# Fuzzy Gain Scheduling of PID Controllers

Zhen-Yu Zhao, *Member, IEEE*, Masayoshi Tomizuka, *Member, IEEE*, and Satoru Isaka, *Member, IEEE*

***Abstract*—This paper describes the development of a fuzzy gain scheduling scheme of PID controllers for process control. Fuzzy rules and reasoning are utilized on-line to determine the controller parameters based on the error signal and its first difference. Simulation results demonstrate that better control performance can be achieved in comparison with Ziegler–Nichols controllers and Kitamori's PID controllers.**

## I. Introduction

THE BEST-KNOWN controllers used in industrial control processes are proportional-integral-derivative (PID) controllers because of their simple structure and robust performance in a wide range of operating conditions. The design of such a controller requires specification of three parameters: proportional gain, integral time constant, and derivative time constant. So far, great effort has been devoted to develop methods to reduce the time spent on optimizing the choice of controller parameters [8], [15]. The PID controllers in the literature can be divided into two main categories. In the first category, the controller parameters are fixed during control after they have been tuned or chosen in a certain optimal way. The Ziegler–Nichols tuning formula is perhaps the most well-known tuning method [5], [19]. Some other methods exist for the PID tuning (see e.g., [1], [6], [7]). The PID controllers of this category are simple, but cannot always effectively control systems with changing parameters, and may need frequent on-line retuning. The controllers of the second category have a structure similar to PID controllers, but their parameters are adapted on-line based on parameter estimation, which requires certain knowledge of the process, e.g., the structure of the plant model [2], [17]. Such controllers are called adaptive PID controllers in order to differentiate them from those of the first category.

The application of knowledge-based systems in process control is growing, especially in the field of fuzzy control [9], [10], [12]–[14]. In fuzzy control, linguistic descriptions of human expertise in controlling a process are represented as fuzzy rules or relations. This knowledge base is used by an inference mechanism, in conjunction with some knowledge of the states of the process (say, of measured response variables) in order to determine control actions. Although they do not have an apparent structure of PID controllers, fuzzy logic controllers may be considered nonlinear PID controllers whose parameters can be determined on-line based on the error signal and their time derivative or difference.

In this paper, a rule-based scheme for gain scheduling of PID controllers is proposed for process control. The new scheme utilizes fuzzy rules and reasoning to determine the controller parameters, and the PID controller generates the control signal. It is demonstrated in this paper that human expertise on PID gain scheduling can be represented in fuzzy rules. Furthermore, better control performance can be expected in the proposed method than that of the PID controllers with fixed parameters.

## II. PID Controller

The transfer function of a PID controller has the following form:

$$G_c(s) = K_p + K_i/s + K_d s \tag{1}$$

where $K_p$, $K_i$, and $K_d$ are the proportional, integral, and derivative gains, respectively. Another useful equivalent form of the PID controller is

$$G_c(s) = K_p(1 + 1/(T_i s) + T_d s) \tag{2}$$

where $T_i = K_p/K_i$ and $T_d = K_d/K_p$. $T_i$ and $T_d$ are known as the integral and derivative time constants, respectively.

The discrete-time equivalent expression for PID control used in this paper is given as

$$u(k) = K_p e(k) + K_i T_s \sum_{i=1}^{n} e(i) + \frac{K_d}{T_s} \Delta e(k).$$

Here, $u(k)$ is the control signal, $e(k)$ is the error between the reference and the process output, $T_s$ is the sampling period for the controller, and $\Delta e(k) \triangleq e(k) - e(k-1)$.

The parameters of the PID controller $K_p$, $K_i$, and $K_d$ or $K_p$, $T_i$, and $T_d$ can be manipulated to produce various response curves from a given process. Finding optimum adjustments of a controller for a given process is not trivial. In the following section, an on-line gain scheduling scheme of the PID controller based on fuzzy rules is introduced.

## III. Fuzzy Gain Scheduling

Fig. 1 shows the PID control system with a fuzzy gain scheduler. The approach taken here is to exploit fuzzy rules and reasoning to generate controller parameters.

It is assumed that $K_p$, $K_d$ are in prescribed ranges $[K_{p,\min}, K_{p,\max}]$ and $[K_{d,\min}, K_{p,\max}]$, respectively. The ap-

Manuscript received April 10, 1992; revised October 3, 1992.
Z.-Y. Zhao was with the Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA 94720, and is currently with Omron Advanced Systems, Inc., in Santa Clara, CA.
M. Tomizuka is with the Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA 94720.
S. Isaka is with Omron Advanced Systems, Inc., Santa Clara, CA 95054.
IEEE Log Number 9209681.