FUZZY PID CONTROLLER FOR THERMO-OPTICAL PLANT

J. Paulusová, L. Körösi

Institute of Robotics and Cybernetics,

Slovak University of Technology, Faculty of Electrical Engineering and Information Technology

Abstract

In this paper method of design of self-tuning fuzzy PID controller is addressed, proposed and tested. Fuzzy logic is used to tune each parameter of PID controller. The proposed controller is tested in control of the thermo-optical plant. This paper deals with theoretical and practical methodology, offering approaches for control design and its successful application.

1 Introduction

The PID algorithm is both simple and reliable, has been applied to thousands of control loops in various industrial applications over the past 60 years. However, not all industrial processes can be controlled using conventional PID algorithms.

Recently, expansion of modern methods of control can be observed, having undoubted advantages compared to classic conventional methods. Fuzzy rule-based systems are trying to emulate human style of verbalization, which is characterized by specific inaccuracy in verbal formulation of an individual logical statement. Knowledge base of a fuzzy system is set-up by experts' knowledge, formulated in the form of IF – THEN decision making rules, which are close to human style of verbalization of dependencies. Utilizing these rules it is possible to model systems relatively simply, where mathematical model is too complicated, not completely known or includes large vagueness. Such a model can be applied anywhere, where it is impossible to implement mathematical description of controlled system, eventually mathematical description is too complex and useless for the control purposes.

Design of self-tuning fuzzy PID controller (FPID) is presented in this paper. Control of the thermo-optical plant by using FPID overcomes the appearance of nonlinearities and uncertainties in the systems. FPID is the combination of a classical PID and fuzzy controller [3].

Firstly, theory of design of FPID is described. Then an application example is presented. The last section offers the conclusions.

2 Fuzzy PID Controller

PID control is the most common form of feedback control. It was an essential element of early governors and it became the standard tool when process control emerged in the 1940s. In process control today, more than 95% of the control loops are of PID type, most loops are actually PI control. PID controllers can these days be found in all areas where control is used, see [2].

The control algorithm for the PID controller is

$$u(t) = Pe(t) + I\int_0^t e(\tau)d\tau + D\frac{de(t)}{dt} \tag{1}$$

where $u(t)$ is the input signal to the plant model, the error signal $e(t)$ is defined as $e(t)=w(t)-y(t)$, $w(t)$ is the reference input signal, $y(t)$ is output signal, t is time or instantaneous time (the present) and τ is variable of integration; takes on values from time 0 to the present t. The control signal u from the controller to the system is equal to the proportional gain P times the magnitude of the error plus the integral gain I times the integral of the error plus the derivative gain D times the derivative error.

PID controlled system is shown in Fig. 1, see [5].

Transfer function of the most basic form of PID controller is

$$G_R(s) = \frac{U(s)}{E(s)} = P + \frac{I}{s} + Ds \tag{2}$$

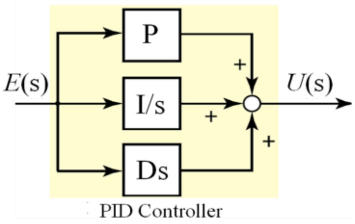


Figure 1: PID Controlled System

The structure of fuzzy controller is shown in Fig. 2 [4].

A good selection of input and output variables of fuzzy system is a fundamental prerequisite of its proper function. For design of fuzzy P, PI, PD, PID or state-space controllers, input or output variables used in fuzzy control rules are predetermined.

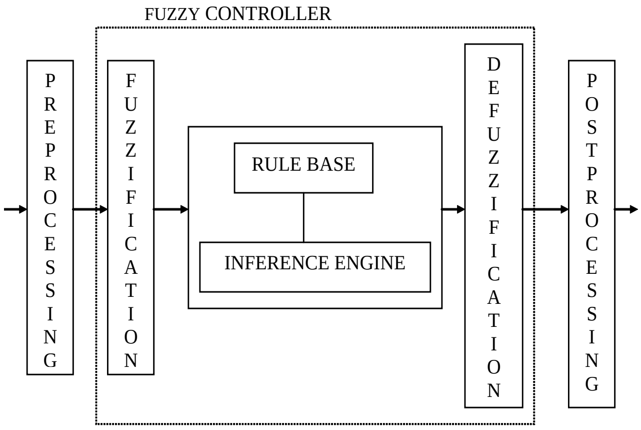


Figure 2: Block scheme of a fuzzy controller

However, fuzzy controllers are very often designed to control systems, which were up till now controlled only by human operators, by means of rules formulated by them. Similar are modelled systems, behaviour of whose it is possible to describe only in form of experts statements. In cases like this, first analysis of these linguistic rules is needed and designation, which of those variables carries relevant information with it.

