Journal of Process Control 19 (2009) 1011–1023

Contents lists available at ScienceDirect

Journal of Process Control

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

Online tuning fuzzy PID controller using robust extended Kalman filter

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ARTICLE INFO

Article history:
Received 14 September 2008
Received in revised form 30 December 2008
Accepted 10 January 2009

Keywords:
Fuzzy
PID controller
Extended Kalman filter
Robust extended Kalman filter (REKF)
Real-time

ABSTRACT

Fuzzy PID controllers have been developed and applied to many fields for over a period of 30 years. However, there is no systematic method to design membership functions (MFs) for inputs and outputs of a fuzzy system. Then optimizing the MFs is considered as a system identification problem for a nonlinear dynamic system which makes control challenges. This paper presents a novel online method using a robust extended Kalman filter to optimize a Mamdani fuzzy PID controller. The robust extended Kalman filter (REKF) is used to adjust the controller parameters automatically during the operation process of any system applying the controller to minimize the control error. The fuzzy PID controller is tuned about the shape of MFs and rules to adapt with the working conditions and the control performance is improved significantly. The proposed method in this research is verified by its application to the force control problem of an electro-hydraulic actuator. Simulations and experimental results show that proposed method is effective for the online optimization of the fuzzy PID controller.

1. Introduction

Nowadays, conventional proportional-integral-derivative (PID) controllers are commonly used in industry due to their simplicity, clear functionality and ease of implementation. Meanwhile, fuzzy control, an intelligent control method imitating the logical thinking of human and being independent on accurate mathematical model of the controlled object, can overcome some shortcomings of the traditional PID. But the fuzzy is a nonlinear control and the output of the controller has the static error [1]. The reason is that when the fuzzy input value is in the stable area defined by a membership function, the fuzzy control output is same which is near or reaches zero command. Then fuzzy PID control which combines the traditional PID control and the fuzzy control algorithm is a solution [2–5]. Fuzzy PID control technique has been applied to many successful applications to a variety of consumer products and industrial systems such as position control of slider crank mechanisms [2], position control of shape memory alloy actuator [3], and speed control for high performance brushless servo drives [4], etc. However, the fuzzy PID controllers proposed in these reaches are experimentally designed based on working conditions of the control systems and their dynamic responses. Consequently, the design of fuzzy rules depends largely on the experience of experts. There is no systematic method to design and examine the number of rules, input space partitions and membership functions [6,7]. Hence, the typical fuzzy PID controllers cannot adapt for a wide range of working environments with large variation of perturbations [13]. As a result, another control technique such as robust control, intelligent theory, or estimation methods is needed to combine with the fuzzy PID to overcome this weakness [8–13]. By using these advanced techniques, the parameters of the fuzzy PID controller will be adjusted about the shape and position of the input/output MFs to minimize the control error. And Kalman estimation technique is an effective solution for controller training purpose.

Kalman filter is a powerful mathematical tool for stochastic estimation from noisy sensor measurements [14–16]. It makes an approximation of the system states, called the priori estimate, which is used to predict the measurement that is about to arrive. It recursively conditions the current estimate on all of the past measurements, and generally converges in a few iterations. A Kalman filter that linearizes about the current mean and covariance is referred to as an extended Kalman filter (EKF) which has been widely applied in many engineering fields and control system designs. However, the conventional Kalman filters are just accurate for problems with small nonlinearities and nearly Gaussian noise statistic. Meanwhile, most physical systems contain large nonlinearities and uncertainties. Moreover, the noise in the measurements is a combination of errors coming from many different sources and generally does not have a Gaussian distribution. Then they can perform very badly due so-called wrong measurements. It is therefore a challenge to find a robust filter, which is able to detect the wrong measurements and to handle them accordingly [17–29]. Finally, the robust filter is applied to optimization purpose of the fuzzy PID controller.

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doi:10.1016/j.jprocont.2009.01.005

In order to solve the above control problems, this paper proposes an online tuning fuzzy PID based on a robust extended Kalman filter (REKF) to get better control performance with higher stability. The REKF is a combination of an extended Kalman filter (EKF) and the results in [23–25] which are used to robustify the EKF. Here, a set of the fuzzy PID parameters is similar to a state vector which represents the control ability. Once this vector designed for the system fits completely with the working condition, the performance error becomes zero. In other words, the control system error is caused by the weakness in controller ability and also the environment noise. If the optimization process of the fuzzy PID controller is consider as a filter, then the set of ideal state vectors for the controller is as a process model while the set of state vectors used to control the system is as a measurement model. Consequently, the different between the process and the measurement models, measurement error, is related to the control system error. Therefore, the task of the REKF is to directly estimate the ideal state vector of the fuzzy PID controller for the next step based on the current control error, the current state vector, and previous information. Then the MFs and fuzzy rules are updated online together to minimize the system error function. Consequently, the fuzzy PID inference has higher learning ability and the control qualities are improved significantly even in the case of complicated system and disturbance environment. To verify the overall proposed control system with its advantages, a co-simulation between AMESim [30] and Matlab/Simulink, and also real-time experiments are carried out for a special case like force control of an electro-hydraulic system. Simulation and experimental results show the effectiveness of the hybrid actuator using proposed control method to reach the force control target.

