Control Engineering Practice 48 (2016) 22–36

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Integrated torque vectoring and power management framework for electric vehicles

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ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form
6 July 2015
Accepted 11 December 2015
Available online 29 December 2015

Keywords:
Integrated control
Vehicle dynamics
Electric vehicles
Stability control
Optimization

ABSTRACT

An integrated vehicle control framework is presented, which uses torque vectoring across independently driven wheels for control. The approach is general in nature, but is particularly well suited for electric vehicles due to increased control bandwidth. The novel algorithm optimizes wheel torque outputs in real time, constraining against power management, traction control, chassis configuration, actuator limits, and fault-case limitations. The structure is modular, and designed to adapt for differing vehicles with minimal re-tuning. Simulation and experimental results are provided for a modified electric SUV platform, under a range of dynamic maneuvers in 4WD, FWD, and RWD modes.

1. Introduction

Electric vehicles are a promising alternative to internal combustion designs, and provide many opportunities for improvement. One benefit is packaging flexibility, and the ability to distribute multiple motors to each corner. Another is faster actuator response, which is bi-directional and provides more control bandwidth than clutch and brake-based designs. This paper explores the control of an independently driven 4-wheel-drive (4WD) electric vehicle, maximizing the benefits of distributed wheel motors to apply torque vectoring for stability control.

Commercially, existing Electronic Stability Programs (ESP) are already developed by vehicle manufacturers such as Ford (Tseng, Ashrafi, Madau, Allen Brown, & Recker, 1999), BMW (Kaspar, Ludwig, Bünte, Hohmann, & Kaspar, 2014), Toyota (Hattori, 2003), Mitsibubishi (Miura, Ushiroda, Sawase, Takahahi, & Hayashikawa, 2008), and GM (Ghoneim, Chen, Pylypchuk, Moshchuk, & Litkouhi, 2011). A simplified generic layout of a modern control system is visualized in Fig. 1.

Most systems use a model reference approach, where the vehicle follows a projected vehicle dynamic response. This action is accomplished with three major logical blocks, consisting of:

1. A driver interpreter taking the steering wheel angle (*SWA*) to generate reference yaw rate (r_{ref}) responses using current vehicle velocities (V_x, V_y) or accelerations (a_x, a_y).
2. A closed loop stability controller requesting yaw moments (M_Z), using feedback yaw rate (r_{fb}), heading errors (β), or accelerations (a_x, a_y).
3. A torque allocator, which assigns the torque (T_i) at each individual wheel given individual tire conditions such as slip (α, λ).

1.1. Stability control

The driver interpreter and stability controllers function at the body level, and can use torque vectoring or differential braking as control actions (Liebemann, Meder, Schuh, & Nenninger, 2004). In this, an analytic vehicle model generates the desired response, and this value is compared against sensor feedback for the stability control loop. 2 degree of freedom bicycle models are often used to describe the vehicle, and accounts for tire slip, pitch, and yaw motion.

Various controller architectures can modulate yaw moments for stability control. Examples include sliding mode (Goggia et al., 2015), proportional (De Novellis et al., 2013), optimal (Yang, Wang, & Peng, 2009), or LQR (Siampis, Massaro, & Velenis, 2013) approaches. In Sabbioni, Cheli, Vignati, and Melzi (2014) and De Novellis et al. (2013), proportional approaches are compared against sliding mode and LQR approaches respectively. In both

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http://dx.doi.org/10.1016/j.conengprac.2015.12.012
0967-0661/

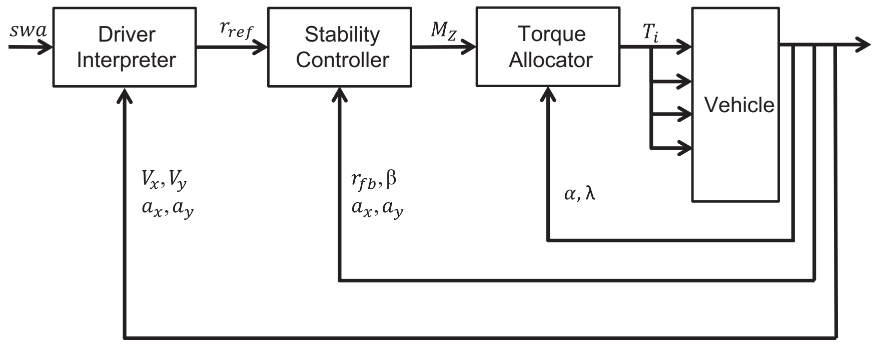

Fig. 1. Standard system layout.

cases, proportional strategies offered comparable performance with modeling sensitivity and will be used in this work.

