Proceedings of AVEC '06
The 8th International Symposium on Advanced Vehicle Control, August 20-24, 2006, Taipei, Taiwan
AVEC060209

On Road Vehicle Motion Control-
striving towards synergy

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This paper summarizes the work on road vehicle motion control, with focus on different strategies to achieve synergetic effects for over-actuated systems, and gives an overview of related work, especially from aircraft and robotics research. A systematic categorization of the strategies with respect to the physical principles of the motion generation, the realm of the control action and the controller structure is proposed to facilitate the comparison.

Topics / Vehicle Dynamics & Control.

1. INTRODUCTION

In the last decade, computerized control of vehicle motion has grown strong and is of increasing importance. Recent studies show that *stability control systems* reduce the amount of skidding accidents by 25% [1].

Lately, control of steering [2] and suspension [3], aiming for improved safety and achieving a better compromise between handling and comfort, has entered more broadly on the market. Along with the additional possibility to combine different configurations, the study of the possible synergetic and conflicting effects has gained significant interest.

Since electronics were introduced in vehicles, engineers have found an ever expanding range of application. In [4], this process is divided into three stages; the two first covered the development to the late 80's and the last stage, destined to start in the 90's and lasting into 2000, would be categorized by smart actuators and that *designers will escape from the mechanical function replacement and "add-on" approaches that have categorized stage 1-2*. In the same manner [5] introduced the concept of *Integrated Vehicle Control* based on the question: *What would the car be like if the microprocessor had been invented before the automobile?* Since then, numerous works on the subject of combining steering, traction, brakes and suspension have been published under names like *Active Chassis Control*, *Integrated Vehicle Control*, *Integrated Chassis Management*, *Vehicle Dynamics Management*, *Global Chassis Control*, etc. This variety of names indicates one of the challenges related to control of vehicle motion, and the aim of this work is to bring some clarification by categorizing the research and development work done so far.

A wider perspective of this theme is often referred to as *driver assistance systems* and spans from planning assistance to collision mitigation and post-crash activities. This has been a popular theme for overview papers during the last years (e.g. [6, 7]), while other approaches discuss selected vehicle configurations or control approaches (e.g. [8, 9]).

In this work focus is on a systematic way to categorize the *functional* aspects of various approaches to road vehicle motion control in terms of *how the vehicle motion is generated*, *what actuators are available*, *when they are active*, and *how different control tasks are dependent on each other* as described in section 2. It is seen that over-actuation is a major subject and in section 3, this is discussed more thoroughly also considering motion control from robotics and aeronautics. Based on the essence of these inputs, section 4 addresses possible future directions and related areas with significant research potential found from the categorization.

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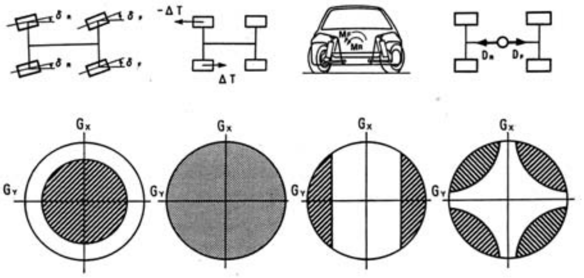

Fig. 1 Effective range of different control concepts according to [13].

2. CATEGORIZATION FOR ROAD VEHICLE MOTION CONTROL

This section proposes a systematic categorization with respect to the physical principles of the motion generation, the realm of the control action and the controller structure.

2.1 Principles of Vehicle Motion Generation

The first distinction employed here relates to how the motion is affected. Most control principles can be related to the linear and non-linear characteristics of the tyre-road contact which is and has been widely studied [10]. The effects can be summarized as direct effects of steering/tyre slip angle and camber[1] to generate lateral force, and direct effects on traction/braking to generate longitudinal forces. The wheel load influences both longitudinal and side force indirectly by defining the maximum possible transfer force. For combined conditions (longitudinal slip and tyre side slip) this transfer force needs to be distributed in an elliptic fashion between longitudinal and side force. This interdependence was the main reason for introducing the anti-lock braking system (ABS) in 1978 [11] to guarantee steerability through restriction of longitudinal slip.

