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Design and Critical Evaluation of an Intelligent Fuzzy Logic Controller for Nonlinear CSTR Process

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ABSTRACT

This paper presents a new robust Fuzzy controller that extends the concepts of advanced process control in new directions by performing servo-tracking and disturbance rejection simultaneously. An attempt has been made to analyze the efficiency of an intelligent fuzzy controller (IFLC) on Nonlinear CSTR Level loop. Analysis of the effects studied through computer simulation using Matlab/Simulink toolbox. Here the conventional PID controller parameters are designed based on Ziegler-Nicholas method and its servo & regulatory responses are compared with Fuzzy logic controller based on mamdani model. It is observed from the results of Fuzzy Logic controller performs in no overshoot, faster settling time, better set point tracking and produces lower performances indices like Integral square error (ISE*).*

Keywords: *Fuzzy Logic, PID, ISE, Ziegler Nicholas*

1. INTRODUCTION

1.1 Background

About 95% of process control loops are of PID or PI type. Since its inception over eighty years ago, the proportional-integral-derivative (PID) control structure has remained the most commonly used single-input single-output (SISO) technique in industry, primarily because it is one of the simplest. PID control is often combined with other technologies to build the complex automation systems that are used in many industries. Chemical and petrochemical control strategies are often organized in a hierarchy of functions, with scheduling and optimization functions running on top of the hierarchy, multivariable predictive controllers in the middle and PID controllers at the lower level, directly sending control signals to actuators.

Conventional PID controllers are of one-degree-of-freedom (1DoF) type. The degree of freedom of a control system is defined as the number of closed-loop transfer functions that can be adjusted independently. A conventional 1DoF PID controller can either perform servo tracking or disturbance rejection at a time, but not simultaneously. Thus, in industries employing servo control where set point changes are tracked effectively, almost all the disturbances including the major ones are neglected. Similarly in industries employing regulatory control, the response is unaffected by the disturbances. But even a slight variation in set point can't be tracked effectively.

To overcome the drawbacks of a conventional PID controller, an enhanced controller that is capable of achieving satisfactory servo tracking without sacrificing regulatory performance was needed. The model dependent control framework, lack of efficient tuning techniques and the need for extensive background in control theory prevents complex control structures from being found in industrial control applications. Thus, the focus was towards the development of an Intelligent Fuzzy Logic Controller rather than a complex control structure.

1.2 Defects of conventional PID controllers

A general form of PID control system is shown in Fig. 1. Where the controller consists of a compensator *C(s)*, and *P(s)* is the transfer function from the manipulated variable *u* to *y*. The output of the controller *C(s)* is given to the process *P(s)* through a final control element. *r* is the desired value of the process variable(set point) and the process is subjected to a disturbance *d*.

The purpose of the system is to keep the process variable close to the desired value in spite of disturbances. In order to simplify this problem, two assumptions are introduced as per [5].

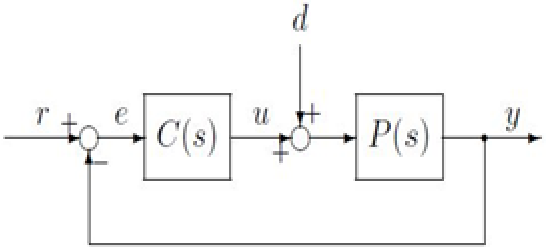


Fig. 1. PID controller structure

Considering the transfer function of the plant to be,

$$P(s) = e^{--0.2s}/(1+s) \qquad (1)$$

The disturbance optimal parameters obtained by the Chien-Hrones-Reswick(abbreviated as CHR) formula are

$$K_p = 0.6,\ T_i = 0.4,\ T_d = 0.084 \qquad (2)$$

For the above parameter setting, the closed-loop responses become as given by the solid lines in Fig. 2(a) and Fig. 2(b)

They show that the disturbance response is optimal but the set-point response suffers from the overshoot larger than 50%. On the other hand, the set-point optimal parameters by the CHR formula are

$$K_p = 4.75,\ T_i = 1.35,\ T_d = 0.094 \qquad (3)$$

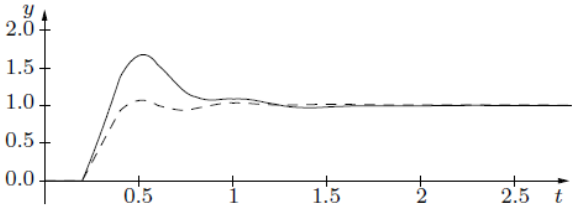


Fig. 2(a). Set-point response of PID control system

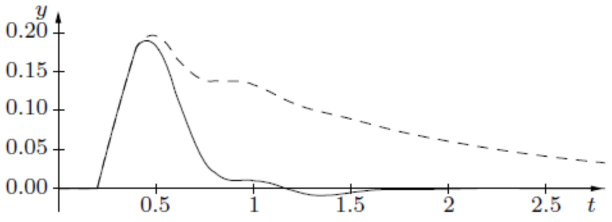


Fig. 2(b). Disturbance response of PID control system

For this parameter setting, the closed-loop responses become as given by the dotted lines in Fig. 2(a) and Fig.2 (b). Now, the set-point response is fine with a small overshoot, but the disturbance response deteriorates substantially. So, we cannot optimize the set-point response and disturbance response at once.