1.2. Torque allocation

Torque allocation functions primarily at the tire level, and assigns the actuator output. Within this domain, traction control (Shino, Miyamoto, Wang, & Nagai, 2000; Yin, Oh, & Hori, 2009) is considered as it affects the force transmission limit of a tire. Existing traction control strategies (Beyer & Dominke, 1994) involve torque cut-offs or anti-lock braking systems (ABS) when slip is detected.

Torque vectoring is often used to generate yaw moments for stability control, and must operate within actuator limits and friction capacity. It may be distributed in longitudinal (Piyabongkarn, Lew, Rajamani, Grogg, & Yuan, 2007), lateral (Sawase & Ushiroda, 2008), or combined (Jalali, Uchida, Lambert, & McPhee, 2013; Osborn & Shim, 2006) directions with differing effects.

1.3. Power efficiency

Electric vehicles generally provide less driving range than internal combustion models of similar class. Power management and efficiency optimization literature has traditionally focused on torque-splitting strategies for hybrid engines in parallel (Won, Langari, & Ehsani, 2005) or serial (Xiong, Zhang, & Yin, 2009) configurations. However, few works focus on optimization for fully electric layouts with identical electric motors at each wheel. Torque vectoring stability controllers simultaneously optimizing for energy efficiency and dynamic performance (Mutoh, Kato, & Murakami, 2011; Sumiya & Fujimoto, 2012) exist, but only activate once there is a feedback error, which usually involves slip. Therefore, optimizing power use under non-slip or constant-speed conditions is an opportunity for further development.

1.4. Integrated control

There are multiple methods of integrating control loops within the vehicle system. For example, distributed approaches (Karogal & Ayalew, 2009; Miura et al., 2008; Sato, Inoue, Tabata, & Inagaki, 1993) treat multiple controllers individually and sum their outputs. However, the control actions aggregate all at the tire contact patch, and potential conflicts can occur. To resolve this, algorithms can prioritize loops (Sawase & Sano, 1999) or switch controller functions based on the vehicle state (Burgio & Zegelaar, 2006). This is highlighted in Sawase and Sano (1999) for Mitsubishi's 4WD controller, which shows how the active yaw and stability controllers can command torque vectors of opposing direction in a combined slip scenario. The solution involved a case-based decision matrix, but this is indicative of a system merely tuned for "peaceful coexistence". In this, vehicle stability is attained at the cost of intentionally reduced control, and results in sub-optimal or discontinuous responses. This gives motivation for the development of a general, integrated structure.

Optimization approaches offer one possible solution, by using a cost function with multiple terms to account for multiple control objectives. Weights assigned to each term prioritize or penalize each component, resulting in a best-compromise solution. In Sumiya and Fujimoto (2012), a cost function simultaneously penalizes lateral slip and power loss, but longitudinal slip ratios are not considered. In Hattori (2003) and Li, Shen, and Yu (2006), longitudinal slip penalties are added while minimizing force and yaw moment errors, but actuator constraints are not enforced.

1.5. Proposed approach

While individual aspects of 4WD vehicle control are well studied, this paper proposes an integrated approach which is different from typical solutions. Typical solutions fall into two categories: distributed approaches, which run into issues of tuning multiple control loops, and cost function optimization, which encounter problems with non-convex functions and weight selection. Also, additional terms in a cost function naturally dilute the tracking priority of any one component. This creates a problem for highly integrated systems. For example, the final solution cannot guarantee operation within the constraints of individual terms, such as actuator limits. One failure case would then be the command of higher forces than actually achievable at high speeds, where available torques fade. Furthermore, weights within the cost function are often manually tuned to a static value, which draws a similarity to the prioritization problem of the distributed approach.

The Holistic Corner Controller (HCC) is hereby proposed as a solution. Multiple control objectives are aggregated as optimization constraints rather than through a cost function, and minimizes the problem of weight-based prioritization by using only one term. Directly specifying grip margins as a solution constraint improved performance over previous iterations of the formulation. The HCC itself began as an analytic cost-based formulation as outlined in Ghoneim et al. (2011), tuned with stability analysis in Fallah, Khajepour, Fidan, Chen, and Litkouhi (2013), and first implemented in Athari et al. (2013).

The HCC uses an objective function to allocate actuator outputs for torque vectoring, similar to the layouts of Hattori (2003) and Kang and Heo (2012). In Hattori (2003), a Jacobian matrix based on a brush model predicts tire force as a function of slip. This approach involves coefficients of cornering and vertical stiffness, which adds modeling error into the optimization process. The HCC improves upon this by directly applying a force-based formulation instead, and places the tire model as an outer constraint. As a result, linear assumptions or estimation noise does not impact operation until physical limits are reached. If reached, lower