Fuzzy controller is basically a simple computing unit, which needs relatively small amount of arithmetical operations. Problems can be defuzzification (enumeration of integral), but this is often substituted by simple and fast summation. Eventually simple computing inference mechanism can be used [1]. FPID controller means that the three parameters *P*, *I*, *D* of PID controller are automatically tuned by using fuzzy tuner, see Fig. 3.

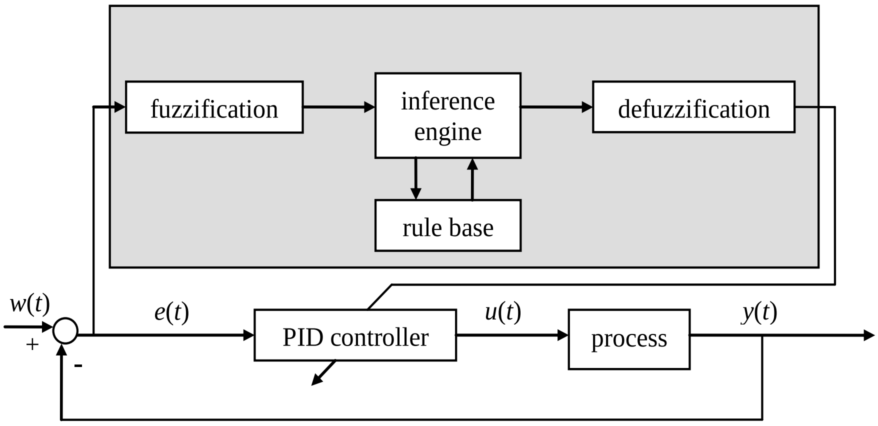


Figure 3: Structure of FPID

Since the proposed controller uses a nonlinear fuzzification algorithm and output membership functions, the controller can be considered as a nonlinear PID where parameters are tuned on-line based on error $e(t)$ and change of error $\Delta e(t)$ compared to set-point $w(t)$ [1].

The rules designed are based on the characteristic of the process and properties of the PID controller. Therefore, the fuzzy reasoning of fuzzy sets of outputs is gained by aggregation operation of fuzzy sets inputs and the designed fuzzy rules. The aggregation and defuzzification methods, respectively max-min and centroid method are used. Regarding the fuzzy structure, there are two inputs to fuzzy inference: error $e(t)$ and derivative of error $\Delta e(t)$, and three outputs for each PID controller parameters respectively P', I' and D'. Mamdani model is applied as structure of fuzzy inference with some modification to obtain the best value for P, I and D. Fuzzy inference block of the controller design is shown in Fig. 4, see [9].

