

Adaptive Regenerative Braking for Electric Vehicles with an Electric Motor at the Front Axle using the State Dependent Riccati Equation Control Technique

SVEN JANSEN, MOHSEN ALIREZAEI, STRATIS KANARACHOS

Technical Sciences

TNO

Steenovenweg 1, 5708 HN Helmond

THE NETHERLANDS

stratis.kanarachos@tno.nl <http://www.tno.nl>

Abstract: - In this paper a novel adaptive regenerative braking control concept for electric vehicles with an electric motor at the front axle is presented. It is well known that the “phased” type regenerative braking systems of category B maximize the amount of regenerative energy during braking. However, there is an increased risk of maneuvering capability loss especially during cornering. An integrated braking controller which determines - in a single step - the desired yaw moment and allocates the braking demand between hydraulic brakes and electric motor during cornering is designed using the State Dependent Riccati Equation (SDRE) method. A unique method for deriving the State Dependent Coefficient (SDC) formulation of the system dynamics is proposed. Soft constraints are included in the state dynamics while an augmented penalty approach is followed to handle hard constraints. The performance of the controller has been evaluated for different combined cornering-braking scenarios using simulations in a Matlab/Simulink environment. For this an eight degrees of freedom (DOF) nonlinear vehicle model has been utilized. The numerical results show that the controller is able to optimize (locally) the amount of regenerative braking energy while respecting system’s constraints such as tire force saturation, vehicle yaw rate and slip angle errors.

Key-Words: - regenerative braking and cornering, stability, State Dependent Riccati Equation controller, optimization, state estimation

1 Introduction

In the automotive sector the rising fuel prices and the continuously stricter emissions legislation put pressure on the research and development of systems that can recuperate energy. Regenerative braking systems recover part of the kinetic energy by utilizing one or more electric motors during braking and therefore can substantially reduce fuel consumption and CO₂ emissions. However, brake energy recovery is mainly limited by three factors: a) the maximum brake torque provided by the generator, b) the charge rate of the battery and c) the available tire-road friction. Due to above a braking system has to utilize also friction braking. Main subject of the present paper is the development of an integrated controller that maximizes the recuperated energy by optimally distributing the braking demand among the actuators while respecting system’s constraints. The integrated controller has a coordination role and thus acts at a higher level. The lower level control part is not addressed in this paper.

Until now a number of studies have been conducted regarding different regenerative braking strategies and their implications on vehicle stability. For example, in reference Hancock et al [2012] a study regarding regenerative braking and its impact on vehicle’s fuel economy and stability was presented. A regenerative braking system at the rear axle of a sport vehicle equipped with a conventional Anti-Lock Braking System and Electronic Stability Program was considered. The braking strategy was focused on maximizing the rear braking force. It was shown through simulations that in the case of low friction surfaces regenerative braking can significantly compromise vehicle stability during cornering. A solution proposed by the authors was to redistribute the regenerative braking force based on the actual wheel slip. The authors used a six body DOFs and four wheel rotational DOFs vehicle model. The tires were modeled according to the nonlinear Magic Formula Tire Model. Steering, driveline and suspension systems were assumed to be rigid bodies. Longitudinal and lateral weight transfer was considered.

$$\dot{\varphi} = -\frac{(c_{\varphi 1} + c_{\varphi 2} - m \cdot g \cdot h')}{k_{\varphi 1} + k_{\varphi 2}} \cdot \varphi - \frac{m \cdot h' \cdot u_f + (m \cdot h'^2 + I_y - I_z) \cdot r}{k_{\varphi 1} + k_{\varphi 2}} \cdot r$$

$$F_{x1r} = \frac{M_{fr1r} + M_{rb}/2}{R} - \frac{I_w \cdot \dot{u}_f}{R} \approx \frac{M_{fr1r} + M_{rb}/2}{R}$$

$$F_{x1l} = \frac{M_{fr1l} + M_{rb}/2}{R} - \frac{I_w \cdot \dot{u}_f}{R} \approx \frac{M_{fr1l} + M_{rb}/2}{R}$$

$$F_{x2r} = \frac{M_{fr2r}}{R} - \frac{I_w \cdot \dot{u}_f}{R} \approx \frac{M_{fr2r}}{R}$$

$$F_{x2l} = \frac{M_{fr2l}}{R} - \frac{I_w \cdot \dot{u}_f}{R} \approx \frac{M_{fr2l}}{R}$$