Real Time Fuzzy PID Controller Structures

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Abstract: The following paper presents approaches to the design of three fuzzy logic controller (FLC) structures based on a proportional-integral-derivative (PID) control law. By combining of an incremental fuzzy PI structure and a fuzzy PD structure, a fuzzy PID control strategy can be implemented from two input variables. The second in the paper presented structure is based on simplification of the incremental fuzzy PI structure. The third structure has proportional, integral and derivative separate parts with separate rule bases. All three structures are implemented as real-time controllers and assessed on a simple magnetic suspension system.

Key-Words: Fuzzy logic control, fuzzy PID control, real-time control, magnetic suspension system

1 Introduction

Fuzzy control technique has been widely used in industrial processes, particularly in situations where conventional control design techniques are difficult to apply. The main advantage of the fuzzy logic controller (FLC) is that it can be applied to plants that are difficult to obtain the mathematical model, and the controller can be designed to apply heuristic rules that reflect experiences of the human experts. Recently, fuzzy-logic and conventional control design methods are combined to design proportional-integral-derivative fuzzy logic controller (PID-FLC), such as [1], [2], [3], [4].

This paper presents the structure and advantages of the decomposed PID-FLC as an alternative to the fuzzy logic - PID complete design, which require three inputs, that will substantially expand the rule-base and make the design more difficulty. The decomposed PID-FLC, as we proposed in [5], is based on the fuzzy inference break-up method and the simplification of the decomposed inference. In [6] the simple decomposed PID-FLC has been compared with discrete PID controller. The main question is, if the simplification of the PID-FLC structure do as a good job as the non-simplified PID-FLC form. In this paper, the simple decomposed PID-FLC is tested and compared with two types of the PID-FLCs. All PID-FLCs are realised by the same hardware and software tools and applied to a simple magnetic suspension system. Experimental results for setpoint changes, load disturbances, robustness and performance analysis of different configurations are presented.

In the next section the structure of the decomposed PID-FLC is presented. In section 3 the fuzzy PI + fuzzy PD control structure and the fuzzy PD + fuzzy I control structure, as alternative to decomposed PID-FLC, are shown. In section 4 magnetic suspension system as an experimental process, is described and control experiments and performance comparisons are evaluated. Finally some conclusions are given in the last section.

2 Decomposed PID-FLC

The basic idea of the discrete PID-controller is to choose the control law by considering error $e(k)$, change-of-error $de(k) := (e(k) - e(k\text{-}1))/T$ and the numerically approximated integral of error $ie(k) := ie(k\text{-}1) + Te(k\text{-}1)$. The PID control law is

$$u_{PID}(k) = K_P \cdot e(k) + K_D \cdot de(k) + K_I \cdot ie(k) \quad (1)$$

where K_P is a proportional constant, $K_D = T_D/T$ is a differential constant and $K_I = T/T_I$ is an integral constant. For a linear process the control parameters K_P, K_D and K_I are designed in such a way that the closed-loop control is stable. In the case of non-linear processes which can be linearised around the operating point, conventional PID-controllers also work successfully. However, the PID-controller with constant parameters in the whole working area is robust but not optimal. In this case, tuning of the PID-parameters is performed.

The output of the general fuzzy controller $u(kT)$ is given by

$$u(kT) = \mathcal{U}\big(e(kT), de(kT), ie(kT)\big), \tag{2}$$

where $\mathcal{U}(\cdot)$ is a non-linear function determined by fuzzy parameters.

