LPV design of adaptive integrated control for road vehicles *

Péter Gáspár, Zoltán Szabó and József Bokor

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

Abstract: The paper presents a multi-layer supervisory architecture for the design of adaptive integrated control systems in road vehicles. The performance specifications are guaranteed by the local LPV (Linear Parameter Varying) 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 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.

Keywords: vehicle control, integrated control, LPV control, robust stability and performance.

1. INTRODUCTION AND MOTIVATION

Conventionally, the control systems of vehicle functions to be controlled are designed separately by the equipment manufacturers and component suppliers. One of the problems of independent design 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 second problem is that both hardware and software will become more complex due to the dramatically increased number of sensors and signal cables and these solutions can lead to unnecessary hardware redundancy, see Gordon et al. (2003); Johansen and Murray-Smith (1997).

The demand for the integrated vehicle control methodologies including the driver, vehicle and road arises at several research centers and automotive suppliers. The purpose of integrated vehicle control is to combine and supervise all controllable subsystems affecting vehicle dynamic responses. 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.

Recently, several important papers have been presented in this topic, see e.g. Yu et al. (2008); Pousso Vass et al. (2008); Trachtler (2004); Pita-Gil et al. (2009).

For achieving an integrated control a possible solution 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, which cannot be handled by the existing design tools, the formulation of a suitable performance specification is the main obstacle for this direct global approach. In the framework of available design techniques formulation and successful solution of complex multi-objective control tasks are highly nontrivial, see, e.g., Burgio and Zegelaar (2006); Gáspár et al. (2008).

Another solution to the integrated control is a decentralized control structure, in which there is a logical relationship between the individually-designed controllers. The advantage of this solution is that the components with their sensors and actuators can be designed by the suppliers independently, see e.g., Xiao et al. (2011). However, the local controllers require a group of sensors and hardware components, which may lead to different redundancies, see Hencley and Alleyne (2010); Lu and Filev (2009).

This paper proposes a multi-layer supervisory architecture for integrated control systems in road vehicles as illustrated in Figure 1. The role of the supervisor is to meet performance specifications and avoid 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 gathered from monitoring components.
and fault-detection and identification (FDI) filters. 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. The reconfigurable and fault-tolerant operations of a local controller assume that it is able to handle the monitoring and fault messages of the supervisor. 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. In the proposed solution local control components are designed by LPV methods by taking into consideration the additional scheduling variables received from the supervisor.

The advantage of the architecture for integrated vehicle control is that the complexity of the vehicle model is divided into several parts. In the formalism of the control-oriented model the messages of the supervisor must be taken into consideration. Consequently, the signals of monitoring components and FDI filters are built in the performance specifications of the controller by using parameter-dependent weighting. In this way the operation of a local controller can be extended to reconfigurable and fault-tolerant functions.

The structure of the paper is as follows. In Section 2, as an illustration, the control-oriented LPV modeling and the selection of monitored components are presented. In Section 3 the weighted strategy in the closed-loop interconnection structure and the control design based on LPV methods, are illustrated. In Section 4 the integrated control mechanism is presented through simulation examples. Finally, Section 5 contains concluding remarks.

2. CONTROL-ORIENTED LPV MODELING

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. The longitudinal force is generated by the driveline and the brake systems. The suspension system is also able to improve 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. The longitudinal force is generated by the driveline and the brake systems. The suspension system is also able to improve pitch and roll stability.

2.1 LPV modeling of vehicle dynamics

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 \( \rho \) 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 \( u_f = \Delta F_f \). 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: \( u_d = \delta_f \). The measured signals are the lateral acceleration and the yaw rate.

Fig. 2. Vehicle model with lateral dynamics

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, see Figure 2. The control inputs are generated by the suspension actuators: \( u_s = [f_{fr}, f_{fr}, f_{fr}, f_{fr}]^T \). The measured signals are the relative displacements between the sprung and unsprung masses over the wheels.

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: \( u_r = [u_{rf}, u_{rr}]^T \). The measured signals are the lateral acceleration and the roll rate.

The nonlinear effects of the forward velocity, the adhesion coefficient in the lateral direction and the nonlinear characteristics in the suspension spring and damper components are taken into consideration, see Song et al. (2002). It is assumed that these signals are measured or available. The nonlinear model can be transformed into an LPV model in which nonlinear terms are hidden with suitably defined scheduling variables. The scheduling vectors are selected as the following forms: \( \rho_s = [\mu, \mu/v, \mu/v^2, 1/v]^T \), \( \rho_u = [\rho_{k[f]}, \rho_{k[s]}]^T \).

\[ \begin{align*}
& G(\rho) \quad W_p \quad \Delta_m \quad d_w \quad W_r \\
& K(\rho) \quad y \quad n \quad W_s \\
& w
\end{align*} \]

Fig. 3. The closed-loop interconnection structure

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, see Figure 3.