Generating yaw moment by braking individual wheels was introduced with the Mercedes S-series as *Electronic Stability Program* (ESP) in 1995 [12], but due to trade mark reasons, it is on the market under several different names such as DSC, DSTC, ESC, ESP, PSM, StabiliTrack, VDC, VSA, VSC etc. To be able to compare these and other systems, they are categorized according to their {direct, indirect} effect on {longitudinal, lateral, roll, yaw, ..} motion through {steer, camber, traction, brake, load distribution, ..} control.

Direct yaw control through active rear differential and brake intervention has been a popular subject in Japan which also can be seen in performance production vehicles such as Subaru Impreza, Mitsubishi Evolution and Honda Legend.

A highly relevant question before digging too deep into the actual realizations is *what configurations make sense?* There are various approaches to address this (e.g. [13, 14, 15]) and a popular way to present results are based on the resulting friction ellipse. Figure 1 shows one example where the effective range for different configurations are indicated with shaded areas.

With the increasing numbers of possible actuators it is also relevant to have a more systematic separation between *'axle'* and *'wheel'*. For example, the term *'four wheel steering'* (4WS) is widely used for systems where the steering angles on each axle's wheels are coupled. To separate this from systems with wheels that are independently steerable, it is suggested to refer to coupled systems as *axle steering*. This principle is also highly relevant for driveline configurations as left/right independent wheel torque is subject to extensive research and development.

From figure 1 the importance to also be clear about what is directly coupled to the driver can be seen: It is concluded in [13] that 4WS is effective at lower acceleration levels. However, it is important to remember that the statement in this case is based on analysis of controller designs that can only affect the rear axle steering angle.

2.2 Realm of Control Action

In the context of vehicle control, the usage of *'active'* and *'passive'* is highly relevant due to the confusion it tends to cause when 'active' in the sense that it adds energy to the system is mixed up with 'active' in the sense of being able to affect/influence the system. Here, it is suggested to use the term 'active' for the first case and elaborate some more on how the system is influenced, using the control engineering terms of open loop, adaptive open loop, closed loop, and adaptive closed loop control. These aspects are summarized for the general case in figure 2. For a shock absorber, x would be the (compression) velocity and y the (compression) force.

To illustrate, consider rear axle steering that gained interest in the late 80's. The Honda Prelude was first on the market in 1987 with a non-linear but speed insensitive steering ratio between the front and rear axles so that small angles give equally directed steering and larger give opposite steer (open loop)[2]. Taking it one step further, the rear steering gain can depend on vehicle speed (adaptive open loop) which was launched in 1989 in the BMW 850i [14]. Systems that depend on feedback of measurements or estimates of yaw rate, roll rate and/or lateral acceleration are closed loop and can be used to improve the vehicle's yaw stability. The fourth category requires that the closed loop is adaptive to changes in vehicle or driver behavior.

For the steering example, active-passive classification is of less interest since even standard servo-assisted, statically tuned, front axle steering systems are active. For suspensions it is of more importance especially because

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[1] Camber can be used to influence the force generation, both directly by camber steering or indirectly by through tilting achieve a more beneficial contact patch or even to alter between parts of the tyre with different properties [7].

[2] In this sense it is same as 'tuning' of mechanical parameters.

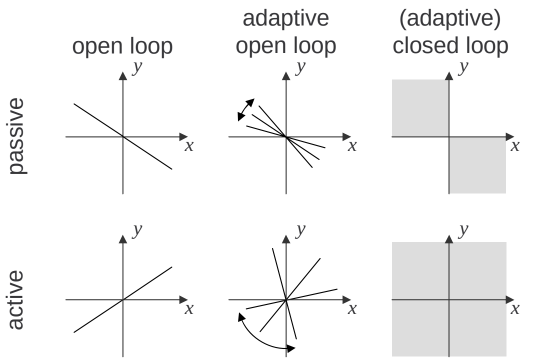

Fig. 2 Realm of Control Action, shaded areas indicate feasible regions.

of the energy consumption[3]. It might even be relevant to separate between slow and fast systems [16]. Although traditionally suspension control has primarily been considered as means to improve ride, its possibilities to improve tyre-road contact and the ever-present compromise between ride and handling makes it highly relevant also for integrated approaches [17].