In the case when we assume the structure of fuzzy PID controller with three input variables (error $e(k)$, change-of-error $de(k)$ and integral of error $ie(k)$) and one output variable with m base fuzzy sets on each fuzzy variable, we get one rule base with maximum m^3 rules. The control algorithm of the general fuzzy PID controller is given by

$$u(kT) = defuzz\{R \circ fuzz(e(k)) \circ fuzz(de(k)) \circ fuzz(ie(k))\}, \tag{3}$$

where $fuzz(\cdot)$ is the fuzzification operator, $defuzz(\cdot)$ is the defuzzification operator, $\circ$ is the composition operator of fuzzy relations and R is the fuzzy relation of the fuzzy controller rule-base. Because of the multidimensionality of the fuzzy relation R, the composition rule of inference (3) is difficult to perform. To overcome this difficulty and to minimize the number of rules the simplification of the fuzzy PID structure is proposed in [5]. The basic idea is to decompose of multivariable control rule base into three sets of one dimensional rule bases for each input. The output of the decomposed fuzzy controller $u(kT)$ is given by

$$u(kT) = defuzz\{R_E \circ fuzz(e(kT)) \wedge R_{DE} \circ fuzz(de(kT)) \wedge R_{IE} \circ fuzz(ie(kT))\}, \tag{4}$$

where R_E, R_{DE} and R_{IE} are fuzzy relations of separate rule-bases and $\wedge$ is the fuzzy intersection operator. The main advantage of the decomposition and simplification is reduction of linguistic rules. In the case when we assume the structure of decomposed fuzzy PID controller with three input variables and one output variable with m base fuzzy sets on each fuzzy variable, we get three rule bases with maximum m rules in each rule base.

To simplify the realisation of the decomposed fuzzy controller (4) a decomposition of entire fuzzy system inclusively the deffuzification procedure is proposed. An incremental form of the integral part is realised. Outputs of separate parts of the decomposed PID-FLC are given by

$$\begin{aligned} u_P(k) &= defuzz\big(R_E \circ fuzz(e(k))\big) \\ u_D(k) &= defuzz\big(R_{DE} \circ fuzz(de(k))\big) \\ u_I(k) &= u_I(k-1) + T \cdot defuzz\big(R_{IE} \circ fuzz(e(k))\big) \end{aligned} \tag{5}$$

and the fuzzy intersection operator is substituted with sum of defuzzified outputs. The new output of the fuzzy controller $u(kT)$ is given by

$$u(k) = u_P(k) + u_D(k) + u_I(k) \tag{6}$$

and the structure is shown in Figure 1.

K_e, K_{de}, Ku_P, Ku_D and Ku_I are scaling factors.

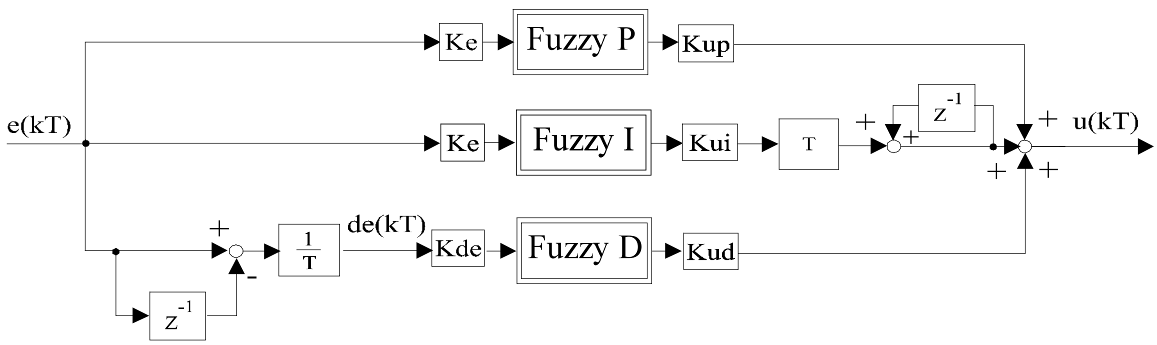


Fig. 1: The structure of the decomposed PID-FLC realised with equation (6).

