Plug and Play Design in the Electric Vehicle Systems

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Abstract: The plug and play concept focuses on the design of complex control systems with multiple functional building blocks. Each of the blocks fulfills certain specifications, is designed separately and might be delivered by different vendors. Concerning vehicle systems complexity is handled in the integrated design framework built around a supervisory architecture. This paper investigates the possibilities of the plug and play design built in the supervisory integrated control. The supervisory control makes decisions about the necessary interventions, guarantees coordination between components and meets performance specifications. The well-defined interfaces provide that the decisions are propagated between the supervisor and the local components. Therefore the interfaces between components have crucial roles. The concept of the plug and play design is presented and several design methods based on the weighting strategy in the closed-loop interconnection structure are proposed.

Keywords: electric vehicle, plug and play, robust control, qLPV design

1. Introduction

The demand for the integrated vehicle control methodologies including the driver, the vehicle and the road arises at several research centers and automotive suppliers, see, e.g., [6], [16]. The purpose of the integrated control is to combine and supervise all controllable subsystems affecting vehicle dynamic responses. In more details it means that multiple-objective performances from available actuators must be improved, sensors must be used in several control tasks, the number of independent control systems must be reduced and at the same time the flexibility of control systems must be enhanced, see e.g. [2], [4], [9].

A possible approach to the integrated control may be to set the design problem for the entire vehicle and include all the performance demands in a single specification. In the framework of available design techniques the formulation and successful solution of complex multi-objective control tasks are highly nontrivial. In the integration of various control components, which operate only in some limited part of the overall operating regime of the plant, the multiple model approach is proposed.

Another approach to the integrated control is the supervisory decentralized control structure where the components are designed independently, see, e.g., [5], [15]. The role of the supervisor in the integrated control is to guarantee the coordination of the local controllers in order to meet global performance specifications, guarantee priority between controllers and reduce conflicts between them. The concepts of an agent and a multi-agent system is proposed by [12]. Conflicts between agents, which naturally arise in such systems due to the dependencies between the partial problems the agents solve, are handled by supervisory activities by adequately coordinating the agents.

The integrated control creates the possibility of the plug and play design, which is important in the industrial applications. In [11] the plug and play control concept is presented and a number of problems and solutions are proposed for the industrial requirements. In [13] a hierarchical control architecture applied to several complex dynamic systems is presented.

In this paper the concept of the plug and play design in connection with the integrated supervisory control is presented for vehicle systems. In the design of the integrated control the LPV (Linear Parameter Varying) methods play an important role. LPV methods are well elaborated and successfully applied to various industrial problems. Moreover, in LPV methods both performance specifications and model uncertainties are taken into consideration.

2. Concept of the supervisory integrated control

2.1. Architecture of the integrated control

The integrated control proposed in the paper is based on a supervisory decentralized control structure, which is illustrated in Figure 1. The supervisor is a high-level controller which is able to handle the effects of individual control components on vehicle dynamics. The advantage of this solution is that the components with their sensors and actuators can be designed by the suppliers independently.

The supervisor has information about the current operational mode of the vehicle, i.e., the various vehicle maneuvers or the different fault operations gathered from monitoring components. In addition it is able to make decisions about the necessary interventions into the vehicle components. The communication between the supervisor and the local control components is performed by using a CAN bus and a well-defined interface.

A local controller must meet the predefined performance specifications based on the measured signals. 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 controller is able to modify or reconfigure its normal operations in order to focus on other performances instead of the actual performances. It is often able to detect different faults and can adapt to the dynamic properties of the faulty plant or changes in the environment. In this way the operation of a local controller can be extended to reconfigurable and fault-tolerant functions.

