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Vehicle motion control with subsystem prioritization

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ABSTRACT

This paper presents a new approach for integrated vehicle motion control, coordinating multiple vehicle subsystems of a passenger car including friction brake system, near-wheel drive electric motors, wheel steer actuators, camber angle actuators, dynamic tire pressure system and actuators generating additional normal forces. The proposed algorithms are based on restriction weights into the cost function of optimization-based control allocation. Hardware-in-the-loop investigation using a test rig with hardware components of friction brake system and dynamic tire pressure system showed that the proposed approach allows to achieve lower energy consumption and energy losses without significant impairment of motion stability and vehicle handling as compared to conventional control allocation.

1. Introduction

Integrated vehicle control with several active subsystems, called multi-actuated vehicle, allows to handle various control objectives such as motion stability, vehicle handling, driveability, energy consumption and others. The industrial example of the fusion of control objectives is that Jaguar Land Rover initiated the development of a control system to recover energy from braking on corners and stability controls. Thereby, the search of internal reserves is carried out to minimize energy consumption not only in the drive cycle but also during curvilinear and emergency manoeuvres. Another academic example is the minimization of tire energy dissipation in the framework of G-vectoring control [1]. It allows to reduce total dissipation energy during the vehicle motion. Moreover, the minimization of tire energy dissipation has a positive influence on tire wear during vehicle operation. In the long-term operation, its lifetime is increased reducing the vehicle operation costs.

Several techniques can be applied to the integrated control on over-actuated systems. Control allocation is one of the most extensively studied methodologies in this regard [2]. The methods of control allocation, such as direct, pseudo-inverse, daisy-chain, optimization-based and others, are well described theoretically in Ref. [3]. Many of them are intensively used in automotive field.

Pseudo-inverse control allocation based on Moore–Penrose inversion is an effective technique from the point of view of computational cost, because it requires only algebraic computation [4]. Similar allocation methods are used: in Ref. [5] yaw rate control with coordination between individually driver electric motors; in Ref. [6] force allocation and coordination between steer-by-wire and individual-wheel electric powertrain; in Ref. [7] coordination between steer-by-wire and brake-by-systems in the case of actuator failure. However, classical pseudo-inverse control allocation neglects actuator dynamics and limits.

Optimization-based control allocation with position, rate and acceleration constraints can effectively solve the allocation problem; however, it imposes high computation demand in real-time applications. This kind of control allocation is the most commonly used and some examples of its application are: in Ref. [8] quadratic programming-based control allocation is proposed for different vehicle configurations including front/rear steering and individual torque control for each wheel; in Ref. [9] a control algorithm is developed based on dynamic inversion of a non-linear vehicle model and force allocation using non-linear optimization with optimization constraints including adhesion potential utilization and limits of actuator dynamics. To reduce a number of iterations and, as a result, computational load, the accelerated fixed-point method can be used with termination of iterations while solution

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distance exceeds allocation tolerance to improve convergence rate and reduce computational complexity [10]. Another approach is the hybrid steepest descent method for tire force allocation [11] to reduce computational load, when tire forces trend in the optimal direction, but their values are not necessary optimal at each instant. Instead of optimization-based control allocation, which requires a solution at each instant, dynamic control allocation using dynamic update laws for control inputs is proposed in Ref. [12].

Research issues of control allocation cover topics such as approximation of nonlinear allocation, adaptation of control allocation to uncertainties and disturbances, representation of actuator dynamics and others. In this paper, the emphasis will be given to the achievement of multiple control objectives. The cost function of control allocation problems typically covers two terms related to (i) minimization of allocation error and (ii) control actuations. The following additional terms can be implemented into the cost function (Fig. 1):

- Instantaneous power consumption of in-wheel motors in different modes [13].
- Electric and mechanical losses of electric motors [14,15].
- Longitudinal wheel slip ratios [16].
- Tire energy dissipation [1].
- Auxiliary cost terms, such as overall input motor power, standard deviation of wheel slip ratios, total longitudinal slip power loss and sum of the tire force coefficients [17].