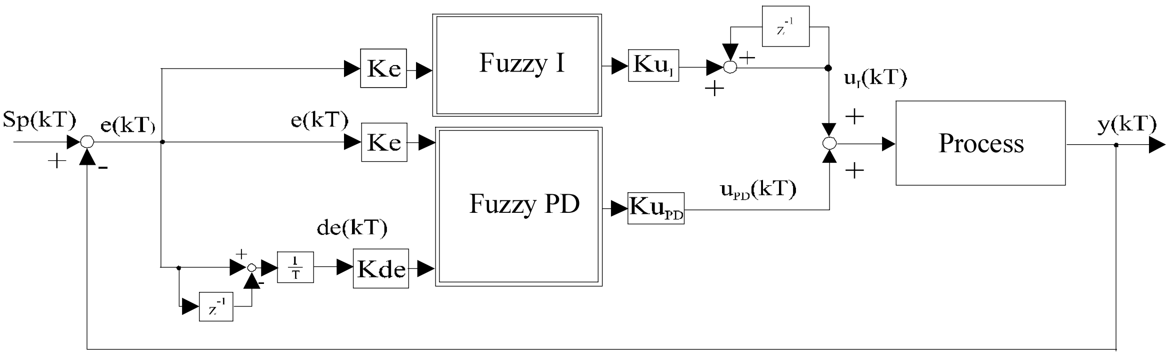
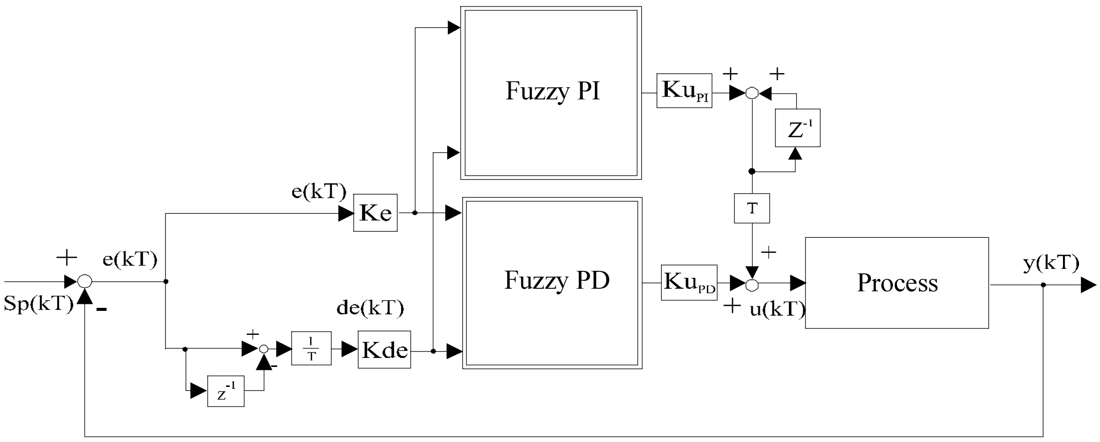


Fig. 2: Control system with PD+I – FLC



Fig, 3: Control system with PD+PI-FLC

3 Alternative PID Fuzzy Controller Structures

The usual FLC structure is the PD-FLC or PI-FLC. The PI-like FLC adds damping to a system and reduces steady-state error, but yields penalized rise time and settling time. The PD-like FLC adds damping and reliably predicts large overshoots, but does not improve the steady-state response. In order to meet the design criteria of zero steady-state error, overshoot and rise time, PID control should be used. In some previous literature [2], [4] hybrid fuzzy PID controllers have been proposed.

3.1 PD Fuzzy + I Fuzzy Controller

The PD+I FLC was proposed by Ng and Li [7]. The control law of the PD+I - FLC is constructed by sum of the fuzzy PD action and the fuzzy integral action. The structure of the simple control system with PD+I-FLC is shown in figure 2.

The characteristic of the PD+I – FLC is a combination of a two-dimensional rule base for the PD control and an one-dimensional rule base for the incremental integral control.