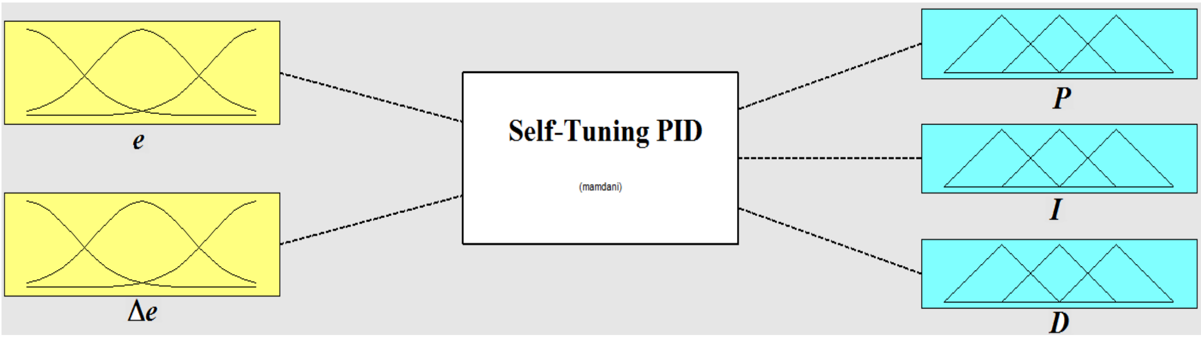


Figure 4: Fuzzy inference block

Suppose the variable ranges of the parameters P, I and D of PID controller are $<P_{min}, P_{max}>$, $<I_{min}, I_{max}>$, and $<D_{min}, D_{max}>$ respectively. The range of each parameter was determined based on the simulation of PID controller (and also practical experiments) to obtain a feasible rule bases with high inference efficiency. Therefore, they can be calibrated over the interval <0, 1> as follows:

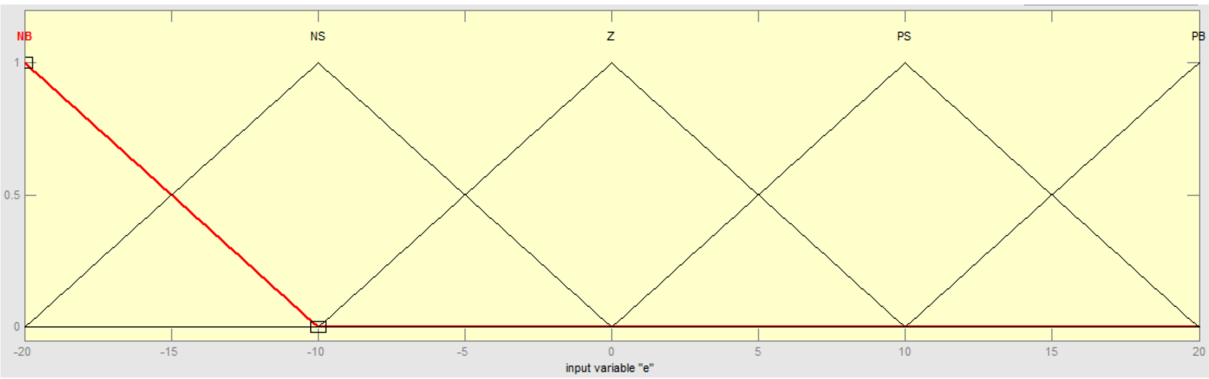
$$
\begin{aligned}
P' &= \frac{P - P_{min}}{P_{max} - P_{min}} \\
I' &= \frac{I - I_{min}}{I_{max} - I_{min}} \\
D' &= \frac{D - D_{min}}{D_{max} - D_{min}}
\end{aligned}
\tag{3}
$$

The membership functions of these inputs fuzzy sets are shown in Fig. 5. The linguistic variable levels are assigned as NB - negative big, NS - negative small, ZE - zero, PS - positive small, PB - positive big. These levels are chosen from the characteristics and specification of the process (the chemical reactor, see case study). The membership functions of outputs P', I' and D', are shown in Fig. 6. The linguistic levels of these outputs are assigned as S - small, MS - medium small, M - medium, MB - medium big, B - big, where the ranges <0, 1>.

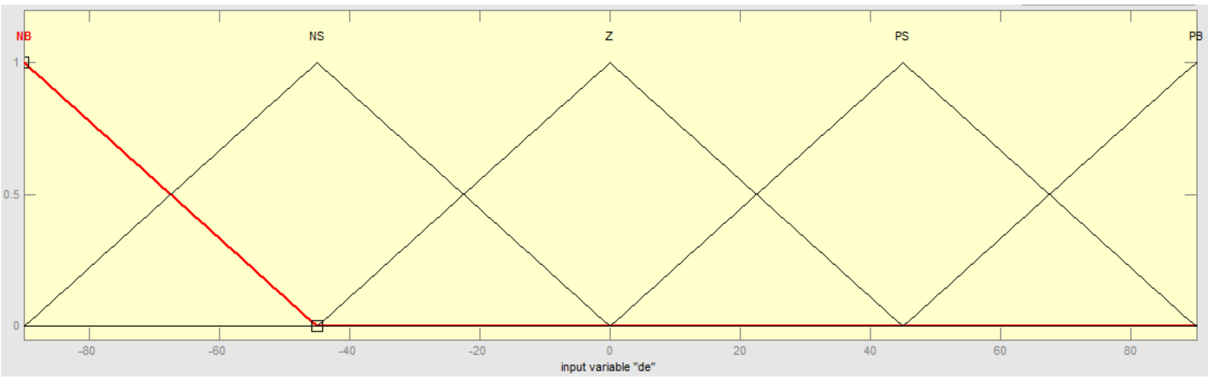
Generally, the fuzzy rules are dependent on the controlled plant and the type of the controller and from practical experience. Regarding the above fuzzy sets of the inputs and outputs variables, the fuzzy rules are performed in rules table, see Table 1 and i-th rule is composed as follows:

$$IF\ e(t)\ is\ A_{1i}\ and\ \Delta e(t)\ is\ A_{2i}\ THEN\ P' = B_i\ and\ I' = C_i\ and\ D' = D_i \tag{4}$$

A_{1i}, A_{2i}, B_i, C_i, and D_i are linguistic values determined by fuzzy sets on the universe of input and output variables.



a)



b)

Figure 5: Membership functions of $e(t)$ (a) and $\Delta e(t)$ (b)

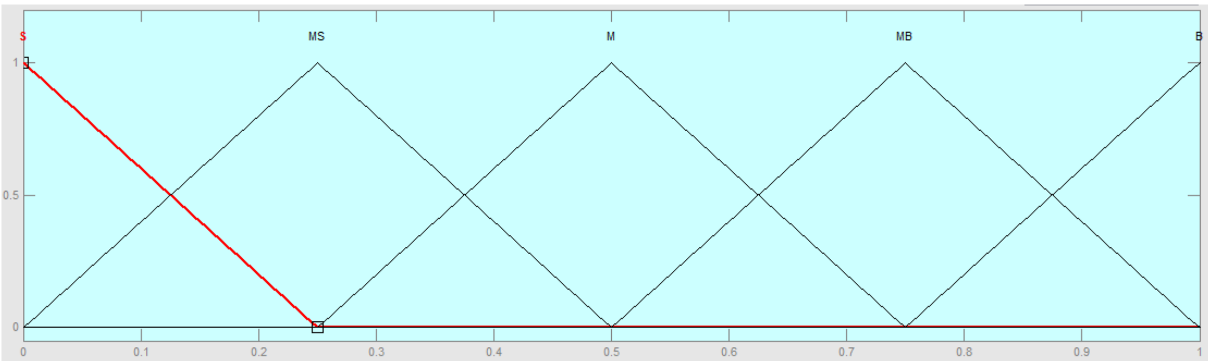


Figure 6: Membership functions of *P*', *I*', *D*'

Table 1: RULES OF THE FUZZY INFERENCE

$\Delta e/e$	*NB*	*NS*	*ZE*	*PS*	*PB*
NB	*S*	*S*	*MS*	*MS*	*M*
NS	*S*	*MS*	*MS*	*MS*	*MB*
ZE	*MS*	*MS*	*MS*	*MB*	*MB*
PS	*MS*	*MS*	*MB*	*MB*	*B*
PB	*MS*	*MB*	*MB*	*B*	*B*

3 Case Study and Simulation Results

The thermo-optical plant is a simple laboratory physical model of the thermodynamical and optical system called DIGICON USB thermo-optical plant (Fig. 7). Its thermal channel consists of one heater represented by an electric bulb and one cooler represented by a small fan [7]. The output of this channel is the temperature inside the tube. Measurement of the output value is performed by a thermal sensor. The second dynamics is represented by the optical channel. Within this it is possible to generate the light by LED and measure the intensity of the light by the photoresistor. The optical channel is even more comfortable for conducting experiments because the time constants are much smaller compared to the thermal channel. The base of the model covers also the electronic part. This part includes one connector for input (voltage) and two others connectors for data communication. One of these is used for communication with the data acquisition card AD512 and another one is the USB port that can be connected directly to the computer (instead of using an expensive data acquisition card). The front panel of the base has five information LEDs. The body of the electronic part is equipped by integrated circuits for communication and signal conversion [7].

