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Analog Fuzzy Implementation of a Vehicle Traction Sliding-Mode Control

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Introduction

In recent times the availability of high technology security systems inside common car vehicles has become very popular. The aim of these systems is to make car transportation safe and comfortable.
The goal of vehicle traction control, which includes both antiskid braking and antispin acceleration, is to enhance vehicle performance and handling while avoiding excessive wheel slippage even in bad road conditions.
The main problem to deal with is that the road adherence is an imprecise function of many parameters strongly affected by road conditions. In this paper we propose a very robust control which can consider adherence and other model uncertainties, regulating the wheel slip at any desired value with good precision properties.
Because of commercial interest, often reports of advancement in this field are not available to the research community. Nevertheless in [1] a robust discrete-time control algorithm for vehicle traction is presented and experimentally tested and many papers address the application of fuzzy techniques to automotive engineering. In [4] there is a taxonomy of most important applications of fuzzy logic in this field, while [5], [6] and [8] contain respectively ABS, idle speed control and suspension system control applications.
In this paper a sliding-mode control has been designed to provide stability and reliability. Once designed the control surface has been fuzzified and implemented with an analog fuzzy circuit (AFE301) which uses a 0.7 μm CMOS technology provided by SGS-THOMSON MICROELECTRONICS. This implementation is carried out with an automatic design flow, and features a high computational efficiency at a very low cost, especially when compared to a digital one, which would require converters and other small accessory circuitry. Moreover, the controller response time is less than 1μs. This can afford, for example, the designing of a shared architecture for the slippage control of each wheel using a single fuzzy controller.
The compatibility between fuzzy logic and sliding mode control is theoretically investigated in [7].
Simulations of the closed-loop control have been done for the antiskid braking, considering a simplified vehicle dynamic model, and measurement from AFE301. Results show that the slip coefficient of the wheel is kept equal to the target value with good approximation.

1 Vehicle and Wheel Slip Model

Following the formulation proposed in [1], a simple model which is able to describe both the acceleration and deceleration case can be developed by applying Newton's laws.

The acceleration of the vehicle is determined by

$$\dot{V} = \frac{N_w F_t - F_v(V)}{M_v} \tag{1}$$

where N_w is the number of wheels; M_v is the mass of the vehicle; $F_t = \mu(\lambda) N_v$ is the tractive force from the wheel which is proportional to the normal force at the tire and the adhesion coefficient $\mu(\lambda)$; $F_v(V)$ is the aerodynamics friction. The angular acceleration of the wheel can be expressed as

$$\dot{\omega}_w = \frac{[T_e - T_b - R_w F_t - F_w(\omega_w)]}{J_w} \tag{2}$$

where J_w is the wheel inertia; T_e the engine torque; T_b the braking torque; R_w the wheel radius; and $F_w(\omega_w)$ the viscous friction torque. The adhesion coefficient $\mu(\lambda)$ is a function of the slip coefficient of the wheel, defined as

$$\begin{aligned} \lambda &= \frac{\omega_w - \omega_v}{\omega_w} \qquad \text{if } \omega_w > \omega_v \\ \lambda &= \frac{\omega_w - \omega_v}{\omega_v} \qquad \text{if } \omega_w < \omega_v \end{aligned} \tag{3}$$

where $\omega_v = V / R_w$ is the equivalent angular velocity of the vehicle. The quantity λ measures the slip of the tire when a driving or braking torque is applied. Hereinafter we shall consider the deceleration case $\omega_v > \omega_w$ (or equivalently $\lambda < 0$). Letting $x_1 = \omega_v$, $x_2 = \omega_w$ and defining the functions $f_1(x_1) = F_v(R_w x_1) / (M_v R_w)$, $f_2(x_2) = F_w(x_2) / J_w$ the overall model can be rewritten in the usual input-state-output form

$$\begin{aligned} \dot{x}_1 &= -f_1(x_1) + c_1 \mu(\lambda) \\ \dot{x}_2 &= -f_2(x_2) - c_2 \mu(\lambda) + \frac{1}{J_w} u \\ \lambda &= \frac{x_2}{x_1} - 1, \qquad x_2 < x_1 \end{aligned} \tag{4}$$

where: $u = T_e - T_b$, $c_1 = \dfrac{N_w N_v}{M_v R_w}$, $c_2 = \dfrac{N_v R_w}{J_w}$.

2 Sliding-Mode Control Law

The traction model (4) involves nonlinearities, parametric uncertainties, non-modeled dynamics. A robust controller is hence necessary in order to regulate the wheel slip λ to a desired value λ_d. Sliding-mode control meets these requirements. It is able to provide stability and small error tracking despite model uncertainties ranging within a prescribed set. Moreover, it yields a *static* nonlinear feedback law which is well suitable for the fuzzy implementation described in the following sections.