3.2 PD Fuzzy +PI Fuzzy Controller

The PD+PI-FLC is presented by Kwok [8] and it is consist of a PD-FLC in parallel with a PI-FLC. The basic control diagram is shown in Figure 3. The characteristic of the PD+PI – FLC is a combination of a two-dimensional rule base for the PD control and a two-dimensional rule base for the PI control.

4 Real-Time Experiments

The real-time application of the fuzzy control for the simple magnetic suspension system (steel ball in a magnetic field) is realised. The magnetic suspension system including an electromagnet, a current amplifier, and a optical position measurement system is inherently nonlinear and unstable. Our fuzzy logic controller based on the personal computer (PC) is extended by the OMRON FB-30AT fuzzy board (with the fuzzy processor FP 3000). An eight channels analog to digital (A/D) converter and two channels digital to analog (D/A) converter with 12 bit resolution is realised on the plug-in PC board. The first cannel of the A/D converter is used to measure input of the control system, namely: ball position which is output of the optical position measurement system. The fuzzy controller software was implemented in ANSI-C. The real-time sampling frequency of 1 kHz was attained. The realisation of the model is presented on Figure 4.

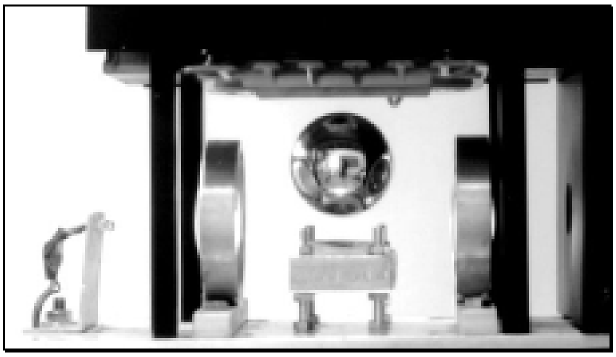


Figure 4: The realisation of the model.

The basic principle of our electromagnetic suspension system with mathematical model and nominal parameters are described in [9].
All fuzzy inputs are divided into three base membership functions: negative (N), zero (Z) and positive (P). Trapezoid and triangular membership functions with 50% overlap are applied to the error fuzzy input E and the derivative of error fuzzy input DE of the fuzzy controller.

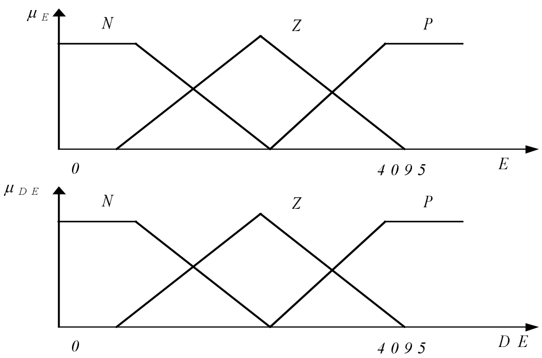


Fig. 5: Input membership functions

The output of the controller is the output voltage (ranges of 0 to 10V) from the D/A converter. Singleton memberships functions are applied to fuzzy outputs. Singleton output membership functions are shown on figure 6

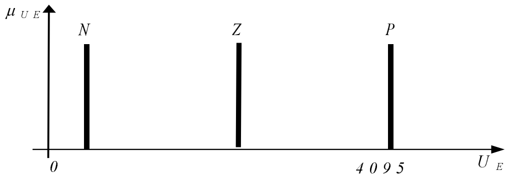


Fig. 6: Output membership functions

The inference is performed using the minimum operator and the composition is done using the maximum operator (Mamdani type of the inference engine). The centre of Gravity defuzzification method is implemented.
The knowledge base of the decomposed PID-FLC realised with equation (6) is composed by three inference rule bases: the proportional rule base, the differential rule base and the integral rule base. Three rules of the rule base for the proportional part of the fuzzy controller are described in table 1.

Table 2: The rule base of the proportional part of the fuzzy PID controller.