From the I/O characteristic, the working point WP=(3.33;20) was chosen, where the step response was measured. The thermo-optical plant is aperiodic process, so time constants T with transport delay Td can be determined from its step response, see (Vítečková et al., 2000).

The equations are:

$$\left.\begin{aligned} T &= 1.245\left(t_{0.7} - t_{0.33}\right) \\ T_d &= 1.498 t_{0.33} - 0.498 t_{0.7} \end{aligned}\right\} \Rightarrow G(s) = \frac{K}{Ts+1} e^{-T_d s} \qquad (5)$$

where times $t_{0.33}$ and $t_{0.7}$ are obtained from the step response, see Fig. 9.

Figure 7: Thermo-optical plant

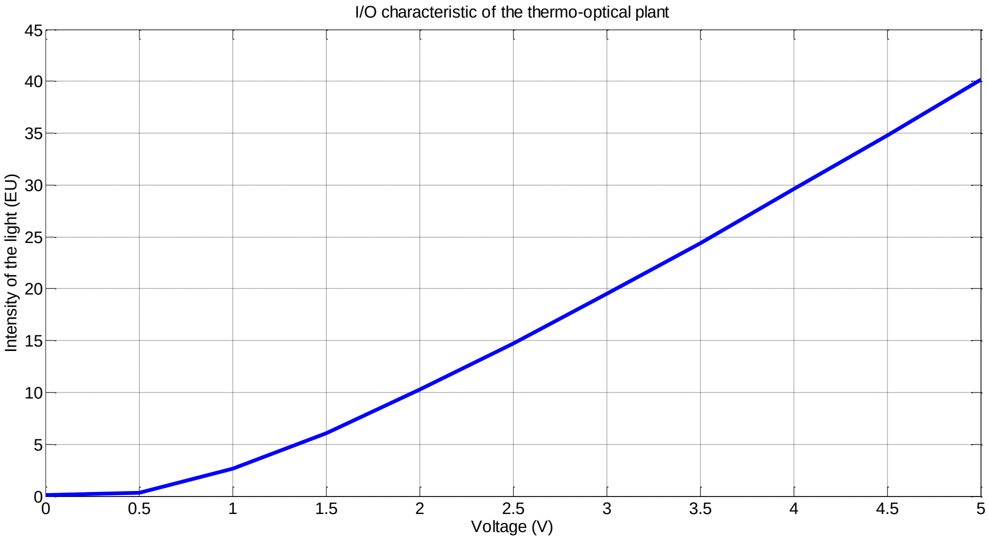


Figure 8: I/O characteristic of the thermo-optical plant

The working point WP_1=(3.5, 24.2) has been chosen. The experiment has been done – step (in time 15 sec.) from WP_2=(3, 19.4) into WP_1 and step response has been done. Then from Fig. 8 transfer function (8) has been calculated. The coefficient of transfer function K is given by (6) from Fig. 8. If the input step isn't unit step, K is given by (7), where Δy and Δu are the values of steady state output variable and input variable, respectively [8].

$$K = h_s(\infty) \tag{6}$$

$$K = \frac{\Delta y}{\Delta u} \tag{7}$$

Transfer function calculated from the process step response is:

$$G(s) = \frac{6.93}{0.0996s + 1} e^{-0.1102s} \tag{8}$$

The measured plant step response and its approximation (8) are shown in Fig. 9.