The remainder of this paper is organized as follows: Section 2 is the procedure of designing a robust controller and Section 3 presents the simulation and experimental results. Concluding remarks are presented in Section 4.

2. Robust controller design

2.1. Fuzzy pid controller analysis

In this research, the control problem is considered for systems which have single control input and single output. It is known that, PID controller is the most widely used in modern industry due to its simple control structure and easy design. The control signal for a system using a conventional PID controller can be expressed in the time domain as:

$$u_{\mathrm{PID}}(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

where $e(t)$ is the error between desired set point and the system output, $de(t)$ is the derivation of error $e(t)$, $u_{\mathrm{PID}}(t)$ is the control signal for the system and K_p, K_i, and K_d are the proportional gain, integral gain, and the derivative gain, respectively.

But the conventional PID controllers do not yield reasonable performance over a wide range of operating conditions because of the fixed gains used. That is the reason why another control technique needs to be used to tune the parameters of the PID controller. And fuzzy logic is one of the effective solutions.

From (1), three coefficients K_p, K_i and K_d need to be tuned by using fuzzy tuners. Therefore, the detailed fuzzy PID scheme is clearly shown as in Fig. 1.

Through fuzzy logic knowledge, the fuzzy PID tuners which tune PID parameters (K_p, K_i, K_d) can be established by using the following equation:

$$K_a = K_{a0} + U_a \Delta K_a, \ U_a \in [0,1], \quad a \text{ is } p, \ i \text{ or } d \tag{2}$$

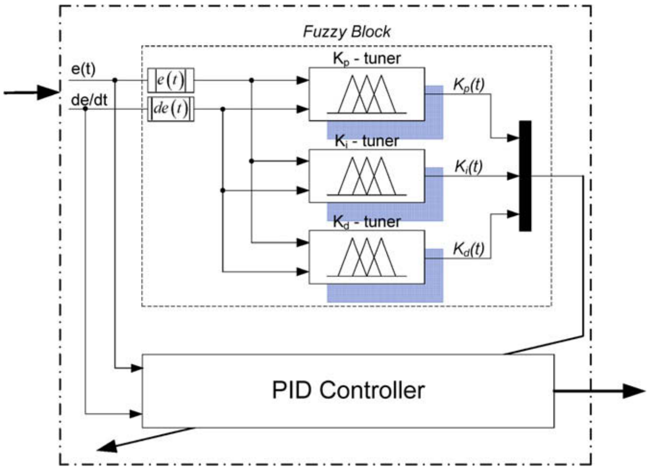

Fig. 1. The configuration of fuzzy PID control block.

where U_a is the parameter obtained from the output of the tuning fuzzy controllers, $\Delta K_a = K_{a1} – K_{a0}$ is the allowable deviation of K_a. K_{a0}, K_{a1} are the minimum and maximum values of K_a determined from experiments, respectively.

From (2) and Fig. 1, three coefficients K_p, K_i and K_d are tuned by using the three independent fuzzy tuners. Consequently, the three separate fuzzy P, I and D controllers are combined to form the overall fuzzy PID controller.

There are two inputs to the fuzzy controllers: absolute error $|e(t)|$ and absolute derivative of error $|de(t)|$. The ranges of these inputs are from 0 to 1, which are obtained from the absolute values of system error and its derivative through scale factors chosen from the specification of the nonlinear system. For each input variables, triangle membership functions (MFs) are requested to use. Because all of the MFs are triangle shapes, so we can express these MFs as follows:

$$f_{ji}(x) = \begin{cases} 1 + \frac{(x-a_{ji})}{b_{ji}^-} & \text{if } (-b_{ji}^-) \le (x - a_{ji}) \le 0 \\ 1 - \frac{(x-a_{ji})}{b_{ji}^+} & \text{if } 0 \le (x - a_{ji}) \le (b_{ji}^+), \quad j = 1, 2, \ldots, N \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where x is the input; the a_{ji}, b_{ji}^- and b_{ji}^+ are the centroid, left half-width, and right half-width of the jth triangle membership function of the ith input, respectively. N is the numbers of triangles.

Each of the fuzzy P, I and D controllers has one output which is U_p, U_i and U_d, respectively. In practice, fuzzy control is applied using local inferences. That means each rule is inferred and the results of the inferences of individual rules are then aggregated. The most common inference methods are: the max-min method, the max-product method and the sum-product method, where the aggregation operator is denoted by either max or sum, and the fuzzy implication operator is denoted by either min or prod. Especially the max–min calculus of fuzzy relations offers a computationally nice and expressive setting for constraint propagation. Finally, a defuzzification method is needed to obtain a crisp output from the aggregated fuzzy result. Popular defuzzification methods include maximum matching and centroid defuzzification. The centroid defuzzification is widely used for fuzzy control problems where a crisp output is needed, and maximum matching is often used for pattern matching problems where we need to know the output class. Hence in this study, the fuzzy reasoning results of outputs are gained by aggregation operation of fuzzy sets of inputs and designed fuzzy rules, where max-min aggregation method and centroid defuzzification method are used. In the proposed fuzzy controller, we can compute the control output U_p, U_i or U_d with a pair of inputs: