Expert Systems with Applications 38 (2011) 10124–10132

Contents lists available at ScienceDirect

Expert Systems with Applications

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

An error-based on-line rule weight adjustment method for fuzzy PID controllers

Onur Karasakal *, Mujde Guzelkaya, Ibrahim Eksin, Engin Yesil

Istanbul Technical University, Faculty of Electrical and Electronics Engineering, Control Engineering Department, Maslak, TR-34469 Istanbul, Turkey

ARTICLE INFO

Keywords:
Fuzzy PID controller
Self-tuning
Fuzzy rule weighting

ABSTRACT

In this study, a new method is proposed for the adjustment of the fuzzy rule weights of the fuzzy PID controllers in an on-line manner. For this purpose, the transient phase of the unit response of the closed loop system is taken into consideration. The transient phase of the response is assumed to be divided into certain regions which are assigned in accordance with the number of membership functions defined for the error input of the fuzzy logic controller. Then, the relative importance or influence of the fired fuzzy rules of the fuzzy logic controller are determined for each region and the meta-rules are derived for the adjustment of corresponding fuzzy rule weight values to obtain an 'efficient' and 'appropriate' control signal that will achieve a "desired" system response. Since the value of system error varies during the transient system response and it is on hand for each region and sampling time, the weight tuning is accomplished using this error value. For this purpose, two simple functions based on the absolute value of the normalized system error are directly used for the assignment of the rule weights by an adequate arrangement in accordance with the meta-rules derived. By these assignments the error value is charged as the tuning variable of the rule weights and thus an on-line self tuning rule weight assignment is accomplished. The effectiveness of the proposed self tuning method is demonstrated on linear and non-linear systems by simulations and a real time application is done on Process Control Simulator.

1. Introduction

It is well known that most of the industrial processes are still using the conventional PID controllers because of their simple control structure, ease of design and effectiveness for linear systems (Chen, 1996). On the other hand, most of the real systems are of higher order, have time delays or nonlinearities or without of precise mathematical model. Due to their linear structure, conventional PID controllers are usually not effective for this kind of real systems. Thus, fuzzy logic is extensively used in processes where system dynamics is either very complex or exhibit a highly non-linear character. The first fuzzy logic control (FLC) algorithm, implemented by Mamdani (1974), was constructed to synthesize the linguistic control protocol of a skilled human operator.

In literature, various types of fuzzy PID (including PI and PD) controllers have been proposed. In general, the application of fuzzy logic to PID controller design can be classified into two major categories according to the way of their construction (Xu, Hang, & Liu, 2000):

(i) The gains of the conventional PID controller are tuned on-line in terms of the knowledge base and fuzzy inference, and then the conventional PID controller generates the control signal (He, Shaoua, & Xu, 1993; Soyguder, Karakose, & Alli, 2009; Zhao, Tomizuka, & Isaka, 1993).

(ii) A typical fuzzy logic controller (FLC) is constructed as a set of heuristic control rules, and the control signal is directly deduced from the knowledge base and the fuzzy inference as it is done in Mc Vicar-Whelan or diagonal rule base generation approaches (Mizumoto, 1992; Palm & Driankov, 1996; Xu, Liu, & Hang, 1998).

The controllers in the second category are referred to fuzzy PID controllers, because, from the input-output relationship point of view, their structures are analogous to that of the conventional PID controller. In literature there are several researches on the structure of PID type FLCs (Chen, Tung, Tsai, & Fan, 2009; Duan, Li, & Deng, 2008; Guzelkaya, Eksin, & Gurleyen, 2001; Li & Gatland, 1996; Qiao & Mizumoto, 1996). Additionally, the design parameters of the fuzzy PID controllers can be summarized within two groups (Hu, Mann, & Gasine, 1999):

(a) structural parameters, and
(b) tuning parameters.

Structural parameters include input/output (I/O) variables to fuzzy inference, fuzzy linguistic sets, membership functions (MF), fuzzy rules, inference mechanism and defuzzification mechanism. Tuning parameters include input/output (I/O) scaling factors (SF) and parameters of membership functions. The structural parameters are generally determined during off-line design where the tuning parameters can be recalculated during on-line adjustments of

* Corresponding author. Tel.: +90 212 2853583; fax: +90 212 2852920.
E-mail address: onur_karasakal@yahoo.com (O. Karasakal).

0957-4174/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.eswa.2011.02.070

the controller to enhance the process performance, as well as to accommodate the adaptive capability to system uncertainty and process disturbance.

In the case of the real systems have nonlinearities, parameter changes, modeling errors, disturbances, etc., the usage of fixed value scaling factors may not be sufficient to achieve the desired system performance. Therefore to overcome these kinds of disadvantages, a lot of heuristic and non-heuristic tuning algorithms for the adjustment of scaling factors of fuzzy controllers have been presented in literature (Chung, Chen, & Lin, 1998; Guzelkaya, Eksin, & Yesil, 2003; Karasakal, Guzelkaya, Yesil, & Eksin, 2005; Mudi & Pal, 1999; Qiao & Mizumoto, 1996; Woo, Chung, & Lin, 2000).

