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Model-based Corner Braking Control for Electric Motorcycles

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Abstract: Electrification of vehicle propulsion is also applied to motorcycles, allowing for new power train architectures like all-wheel driven motorcycles by using hub motors. The additional degrees of freedom of such an all-wheel driven power train can be used for enhancing safety, especially during cornering. In this contribution, an efficient model predictive control allocation (MPCA) algorithm is developed for this task, which distributes the electric braking force between front and rear wheel. It is shown that the method reduces the unwanted and possibly dangerous brake steer torque while braking a motorcycle in a curve.

Keywords: Electronic Stability Control, Brake Systems, Electric Vehicle

1. INTRODUCTION

For driving dynamics control, all-wheel power trains in particular offer additional degrees of freedom, which can be used to enhanced safety. Electrification of power trains support the application of all-wheel driven vehicles, since, on the one hand, electric energy can easily distributed and, on the other hand, electric motors can even be built so small that they can be installed as hub drives. Additionally, the efficiency of electric vehicles is higher and the motors can also be used for non-wearing braking of the vehicle.

While many concepts of all-wheel power trains like torque vectoring can be found for passenger or other cars, only few concepts are known for motorcycles. However, motorcycles can benefit in several ways from a two-wheel driven power train. It offers significant additional recuperation possibility, i.e. regaining the braking energy by using the electric motors to decelerate the bike and transforming the braking energy to electric energy, since approximately 70% of the braking force is usually applied on the front wheel. Also, this recuperative braking is non-wearing and offers an easy electronic controllability through the motor controllers, thus allowing enhanced braking safety systems even for low cost motorcycles. In this contribution, a curve adaptive brake force distribution strategy for an electric all-wheel driven motorcycle is presented, which significantly enhances driving safety in these situations.

In literature, some works on braking strategies for motorcycles like Corno et al. (2008) can be found for straight driving. In Vavryn and Winkelbauer (2004), however, it is shown that more motorcycle accidents happen while cornering. Basic investigations on motorcycles braking in a curve can be found in Weidele (1994). There, the driving dynamics for motorcycles while cornering are derived and the brake steer torque (BST) as an important physical quantity is introduced. The BST results from a displacement of the tire contact point with regard to the plane of the steering axis. It acts on the steering such that the motorcycle further turns in the curve if the torque is not compensated by the driver. Therefore, braking while cornering leads to a righting of the motorcycle whereby the desired trajectory can not be followed. However, leaving the trajectory while cornering can result in dangerous situations like leaving the lane, which could lead to a serious accident. Weidele (1994) concludes that there is a high potential for security enhancement for motorcycles especially while cornering by keeping the BST small. It is also pointed out that a restriction of the braking force at the front wheel would reduce the BST, however, no braking strategy is derived. It was also shown that the BST significantly rises with high braking force gradients, e.g. in emergency braking situations. This makes it impossible for the driver to compensate the BST in these situations.

A strategy to decrease the BST by a mechanical system is presented in Schröter et al. (2012). To compensate the BST, it is proposed to shift the steering axis sideways during cornering so that it is in plane with the tire contact point. However, such a system is complex due to the additional mechanical degree of freedom which has to be realized on the frame/steering connection.

Hence, this contribution focuses on the adaptive brake force distribution to reduce BST in electric motorcycles. There, it can easily be realized if an electric hub motor is additionally available at the front wheel. The proposed braking assistance system enhances safety by also taking the gradient of the BST into account. This brake force distribution can be seen as a control allocation problem with constraints. Based on the efficient model predictive control allocation (MPCA) algorithm for an all-wheel driven electric car presented in Bächle et al. (2015), a real-time capable model-based algorithm for brake force distribution will be presented in the following. The proposed algorithm is used to decrease the occurring BST while braking in a

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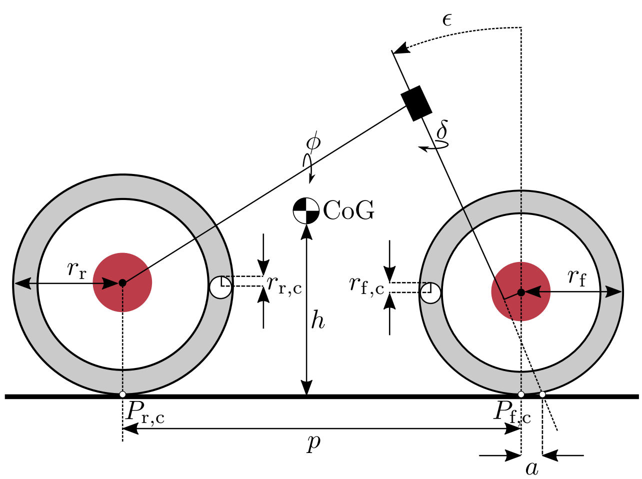

Fig. 1. Schematics of the motorcycle

Table 1. Motorcycle parameters

parameter	description
p	wheelbase (dist. between the tire contact points)
a	trail (hori. dist. between front tire contact point and steering axis virtual intersects the ground)
h	height of the center of gravity
$r_{\rm r}$ and $r_{\rm f}$	radius of the rear and front tire, resp.
$r_{\rm r,c}$ and $r_{\rm f,c}$	radius of the rear/front tire cross section
ϵ	caster angle
δ	steering angle
ϕ	roll angle
$P_{\rm r,c}$ and $P_{\rm f,c}$	contact point of the rear/front tire

curve, nevertheless the requested total braking force is still provided with only very little deviations.