Depending on additional control objectives, the number of auxiliary terms into the cost function can be increased. Nevertheless a multi-term cost function has the following undesired features:

- Characteristic of auxiliary terms should be known and described by an approximation polynomial or presented as a look-up table. Examples are the efficiency map of electric motors, characteristics of electric losses or tire power dissipation, etc. Some of them like an efficiency map can be found from the specification of electric motor, when others like tire power dissipation require additional investigation.
- A mixture of auxiliary terms into the cost function can cause smoothing or even non-convexity in the case when the weights of auxiliary terms are close to the weights of main terms. As a result, the number of required iterations and total computational load will increase.
- The extreme of a cost function depends on the pre-defined weights of all terms, when their values are independent from vehicle manoeuvres.

Instead of the introduction of auxiliary terms into the cost function, another approach is a penalization of control inputs according to additional control objectives. In this case, a variable weighting matrix is used to penalize control inputs. The following examples demonstrate various applications of the penalization of control inputs:

- Coordination of brake pressures according to normal force distribution during heavy vehicle braking to obtain better vehicle stability [18].
- Weighting matrix defined as a function of friction circles for the investigation of manoeuvrability of six-wheeled and skid-steered vehicle for on-road and off-road conditions [19].
- Elements of weighting matrix being used as reliability indicators of actuators where the distribution of control demand takes into account actuator health and failures [20].
- Saturation of longitudinal forces being realized by the definition of the weighting matrix taking into account normalized tire slip [21].
- Saturation of longitudinal and lateral forces taking into account wheel slips and slip angles [22].
- Dynamic weight scheduling to achieve lower energy consumption without significant impairment of stability of motion and vehicle handling compared to control allocation with fixed weight distribution [23].

The research aim of the paper is (1) to demonstrate that additional control objectives such as the reduction of energy consumption of electric motors and energy losses in tire-road contact can be achieved via subsystem coordination without a complex cost function; (2) to propose an algorithm for the penalization of control inputs, further called as subsystem prioritization; and (3) to investigate the proposed solution using a test rig and to compare with conventional control allocation without subsystem prioritization.

The coordinated vehicle subsystems are (i) friction brake system, (ii) near-wheel drive electric motors, (iii) wheel steer actuators, (iv) camber angle actuators, (v) dynamic tire pressure system, and (vi) actuators generating additional normal forces through external spring, damping and stabilizer forces. The additional features of the paper can be pointed as:

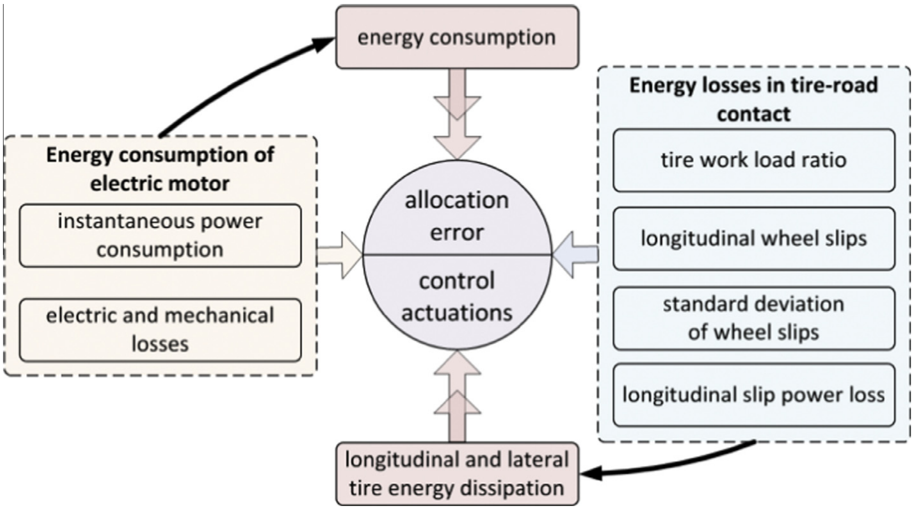

Fig. 1. Energy-relevant objectives for control allocation.