E	*N*	*Z*	*P*
U_P	*N*	*Z*	*P*

The differential part and the integral part of the fuzzy logic controller are realised with the same type of one-term rules. However, the knowledge base of the decomposed fuzzy controller is defined by nine rules.
The knowledge base of the PD+I FLC shown on figure 2 is composed by two inference rule bases: the two-dimensional proportional-differential rule base and the one-dimensional integral rule base. In this case, the controllers knowledge base is defined by twelve rules ($3^2 + 3^1$). Nine two-term rules of the two-dimensional rule base are described in table 2.

Table 2: The two-dimensional rule base

		E		
	U_{PD}	*N*	*Z*	*P*
DE	*N*	*N*	*N*	*Z*
	Z	*N*	*Z*	*P*
	P	*Z*	*P*	*P*

According to the structure presented on figure 3, the knowledge base of the PD+PI-FLC consist of two two-dimensional inference rule bases: the proportional-differential rule base and the proportional-integral rule base.
In the case, the PD rule base and the PI rule base contain different rules, the controller knowledge base is defined by eighteen rules ($3^2 + 3^2$). Obviously, so long as we take the unified quantization method and the appropriate scaling factors, both PI and PD control rules can be realised through unified fuzzy control rule base. It means that a knowledge base can be implemented by using one rule base with nine two-dimensional rules. The advantage of this approach is in simplifying the control rule base significantly. On the other hand, the disadvantage of this approach is that the