In this framework performance requirements are imposed by a suitable choice of the weighting functions \( W_p \). The proposed approach realizes the reconfiguration of the performance objectives by a proper scheduling of these weighting functions.

### 2.2 Monitored components

The local components also include units for monitoring vehicle operations and FDI filters, see Figure 1. 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., a variable is needed to reduce the rollover risk: a variable is needed to reduce the harmful effects of abrupt braking; and a variable is also required to take a detected failure of an active component into consideration. In the following several examples for monitored components are presented:

A./ 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.

B./ Another control task is to follow a road by using a predefined yaw rate (angle). In this case the current yaw rate must be monitored and the difference between the reference and the current yaw rate is calculated. The purpose of the control is to minimize the tracking error: \( \dot{z}_\psi = \hat{\psi}_{cmd} - \hat{\psi}_{ref} \).

C./ 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 \( \Delta F_{ty} = k_t \phi_t \), where \( \phi_t \) is the monitored roll angle of the unsprung mass. The normalized lateral load transfer is introduced: \( \rho_l = \frac{\Delta F_{ty}}{m_g} \). 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.

D./ The pitch angle of the sprung mass may increase significantly during a sudden and hard braking. Pitch stability is achieved by limiting the longitudinal load transfers to below a predefined level. The normalized longitudinal load transfer is the normalized value of the pitch angle: \( \rho_p = \frac{\theta - \theta_{\text{max}}}{\theta_{\text{max}}} \), where \( \theta \) is the monitored pitch angle and \( \theta_{\text{max}} \) is the maximal value of the pitch angle. The aim of the control design during braking is to reduce the pitch dynamics if the normalized longitudinal load transfer exceeds a critical value.

E./ The fault-tolerant control requires fault information in order to guarantee performances and modify its operation, see Staroswiecki (2006). As an example the fault information provided by a fault detection filter is given by \( \rho_D = f_{act}/f_{\text{max}} \), where \( f_{act} \) is an estimation of the failure (output of the FDI filter) and \( f_{\text{max}} \) 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 \( f_{act} \) represents the rate of the performance degradation of an active component.

F./ In the control design the distribution of the wheel forces must also be taken into consideration in order to avoid actuator saturation. In a front-wheel-driven vehicle the traction force is distributed between the front wheels by using the differential gear. The steering angle has a construction limit (\( \delta_{\text{crit}} \)), therefore when the maximal steering angle is reached the lateral dynamics of the vehicle must be fulfilled by the brake moment. During braking the load of wheels is modified due to the pitch dynamics of the vehicle. The braking of the front wheels must be stronger while the braking of the rear wheels must be reduced. The wheel forces must be monitored in the view of the momentary friction margin of the tire. It requires the estimation of friction coefficient \( \mu \), which is also necessary for the determination of maximal cornering velocity. An estimation method for the adhesion coefficient was proposed by Gustafsson (1997).
The maximal longitudinal force of the wheels \( F_{i,\text{max}} \) is calculated and it is compared to the momentary longitudinal wheel forces \( F_i \). The variable \( \nu = \max \{F_i/F_{i,\text{max}}\} \) is the maximal value between the force ratios considering all the wheels and \( \nu_{\text{crit}} \) is a design parameter. A weighting factor \( \rho_{\text{act}} \), which depends on the vehicle operation, i.e., the traction and the brake, will be used in the weighing strategy of the control design, see Figure 4. This factor might depend on other parameters less such as forward velocity, lateral loads, maneuvers.

![Fig. 4. Weight \( \rho_{\text{act}} \) for control inputs](image)

The role of the supervisor is to coordinate the local components and handle the interactions between them. The information provided by the supervisor is composed of messages and signals sent by the monitoring components and FDI filters. Based on this information the supervisor is able to make decisions about the necessary vehicle maneuvers and guarantee the reconfigurable and fault-tolerant operation of the vehicle: 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.

3. CONTROL DESIGN BASED ON LPV METHODS

3.1 Weighted strategy in the interconnection structure

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 \( \psi_{\text{cmd}} \). The command signal is a predefined yaw rate signal and the performance signal is the tracking error: \( \dot{\psi}_d = \dot{\psi}_v \), which is the difference between the actual yaw rate and the yaw rate command.

