ON PID CONTROLLER DESIGN USING KNOWLEDGE BASED FUZZY SYSTEM

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Abstract. *The designing of PID controllers is a frequently discussed problem. Many of the design methods have been developed, classic (analytical tuning methods, optimization methods etc.) or not so common fuzzy knowledge based methods. The aim of design methods is in designing of controllers to achieve good setpoint following, corresponding time response etc. In this case, the new way of designing PID controller parameters is created where the above mentioned knowledge system based on the relations of Ziegler-Nichols design methods is used, more precisely the combination of the both Ziegler-Nichols methods. The proof of efficiency of the proposed method and a numerical experiment is presented including a comparison with the conventional Ziegler-Nichols method.*

Keywords

Feedback control, fuzzy system, knowledge base, PID controller, Ziegler-Nichols design methods.

1. Introduction

As it is written in [1] two expert system approaches exist. The first one, the fuzzy rule base way for controlling processes for which suitable models do not exist or are inadequate. The rules substitute for conventional control algorithms. The second way originally suggested in [2] is to use an expert system to widen the amounts of classical control algorithms.

The system of designing a PID controller (its parameters) with a knowledge base is created which is built on know-how obtained from the Ziegler-Nichols designing methods, the combination of the frequency response and step response Ziegler-Nichols methods and its mutual conversion. The system created in this way is determined to design parameters of a classical PID controller, which is considered in closed feedback control.

2. Ziegler-Nichols Design Methods

These classical methods for the identification of the parameters of PID controllers were presented by Ziegler and Nichols in 1942. Both are based on determination of process dynamics. The parameters of the controller are expressed as a function by simple formulas [3].

The transfer function of the PID controller using these methods is expressed as:

$$G_R(s) = K\left(1 + \frac{1}{T_i s} + T_d s\right). \tag{1}$$

2.1. The Frequency Response Method

The first Ziegler-Nichols method is based on the frequency response of the system. The essence is to find the point – the ultimate point P_u on the Nyquist curve of the transfer function of the system, where the Nyquist curve intersects the real negative axis (Fig. 1). Frequency corresponding to the ultimate point is then f_{Pu}. This point is characterized by the parameters K_u and T_u – called the ultimate gain and the ultimate period. The ultimate gain K_u may be determined as:

$$K_u = -\frac{1}{P_u}, \tag{2}$$

the ultimate period as:

$$T_u = \frac{2\pi}{f_{P_u}}. \tag{3}$$

In the other way the parameters K_u and T_u can be obtained so that controller is connected to the system, parameters are set as $T_i = \infty$ and $T_d = 0$ (it means that the control action is proportional). The gain is then increased until the system starts to oscillate. The period of this oscillation is T_u and the gain when the oscillations appear is K_u.

Parameters of a PID controller from the Ziegler-Nichols frequency response method are expressed as

(Tab. 1).

Tab.1: PID controller parameters obtained from the Ziegler-Nichols frequency response method [3].

	K	T_i	T_d
PID	$0{,}6K_u$	$0{,}5T_u$	$0{,}125T_u$

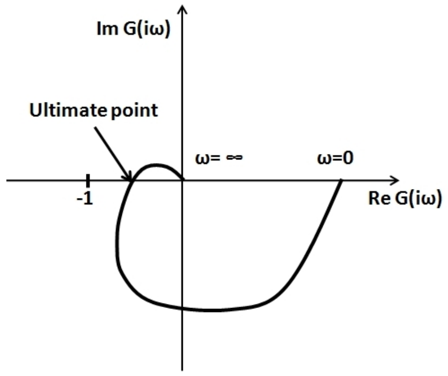

Fig. 1: The ultimate gain K_u, and the ultimate period T_u defined in the Nyquist diagram [4].

There are also some limitations using this method – the Nyquist curve may restrict the real axis only in one point [3].

2.2. The Step Response Method

The time domain method is based on a registration of the open-loop unit step response of the system. The parameters of a PID controller are directly given from the function of the parameter a, and dead time L which are obtained so that the tangent is drawn at the maximum of the slope of the unit step response (Fig. 2). The intersection of the tangent with axis y and the distance of this intersection and the beginning of the coordinate axis determine the parameter a. The dead time L is the distance of the intersection of the tangent with time axis (axis x) and also the beginning of the coordinate axis [3], [4]. The parameters of a PID controller from the Ziegler-Nichols step response method are expressed as (Tab. 2).

