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Automatic motor speed reference generators for cruise and lateral control of electric vehicles with in-wheel motors

C. Pomponi [a], S. Scalzi [a], L. Pasquale [b], C.M. Verrelli [a,*], R. Marino [a]

[a] Electronic Engineering Department of the University of Rome Tor Vergata, Via del Politecnico 1, 00133 Rome, Italy
[b] 'Power Electronics Machines and Control' Group, Faculty of Engineering, University of Nottingham, Innovation Park, NG7 2TU, UK

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ABSTRACT

Motor speed reference generators have been recently presented in the literature for the cruise control of electric vehicles powered by centralized electric motors. Steady-state operation at a safe tire longitudinal slip is guaranteed to be achieved in the presence of uncertain external conditions. In this paper, a generalization of the aforementioned result to electric vehicles that make use of two in-wheel motors and are required to perform a bend manoeuvre is provided. A new cruise and lateral control is presented. The two in-wheel rear motors provide propulsion, while being capable of acting as a rear differential. The key point relies on the definition of suitable references for the two motor speeds, so that motor speed control algorithms can be directly inherited from the electric machine control literature, while intrinsically robust motor speed control loops can be additionally incorporated. Both CarSim simulations and experiments are included to illustrate the practical effectiveness of the proposed approach.

1. Introduction

Vehicle control and estimation problems attract the interests of the research community. Such problems involve the design of: robust yaw moment controls to improve vehicle handling and stability (Du, Zhang, & Naghdy, 2011); vision-based lane-keeping controls for non-autonomous and autonomous vehicles (Marino, Scalzi, & Netto, 2011, 2012); integrated controls of front and rear active differentials to improve vehicle dynamics (Marino & Scalzi, 2009); sliding mode observer-based traction controllers to achieve a desired wheel slip for maximum deceleration in a minimum amount of time (Ünsal & Kachroo, 1999); cascaded wheel slip controls for wheel slip and acceleration regulation (Pasillas-Lépine, Loría, & Gerard, 2012); decoupling controls on the front and rear steering angles for four-wheel steering vehicles (Marino & Cinili, 2009) (see also Ackermann, 1994); yaw stability controls (Zhou & Liu, 2010); wheel slip controllers for automotive brakes (Johansen, Petersen, Kalkkuhl, & Lüdemann, 2003); hierarchical algorithms for lane keeping assistance (Lee, Choi, Yi, Shin, & Ko, 2014); differential braking controls (Barbarisi, Palmieri, Scala, & Glielmo, 2009); hybrid anti-lock brake systems with extended braking stiffness estimation (Hoàng, Pasillas-Lépine, De Bernardinis, & Netto, 2014). Additional results can be found in Canale, Fagiano, Milanese, and Borodani (2007), Cerone, Milanese, and Regruto (2009), Chu et al. (2012), Corno, Panzani, and Savaresi (2013), Ohara and Murakami (2008), You, Hahn, and Lee (2009) and Zheng and Anwar (2009) (see also Consolini & Verrelli, 2014; D'Ambrosio, Sbarra, Tiberti, Verrelli, & Consolini, 2018; Li, Yang, Gao, & Li, 2016; Suh et al., 2016; Wang, Jing, Hu, Yan, & Chen, 2016).

On the other hand, a green, energy-efficient, secure and safe transport technology is constituted by electric vehicles powered by electric motors (see for instance Hori, 2004; Zhang, Li, Yu, He, & Yu, 2017 and references therein; see also De Novellis, Sorniotti, Gruber, & Pennycott, 2014; Mutoh, Kazama, & Takita, 2006; Tahami, Kazemi, & Farhanghi, 2003; Yuan & Wang, 2012). In particular, in-wheel motors lead to: simple packaging of the drive-train, with improved vehicle handling and safety (see Alipour, Sabahi, & Bannae Sharifian, 2015; Lovatt et al., 2011); replacement of the mechanical differential with the electric differential (see Yang & Xing, 2008 and references therein; see also Chen & Wang, 2012; Haddoun et al., 2008, 2010; Haddoun, Khoucha et al., 2007; Perez-Pinal, Nuñez, Alvarez, Cervantes, & Emadi, 2007; Tabbache, Kheloui, & Benbouzid, 2011); improved safety, reduction in mass and increase of energy efficiency (Zhang et al., 2016).

One typical goal in control problems concerning vehicles with electric motor propulsion is cruise control, i.e., the regulation of the vehicle longitudinal speed to a constant reference. Automatic speed control provides, in fact, the opportunity to increase safety by eliminating

* Corresponding author.
E-mail address: verrelli@ing.uniroma2.it (C.M. Verrelli).

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human errors that are the first cause of accidents.[1] With this respect, a solution to the problem of regulating the vehicle longitudinal speed v_x to the corresponding constant reference v_{x*} is presented in Marino, Scalzi, Tomei, and Verrelli (2013) and then extended to the case of slip constraints in Marino, Pasquale, Scalzi, and Verrelli (2015). In particular, the cruise control problem is transformed in Marino, Scalzi et al. (2013) into the problem of regulating the motor speed ω to a suitable feedback-based motor speed reference, whose role is to exponentially estimate the uncertain motor speed reference ω_* corresponding to v_{x*}. Such motor speed reference ω_* is uncertain, owing to all the uncertainties characterizing the specific vehicle and the external conditions.

However, the vehicle longitudinal speed reference v_{x*} is only exogenously given in Marino, Scalzi et al. (2013); it is not automatically (internally) adjusted *via* feedback in response to uncertain external conditions, such as tire–road adhesion coefficients and road slopes. The tire-longitudinal slip at steady-state is not guaranteed to be kept in safe regions. This limitation is then overcome in Marino et al. (2015), in which the contraction theorem (see similar ideas in Nilsson et al. (2016)) is applied to a smooth desired design function in the (ω, v_x)-plane in order to drive the pair (ω, v_x) into safe tire longitudinal slip-regions. Anyway, only vehicles powered by a single electric motor (with fixed transmission gear ratio) are considered in Marino, Scalzi et al. (2013) and Marino et al. (2015): manoeuvres are restricted to be straight ones, whereas the yaw rate and lateral speed dynamics are not taken into account.

In this paper, whose contribution builds on the approach foreseen in Coelingh and Solyom (2012), electric rear-wheel drive vehicles are considered. They are equipped with two independent rear motors (one per tire). These motors provide propulsion, while being capable of acting as a rear differential. The aim is thus to extend the results in Marino, Scalzi et al. (2013) and Marino et al. (2015) (Section 2) to the more general case in which the vehicle is required to perform a bend manoeuvre (with constant curvature radius). The key point relies on the design of reference generators for the motor speeds, instead of directly controlling the motor torque. Treating the rotor speeds as independent control inputs allows for naturally addressing and solving the cruise and lateral control problem, even in the presence of slip constraints. No exact model knowledge, which is unreasonable due to the lumped nature of the approximated model used in the control design, is assumed. Furthermore, no lateral velocity measurements are required. Suitable reference signals for the motor speeds are generated by a contraction mapping algorithm and without any *a priori* knowledge about the occurrence of a specific external condition. Such references converge to a steady-state operating point with safe tire longitudinal slips. The resulting solution – presented in the paper through design steps of increasing complexity – thus simultaneously generalizes: (i) Marino, Scalzi et al. (2013), in the absence of slip constraints (Section 3); Marino et al. (2015), in the presence of slip constraints (Section 4). Both realistic CarSim simulations (including electric motors dynamics) and experiments (Section 5) on an autonomous scaled vehicle (1:10) illustrate the effectiveness of the proposed approach, in the presence of complex dynamics and practical aspects that have been neglected at the design stage.

[1] See Bageshwar, Garrard, and Rajamani (2004), Chen and Wang (2011), Corona and De Schutter (2008), Desjardins and Chaib-draa (2011), Hosseinnia, Tejado, Milanés, Villagrá, and Vinagre (2014), Luo, Chen, Zhang, and Li (2015), Naranjo, González, García, and de Pedro (2006), Naranjo, González, Reviejo, García, and de Pedro (2003), Nilsson et al. (2016), Rajamani and Zhu (2002), Reichhartinger and Horn (2016) and Wang, Xu, Liu, Sun, and Chen (2014) for the general description of the cruise control problem, including its variant named 'adaptive cruise control' (in which a safe distance between the vehicle and the immediately preceding one is also required to be maintained).