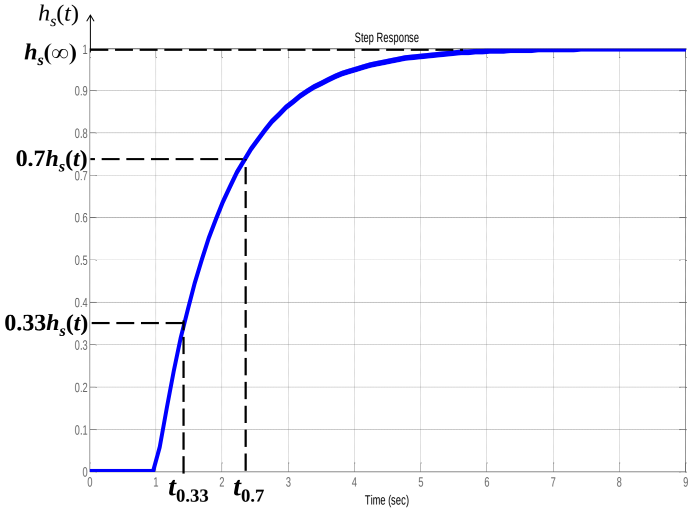


Figure 8: Aperiodic step response

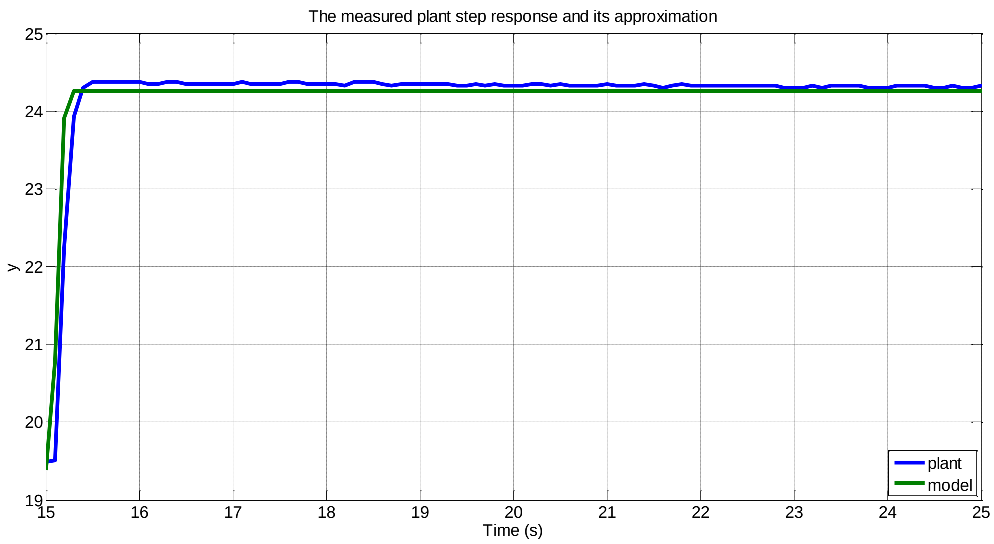


Figure 9: The measured plant step response and its approximation (8)

PI controllers were designed for transfer functions (8) by optimum magnitude method (OM) and Naslin method (NM). Transfer functions of controllers are

$$\begin{aligned} G_{R_{OM}}(s) &= 0.0765 + \frac{0.7098}{s} \\ G_{R_{NM}}(s) &= 0.0109 + \frac{0.3316}{s} \end{aligned} \tag{9}$$

Time responses of the reference and output variables with designed PI controllers are shown in Fig. 10.