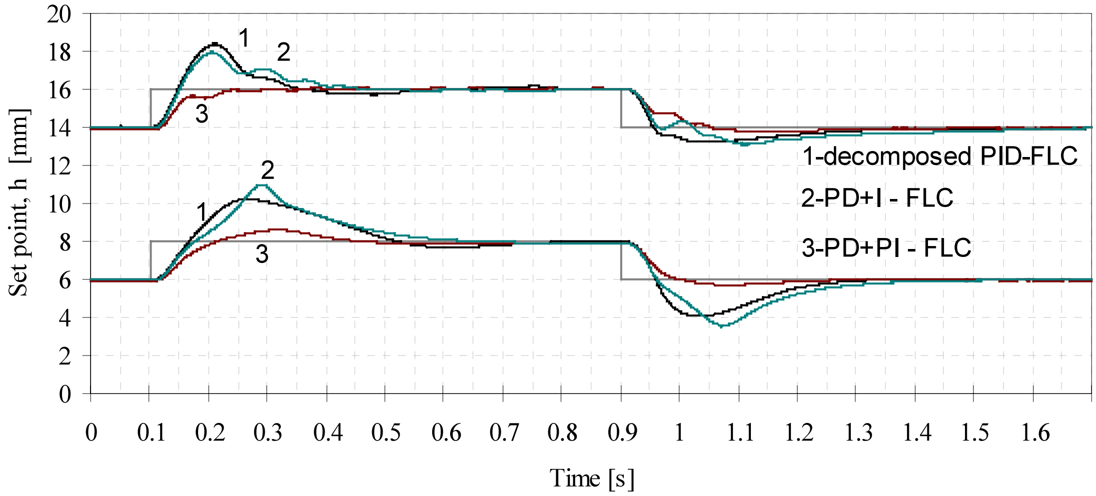


Fig. 7: Comparison of Time Responses Under Step Set-Point Changes

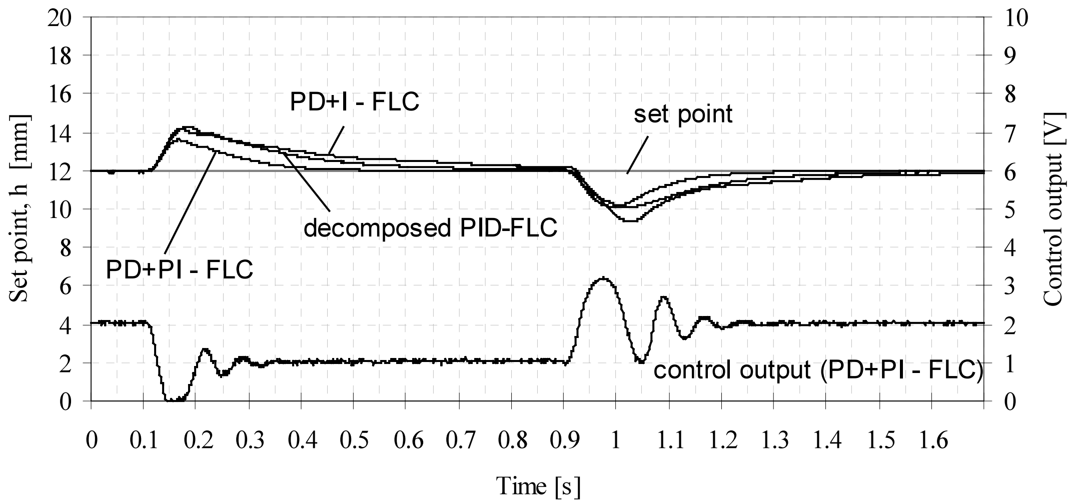


Fig. 8: Comparison of Time Responses Under Load Disturbances

controller parameters are coupled with each other and have to be regulated in combination.
The real-time implementation of the control for the magnetic suspension system allowed to perform several interesting experiments where the fuzzy controller proved to be very efficient. Two types of real time experiments have been done: experiments for set-point changes and experiment for load disturbances.

4.1 Comparison of Time Responses Under Step Set-Point Changes

In order to compare the effectiveness of all three fuzzy PID controllers we test time responses for the control at the same set-point changes. The optimisation of scaling factors for the set-point h=12 mm was done.
Figure 7 shows a comparison of the step responses of all three fuzzy PID structures in two regions (14 and 6 mm), where process dynamic performances are different. Experiment contains set point changes in positive (14-16 mm) and negative (16-14) direction. Both curves, signed with no. 1 in Figure 7 represents step responses of the magnetic suspension system yielded by the decomposed PID-FLC. It is evident that the overshoot is big and the settling time is long at set-point changes in all regions. In order to reduces overshoot and settling time, we have been used PD+I – FLC. Curves, signed with no. 2 in Figure 7 shows that step responses are not obviously improved. On the other hand, the PD+PI – FLC yields step responses with a small overshot and short

settling time as is shown with curves no. 3 in Figure 7.

4.2 Comparison of Time Responses Under Load Disturbances

Figure 8, respectively, show the responses of all three fuzzy PID controller structures due to load disturbances applied at t=0.1 s and t=0.9 s. As a result, PD+PI – FLC shows the best regulation against step load variations. The PD+I – FLC and the decomposed PID – FLC are less efficient (the overshoot is bigger and the settling time is longer).

5 Conclusion

Three PID – FLC structures have been compared and tested as a real-time controller for a magnetic suspension system. The model of the magnetic suspension system has been realised by the simple electromagnet and the steel ball.

The PD+I - FLC is widening of the usual PD - FLC structure. The fuzzy integral part is set aside to improve the steady-state response. By introducing the combination of PD fuzzy controller and PI incremental fuzzy controller, the PID fuzzy control can be implemented with two separated two-term control rule bases. The main advantage of decomposed PID - FLC is its simplicity and reduction of linguistic rules. It is evident from test results that performances of all three PID controllers are able to stabilise the magnetic suspension system. A step response of the PD+PI - FLC is superior to step responses of PD+I – FLC and decomposed PID - FLC. This is due to the simplification of the multivariable structure of decomposed PID and the lack of a good mapping property of the multivariable knowledge base. A loss of accuracy must be accepted. It should be mentioned that results of the simple fuzzy controller have been obtained by the basic shape of membership functions. It could be expected that fine tuning of membership functions will result in better performance (smaller overshoot). Further research will be directed to the control of theoretic aspects of decomposed fuzzy PID control in vague environments like stability analysis or robustness.

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