2. Preliminaries

In this section, the main concepts and results of Marino, Scalzi et al. (2013) and Marino et al. (2015) are preliminarily reported for the sake of clarity and completeness. Such results will be theoretically generalized, in the subsequent Sections 3 and 4, to the cruise and lateral control of electric rear-wheel drive vehicles equipped with two in-wheel motors and performing bend manoeuvres with constant curvature radius.

2.1. Starting from Marino, Scalzi et al. (2013) and Marino et al. (2015)

Electric vehicles powered by a centralized electric motor, whose speed ω can be quickly controlled, are considered in Marino, Scalzi et al. (2013) and Marino et al. (2015). In particular, since electric motors exhibit rather flat power curves and wide ranges of operating speeds, the attention in the aforementioned papers is restricted to electric vehicles with fixed transmission gear ratio (like certain micro-cars and the BMW i3). Let $\mu \in M \subset \mathbb{R}^3$ be an uncertain parameter vector taking the same value for each driving wheel and including the description of external conditions such as: tire–road adhesion coefficient $\mu^{[1]}$, road slope $\mu^{[2]}$ and drag force $\mu^{[3]}$, with M being the compact set (Reed & Simon, 1980):

$$M = \left[\mu_a^{[1]}, \mu_b^{[1]}\right] \times \left[\mu_a^{[2]}, \mu_b^{[2]}\right] \times \left[\mu_a^{[3]}, \mu_b^{[3]}\right]$$

and $\mu_a^{[1]}$, $\mu_b^{[1]}$, $\mu_a^{[2]}$, $\mu_b^{[2]}$, $\mu_a^{[3]}$, $\mu_b^{[3]}$ being boundary values. The approaches in Marino, Scalzi et al. (2013) and Marino et al. (2015) rely on the assumption that a suitable uncertain smooth function $g_\mu(\cdot)$ exists, such that (in the domain of practical interest) the longitudinal speed satisfies

$$v_x = g_\mu(\omega)$$

and

$$\frac{\mathrm{d}g_\mu(\omega)}{\mathrm{d}\omega} \geq c_g > 0,$$

with c_g being any sufficiently small positive real. According to the inverse function theorem (Marino, Tomei, & Verrelli, 2010), the constant motor speed reference

$$\omega_* = g_\mu^{-1}(v_{x*})$$

corresponds to the constant longitudinal speed reference v_{x*} belonging to the range of the function $g_\mu(\cdot)$. The uncertain nature of the function $g_\mu(\cdot)$ (due to its dependence on μ) is consequently inherited by the motor speed reference ω_*.

2.2. The cruise control action in Marino, Scalzi et al. (2013)

In Marino, Scalzi et al. (2013), the regulation of the vehicle longitudinal speed to the given constant v_{x*} – or equivalently the regulation of the motor speed ω to the corresponding motor speed reference ω_* – is achieved through the design of a suitable smooth estimate $\bar{\omega}_*$, which, on the basis of the (available) vehicle longitudinal speed regulation error,[2] $\tilde{v}_x = v_x - v_{x*}$, is able to recover the uncertain ω_*. This motor speed reference estimate is given by

$$\bar{\omega}_* = \omega_{*k} - \varepsilon \int_0^{\cdot} \tilde{v}_f(\tau)\mathrm{d}\tau - k_p \tilde{v}_f,$$

where: (i) ω_{*k} is an initial estimate for $g_\mu^{-1}(v_{x*})$; (ii) ε, k_p are the constant positive (sufficiently small) gains of the integral and proportional

[2] The definition of the regulation error for the vehicle longitudinal speed comes from the nonlinear framework of Marino, Scalzi et al. (2013) so that, as in Marino, Scalzi et al. (2013), it is defined as the difference between the actual longitudinal speed and its reference (in place of the difference between such reference and the actual speed – typically used in linear control design scenarios –). The same notation is used for the definition of the regulation errors that are further introduced in the paper.