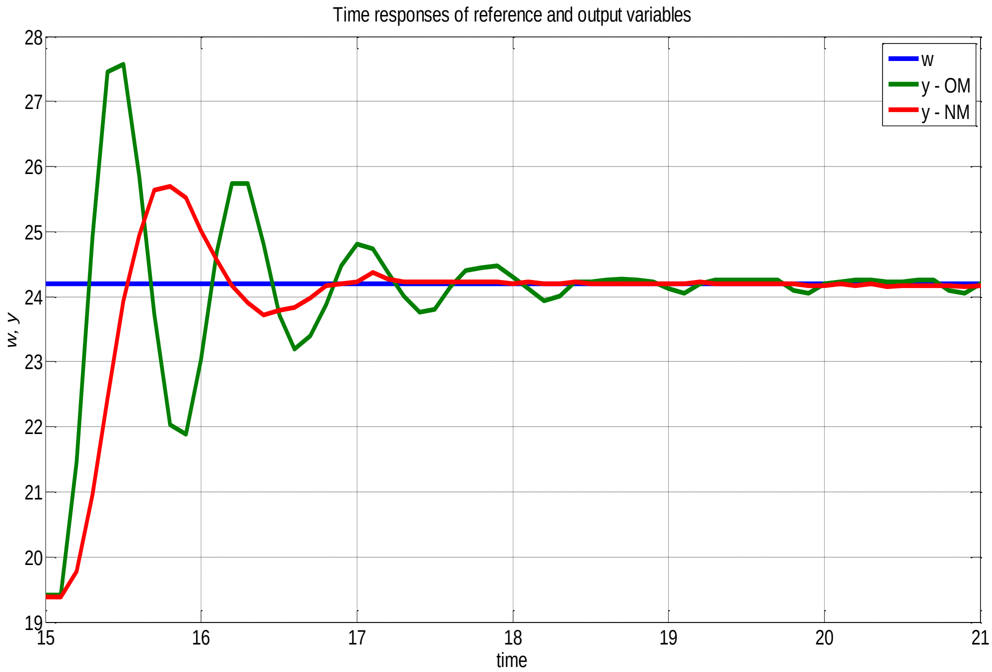


Figure 10: Comparison of PI controllers

FPID consists of fuzzy and PID block with some modifications refers to the formula, which is applied to calibrate the value of *P'*, *I'*, *D'* from fuzzy block to obtain of *P*, *I*, and *D*. Each parameter has its own calibration. Suppose the variable ranges of the parameters *P*, *I* and *D* of PID controller are respectively $P \in \langle 0.01; 0.08 \rangle$, $I \in \langle 0.31; 0.71 \rangle$, $D \in \langle 0; 0.01 \rangle$.

Time responses of the parameters: *P*, *I* and *D* are shown in Fig. 11.

FPID is compared with the conventional PI controllers, see Fig. 12.

The self-tuning fuzzy PID controller achieves better tracking response than conventional PI controller. It is indicated by faster rise time, faster settling time, less overshoot and zero steady state error.