2.DESIGN OF FUZZY LOGIC CONTROLLER

The conventional PID controller cannot anticipate and prevent errors as it is insensitive to modeling errors. The feedback control is the basic technique to compensate the load disturbance entering the system. Feedback control has the potential to eliminate the effects with several drawbacks such as:

- It rejects load disturbance after it enters into the system,
- It cannot give good control when large delay is present.

In an attempt to minimize such drawbacks, an intelligent fuzzy logic based controller is augmented to the existing feedback controller and the effects are studied through computer simulation.

The block diagram of the integrated intelligent fuzzy logic control system is shown in Fig. 3. The main advantage of this configuration is that it can improve the performance of the existing system without modifying the hardware components. This type of control system can be applied to all kind of processes.

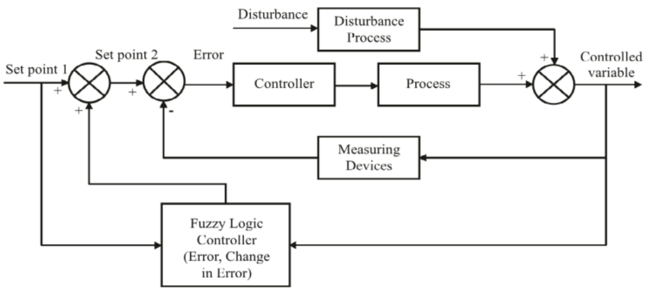


Fig. 3 Block Diagram of Fuzzy Logic Controller

The development of fuzzy logic control consists of the following steps:

1. Specify the range of controlled variable and manipulated variables;
2. Divide these ranges into fuzzy sets and attach linguistic labels which can be used to describe them;
3. Determine the rules (rule base), which relate the manipulated variable and controlled variable, to specify control action;
4. Application of a suitable defuzzification method.

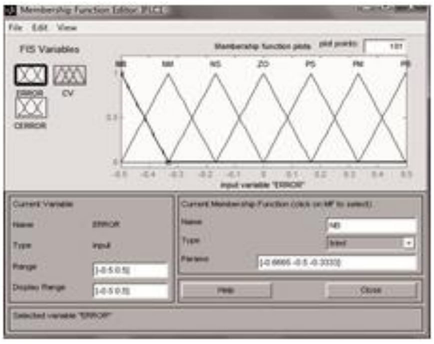
The number of necessary fuzzy sets and their ranges were designed based upon the experience gained on the process. The standard fuzzy set consists of three stages: Fuzzification, Decision- Making Logic and Defuzzification [5].

3. DEVELOPMENT OF FUZZY LOGIC CONTROLLER

3.1 Fuzzification stage

This stage converts a crisp number into a fuzzy value within a universe of discourse. The triangular membership functions with seven linguistic values for error and change in error is used and is shown in Figs. 4a and 4b.

The linguistic values are NB(Negative Big), NM(Negative Medium), NS(Negative Small), ZO(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big).



plot points: 101

Name ERROR

Type input

Range [-0.5 0.5]

Display Range [-0.5 0.5]

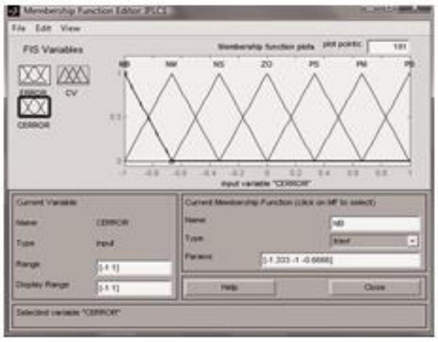
Name NB

Type trimf

Params [-0.6666 -0.5 -0.3333]

Selected variable "ERROR"

Fig 4(a) Membership functions for Error



plot points: 101

Name CERROR

Type input

Range [-1 1]

Display Range [-1 1]

Name NB

Type trimf

Params [-1.333 -1 -0.6666]

Selected variable "CERROR"

Fig 4(b) Membership functions for Change in Error

3.2 Decision Making Stage

This stage consists of fuzzy control rules which decide how the fuzzy logic control works. This stage is the core of the fuzzy control and is constructed from expert knowledge and experience. Based on the knowledge gained by analyzing the feedback control system decision making logic is given in

Table I where 49 rules are used. The fuzzy logic control rule will be of the following type:

IF (condition) AND (condition) THEN (action).