2.3 Control Structure

Along with the increasing availability of actuators, the need to distribute effort wisely has gained significant interest during the last decade. The distribution as a concept is far from new; steering linkages, differential gears and anti roll bars have performed these tasks mechanically since decades. The new aspect is instead that several actuation concepts can and will affect the same degree of freedom of the vehicle’s motion. This is both an advantage and a problem that has been studied since the late 80’s leading to a variety of proposals. The following classifications[4] provide some clarification:

Several systems trying to control the same actuator(s) require that the actuator input signal(s) are *unified*. By *arbitration*, only one system at a time can act which makes the unification easier but at the same time limits the performance. A natural extension is to *coordinate* the signal by allowing several systems to be active at the same time. This implies a greater knowledge of the coordinator in the sense that it must somehow understand the effects of the combinations. In [9], means to provide this in terms of neural nets and fuzzy logic are discussed.

Systems of today are often organized to handle one type of actuators on multiple or all wheels that require them to have internal distributions; most common are brakes and driveline. Since the generation of a tyre’s lateral, longitudinal and vertical forces are highly interdependent, several such *coexisting* systems that act on different sets of actuators can interfere with each other. Figure 3 illustrates the differences between *parallel*, *hierarchical* and *cooperative* coexistence. A typical example is yaw control by rear axle steering and traction/brake force distribution that gained interest in Japan during the 90’s.

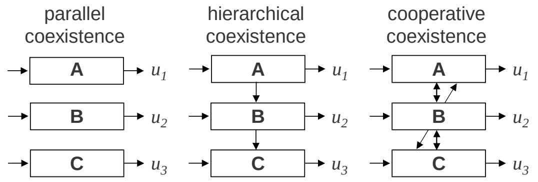

Fig. 3 Various types of coexistence.

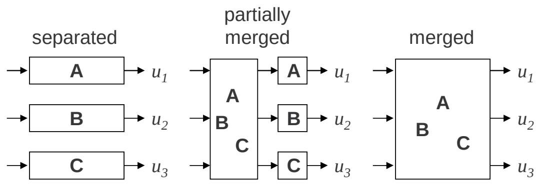

Fig. 4 Various merging approaches. Partial merging means that some of the original functionality (A,B,C) is merged and some not.

Parallel coexisting[5] concepts rely on a development of the individual systems that ensures no critical interferences. This requires no overhead when including more subsystems but may suffer from poor performance. When the applied systems can be separated in terms of control objective and frequency range, this method can still yield satisfactory results. This is suggested in [18] where effort is spent on a parallel coexistence, based on the conclusion that traction and brake intervention is suitable for yaw rate control, while active rear steering controls body side-slip.

Hierarchical coexistence is a step towards more awareness with a unidirectional information flow where one system acts independently and the others adapt. With the configuration from above, [19, 20] have the steering acting independently while the resulting yaw moment from driveline and brakes adapts.

Cooperative coexistence is based on mutual information exchange as suggested by e.g. [21, 16, 22]. As the information exchange between the subsystems in a cooperative coexistence increases, the next step is to merge the functionality as illustrated in figure 4. Partial merging has been a popular way to deal with the combination above, where rear steering angle and resulting yaw moment from driveline and brakes are merged [23, 24]. The distribution of tractive and brake torques is then done independently of the steering. This has a significant advantage in that the partitioning can be done such that the number of inputs and outputs are the same, allowing conventional multivariable control approaches to be applied.

If merging of systems comes to a global approach of distributing desired tyre forces or influencing variables

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[3] Suspension types that are passive and adaptive open loop or closed loop are often called semi-active.

[4] The considerations are primarily from a functional perspective, i.e. *system* can be interpreted as a functionality being either a whole or parts of a sensor-controller-actuator configuration.

[5] A mere juxtaposition without modification of individual systems and no information exchange.

to control vehicles motion, it may be called *allocation*. Methods for this will be further discussed in the following section.