This paper is structured as follows: Section 2 introduces the proposed motorcycle power train architecture and the system modeling. In Section 3, the optimization problem is set up and the MPCA algorithm is presented. Section 4 presents the achieved results, where the algorithm was applied to an elaborated motorcycle simulation (IPG MotorcycleMaker, IPG Automotive GmbH (2015)). The paper closes with some conclusions and an outlook on future work in Section 5.

2. SYSTEM MODELING

In this section, the underlying system architecture is presented and its model equations are derived. A schematic view on the considered electric all-wheel driven motorcycle is shown in Fig. 1. The descriptions of the parameters are given in Table 1. The red circles represent the electric hub motors. For the sake of simplicity of presentation, it is assumed that the motors provide enough torque for all braking scenarios, so no additional electro-mechanical braking system is considered in this paper.

2.1 Longitudinal force

For the investigation of a motorcycle braking scenario, it is obvious that the main goal is the compliance of the desired longitudinal force. Fig. 2 shows the acting forces at the wheels in a bird's eye view of the motorcycle.

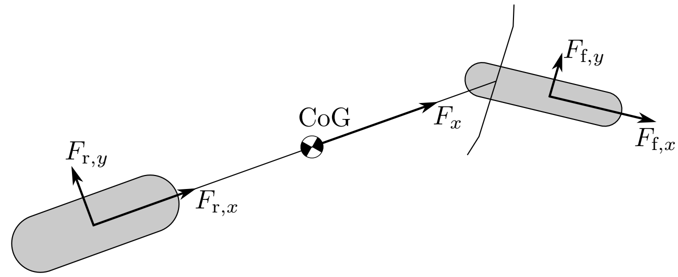

Fig. 2. Acting forces at the motorcycle's wheels

To calculate the longitudinal force F_x, the kinematic steering angle $\delta_{\rm k}$ (Cossalter (2006)) is needed. In this work, the pitch angle is neglected, so the kinematic steering angle is given by

$$\delta_{\rm k} = \arctan\left(\frac{\sin\delta\cos\epsilon}{\cos\phi\cos\delta - \sin\phi\sin\delta\sin\epsilon}\right). \tag{1}$$

Using this formulation, the resulting longitudinal force is defined as

$$F_x = F_{{\rm r},x} + F_{{\rm f},x}\cos\delta_{\rm k} + F_{{\rm f},y}\sin\delta_{\rm k}\,, \tag{2}$$

where the index $i \in \{\rm f, r\}$ represents the respective value at the front or rear wheel and F_x and F_y are the longitudinal and lateral force components. Due to the fact that the steering angle is very small, the summand with the lateral force is neglected. The acting longitudinal forces at the wheels $F_{i,x}$ are directly imposed by the hub motors according to

$$F_{i,x} = \frac{T_{{\rm act},i}}{r_i}, \quad i \in \{\rm f,r\}\,. \tag{3}$$

For the validity of this equation, the wheels must operate in the stable region (cf. Pacejka and Besselink (2012)), i.e. the forces have to be inside the friction circle. This leads to the boundaries

$$F_{i,x}^- = -\sqrt{\mu_i^2 F_{i,z}^2 - F_{i,y}^2} \le F_{i,x} \le F_{i,x}^+ = \sqrt{\mu_i^2 F_{i,z}^2 - F_{i,y}^2}\,, \tag{4}$$

where μ_i is the friction coefficient. Using (3) this leads to

$$T_{i,x}^- = r_i F_{i,x}^- \le T_{{\rm act},i} \le T_{i,x}^+ = r_i F_{i,x}^+ \tag{5}$$

for the limits of the acting torques.

For this contribution, the forces and the friction coefficients are assumed to be available for control, which can be realized in practical applications by appropriate estimation routines, see e.g. Doumiati et al. (2013).

2.2 Hub motors

The hub motors are modeled as first-order lag elements with unity stationary gain and time constant $T_{\rm m}$. The state-space representation of the actuator model is

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}, \quad \boldsymbol{y} = \boldsymbol{I}_2\boldsymbol{x} \tag{6}$$

$$\text{with} \quad \boldsymbol{A} = -\frac{1}{T_{\rm m}}\boldsymbol{I}_2, \quad \boldsymbol{B} = \frac{1}{T_{\rm m}}\boldsymbol{I}_2\,,$$

where $\boldsymbol{I}_j$ represents a $j \times j$ identity matrix. The state $\boldsymbol{x} = [T_{\rm act,f}, T_{\rm act,r}]^{\rm T}$ contains the actual torques, and the input comprises the desired torques $\boldsymbol{u} = [T_{\rm des,f}, T_{\rm des,r}]^{\rm T}$. In the following, the differential equation of the state-space (6) is abbreviated by the more general form

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}). \tag{7}$$