The rules can be interpreted as follows and then similarly other rules can be interpreted in the same way.

IF error is NB AND change in error is NB THEN Control action is NB.

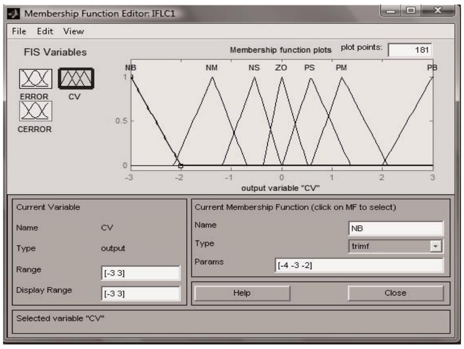
Table I. Integrated Fuzzy Logic Decision Making Logic

E CE CO	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZO
NM	NB	NB	NM	NS	NS	ZO	PS
NS	NB	NM	NS	NS	ZO	PS	PM
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	NS	ZO	PS	PS	PM	PB	PB
PB	ZO	PS	PS	PM	PB	PB	PB

E: Error; CE: Change in Error; CO: Controller Output.

3.3 Defuzzification Stage

It converts fuzzy value into crisp value. In this study centre of area (COA) method [6] is used. The triangular shaped membership function with seven linguistic values is used and it is shown in Fig. 4c. The range of error, change in error and the controller output are made on the basis of practical experience.



plot points: 181

Current Variable
Name CV
Type output
Range [-3 3]
Display Range [-3 3]

Current Membership Function (click on MF to select)
Name NB
Type trimf
Params [-4 -3 -2]

Selected variable "CV"

Fig. 4(c) Membership function for Output

4. SIMULATION RESULTS FOR THE REAL-TIME SYSTEM

4.1 Using MATLAB Simulink

In order to verify the performance of Fuzzy Logic controller and make a comparative study with PID controller, a CSTR level process was chosen.

The plant was initially simulated using MATLAB Simulink software for PID and Fuzzy logic controller. Before experimenting it in real-time, software simulation was preferred in order to have easy troubleshooting and to prevent damage of the plant in case of unexpected results.

The system was identified and found to be:

$$G(S) = \frac{0.011863s + 0.00184055}{s + 0.00231489} \tag{4}$$

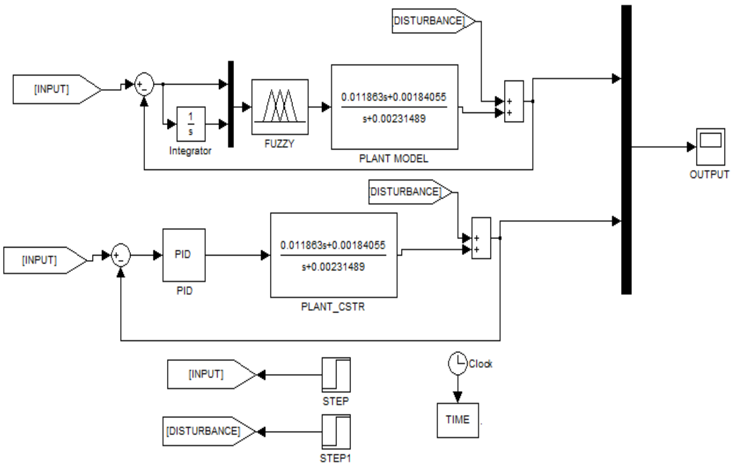


Fig. 5 Implementation of PID and FLC using MATLAB Simulink

Figure 5, shows the implementation of PID and Fuzzy logic controller using MATLAB Simulink for the process considered.

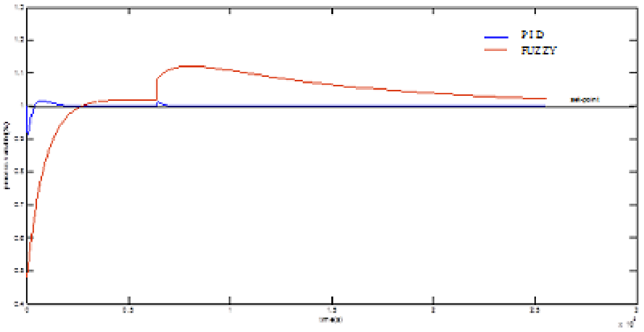


Fig.6 *Response of PID and FLC using MATLAB Simulink*

Figure 6, shows the response PID controllers for the same liquid level CSTR process for tuned values of K_p,T_i and T_d.

Here, the process variable of Fuzzy controller is found to settle initially with no offset and at the instant the disturbance is given, it shows a slight deviation and settles down immediately with no offset. But, in the case of PID, it is found that the process variable initially tracks the set-point, but with an offset and at the instant the disturbance is given the process variable deviates from the desired set-point.(It is to be noted that the red line indicates PID and the blue line indicates the Fuzzy Logic controller).