3. CHALLENGES OF OVER-ACTUATED MOTION CONTROL

By the introduction yaw control by individual brake intervention, the vehicle turned into an over-actuated system [25], because the yaw motion degree of freedom can be influenced by four individual brake moments. Due to the simplicity of the working principle, a rule based allocation was feasible, but with an increasing number of available actuators (from e.g. steering and suspension control) affecting the vehicle motion, systematic allocation becomes more and more important.

Aircraft and robotics have had to handle the challenge of over-actuation for decades and the approaches from these fields are, in many cases, relevant also for ground vehicles.

3.1 Aeronautics

For aircraft, the number of actuators (control surfaces and engines) is higher than the number of motion *degrees of freedom* (DOF). Mechanical links between the control surfaces constrained the influencing variables resulting in balanced actuation (one rudder couple for roll, one rudder couple for pitch, ..) with one effective input for each motion DOF. Mechanical links of this kind can also be found in the vehicle (e.g. steering rack) as already discussed.

After fly-by-wire was launched in small scale production in 1976 (Concorde) [26], it went to mass production for military applications in 1980 (Tornado) and for civil aircraft in 1988 (Airbus A320) [27]. The easiest way to replace the mechanical constraints was to interpret them in electronic fashion (e.g. ganging matrices) [28]. With increased computational performance, the implementation of more advanced control approaches has become feasible. For advanced aircraft with unconventional surfaces (e.g. tailless), conventional control techniques became unsuitable and allocation became more important.

Today, the use of multi-variable control techniques to design the flight control laws for aircraft is standard practice. *Dynamic inversion* is the most widely applied of these [29] but when applied on an over-actuated system, it leads to a non-unique solution. The space defined by necessary additional parameters represent the possible design freedom to improve the behavior of aircraft motion. An intuitive constraint for this freedom is *daisy-chaining* [30], where each actuator is used to its saturation before the next is engaged.

More advanced solutions are often based on optimization approaches where the additional constraints can be defined once (offline) or for every increment of the digital control system (online). Usual methods of offline optimization are a variety of generalized inverses (e.g. pseudo inverse) [30]. For online optimization, [30] presented direct allocation in order to check if the desired moment on the aircraft is feasible and if not to cut it to the highest possible one. [28] instead presented different combinations of error minimization and minimization of control activity.

One big advantage of online optimization is the ability to adapt to reconfigurations to guarantee the best possible performance, even in the presence of actuator failures (c.f. adaptive closed loop control as described in section 2.2). From the perspective of road vehicle motion control, reconfigurable control would be very desirable as well, since reliability of the increasing amount of actuators is one of the biggest concerns. The objective functions presented for the optimization are similar for road vehicle motion control.

3.2 Robotics

In the robotics domain, over-actuation is commonly denoted *redundancy*. A manipulator is said to be (kinematically) redundant if the number of its kinematic degrees of freedom (i.e. the dimension of the joint space) is greater than the number of its end-effector degrees of freedom [31]. The kinematic redundancy can be used in different ways according to the manipulator type and specific task. Possible criteria (that may be combined) used are joint speed or torque reduction, dexterity perfection or avoidance of joint limits, collision, or singularity. A variety of methods and algorithms (analytic, jacobian-basted iterative, global, local) [32] are available to exploit the under-determination by providing the necessary number of additional equations which are favorable in terms of the assigned task. In [33], a service robot configurable algorithm, based on constrained least squares optimization, is presented, which is capable of coping with most of the above itemized redundancy-relevant challenges in real time.

As well as for aeronautics, reconfigurable control is desirable but online optimization for allocation possibly plays an even more important role in the robotics domain to avoid singularities. This could be the reason why the approach is more common in robotics than in aeronautic and automotive applications. The biggest challenge of online optimization so far has been to achieve real time capability for the available computational performance.

3.3 Automotive

Since the introduction of individual brake force distribution to control yaw motion, over-actuation is present in most vehicles. The focus on this in research heavily depends on what controller structure is adopted. Coexistence and some partially merged approaches tend to contain less information on this topic, often because the focus is more on traditional multi-variable control or unification of existing systems. Honda and Kanagawa Institute of Technology focus on the choice control objective, and [34] presents the so called β-method; a modification of the moment method [35] for stability analysis which is widely used for yaw control in more recent applications. Focus in these works is on how to combine steering and the resulting yaw torque from driveline and brakes rather than the distribution itself. Toyota and Tokyo University of Agriculture and Technology use a partially merged structure, controlling rear axle steer angle and resulting yaw moment from driveline and brakes, which in turn is partially allocated, often by ganging, e.g. [23, 24].