Tab.2: PID controller parameters obtained from the Ziegler-Nichols step response method [3].

	K	T_i	T_d
PID	$1{,}2/a$	$2L$	$L/2$

2.3. Used Mutual Conversion of Both Ziegler-Nichols Methods

To determine parameters of PID controller the relations of the frequency response method are used expressed as (Tab. 3).

Tab.3: PID controller parameters obtained from the Ziegler-Nichols frequency response method [3].

	K	T_i	T_d
PID	$0{,}6K_u$	$0{,}5T_u$	$0{,}125T_u$

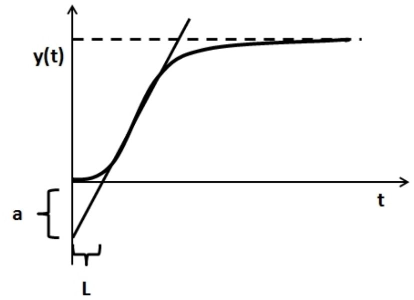

Fig. 2: Characterization of a unit step response in the Ziegler-Nichols step response method [3], [4].

But the ultimate gain K_u and the ultimate period T_u (whose importance is described above) are obtained from unit step response (Fig. 3) of the controlled system and one of the conversion is used by the dead time L and the delay time D. For understanding it is important to explain these two times L and D and how to obtain these constants from unit step response of the controlled system.

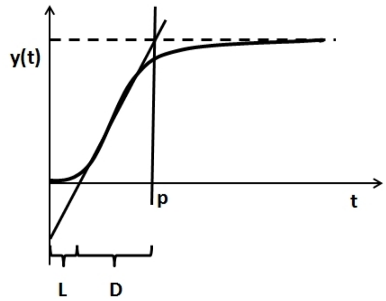

Fig. 3: Characterization of a unit step response of the controlled system with the representation of the dead time L and the delay time D [3], [5].

It is necessary to draw a tangent at the maximum of the slope of the step response. The dead time L has the same importance as in the step response design method. The delay time D is the distance between the intersection of the tangent and the time axis and the point p on the time axis. The point p is created so that in the intersection of the tangent and the maximum of the unit step response of the controlled system is the perpendicular to the time axis raised and the intersection of the perpendicular and the time axis is the point p [3].

The ultimate gain K_u and the ultimate period T_u are then defined as:

$$K_u \cong \frac{\pi}{2}\frac{D}{L}+1\,, \tag{4}$$

$$T_u \cong 4L\,. \tag{5}$$

3. The Definition of the Controlled System

The first thing is to define the controlled system. It could be defined in many ways; in this case the controlled system is defined by a transfer function. The determining parameters are constants *A*, *B* and *C* from the denominator of the transfer function of the controlled system in a form:

$$G_S(s) = \frac{1}{As^2 + Bs + C}. \tag{6}$$

The constants *A*, *B* and *C* are the inputs variables of the knowledge base system which as it was explained above, is used for identifying the parameters of a classical PID controller. The constant *A* can be from the range from 0 to 22, the *B* from 0 to 20 and the *C* from 0 to 28.

4. Knowledge Based System of Identification of Parameters of a PID Controller

The constants *A*, *B* and *C* as the inputs of the knowledge based system are represented in (Fig. 4) so as the outputs *KKNOW*, *TIKNOW* and *TDKNOW* which are also constants and are used as parameters of the classical PID controller.

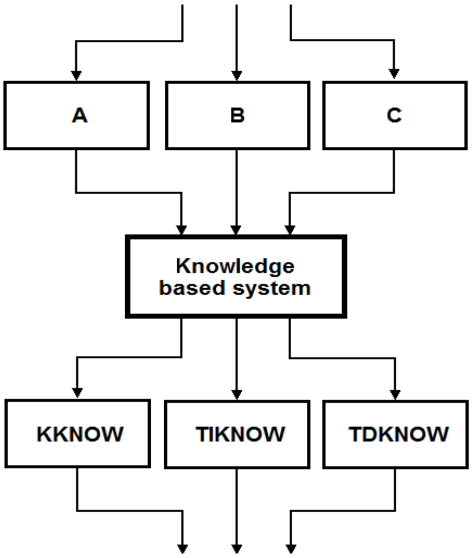

Fig. 4: The representation of inputs and outputs of the created knowledge based system.