The weighting function of the tracking error is selected as: \( W_{\psi,\psi} = 100(T_{\psi1} + 1)/(T_{\psi2} + 1) \), \( W_{\psi,\delta} = \phi_P(T_{\psi3} + 1) \), \( W_{\psi,\delta} = \phi_P(T_{\psi4} + 1) \), where \( T_{\psi} \) is time constants. The trade-off between passenger comfort and suspension deflection is due to the fact that it is not possible to guarantee them together simultaneously. A large gain \( \phi_{\delta,\psi} \) and a small gain \( \phi_{\delta,\psi} \) correspond to a design that emphasizes passenger comfort while choosing \( \phi_{\delta,\psi} \) small and \( \phi_{\delta,\psi} \) large corresponds to a design that focuses on suspension deflection.

The idea of the reconfigurable suspension system is based on the fact that active suspension systems are 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. The weighting functions are \( W_{\psi,\phi} = \phi_P(T_{\phi7} + 1) \), \( W_{\phi,\phi} = \phi_P(T_{\phi8} + 1) \), where \( \phi_P \) are parameter-dependent gains. In normal cruising, i.e., when \( |\phi_R| < \phi_s \) and \( |\phi_P| < \phi_P \), the suspension system focuses on the conventional performances. If \( \phi_{\psi,\delta} \) and \( \phi_P \) do not exceed their critical values, the controller must create a balance between passenger comfort and road holding. If \( \phi_{\psi,\delta} \) exceeds a critical value the controller must focus on suspension deflection. If \( \phi_P \) exceeds a predefined critical value, i.e., when \( |\phi_P| < \phi_P \), the controller must focus on pitch stability. In an emergency, i.e., when \( |\phi_R| > \phi_s \), the suspension system must reduce the rollover risk and guarantee passenger comfort (and pitch angle) is no longer a priority.

3.2 Control design

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 \( L_2 \) norm from \( w \) to \( z \) is less than \( \gamma \). The existence of a controller that solves the quadratic LPV \( \gamma \)-performance problem can be expressed as the feasibility of a set of Linear Matrix...
Inequalities (LMIs), which can be solved numerically. The constraints set by the LMIs are not finite. The infiniteness of the constraints is relieved by a finite, sufficiently fine grid. To specify the grid of the performance weights for the LPV design the scheduling variables are defined through lookup-tables. Gridding reflects the qualitative changes in the performance weights, i.e., the scheduling variables \( \rho \). If the rate bound on \( \rho \) is assumed a less conservative result for the class of systems is yielded. Stability and performance are guaranteed by the LPV design process, see Packard and Balas (1997); Wu et al. (1996).

In order to provide a formal test of the achieved control configuration on a global level, one have to formulate the problem globally. Only on this extended level the performance variables which are relevant for the whole vehicle are available. Once the local controllers are designed, however, it is possible to perform an analysis step in the same robust control framework at a global level, for details see Langbort et al. (2004). This might be a highly computational intensive procedure. Therefore in practice this step is often skipped and the quality of the control overall control scheme is assessed through simulation experiments.

4. SIMULATION EXAMPLE

As an illustration an integrated control which includes active steering, anti-roll bars, a suspension system and a brake system 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 maneuver, 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 km/h. Throughout the simulation three control systems are designed. The distributed control system designed by using the proposed supervisory framework is compared to the distributed solution without a supervisor.

Figure 5 shows the time responses of the tracking control based on a supervisory control. 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 bar cannot generate stabilizing moment to balance the overturning moment. When there is a fault 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. The reason for this is that in the fault case the critical value of \( R_a \) is smaller than in the fault-free case.

The supervisor sends \( \rho_R \) and \( \rho_D \) 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 \( \rho_R \), \( \rho_P \) and \( \rho_D \) signals to the active suspension system, which provides road holding and passenger comfort. The control design is based on the LPV method since it is able to handle parameter dependence in the weighting strategy and guarantee that the designed controller meets the performance specifications.

In the following examples the supervisory controller is compared to the conventional distributed controller. In order to compare these cases weighting functions are used in the design of the conventional controller. Figure 6 shows the operations of the controlled systems in a fault-free case and Figure 7 shows their operations when there is a float failure in the active anti-roll bar at the front. The examples illustrate the benefit of the proposed solution, which uses a supervisor over the completely decentralised approach, i.e., the required control inputs and the control energy are considerably smaller.
that the supervisory integrated control meets the defined requirements by using the LPV method. This method guarantees fast and reconfigurable and fault-tolerant operation of the vehicle. The design of local vehicle controllers has been carried out by using the LPV method. This method guarantees that the supervisory integrated control meets the defined performance specifications.

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. It has been shown that the performance specifications are formalized in parameter-dependent weighting. The design of local vehicle controllers has been carried out by using the LPV method. This method guarantees that the supervisory integrated control meets the defined performance specifications.

5. 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.

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. It has been shown that the performance specifications are formalized in parameter-dependent weighting. The design of local vehicle controllers has been carried out by using the LPV method. This method guarantees that the supervisory integrated control meets the defined performance specifications.

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