The first seen allocation by optimization comes from a cooperation between Nihon University and Honda [36], suggesting to use front and rear axle steering and individual wheel torques to minimize the tracking error. At Toyota, allocation through optimization of tyre forces is introduced for pure torque distribution in [37] and is later extended to also consider wheel angles, e.g. [38].

With [39], these thoughts have also spread to Kanagawa Institute of Technology, and similar ideas are seen in Europe as well: [40] presents a approach, similar to [38] and [39] and later extends this to also include load distribution [41]. The adaption of the allocation problem to a specific configuration that simplifies the solving is common for these approaches. In [39, 40], the desired motion is used as a constraint (implying that it is always achievable) to reduce the number of unknowns in the allocation problem.

A slightly different approach is suggested in [42] where the allocation is formulated as a generic problem with all tyre forces as free variables and a cost function to reduce tracking error. Adaption to tyre force limitations and different configurations is handled online through their resulting constraints on the tyre forces. In [43], variable camber angle is added and constraints for actuator rate limitations are introduced, as well as an addition for the direct allocation problem which can even handle situations where the physical driving limits are reached.

Another approach inspired by flight and robotics control is presented in [44] where allocation is done directly on wheel angles, wheel torque and load distribution. This is achieved generically for the presently available actuator configuration, thus providing easy reconfiguration in case of actuator failures. The optimization problem is linearized and solved with a least squares algorithm at a fixed sample rate, preparing for real time applications. Actuator limitations and rate saturations are considered here in terms of equality and inequality constraints. A further indication that allocation through optimization is gaining in popularity can be seen by publications from suppliers, e.g. [45].

Though, not all European research is based on allocation, [46] proposes a behavioral-based approach to reach integration with a combination of hierarchical coexistence and fuzzy coordination. [47] and [48] investigates the benefits and implementation of yaw control by combining traction/braking with load distribution and steering, respectively.

4. POSSIBLE FUTURE DIRECTIONS FOR ROAD VEHICLE MOTION CONTROL

The work referenced in the introduction shows a strong belief in mechatronic vehicles. The evolution until today does not speak against this; yaw control by individual brake intervention is mature enough to be standard equipment, the mechanical coupling between driver and steering is relaxed [2], air suspension, roll stabilization [3] and adaptive damping [49] are available (at least on premium cars), even integration of brake and suspension control has reached the market of mass production vehicles [17, 50].

Still, the suppliers of these systems have grown strong and as more and more of the vehicle characteristics are software defined, the roles of OEMs and suppliers have to be clarified in order for the integration to the reach a wider market. Despite ongoing standardization work [51], publications show that suppliers seek to keep a significant part of the top level vehicle control (e.g. [52, 53, 54]) while OEMs aim at reclaiming the control that also affects brand-specific characteristics down to a smart actuator level [55]. In [16], this is identified as an increasing total cost, and to avoid this, a compromise is suggested based on cooperative control where the stability functionality is kept by the suppliers.

In a longer perspective, the partitioning has to evolve to maximize performance for cost. Otherwise it will open up for new operators. In this perspective, the authors believe that the aircraft and robotics research also will be adopted by the automotive industry. Thus it is believed that the adoption of online optimization for allocation will be relevant for further research. It is especially important to understand the quite complex implications of the (highly) non-linear behavior of the tyre force generation on the allocation problem formulation.

It is also seen that the road friction coefficient is used as a parameter in model-based approaches which might require measurements or estimations of higher accuracy than today. Therefore sensor fusion for improved state estimation and dynamic inversion (model adaption) will continue to be a relevant research topic. Additionally, the driver-vehicle interaction, which is not considered in this paper, needs proper attention. Ultimately and possibly independent of the latter topics, the integrated approaches can also be used to choose configuration and thus being a vital part in concurrent engineering of hardware and software.

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