5. PERFORMANCE ANALYSIS

The following performance index parameters were obtained for PID and FLC. From the performance index parameters shown in Table1, it is seen that the performance index parameters are minimum for Fuzzy logic controller than that for PID controller for both servo and regulatory response. Since FLC controllers give minimum performance index parameter values, they are found to be much better than the conventional PID controllers in their performance.

TABLE I. Performance index for FLC and PID

	PID CONTROLLER		FLC	
	SERVO RESPONSE	REGULATORY RESPONSE	SERVO RESPONSE	REGULATORY RESPONSE
ITAE	1.46727E+8	5.79748E+8	5.0709E+7	6.86344E+7
IAE	1.11205E+6	1.68736E+6	396000	469616
ISE	2.48544E+8	3.00434E+8	6.97359E+7	8.42166E+7

From the real-time simulation results the following observations were made:

- The servo response of a PID controller is found to have a considerable amount of offset. But, in the case of FLC the process output is obtained without any offset.
- It is found that once the disturbance is given to the PID controller by varying the outflow of the CSTR liquid level process, the process variable deviates much from the set-point and settles down after large amount of time.
- It is found that once the disturbance is given to the FLC by varying the outflow of the CSTR liquid level process, the
- Process variable settles down with a very slight deviation from the set-point. Thus, it is observed that a two-degree-of-freedom PID controller serves both servo and regulatory response with a minimized error simultaneously.

CONCLUSION

PID, a structurally simple and generally applicable control structure stems its success largely from the fact that it just works well with a simple and easy to understand structure. This is one of the main reasons it is used as a trustworthy controller in many industries. But, the PID controller itself has some loopholes in the sense it can control the process output either based on set-point variations or disturbance rejection technique only. This problem was not of much importance in early days of PID applications when the change of set-point variable was not required much often, but it is very important in the modern days of process control where the change of set-point variable is frequently required. The comparative study shows that the FLC can solve the problem of the conventional PID controller that the optimal tuning for the disturbance response and the one for the set-point response are not compatible in most cases of practical importance. Though the underlying concepts are new to conventional thinking, they are powerful and show promise.

Coming to the application point of view the proposed FLC plays a significant role in the development of areas like wheelchair and robotic applications where the usage of this controller gives very precise and accurate output compared to the conventional PID ending up in error of up to 5-20% due to the inability to perform servo tracking and disturbance rejection simultaneously which is a complete blunder in case of robotic arms or wheelchair designed for physically challenged.

Thus, the proposed method gives the best performance with much faster rise time, settling time and minimal error meeting the expectations of the industries, even averting disasters in some cases.

APPENDIX

EXPERIMENTAL SETUP

A real time experimental setup for highly nonlinear tank is constructed. The process control system is interfacing DAQ module to the Personal Computer (PC). The laboratory set up for this system is shown in Figure 1.

It consists of a tank, a water reservoir, pump, rotameter, a differential pressure transmitter, an electro pneumatic converter (I/P converter), a pneumatic control valve, an interfacing DAQ module and a Personal Computer (PC).

The differential pressure transmitter output is interfaced with computer using DAQ module in the RS-232 port of the PC. Figure 9 shows the real time experimental setup of a CSTR tank interfaced with LabVIEW. The pneumatic control valve is air to close, adjusts the flow of the water pumped to the CSTR tank from the water reservoir. The level of the water in the tank is measured by means of the differential pressure transmitter and is transmitted in the form of (4-20) mA to the interfacing DAQ module to the Personal Computer (PC).

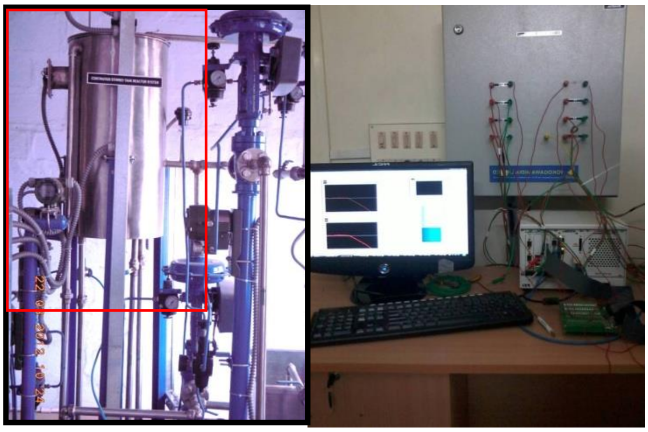


Figure 7 Experimental setup of a CSTR Plant

After computing the control algorithm in the PC control signal is transmitted to the I/P converter in the form of current signal (4-20) mA, which passes the air signal to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow of water in and out of the tank.

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