Engineering Applications of Artificial Intelligence 23 (2010) 1041–1052

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

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

Genetic fuzzy self-tuning PID controllers for antilock braking systems

Abdel Badie Sharkawy

Mechanical Engineering Department, Faculty of Engineering, Assiut University, Assiut 715 16, Egypt

ARTICLE INFO

Article history:
Received 16 June 2008
Received in revised form
18 June 2010
Accepted 23 June 2010
Available online 14 July 2010

Keywords:
Antilock braking system (ABS)
Braking basics
Slip ratio
Decoupled rule bases
Takagi–Sugeno (T–S) fuzzy systems
Self-tuning
Genetic algorithm (GA) and Ziegler–Nichols (Z–N) method

ABSTRACT

Since the emergence of PID controllers, control system engineers are in pursuit of more and more sophisticated versions of these controllers to achieve better performance, particularly in situations where providing a control action to even a minimal degree of satisfaction is a problem. This work is an attempt to contribute in this field. Variations in the values of weight, the friction coefficient of the road, road inclination and other nonlinear dynamics may highly affect the performance of antilock braking systems (ABS). A self-tuning scheme seems necessary to overcome these effects. Addition of automatic tuning-tool can track changes in system operation and compensate for drift, due to aging and parameter uncertainties. The paper develops a self-tuning PID control scheme with an application to ABS via combinations of fuzzy and genetic algorithms (GAs). The control objective is to minimize the stopping distance, while keeping the slip ratio of the tires within desired range. Computer simulations are performed to verify the proposed control scheme. Results are reported and discussed.

1. Introduction

Difficulties in designing an ABS may be classified as follows. First, the vehicle braking-dynamics are nonlinear. Second, there are many unknown environmental parameters, like road coefficient of friction which may be wet, snowy or dry. Finally, parameter changes due to mechanical wear and aging. Recently, a great deal of research has been performed on the antilock brake system (ABS) (Assadin, 2001; Nouilllant et al., 2002; von Altrock Nov., 1997; Choi et al., 2002). Currently, most commercial ABSs are based on look-up tabular approach (Chih-Min Lin and Hsu March, 2003). These tables are calibrated through iterative laboratory experiments and engineering field tests.

The conventional PID controller for automated machines is widely accepted by industry. According to a survey reported in Yu (1999), more than 90% of control loops used in an industry use PID. This is because PID controllers are easy to understand (has clear physical meanings i.e. present, past and predictive), easy to explain to others, and easy to implement. Unfortunately, many of the PID loops that are in operation are in continual need of monitoring and adjustment since they can easily become improperly tuned (Passino and Yurkovich, 1998). Generally speaking, in order to meet the demands of real time operation, self-tuning is necessary.

Motivated by the success of fuzzy controllers in controlling nonlinear, complex, time-varying dynamic processes in real world, there has been steep increase in the research work on the theoretical aspects of fuzzy logic controller (FLC). The main reason is that FLCs essentially incorporate human expertise in the control strategy, exploiting easier understanding of linguistic interpretation.

Among the different types of FLC structures, PI-type and PD-type FLCs are very common (Passino and Yurkovich, 1998; Sharkawy et al., 2003). Other related works have employed different adaptation policies to improve one or more performance indices (Sharkawy, 2005; Mudi. and Pal, 1999; Xu et al., 1998). However, development of PID-type FLCs was not popular because they need the construction of three dimensional rule-base, which complicates the design. Moreover to make PID-type FLC adaptive in nature, the number of free adaptable parameters increases and their interaction and interdependence further complicates the situation (Mann et al., 1999).

The area of auto-tuning of PID controller using fuzzy systems has attracted many authors (Xu et al., 1998; Mann et al., 1999; S.-Z. et al., 1993; Visioli January, 2001; Bhattacharya et al., 2003; Visioli, 1999; Macvicar-Whelan, 1976; Tzafestas and Papanikolopoulos, 1990; Marsh, 1998). A fuzzy self-tuning incremental PID controller has been proposed by He et al. S.-Z. et al. (1993). The controller implements a conventional PID structure, which starts its operation with values of proportional gain, integral time, and derivative time, obtained from the well-known Ziegler–Nichls (Z–N) tuning formula. This scheme implements a supervisory fuzzy system, which adaptively changes the control parameter after each sampling instant to improve the control performance. In another study, a survey for tuning PID controllers with fuzzy

E-mail address: ab.shark@aun.edu.eg

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doi:10.1016/j.engappai.2010.06.011