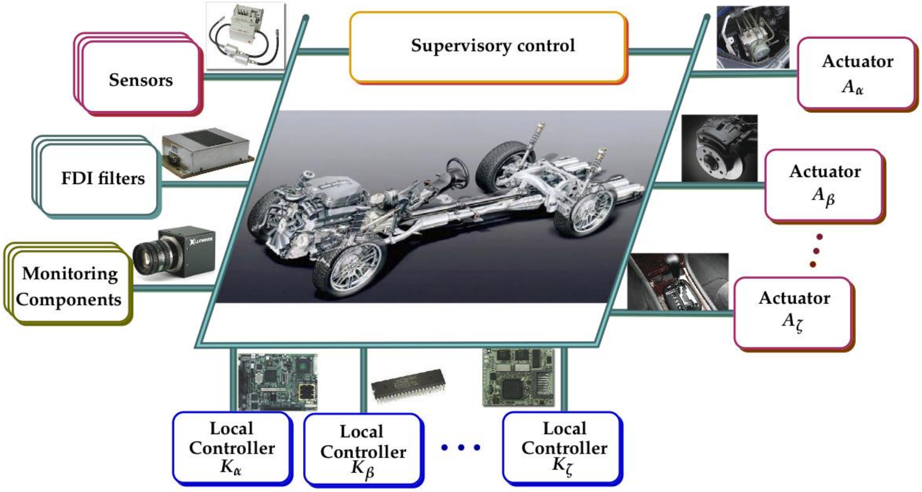


Figure 1. The supervisory decentralized architecture of integrated control

The solution of the problem is that the performance specifications are formalized in a parameter-dependent way in which this parameter depends on the monitoring and fault information. Moreover, the local controller sends messages about the changes to the supervisor and it receives messages from the supervisor about the special requirements. The local controllers often have a hierarchical structure, in which the high-level controller is distinguished from the low-level actuator.

2.2. LPV control of vehicle systems

In the decentralized architecture the signals are propagated between the supervisor and the local components through a well-defined encoded interface. This interface uses the monitoring signals as scheduling variables of the individual LPV 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.

The design of a local controller is based on the standard closed-loop interconnection structure of the model $G(\rho)$, the compensator, and elements associated with the uncertainty models and performance objectives. A typical interconnection structure is shown in Figure 1.

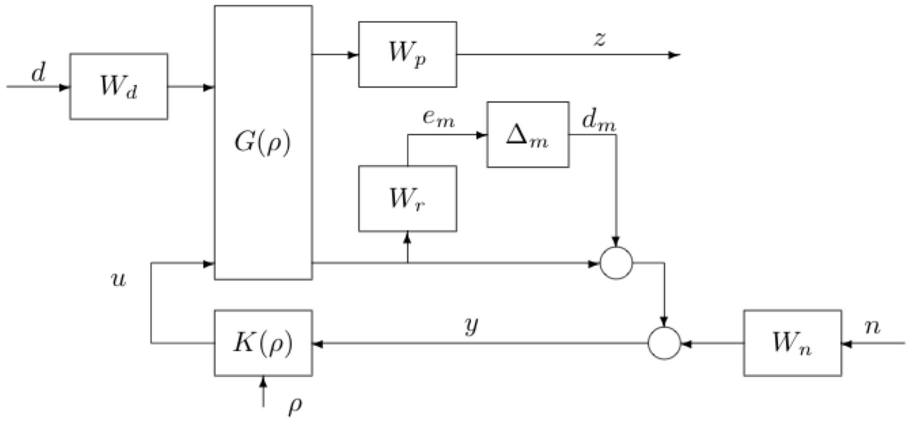


Figure 2. The closed-loop interconnection structure

In this framework performance requirements z are imposed by a suitable choice of the weighting functions W_p. Usually the purpose of weighting functions W_p is to define penalty functions, i.e., weights should be large where small signals are desired and small where large performance outputs can be tolerated. The proposed approach realizes the reconfiguration of the performance objectives by an appropriate scheduling of these weighting functions. The values of the monitoring signals are usually built into the weighting functions applied for performance requirements.

In the augmented plant the uncertainties, such as unmodelled dynamics and parameter uncertainty, are represented by a weighting function W_r and a block Δ_m. The transfer function Δ_m is assumed to be stable and unknown with the norm condition, $\|\Delta_m\|_\infty < 1$. It is assumed that the transfer function W_r is known, and it reflects the size of the uncertainty in the model. The purpose of the weighting functions W_d and W_n is to reflect the disturbance and sensor noises.