2.1 Uncertainties Modeling

Because of intrinsic robustness of sliding mode control, rough assumptions can be made on the functions involved in model (4). In the following we denote with a hat "^" an estimate and with a "Δ" the maximum deviation of a given quantity. The functions $f_i(x)$, *i=1,2* relating to the friction in the range of application of our controller are supposed to be comprised within the range

$$k_i^- x \le f_i(x) \le k_i^+ x \qquad (5)$$

We define $\hat{f}_i(x) = \hat{k}_i x$, with $\hat{k}_i = \frac{k_i^+ + k_i^-}{2}$, and $\Delta k_i = \frac{k_i^+ - k_i^-}{2}$.

The adhesion coefficient $\mu(\lambda)$ is modeled as in [3]. By this, the estimate and deviation can be expressed in terms of the estimate and deviation of the peak value μ_p as

$$\hat{\mu}(\lambda) = \mathrm{sign}(\lambda)\begin{cases} (|\lambda| - 0.15)\frac{\hat{\mu}_p}{0.15} + \hat{\mu}_p & \text{if } |\lambda| \le 0.15 \\ -(|\lambda| - 0.15)\frac{0.34\hat{\mu}_p}{0.85} + \hat{\mu}_p & \text{if } |\lambda| > 0.15 \end{cases} \qquad (6)$$

and $\Delta\mu(\lambda) = |\hat{\mu}(\lambda)|\Delta\mu_p / \hat{\mu}_p$ .The wheel inertia is supposed to be comprised within a lower bound J_w^- and an upper bound J_w^+. Because it is a multiplicative term, the geometric mean $\hat{J}_w = \sqrt{J_w^+ J_w^-}$ is taken as an estimate. Hence

$$\sqrt{\frac{J_w^-}{J_w^+}} \le \frac{\hat{J}_w}{J_w} \le \sqrt{\frac{J_w^+}{J_w^-}}$$

and the maximum deviation of the ratio $\hat{J}_w / J_w$ can be expressed as

$$\Delta J_w = \max\left\{1 - \sqrt{\frac{J_w^-}{J_w^+}},\ \sqrt{\frac{J_w^+}{J_w^-}} - 1\right\} .$$

Parameters c_1 and c_2 have been treated as in (5) by defining proper $\hat{c}_i$ and Δc_i. An estimate $\hat{T}_e$ and a deviation ΔT_e of the engine torque have also been supposed to be available.

2.2 Sliding Surface and Control Law

The sliding surface has been chosen as $s = \lambda - \lambda_d$ which in the *x*-plane corresponds to the line $x_2 = (1 + \lambda_d)x_1$. Following a design procedure inspired by [2], after some computations, the braking torque T_b in terms of state feedback has been determined as

$$T_b = \hat{T}_e - \hat{J}_w[(\hat{k}_2 - \hat{k}_1)x_2 + |\hat{\mu}(\lambda)|(\hat{c}_2 + \hat{c}_1\frac{x_2}{x_1})] \quad + [\Delta T_e + \hat{J}_w(|B| + |A|x_2 + \eta x_1)]\mathrm{sign}(\lambda - \lambda_d) \qquad (7)$$

where

$$|A| = \Delta J_w |\hat{k}_2 - \hat{k}_1| + \Delta k_1 + \Delta k_2$$

$$|B| = (\Delta J_w(\hat{c}_1 + \hat{c}_2) + \Delta c_1 + \Delta c_2)|\hat{\mu}(\lambda)| + (\hat{c}_1 + \hat{c}_2 + \Delta c_1 + \Delta c_2)\Delta\mu(\lambda)$$

parameter $\eta > 0$ governs the trade-off between the time required to reach the desired set-point and the input intensity. Moreover, in order to reduce chattering phenomena and smooth out (7) for fuzzy approximation, the sign function in (7) is replaced by the saturation function

$$\mathrm{sat}\left(\frac{\lambda - \lambda_d}{\Phi}\right)$$

where parameter Φ determines the trade-off between the tracking precision and the control smoothness.

2.3 Stability Analysis

The stabilizing property of the designed control law is now discussed showing that both x_1 and x_2 converge to zero. When the sign function is used in (7), λ converges to the constant value λ_d in a finite time. Then, $x_2 = (1 + \lambda_d)x_1$, and we can reduce our analysis to x_1. In order to use Lyapunov's stability theorem, consider the following function $V(x_1) = \frac{1}{2}x_1^2$. Since $f_1(x_1)$ is an odd function and $\mu(\lambda) < 0$, by eq. (4) one has

$$\dot{V}(x_1) = -x_1 f(x_1) + x_1 c_1 \mu(\lambda) < 0$$

for all $x_1 \neq 0$. By Lyapunov's theorem as $t \to \infty$ both state variables $x_1, x_2 \to 0$. When the sat function is used instead of sign in (7), it can be shown that λ converges to a constant value (which differs from the desired set-point λ_d for a quantity proportional to Φ). Hence the same considerations can be repeated.