In addition to scaling factor tuning algorithms, although there is no systematic method to design membership functions and examine the number of fuzzy rules, the literature also includes some methods to tune the membership functions and fuzzy rules of the fuzzy controllers. Juang, Chang, and Huang (2008), tuned the membership functions by means of genetic algorithm (GA) using a fitness function to improve the system performance. Ahn and Truong (2009) used a robust extended Kalman filter to tune the input membership functions and the weight of the controller output during the system operation process. Teng, Xiang, Wang, and Wu (2004) proposed a genetic weighted fuzzy rule based system in which the parameters of membership functions including position and shape of the fuzzy rule set and weights of the rules are evolved using a genetic algorithm.

Alternatively, Genc, Yesil, Eksin, Guzelkaya, and Tekin (2009) proposed a fuzzy rule base shifting scheme for systems with time to improve system performance. The shifting scheme of the fuzzy rules is tabulated with respect to the normalized dead time, therefore, in some way, the structural parameters of the FLC was tuned in an on-line manner.

In this study, a new method is proposed for the adjustment of the fuzzy rule weights of the fuzzy PID controllers in an on-line manner. For the analysis, the transient phase of the response is firstly assumed to be divided into certain regions which are assigned in accordance with the number of membership functions defined for the error input of the FLC. Then, the relative importance or influence of the fired rules of the rule base is determined for each region and the meta-rules are derived for the adjustment of their weight values to obtain an 'efficient' and 'appropriate' control signal. The weight tuning is accomplished using the system error value which is available for each sampling time during the transient system response. Therefore, simple functions based on the absolute value of the normalized system error are directly used for the assignment of the rule weights by an adequate arrangement in accordance with the meta-rules derived. The effectiveness of the proposed self tuning algorithm is demonstrated on linear and non-linear systems by simulations and a real time application is done on FEEDBACK PCS 327 Process Control Simulator.

The outline of the paper can be summarized as follows: Section 2 includes the fuzzy PID controller structure without a tuning mechanism, the interpretation of rule weights and the proposed on-line rule weight adjustment, Sections 3 and 4 present the simulation and experiment results for various system types, Sections 5 provides the discussions and the conclusions, respectively.

2. The proposed rule weight adjustment method

2.1. Standard fuzzy PID controller

In this study, we will deal with standard fuzzy PID controllers, formed using a fuzzy PD controller with an integrator and a summation unit at the output, as it is shown in Fig. 1.

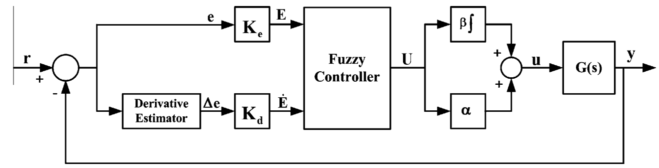

Fig. 1. The closed-loop control structure for fuzzy PID controller.

The output of the fuzzy PID controller is given by

$$u = \alpha U + \beta \int U\,dt \tag{1}$$

The error (e) and the change of error (Δe) are used as the inputs and the change of the control signal (U) is used as the output of the FLC. The input scaling factors K_e for error and K_d for the change of error normalize the inputs to the range in which the membership functions of the inputs are defined. The output scaling factors β and α normalize the output of FLC to an applicable value. The universes of discourse are chosen to be $[-1, 1]$ for the inputs e, Δe and output U.

The symmetrical triangular uniformly distributed membership functions are assigned to each fuzzy linguistic value of the error (e) and the change of error (Δe) as shown in Fig. 2. The linguistic values of e and Δe are denoted as N_i where $i = \{-n, -n+1, \ldots, -2, -1, 0, 1, 2, \ldots, n-1, n\}$ and M_j where $j = \{-m, -m+1, \ldots, -2, -1, 0, 1, 2, \ldots, m-1, m\}$, respectively. In addition the cores of fuzzy sets N_i and M_j are denoted as e_i and Δe_j. Singleton fuzzy membership functions are assigned to the output of the FLC. For this study, the same number of membership functions is taken for the inputs and the output of the FLCs.

Galichet and Foulloy (1995) established the equivalence between fuzzy PID controllers and conventional PID controllers when the fuzzy controllers have product–sum inference method, center of gravity defuzzification method and triangular uniformly distributed membership functions for the inputs and a singleton membership functions for the output. The same result is shown to be valid for the minimum inference engine by Huang, Chung, and Lin (1999).

2.2. The fuzzy rule weights

A comprehensive analysis on the fuzzy rule weights can be found in (Nauck & Kruse, 1998). The weight (w) is a real value variable that can change for each rule and it is generally added to a rule with the phrase "with w". The weight values can be considered as a structural parameter of a fuzzy PID controller. The weight of the rule shows the importance or influence of that fuzzy rule for the inputs at a specified time. The fuzzy rules of FLCs with weights are generally written as;

R_k IF the error (e) is N_k and the change of error (Δe) is M_k
THEN the change of control signal (U) is C_k with w_k

Generally the weights are applied to the rules in two different ways:

(a) The weights are applied to the complete rule. In this case the degree of fulfillment of the rule is changed by the weight.
(b) The weights are applied to the consequent of the rules. In this case, the output of the rule is changed with the weight.

When the singleton membership functions are used at the output part of the rules, the rule weights occur in the sums of the