Finally, the control problem can be formulated in the general $P - K - \Delta$ structure, where P is the generalized plant and Δ contains both the uncertainties and the scheduling variables, see Figure 2.

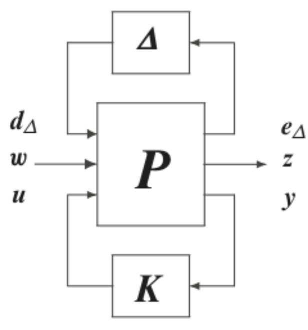


Figure 3: The $P - K - \Delta$ structure

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 the disturbance and the performances is less than the value γ. The minimization task is the following:

$$\inf_K \sup_\Delta \sup_{\|w\|_2 \neq 0, w \in \mathcal{L}_2} \frac{\|z\|_2}{\|w\|_2}. \tag{1}$$

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, for details see [1], [10].

3. Plug and play design

3.1. Motivation of the plug and play design

In the decentralized supervisory control the concept of the plug and play method plays and important role. If a new control component is added, an old control is replaced by a new one, or an old component is removed, the structure of the system (or the control) changes. In these cases the conventional control should be redesigned, which is expensive and takes a long time. This is often not acceptable due to the cost associated with the control design procedure. In the supervisory control concept the supervisory logic must be modified on the highest level. The ultimate goal is to provide a design method for a plug and play control architecture, i.e., the possibility to use sensors and actuators provided by different vendors interchangeably on a core system by guaranteeing a performance level and leaving the global controller intact.

If a new component is added or an old one is replaced by a new one, the dynamics of the entire system may change. A possible way to model the effects of the different components is by using a monitoring signal with its operation range. Then controllers are designed at selected operation points within the range, and finally a family of controllers are implemented as a single controller. As a consequence, during the operation of the system the monitoring signal is used in order to select the appropriate control and adapt to the current operating conditions.

A possible solution of the plug and play design is to apply a set of controllers and the selection of the appropriate control is based on a switching method and monitoring signals. The operation range is divided into several grid points. Then controllers are designed for all the grid points and a finite set of controllers is constructed. The advantage of the solution is that the local controllers are always able to adapt to the new situations by using the monitoring signals.

The vehicle, however, has a large number of monitoring signals, which must be taken into consideration during the operation. There are a few examples. The changes of the adhesion coefficient influence road stability, it may also cause a μ split problem. The saturation of an actuator may cause the unstable operation of a control system. The performance degradation of an actuator leads to insufficient control actions. The fault operation of a sensor may result in the fault intervention of an actuator. As the number of the monitoring signals increases the number of controllers significantly increases.

The solution for the plug and play method proposed in the paper is based on a high-level supervisory control. It is a complex control, which includes monitoring components as additional scheduling variables. It leads to a special LPV structure, since some of the scheduling variables are constant during the operation. For example the fact of an actuator fault, the mass of the vehicle, the height of center of gravity or the actuator dynamics are fixed, thus scheduling variables must be selected constant during the operation.

In what follows this principle is illustrated for the vehicle dynamics example considered in the paper. Each of the actuators and sensors is listed and the weighting policy is presented.

3.2. Actuators

Bound limiter

The intervention of an actuator is related to its construction and operation limits. The construction limit must be taken into consideration all the time, e.g. the value of front-wheel steering must not exceed its upper bound δ_{max}. Brake control also has an operation limit M_{brmax}, which is related to the adhesion factor. The skidding is monitored by the estimation of the longitudinal slips κ.

In order to avoid reaching the steering limit, differential braking and the wheel camber angle must be increased. In order to avoid the skidding of tires, the value of differential braking must be reduced and other control inputs must be increased. Due to the redundancy of the action of different actuators for the same vehicle dynamics the integrated control framework makes it possible to handle this problem by reconfiguration.

Rate limiter

Usually, in the control design the control input of the actuators is assumed to be arbitrarily fast. However, if the bandwidth of the actuators or the signals is disregarded, the control signal does not meet the industrial requirements. Thus, the rate bound on the control input must be estimated and taken into consideration in the control design. In the design a gain is used as a scheduling variable in the weighting function which is applied for the control input. Then a rate bound on the scheduling variable is applied. In the LPV framework the solution leads to the application of the parameter dependent Lyapunov function (PDLF), see [14].

