x_{2ij} - w_{ij}$, and control inputs small over the desired operation range. The performance weighting functions for heave acceleration, suspension deflections and tire deflections are selected as

$$W_{p,az} = \phi_{az}(T_{s1} + 1)/(T_{s2} + 1), \tag{5}$$

$$W_{p,sd} = \phi_{sd}(T_{s3} + 1)/(T_{s4} + 1), \tag{6}$$

$$W_{p,td} = \kappa_{td}(T_{s5} + 1)/(T_{s6} + 1), \tag{7}$$

where T_{si} and κ_{td} are time constants and the parameter dependent gains are

$$\phi_{az} = \begin{cases} 1 & \text{if} \quad |\rho_{kij}| < \rho_1, \\ \frac{|\rho_{kij}| - \rho_2}{\rho_1 - \rho_2} & \text{if} \quad \rho_1 \le |\rho_{kij}| \le \rho_2, \\ 0 & \text{if} \quad R \ge R_s \ \text{or} \ |\rho_{kij}| > \rho_2. \end{cases} \tag{8}$$

$$\phi_{sd} = \begin{cases} 0 & \text{if} \quad |\rho_{kij}| < \rho_1, \\ \frac{|\rho_{kij}| - \rho_1}{\rho_2 - \rho_1} & \text{if} \quad \rho_1 \le |\rho_{kij}| \le \rho_2, \\ 1 & \text{if} \quad R \ge R_s \ \text{or} \ |\rho_{kij}| > \rho_2. \end{cases} \tag{9}$$

In normal cruising the suspension system focuses on the conventional performances based on the parameter-dependent gain, which is a function of the suspension deflection ρ_{kij}. The idea of the reconfigurable suspension system is based on the fact that it is used not only to eliminate the effects of road irregularities but also to generate roll moments to improve roll stability or generate pitch moment to improve pitch stability.

$$W_{p,\theta} = \phi_P(T_{s7}+1)/(T_{s8}+1), \tag{10}$$
$$W_{p,\phi} = \phi_R(T_{s7}+1)/(T_{s8}+1). \tag{11}$$

For a reconfigurable suspension system the parameter-dependent gains are selected as functions of the normalized lateral load transfer ρ_R and the normalized value of the pitch angle ρ_P. If ρ_P exceeds a predefined critical value, i.e., when $|\rho_P| \geqq R_P$, the controller must focus on pitch stability. In an emergency, however, i.e., when $|\rho_R| \geq R_s$, the suspension system must reduce the rollover risk and guaranteeing passenger comfort (and pitch angle) is no longer a priority.

Actuator selection: The generation of the different actuators during the drive is based on a weighting strategy. The weighting for the front wheel steering is

$$W_{act,\delta} = (1-\rho_{act})/\delta_{max}, \tag{12}$$

while the weighting for the brake yaw-moment is

$$W_{act,Mbr} = \rho_{act}/M_{brcrit}, \tag{13}$$

where δ_{crit} is determined by the constructional maximum steering angle and M_{brcrit} is the maximum of brake yaw-moment. In the control design the distribution of the wheel forces must also be taken into consideration. The steering angle is limited by construction (δ_{crit}), therefore when the maximal steering angle is reached the desired lateral dynamics must be achieved by the brake moment. It is also necessary to avoid the skidding of tyres, thus the differential braking must be reduced, while the yaw-motion of vehicle must be controlled by front-wheel steering. By using differential braking the velocity of the vehicle is decreased, which must be compensated for by the driveline with additional energy. Therefore the use of differential braking must be avoided during acceleration and front-wheel steering is preferred. During deceleration the brake is already being used, thus differential braking is preferred for practical reasons, but close to the limit of skidding, front-wheel steering must also be generated. A weighting factor ρ_{act}, which depends on the vehicle operation, i.e., the driving and the braking, will be used in the weighing strategy of the control design, see Figure 4.

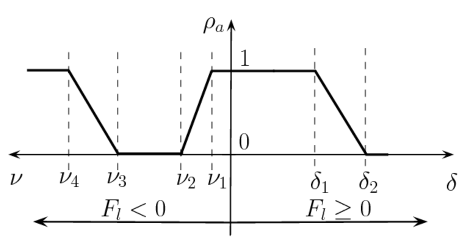


Fig. 4. Relationship between the parameter ρ_a and the actuator selection

VI. Global performances based on the supervisor activity

In order to provide a formal verification of the achieved control performance on a global level, the problem must be formulated globally. Only on this extended level are the performance variables which are relevant for the whole vehicle available. Once the local controllers have been designed, however, it is possible to perform an analysis step in the same robust control framework on a global level, for details see [14]. This might be a highly computation intensive procedure. Moreover the presence of competing multi-objective criteria deny the applicability of this global approach. E.g., in emergency events certain performance components gain absolute priority over others, thus requiring a given performance level for the ignored performance components is not justified. On the other hand the local design guarantees the prescribed performance level for the critical components. Therefore in practice the formal global verification is often omitted and the quality of the overall control scheme is assessed through simulation experiments.