Nomenclature

a_x	the vehicle body acceleration, m/s^2
$a_{i,j,k}$	$i=1,2,3$, $j=1,2, \ldots, 9$, $k=1,2,3$ are the coefficients of the T–S first order output-model
A	area
ABS	antilock braking system
B_1,B_2	fuzzy sets
c	center of Gaussian membership function
c_1, c_2	scaling factors
C_1	the maximum value of friction curve
C_2	the friction curve shape
C_3	the friction curve difference between the maximum value and the value at $\lambda=1$
C_4	the wetness characteristic value
$e(t)$	error of the closed-loop system
F	objective function
F_{IAE}	objective function that uses the stopping distance and IAE as the performance measures
F_{ITAE}	objective function that uses the stopping distance and ITAE as the performance measures
F_N	the normal force, N
FSW	PID controller using fuzzy set-point weighting
G	number of generations
GA	genetic algorithm
G-PID	PID controller in which the three parameters are determined using GAs
H	number of iterations
IFE	incremental fuzzy expert PID control
IAE	integrated absolute error
ITAE	integrated time multiplied by the absolute error
J_{ITAE}	performance index
J_{IAE}	performance index which uses IAE and the stopping distance as the performance measure
J_{ITAE}	performance index which uses ITAE and the stopping distance as the performance measure
J_w	the wheel inertia, kg m^2
k_1,k_2,k_3	constant parameters
K_d	the derivative gain
K_i	the integral gain
K_p	is the proportional gain
K_u	ultimate gain
m	the quarter vehicle mass, kg
n	number of rules
N	negative
NB	negative big
NS	negative small
NVB	negative very big
P	positive
PB	positive big
PS	positive small
PVB	positive very big
PID-Fuzzy	PID controller tuned using initially guessed fuzzy systems
PID-IAE	PID controller tuned by GA using F_{IAE} as the objective function
PID-ITAE	PID controller tuned by GA using F_{ITAE} as the objective function
R	the wheel radius, m
R_e	low reproduction rate
R_h	high reproduction rate
S_x	stop distance, m
SSP	PID controller using fuzzy self-tuning of a single parameter
t_u	oscillation period
T–S	Takagi–Sugeno fuzzy systems
T_d	the derivative time constant
T_i	the integral time constant
u	the braking torque, N m
V	population size
V_x	the speed of the vehicle, m/s
w	positive constant
w_i	firing strength of rule i
Z	zero
Z–N	PID controller tuned by the Ziegler–Nichols tuning method
α	fuzzy tuning parameter
α_w	angular acceleration of the wheel, rad/s^2
γ	positive constant
η_1,η_2	weighting factors
λ	the slip ratio
λ_d	desired value of the slip ratio
μ	membership grade
μ_r	road coefficient of friction
σ	slope of Gaussian membership function
ω	angular velocity of the wheel, rad/s

logic has been made by Visioli January (2001). In his work, several PID control schemes have been simulated for linear systems. Although in most cases, the controllers showed superior performance for linear processes, they could only reduce the peak overshoot at the expense of increasing rise time, and the degradation becomes more and more significant with increasing time delay. This restricted the overall acceptance as a good controller mechanism (Bhattacharya et al., 2003).

Referring to aforementioned works, one may conclude that Z–N method has been widely accepted as a base for tuning PID controllers off- and on-line. This may be referred to the ability of the method to preserve good load disturbance attenuation. Most of these studies however have transformed the tuning problem from using the Z–N tuning parameters to other author-defined parameters and use fuzzy logic as the tuning-tool for the new parameters; (S.-Z. et al., 1993; Visioli January, 2001; Bhattacharya et al., 2003; Visioli, 1999; Macvicar-Whelan, 1976), [others]. This indicates the lack of a generalized approach which can be followed for linear and nonlinear plants. Furthermore, the suitability and application range of the Z–N method are very limited (Marsh, 1998; Zhuang and Atherton, 1993). For example, it is not suitable for plants with a delay to time-constant ratio smaller than 0.15 or larger than 0.6. This method also yields poor damping and high sensitivity and does not achieve robustness of the closed-loop when considerable parameter variations take place.

In this study, a self-tuning PID controller is proposed for the ABS. Controlling the braking torque of an ABS is necessary to avoid locking of the wheels, so that the driver can keep control on the vehicle's motion. Parameter variations and uncertainties imply the need for an auto-tuning operation to achieve the performance consistency. The article describes a generalized procedure for the development of a simple, model free fuzzy PID-type structure as an effective combination of three independent fuzzy systems. Each PID parameter is tuned via first order Takagi–Sugeno (T–S) fuzzy system, whose parameters are optimally determined off-line using a modified genetic algorithm (GA). The control goal is to keep the slipping ratio of the tires within the desired range, while maintaining minimal stopping distance when braking is