3 Analog Fuzzy implementation of controller

A semi-automatic design flow for the computation of the programming values for the fuzzy controller AFE301, a programmable analog fuzzy processor designed using a 0.7μm technology provided by SGS-THOMSON MICROELECTRONICS [13], has been developed at the University of Bologna [9]. It can be divided in two steps: the design of a minimized abstract system and hardware mapping. The steps are as follows:

- The minimization of the rules is performed by a software tool to avoid a waste of silicon area and computational time. This software tool accepts numerical examples as inputs, as well as a linguistic description of the expected behaviour. The linguistic description has to be given in an elementary language named "Fuzzy Description Language" (FDL), which follows the usual fuzzy rule structure with preconditions and consequences, membership functions of either Gaussian or trapezoidal shape, and crisp output consequences (singletons). The numerical values are given as input/output pairs and can be obtained by sampling the whole normalized input range, thus computing the output of the desired controller.
  Rules are automatically generated to outline the behaviour described by the numerical examples. The induction algorithm considers the rules generated by all the possible combinations of preconditions and consequences. Then, an appropriate cost function is defined to evaluate both the mismatching between the system output and the given examples, and the complexity of the

resulting rule set. The best set of rule weights is found by minimizing the cost function which can be shown to feature a unique constrained minimum [10]. These rules are compared with those specified by the user to detect possible inconsistencies and resolve them with a further resort to the examples. The resulting rule set is the structure of an abstract fuzzy system obeying the user specifications. The rules obtained so far are processed to define a minimum rule set leading to the same input/output relationship.

- The error between the desired input/output behaviour of the controller and the actual circuit input/output relationship is minimized by using an analytical model of the analog circuit. The optimal values of such parameters are the final programming voltages levels.

The described software procedure produces the programming sequence for one of these devices that can be used for a fast validation of the designed sliding-mode control policies.
The described procedure has been applied to the control law (7) and resulted in 13 rules. However, this kind of implementation depends on the target slip coefficient. Another implementation has been proposed in order to obtain a parametric control of the slip coefficient. By neglecting the first term of the sum in Eq. (7), this *static* nonlinear feedback law can be split in two parts:

$$\text{SLI} = \Delta T_e + \hat{J}_w (|B| + |A| x_2 + \eta x_1) \tag{8}$$

$$\text{SAT} = \text{sat}\left(\frac{\lambda - \lambda_d}{\Phi}\right) \tag{9}$$

Therefore T_b is obtained by multiplying SLI and SAT, where SAT explicitly depends on the target slip coefficient. The described architecture, sketched in Figure 1, allow us to possibly choose the target slip coefficient according to measured pavement conditions. The described procedure for the analog fuzzy controller implementation has been applied for both (8) and (9) and results in 15 rules for both the $\text{Fuzzy}_{\text{SLI}}$ and $\text{Fuzzy}_{\text{SAT}}$ controllers.
The same control surface can be synthesized with a silicon compiler based on Cadence software [11] which produces the dedicated layout for this specific application. In this case the dedicated fuzzy controller would require a silicon area of about 3.45 mm^2.

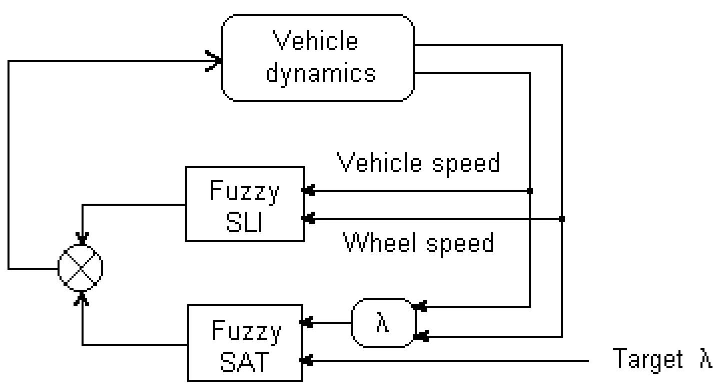

Figure 1 Block diagram of control structure.

The proposed antiskid control acts only when the vehicle speed is higher than 4 km/h. In fact, when the speed is lower than this limit, the control of λ becomes very difficult since both x_1 and x_2 tend to 0. However, in practice this is not restrictive since skid effects are not important in that range. When the vehicle speed is lower than 4 km/h, a suitable constant T_b is applied.