Balance between actuators

The actuator selection depends on several factors such as construction limits, energy requirement and the actuator dynamics. The maximal control input of the steering is determined by their physical construction limits, while in the case of the braking system the constraints are the tire-road adhesion conditions. It is necessary to avoid the skidding of tires, thus in such a case the generation of differential braking must be reduced. The skidding of tires can be monitored by the estimation of the longitudinal slips of the tires κ. These constraints must also be taken into consideration in the control design and must be guaranteed by the supervisor.

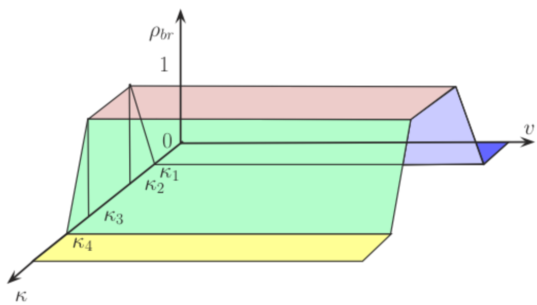
Moreover, the activation of the different components have an energy requirement. By using differential braking the velocity of the vehicle is reduced, which must be compensated for by the driveline with additional energy. Therefore the use of differential braking must be avoided during acceleration and front-wheel steering is preferred. During deceleration the brake is already being used, thus the lateral dynamics is handled by the braking for practical reasons. Thus differential braking is preferred, but close to the limit of skidding, front-wheel steering must also be generated.

According to the inertia of steering, the bandwidths of steering is lower than the bandwidth of differential braking. The fast operation of actuators is an important feature mainly at high velocities. At higher velocities it is recommended to use differential braking, while at lower velocities steering actuation is preferred for practical reasons. The weighting functions for the front wheel steering, brake yaw-moment and suspension moment are selected in the following form:

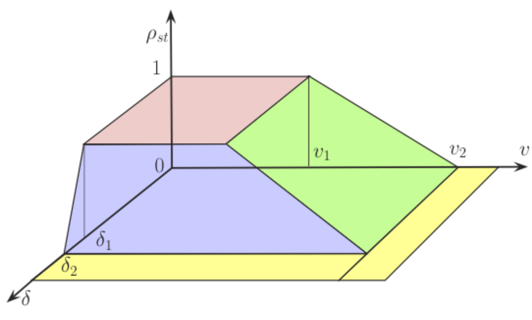
$$W_{act,\delta} = \rho_\delta / \delta_{max} \quad (2)$$

$$W_{act,Mbr} = \rho_{br} / M_{brmax} \quad (3)$$

respectively, where δ_{max} and γ_{max} are determined by the constructional maximum of the steering and the camber angle, while M_{brmax} is the maximum of the brake yaw-moment. Weighting factors ρ_{br}, ρ_δ are chosen to influence the priority of the actuators. Figure 4 shows the characteristics of the weighting factors.



a. Parameter ρ_{st}



b. Parameter ρ_{br}

Figure 4: Selection of parameters ρ_{st} *and* ρ_{br}

When the vehicle is being driven the front wheel steering is actuated, which is determined by factor ρ_{st}, see Figure 4(a). The value is reduced between δ_1 and δ_2, which represents the constructional criterion of the steering system. When the brakes are being applied the tire longitudinal slip angle affects factor ρ_{br}, see Figure 4(b). In this interval differential braking is preferred for practical reasons. It requires an interval to reduce tire skidding and it also requires an interval to prevent chattering between steering and differential braking. Therefore four parameters are designed: κ_1 and κ_2 are used to prevent chattering between steering and braking and κ_3 and κ_4 are applied to prevent the skidding of tires. The weights also depend on the velocity of the vehicle. The effect of the velocity on the weighting factors is the consequence of the interaction between the bandwidth values of the actuators.

3.3. Sensors

The monitoring parameters are critical in the operation of the supervisor, thus in the cooperation of the local control systems. The more signals are used in the control of the entire vehicle the more accurately and safety the control systems can operate. In the following a few important monitoring signals are listed.