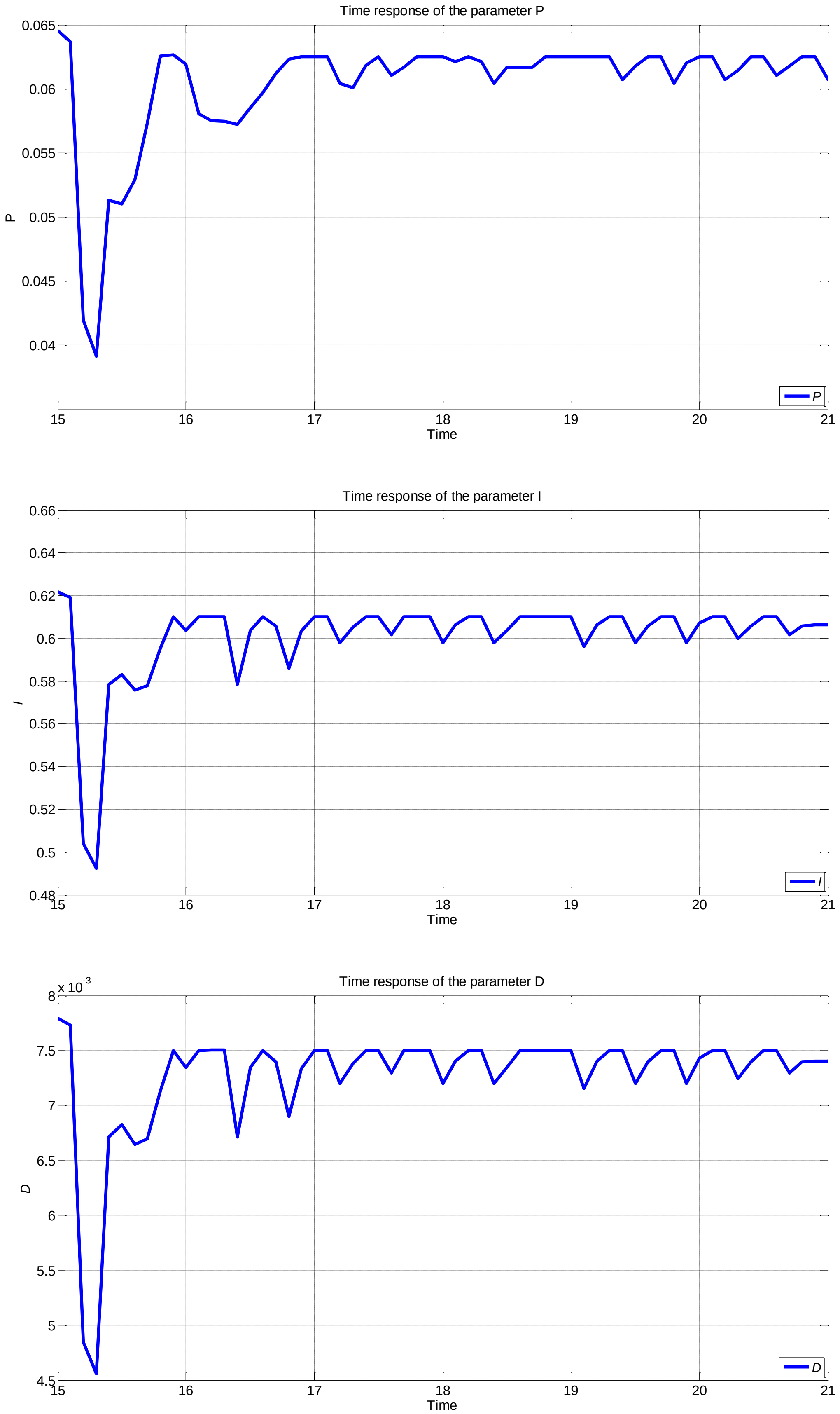


Figure 11: Time responses of the parameters *P*, *I* and *D*

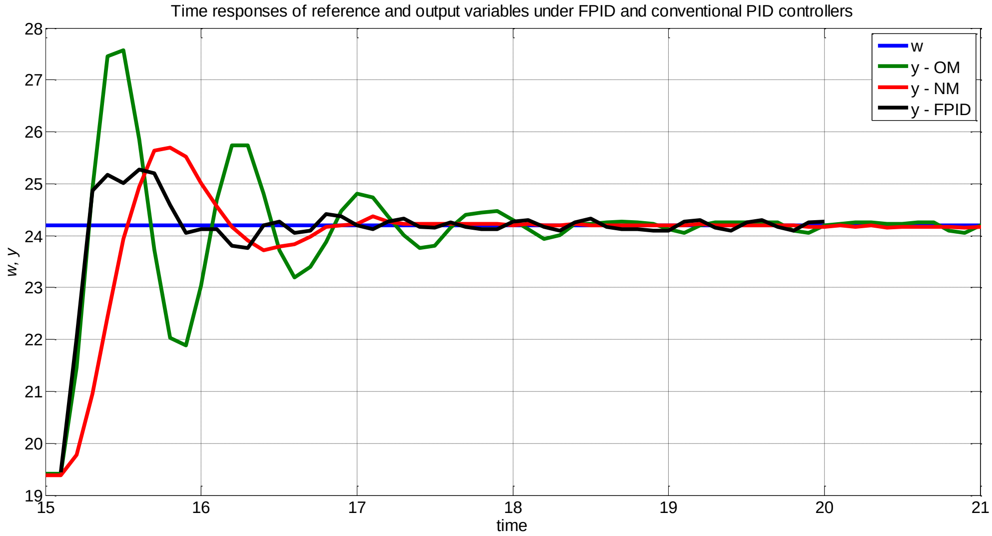


Figure 12: Comparison of FPID with conventional PID controllers

4 Conclusions

Self-tuning fuzzy controller (FPID) was applied to tune the value of the parameters (*P*, *I* and *D*) of the PID controller. FPID controller has been applied to the concentration control in the chemical reactor by manipulating its flow rate. FPID controller was compared with a conventional PI controller. It is obvious, that the FPID controller is faster than the PI controller.

In our future research we are dealing with different similar methods and we would like to compare them with the algorithm which is described in this paper.

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Jana Paulusová and Ladislav Körösi

Institute of Robotics and Cybernetics,
Faculty of Electrical Engineering and Information Technology,
Slovak University of Technology,
Ilkovičova 3,
812 19 Bratislava, Slovak Republic
e-mail: jana.paulusova@stuba.sk, ladislav.korosi@stuba.sk