4.1. Description of Linguistic Variables

The inputs of knowledge based system *A*, *B* and *C* are the linguistic variables expressed by fuzzy sets, for each linguistic variable by three linguistic values – small (S), medium (M) and large (L) (Fig. 5, Fig. 6 and Fig. 7).

The membership functions of all linguistic values have a triangular shape. The shape could be described in three numbers. The first one is the point of the triangle where the membership degree is equal to zero, the same as the third number, and second number is the point, where the membership degree is equal to one.

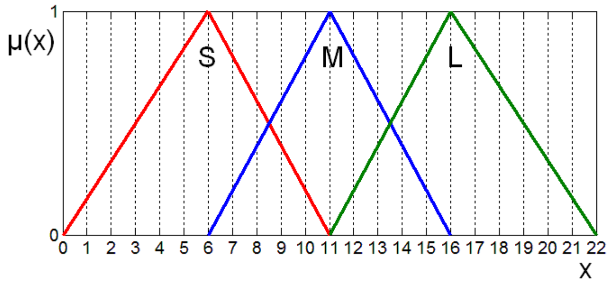

Fig. 5: The shape of the membership function of linguistic values for input linguistic variable *A*.

Description of the shape of the linguistic values of the linguistic variable *A:*

- small (S) [0 6 11],
- medium (M) [6 11 16],
- large (L) [11 16 22].

So according to the description of the importance of three numerical descriptions, the membership function of linguistic value M of input linguistic variable *A* has the shape of an isosceles triangle, and shape of the membership functions for linguistic value S and L is a general triangle.

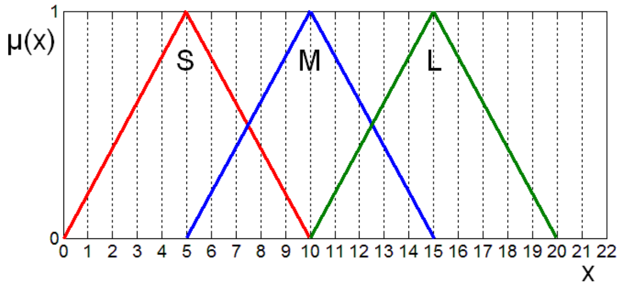

Fig. 6: The shape of the membership function of linguistic values for input linguistic variable *B*.

Description of the shape of the linguistic values of the linguistic variable *B:*

- small (S) [0 5 10],
- medium (M) [5 10 15],
- large (L) [10 15 20].

Membership functions of all linguistic values of linguistic variable *B* have the shape of an isosceles triangle.

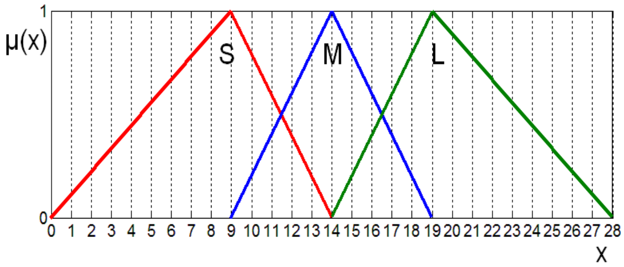

Fig. 7: The shape of the membership function of linguistic values for input linguistic variable *C*.

Description of the shape of the linguistic values of the linguistic variable *C:*

- small (S) [0 9 14],
- medium (M) [9 14 19],
- large (L) [14 19 28].

The membership function of linguistic value M of input linguistic variable *C* has the shape of an isosceles triangle, and the others are general triangles.