The main advantages of the analog implementation with respect to the digital one are the response time and the power consumption. In fact, only the required A/D and D/A converters would need more time and more power than the single fuzzy controller. The relaxation time of AFE301 in this condition is about 600ns. Thus we can assume that the whole feedback structure has a response delay of about 1μs, considering AFE301 and additional circuitry. This ensures a very fast processing of the incoming loop signals.
Moreover, it would be possible to perform the antiskid braking system for the four wheels with the same analog controller sampling and holding vehicle and wheel speed every 4μs.

4 Results

The proposed architecture has been simulated with the simple car dynamic model (1)-(2). Measurements of the static output, carried out from AFE301 with a input resolution of 2.5% of nominal range, have been rearranged and bilinearly interpolated to provide the designed control surface. The closed-loop system has been solved with Runge-Kutta Method.

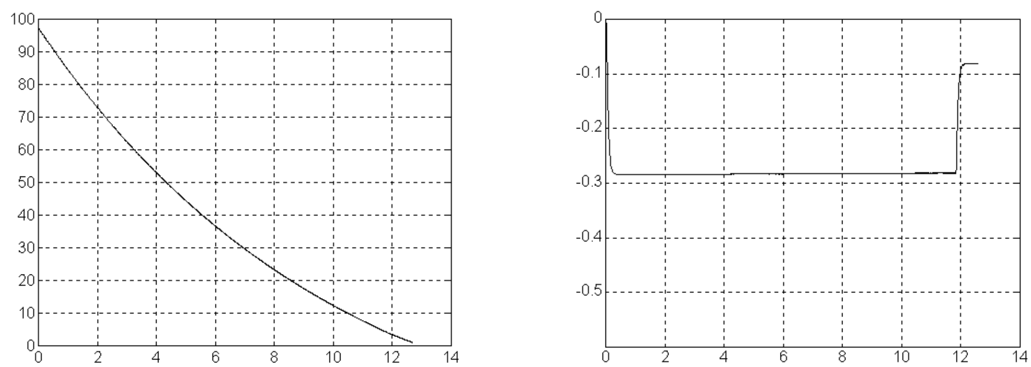

Figure 2 Results of closed-loop simulation for vehicle speed (left) and slip coefficient of wheel (right) when desired slip coefficient is λ_d = -0.3.

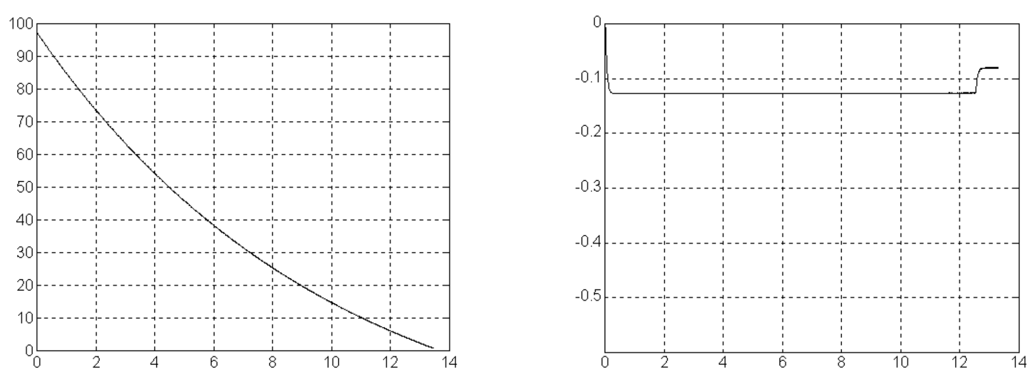

Figure 3 Results of closed-loop simulation for vehicle speed (left) and slip coefficient of wheel (right) when desired slip coefficient is λ_d = -0.15.

Two target values for the slip coefficient have been considered, $\lambda_d = -0.15$ (dry pavement) and $\lambda_d = -0.3$ (wet) with the SLI×SAT implementation. Simulations has been carried out by considering an initial speed value of 100km/h, a nominal mass $\hat{M}_V = 900\ Kg$, $\hat{\mu}_p$=0.5 with an uncertainty of ± 50%, and other uncertainties ranging in ± (5÷20)%. Figure 2 and Figure 3 show that the target value is reached with a constant offset dependent on Φ (see 2.3), and kept with good approximation when the controller is active (vehicle speed higher than 4km/h).

5 Conclusions

In this paper a flexible control of the slip coefficient has been performed. A very robust static nonlinear feedback law has been designed with sliding-mode techniques, and implemented by means of a semi automatic design flow with a programmable analog fuzzy circuit. Results show that the desired slip coefficient is reached and kept with good approximation in compliance with theoretical results.

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