Tracking error

In the control design the purpose is to handle the tracking problem. In trajectory tracking the reference signal is the yaw rate defined by the steering angle of the driver $\dot{\psi}_{ref}$, while the actual yaw rate is a measured signal $\dot{\psi}$. The performance signal is the tracking error, which is the difference between the actual yaw rate and the yaw rate command. The weighting function of the tracking error is selected as:

$$W_{z,e_{\dot{\psi}}} = \gamma_e \frac{T_{d1}s+1}{T_{d2}s+1}, \tag{4}$$

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

Roll dynamics

In order to reduce the chassis roll angle, the dynamic displacement of the height of the roll center $|\Delta h|$ is reduced. In this solution a signal h_{ref} is introduced and applied as a reference signal for the tracking task: $\Delta h_M = |h_{ref} - h_M|$, in which h_M is calculated from the measured γ according to the suspension geometry.

When the roll angle ϕ increases significantly, the variable-geometry suspension control must minimize the roll angle. This configuration is achieved by the selection $h_{ref} = h_{ref,max}$. Note that it is possible to achieve vehicle maneuvers in which there is a balance between two performances, i.e., the reduction of the half-track change and that of the roll angle. In these configurations h_{ref} is selected in an interval $h_M < h_{ref} < h_{ref,max}$. When the suspension system must focus on the trajectory tracking, i.e., in emergency maneuvers, the scheduling variable $\rho_{susp} = 1$ is selected, and the safety factor overrides the other performances. The selection of the variables h_{ref} is the following: $h_{ref} = h_M$ if $\phi \leq \phi_1$, $h_{ref} = (h_{ref,max} - h_M)(\phi - \phi_1)/(\phi_2 - \phi_1) + h_M$ if $\phi_1 \leq \phi \leq \phi_2$, otherwise $h_{ref} = h_{ref,max}$. where ϕ_1, ϕ_2 are design parameters. Note that h_{ref} is also a supervisory variable, since in an emergency it is modified by the set of the scheduling variable $\rho_{susp} = 1$.

FDI sensors

The fault-tolerant control requires fault information in order to guarantee performances and modify its operation. At the level of local control design the reconfiguration is achieved by scheduling the performance weights by a signal ρ_κ related to the fault information and provided by a fault decision block. As a simple example, one might consider $\rho_\kappa = f_{act}/f_{max}$, 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 $\rho_\kappa = [0,1]$. The estimated value f_{act} represents the rate of the performance degradation of an active components.

The operation of the fault-tolerant control is based on two factors: the failure or performance degradation has already been detected and the fault information ρ_κ and the necessary intervention possibilities are built into its control design. Instead of a switching type controller reconfiguration the control structure changes due to a reconfiguration of the performance goal achieved by a scheduling of the performance weights. In order to achieve that, the signals of various fault scenarios provided by FDI filters are built in the performance specifications of the controller.

For example when performance degradation occurs in the operation of a brake circuit the brake yaw moment must be substituted for by using the steering and suspension to provide trajectory tracking. In addition, the effect of the degradation of the brake yaw moment is asymmetric. For example, in the case of a left-hand-side brake circuit fault in the rear the brake is not able to turn the vehicle anti-clockwise, therefore positive M_{br} is not allowed, i.e., $\rho_{br} = 0$. However, if $M_{br} < 0$ then $\rho_{br} > 0$. Consequently, if there is one fault in the brake system the weight of braking ρ_{br} depends on the sign of the desired brake yaw moment M_{br} and a gain $\rho_{\kappa,i}$. In the realization of the gain $\rho_{\kappa,i}$, either $\rho_{\kappa,left}$ or $\rho_{\kappa,right}$ must be set. The modification of ρ_{br} is based on the sign of the desired brake yaw moment and the parameters $\rho_{\kappa,i}$, i.e., $\rho_{br,new} = \rho_{\kappa,i}\rho_{br}$, where $\rho_{\kappa,i}$ is the scheduling parameter.