Outputs of the knowledge based system are constants *KKNOW*, *TIKNOW* and *TDKNOW* which are parameters of a classical PID controller with the transfer function in a form:

$$G_R(s) = KKNOW\left(1 + \frac{1}{TIKNOW \cdot s} + TDKNOW \cdot s\right). \quad (7)$$

The first thing for determining the values of the outputs *KKNOW*, *TIKNOW* and *TDKNOW* is to define the crisp values of the constants K, T_i and T_d, which are identified for every combination of input linguistic values by combination of Ziegler-Nichols methods described above. In total, 27 crisp values (a single element fuzzy set) for each output value K, T_i and T_d are created. The constants K, T_i and T_d are the concrete values (Tab. 4), whose outputs *KKNOW*, *TIKNOW* and *TDKNOW* can take but the resulting values of those outputs are given according to the active rules and then according to the weighted mean.

Tab.4: Crisp values of the constants K, T_i and T_d.

r	K	T_i	T_d
1	4,0540	0,6940	0,1660
2	3,4140	0,5190	0,1250
3	9,9170	0,4550	0,1090
4	6,7920	0,3740	0,0897
5	3,2690	1,2580	0,3020
6	2,9230	0,9160	0,2200
7	6,1340	0,9300	0,2230
8	4,6540	0,7300	0,1750
9	3,6390	0,5860	0,1410
10	7,8510	0,4070	0,0980
11	6,6010	0,5500	0,1320
12	5,5000	0,4810	0,1150
13	4,9240	0,4350	0,1040
14	5,1750	0,8360	0,2010
15	4,4670	0,7190	0,1730
16	4,0910	0,6440	0,1550
17	3,5130	1,0070	0,2417
18	3,2310	0,8410	0,2020
19	3,0770	0,7400	0,1780
20	7,2500	0,7130	0,1710
21	5,9650	0,6270	0,1504
22	5,2960	0,5690	0,1370
23	3,0460	1,0450	0,2510
24	4,5610	1,0710	0,2570
25	4,0150	0,9125	0,2190
26	3,7230	0,8130	0,1950
27	5,1640	0,8090	0,1940

4.2. Knowledge Base of the Fuzzy System

The core of the knowledge base is the definition of the linguistic IF-THEN rules of the Takagi-Sugeno type [2]:

R: If (x_A is A_r) & (x_B is B_r) & (x_C is C_r) then ($KKNOW_r$=K_r) & ($TIKNOW_r$=T_{ir}) & ($TDKNOW_r$=T_{dr}),

where r = 1, 2,…,R is a number of the rule.

The fuzzy conjunction in antecedent of the rule is interpreted as a minimum. The crisp output is determined using the weighted mean value [2], where $\mu_{Ai}(x)$ is the membership degree of the given input x.

Each output is defined as:

$$KKNOW = \frac{\sum_{r=1}^{R}\left\{\min\left[\mu_{A_r}(x_A^*), \mu_{B_r}(x_B^*), \mu_{C_r}(x_C^*)\right]\right\} KKNOW_r}{\sum_{r=1}^{R}\min\left[\mu_{A_r}(x_A^*), \mu_{B_r}(x_B^*), \mu_{C_r}(x_C^*)\right]}, \quad (8)$$

$$TIKNOW = \frac{\sum_{r=1}^{R}\left\{\min\left[\mu_{A_r}(x_A^*), \mu_{B_r}(x_B^*), \mu_{C_r}(x_C^*)\right]\right\} TIKNOW_r}{\sum_{r=1}^{R}\min\left[\mu_{A_r}(x_A^*), \mu_{B_r}(x_B^*), \mu_{C_r}(x_C^*)\right]}, \quad (9)$$

$$TDKNOW = \frac{\sum_{r=1}^{R}\left\{\min\left[\mu_{A_r}(x_A^*), \mu_{B_r}(x_B^*), \mu_{C_r}(x_C^*)\right]\right\} TDKNOW_r}{\sum_{r=1}^{R}\min\left[\mu_{A_r}(x_A^*), \mu_{B_r}(x_B^*), \mu_{C_r}(x_C^*)\right]}, \quad (10)$$

where x_A^*, x_B^*, x_C^* are concrete values of inputs variables. So the output of the system is the crisp value and defuzzification is not required.