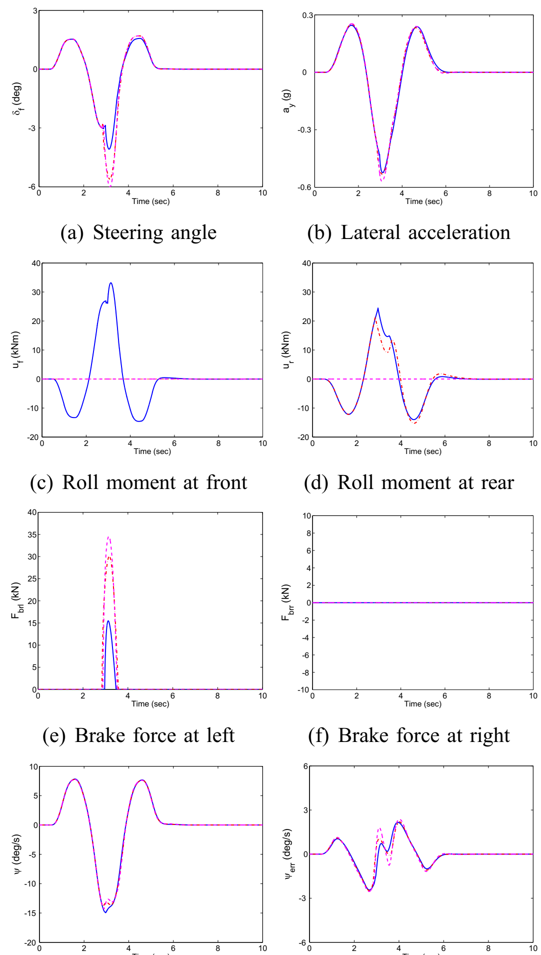
The relationship between the supervisor and the local controllers guarantee that the system meets the specified performances. Applying parameter-dependent weighting a balance between different controllers is achieved. In different critical cases related to extreme maneuvers or performance degradations/faults in sensors or actuators the controllers reconfigure their operations.

However, maneuvers in which different critical performances must be achieved simultaneously may occur. For example in a high-speed cornering maneuver the risk of a rollover increases significantly. The performances are in contradiction: deviating from the lane might cause the vehicle to run off the road while increasing roll dynamics might lead to rollover. This maneuver requires an intensive cooperation between the steering and the brake. The supervisor sends critical signals to these controllers and consequently these control systems are activated. However, reducing the rollover risk the yaw dynamics is modified and the deviation from the predefined path may increase. In contrast reducing the difference from the path might improve the rollover risk. Since both interventions are critical the supervisor is not able to resolve the problem, thus the performances are handled by the actuators with performance degradation. In similar emergency cases the supervisor is able to handle only a trade-off between critical performances.

VII. Simulation examples

As an illustration an integrated control is proposed for tracking the path of the vehicle, guaranteeing road holding and improving pitch and roll stability. In cruising mode, the steering minimises the tracking error while the active anti-roll bars and the suspension system are operating. When the monitoring signals have reached their critical values, the brake is also activated in order to improve roll and pitch stability.

The operation of the integrated control in a heavy vehicle is illustrated in a double-lane-changing manoeuver, which is defined by the signal yaw-rate. The maneuver has a 4 m path deviation over 100 m. The velocity of the vehicle is 120 $\mathrm{km/h}$. The operation of three control systems are shown in Figure 5. The integrated control performs the maneuver in a fault-free operation (solid), operation in which there is a float failure in the active anti-roll bar at the rear (dashed dotted), and operation in which there is a float failure in the active anti-roll bar both at the front and the rear (dashed). During the faulty operation the anti-roll bars cannot generate enough stabilizing moment to balance the overturning moment. When there is a fault in the front anti-roll bar the brake is activated earlier than in the fault-free case. Moreover, the braking lasts longer and the brake forces are greater than in the normal situation.



(a) Steering angle (b) Lateral acceleration

(c) Roll moment at front (d) Roll moment at rear

(e) Brake force at left (f) Brake force at right

(g) Yaw rate (h) Tracking error

Fig. 5. Time responses of the tracking control

The supervisor uses three signals, i.e., the normalized lateral load ρ_R from a component, which monitors the roll dynamics of the vehicle, the normalized longitudinal load ρ_P from a component, which monitors the pitch dynamics and the fault information ρ_D from an FDI filter, which monitors the operation of the active anti-roll bars. The supervisor sends ρ_R and ρ_D signals to the active brake, which focuses on the roll stability. The integration is carried out through the parameter-dependent weighting function used in the design of the brake. The brake activates and generates a yaw moment in order to reduce the influence of the lateral loads. The supervisor also sends ρ_R, ρ_P and ρ_D signals to the active suspension system, which provides road holding and passenger comfort.

VIII. Conclusions

In the paper, a multi-layer supervisory architecture for the design and development of integrated vehicle control systems has been proposed. The local controllers are designed independently by taking into consideration the monitoring and fault signals received from the supervisor. In this architecture the supervisor is able to make decisions about the necessary interventions and guarantee the reconfigurable and fault-tolerant operation of the vehicle. The design of local vehicle controllers has been carried out by using LPV methods. In the control-oriented modelling the monitoring variables and the signals from the FDI filters play an important role. The supervisor sends these signals to the local controllers and handles the interactions and trade-off between these components. The LPV method guarantees that the supervisory integrated control meets the defined performance specifications.

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