3.4. Uncertainties

In order to cope with the complexity problem integrated control design has already reduced the design task to subsystems and individual components. These elements are joined together by a correctly defined interface. This interface connects high level (virtual) signals to actuators and sensors. If a plug and play setting is considered on the connecting points the presence of an uncertainty, usually unmodelled dynamics, should be considered.

The properties of the assumed uncertainty set depend on the diversity of the possible devices that are allowed to be used for a given component. Thus, the specific task for the plug and play design is to specify these uncertainties by setting suitable weights at the given points. These uncertainty models are usually more complex those used in a baseline integrated control design.

The uncertainties of the model are caused by neglected components, unknown or little known parameters. The uncertainties are modelled by both unmodelled dynamics and parametric uncertainties. The estimation of the uncertain interval around its nominal value is important in the control design. If the uncertain interval is selected too large, the designed controller will be conservative. The unmodelled dynamics can be reduced by using a more accurate estimation of a component in the model. For example, if parametric uncertainties of mechanical components are known, the uncertainties for unmodelled dynamics can also be reduced.

As an example, in the suspension design uncertainties are usually modelled as a complex full block with multiplicative uncertainty at the plant input. The weighting function of the unmodelled dynamics is selected $W_{r,comp} = \rho_{g1}(T_{r1}s + 1)/(T_{r2}s + 1)$, with time constant T_{ri} in such a way that in the low frequency domain, uncertainties are about $\rho_{g1}(\%)$ and, in the upper frequency domain they are up to 100%. Parameters in the vertical vehicle model always contain uncertainties, which can be described by their nominal values and ranges of possible variations, e.g., the mass, the damping coefficient, the spring coefficient. If parametric uncertainties are built into the control design, the magnitude of the unmodelled dynamics may be reduced. In the latter case the uncertainty structure contains an uncertainty block, which represents the ignored actuator dynamics and real uncertainty blocks. Thus, it is possible to select the weighting function significantly smaller than in the previous case. It means that in the low frequency domain the modelling error is $\rho_{g2}(= \rho_{g1})$: $W_{r,mix} = \rho_{g2}(T_{r3}s + 1)(T_{r4}s + 1)$.

In addition to these uncertainties in the plug and play framework it is necessary to consider uncertainties related to the interfaces. As an example the high level suspension module produces forces as requested control inputs while the plug and play actuator module receives these forces as reference signals. During the specification on this interface proper weights are necessary in order to guarantee the interoperability. For the high level design the weight specifies a required performance that tells the high level controller to produce force requests compatible with the available actuators. Moreover, the dynamics of the actuator will not necessary be able to follow the requested force, thus an unmodelled dynamics should be modelled on the inputs side. On the actuator side the weight specifies the performance of the tracking problem in order to provide the requested actual forces.

4. Analysis of the entire system

The verification of the specification for the supervisor is a highly nontrivial task and can be performed in the same setting as for the baseline supervisory integrated design.

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 [3], [7]. Concerning the performance assessment the plug and play setting makes it necessary to use a robust LPV setting.

This is a highly computation-intensive procedure, that may be set, as an example, in the robust LPV framework [14], or in the integral quadratic framework [8]. 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 guarantees 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, situations in which different critical performances must be achieved simultaneously may occur. These difficult situations are necessary to examine in different time domain scenarios using a simulation software.

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 control systems. The supervisor sends critical signals to the controllers and consequently these control systems are activated. However, in order to reduce the rollover risk the yaw signals are modified and consequently, the deviation from the predefined path may increase. In contrast reducing the deviation from the path might increase the rollover risk. Since both interventions are critical the supervisor is not able to resolve the problem entirely, thus the performances are handled by the actuators with performance degradation.

5. Conclusion

In the paper the principles of the plug and play design in connection with the supervisory integrated control system have been presented. The relationship between the supervisor and the local plug and play controllers is ensured by a proper parameter dependent weighting strategy that guarantees that the system meets the specified performances. The weighting strategy leads to a complex control task, which includes different types of monitoring components as additional scheduling variables in the LPV design. Concerning actuators, sensors, functions and uncertainties the proposed method is illustrated through several examples based on the weighting strategy in the closed-loop interconnection structure.

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