In total, $r = 27$ rules of the Takagi-Sugeno fuzzy model are used:

1. if (A is S) & (B is S) & (C is S) then ($KKNOW$=K_1) & ($TIKNOW$=Ti_1) & ($TDKNOW$=Td_1),
2. if (A is S) & (B is S) & (C is L) then ($KKNOW$=K_2) & ($TIKNOW$=Ti_2) & ($TDKNOW$=Td_2),
3. if (A is S) and (B is L) & (C is S) then ($KKNOW$=K_3) & ($TIKNOW$=Ti_3) & ($TDKNOW$=Td_3),
4. if (A is S) and (B is L) and (C is L) then ($KKNOW$=K_4) & ($TIKNOW$=Ti_4) & ($TDKNOW$=Td_4),
5. if (A is L) and (B is S) and (C is S) then ($KKNOW$=K_5) & ($TIKNOW$=Ti_5) & ($TDKNOW$=Td_5),
6. if (A is L) and (B is S) and (C is L) then ($KKNOW$=K_6) & ($TIKNOW$=Ti_6) & ($TDKNOW$=Td_6),
7. .if (A is L) & (B is L) & (C is S) then ($KKNOW$=K_7) & ($TIKNOW$=Ti_7) & ($TDKNOW$=Td_7),
8. if (A is L) & (B is L) & (C is L) then ($KKNOW$=K_8) & ($TIKNOW$=Ti_8) &

(*TDKNOW=Td*$_8$),

9. if (A is S) & (B is S) & (C is M) then (*KKNOW=K*$_9$) & (*TIKNOW=Ti*$_9$) & (*TDKNOW=Td*$_9$),
10. if (A is S) & (B is L) & (C is M) then (*KKNOW=K*$_{10}$) & (*TIKNOW=Ti*$_{10}$) & (*TDKNOW=Td*$_{10}$),
11. if (A is S) & (B is M) & (C is S) then (KKNOW=K$_{11}$) & (*TIKNOW=Ti*$_{11}$) & (*TDKNOW=Td*$_{11}$),
12. if (A is S) & (B is M) & (C is M) then (*KKNOW=K*$_{12}$) & (*TIKNOW=Ti*$_{12}$) & (*TDKNOW=Td*$_{12}$),
13. .if (A is S) & (B is M) & (C is L) then (KKNOW=K$_{13}$) & (*TIKNOW=Ti*$_{13}$) & (*TDKNOW=Td*$_{13}$),
14. if (A is M) & (B is M) & (C is S) then (*KKNOW=K*$_{14}$) & (*TIKNOW=Ti*$_{14}$) & (*TDKNOW=Td*$_{14}$),
15. if (A is M) & (B is M) & (C is M) then (*KKNOW=K*$_{15}$) & (*TIKNOW=Ti*$_{15}$) & (*TDKNOW=Td*$_{15}$),
16. if (A is M) & (B is M) & (C is L) then (*KKNOW=K*$_{16}$) & (*TIKNOW=Ti*$_{16}$) & (*TDKNOW=Td*$_{16}$),
17. .if (A is M) & (B is S) & (C is S) then (*KKNOW=K*$_{17}$) & (*TIKNOW=Ti*$_{17}$) & (*TDKNOW=Td*$_{17}$),
18. if (A is S) & (B is S) & (C is S) then (*KKNOW=K*$_{18}$) & (*TIKNOW=Ti*$_{18}$) & (*TDKNOW=Td*$_{18}$),
19. if (A is S) & (B is S) & (C is L) then (*KKNOW=K*$_{19}$) & (*TIKNOW=Ti*$_{19}$) & (*TDKNOW=Td*$_{19}$),
20. if (A is S) & (B is L) & (C is S) then (*KKNOW=K*$_{20}$) & (*TIKNOW=Ti*$_{20}$) & (*TDKNOW=Td*$_{20}$),
21. if (A is S) & (B is L) & (C is M) then (*KKNOW=K*$_{21}$) & (*TIKNOW=Ti*$_{21}$) & (*TDKNOW=Td*$_{21}$),
22. if (A is S) & (B is L) & (C is L) then (*KKNOW=K*$_{22}$) & (*TIKNOW=Ti*$_{22}$) & (*TDKNOW=Td*$_{22}$),
23. if (A is L) & (B is S) & (C is S) then (*KKNOW=K*$_{23}$) & (*TIKNOW=Ti*$_{23}$) & (*TDKNOW=Td*$_{23}$),
24. if (A is L) & (B is M) & (C is S) then (*KKNOW=K*$_{24}$) & (*TIKNOW=Ti*$_{24}$) & (*TDKNOW=Td*$_{24}$),
25. if (A is L) & (B is M) & (C is M) then (*KKNOW=K*$_{25}$) & (*TIKNOW=Ti*$_{25}$) & (*TDKNOW=Td*$_{25}$),
26. if (A is L) & (B is M) & (C is L) then (*KKNOW=K*$_{26}$) & (*TIKNOW=Ti*$_{26}$) & (*TDKNOW=Td*$_{26}$),
27. if (A is L) & (B is L) & (C is M) then (*KKNOW=K*$_{27}$) & (*TIKNOW=Ti*$_{27}$) & (*TDKNOW=Td*$_{27}$).

5. Experimental Verification of the Created System

For the experiment the controlled system is selected with a transfer function in the form:

$$G_S(s) = \frac{1}{3s^2 + 12s + 17}. \qquad (11)$$

For this system two PID controllers are determined, one using only the combination of the Ziegler-Nichols design methods and the second one using the created knowledge based system. Both PID controllers are inserted into a closed feedback loop with an appropriate system and the time response is assessed for the unit step of both closed feedback loops. The timing is displayed in the time response of closed feedback loop with the PID controllers with parameters determined using created knowledge based system and a combination of classical Ziegler-Nichols methods for a unit step (Fig. 8).

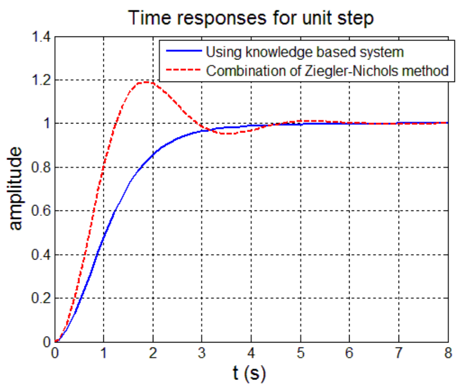

Fig. 8: Time response of the closed feedback loop with a PID controller with parameters determined using created knowledge based system and a combination of classical Ziegler-Nichols methods for a unit step.

For evaluation of a time response the 3 % standard deviation from the steady-state value is chosen.

Tab.5: Time of stabilization.

Time of stabilization (3 % standard) (s)	
Combination of Ziegler-Nichols methods	**Using knowledge based system**
4,1	3,1

For our selected controlled system the difference in time of stabilization as a time response for the unit step is 1 second (Tab. 5). So for this concrete example the difference is approximately 25 %.

The second very noticeable difference is in the overshoot. Using the PID controller tuned by combination of the Ziegler-Nichols method the overshoot is approximately 20 %. Using PID controller identified by the knowledge based system the time step response is in this case without overshoot.

6. Conclusion

The fuzzy knowledge based system which was created is the new non-conventional tool for designing the parameters of PID controllers. It was experimentally verified and it was found that it is very usable for systems with the transfer function in shape (6), where the parameter A is rather small while the parameters B and C rather medium or large. In future research some new rules will be added to extend the class of usable controlled systems types.

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References

[1] ARZEN, Karl-Erik. An Architecture for Expert System Based Feedback Control. *Automatica*. Elsevier, 1989, vol. 25, iss. 6, p. 813-827. ISSN 0005-1098.

[2] BABUSKA, Robert. *Fuzzy Modeling for Control*. Boston: Kluwer Academic Publishers, 1998. ISBN 9780792381549.

[3] ASTROM, Karl J. and Tore HAGGLUND. *PID Controllers: theory, design, and tuning*. 2nd Edition. USA, 1995. p. 343. ISBN 1-55617-516-7.

[4] LEVINE, William S. *The Control Handbook*. 2 Volume Set. Mumbai: Jaico Publishing House, 1999. ISBN 81-7224-785-0.

[5] BALATE, Jaroslav. *Automaticke rizeni*. 1st Edition. Praha: BEN–technicka literatura, 2003. ISBN 80-7300-020-2.

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