

A Fuzzy Decision Support System for Performance Improvement of PID Control Loops in Process Industry

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The performance improvement of PID control loops that involve identifying problems and deciding upon the best way to focus loop optimization at short-term and long-term horizons is very challenging. The decisions regarding performance problems of PID controllers are particularly *semi-structured* in a heterogeneous plant environment where multi-vendor, multi-technology products co-exist. The strategic development of a decision support system for plant-wide implementation would assist the control engineer in qualitative decision making for control loop optimization and maintenance. This paper after identifying key decision requirements for control loop performance improvement provides a fuzzy logic based decision support system for PID controllers. The system is validated by analyzing data from a laboratory heating process.

Key words: PID control, decision support system, fuzzy logic, performance assessment, controller tuning

1. Introduction

A process industry consists of a large number of control loops having multiple products and standards. A control engineer in a pulp and paper industry, for example, has to maintain on an average two thousand Proportional-Integral-Derivative (PID) control loops. Maintaining such a vast number [1] of loops in best possible performance with limited staff is a hilarious task. Research into this area [2] shows that 90% of the control loops in a process industry are of PID family. Although these controllers have a lion share in the process industry, more than 50% have performance problems [1]. The major causes for the poor performance are attributed to the enormity of the number of loops, poor or no supporting environment and the lack of awareness of the staff [3]. However, performance improvement of control loops could significantly contribute to energy saving and quality conformance in process control [1].

Thus, plant-wide control loop performance monitoring and improvement in a process plant is a complex but rewarding task. There is poor support to the control engineer for decision making about performance related problems. The decision making process is semi structured and is often dependent on the competence and experience of the engineer.

1.1 Performance Improvement of Control Loops: Issues and Challenges

As already discussed, PID controllers have the highest share in the process industry. In a semi structured decision environment as this, a Decision Support System (DSS) would be highly effective [4] to measure and decide on steps for optimization which will help improve plant performance by reducing wastage and improving product quality. The issues involved in the development of such a support environment are mostly multifaceted. No international standards exist for PID algorithms used in the controllers. Different manufacturers use different algorithms due to historic reasons of development from pneumatic to analog and to digital [5]. Therefore, control parameters that work well in one controller may not give the same performance in controllers manufactured by other vendors.

In practice, final values for controller parameters are chosen by striking a trade off among the various performance specifications. The trade off is obvious as some of the performance specifications are

mutually contradictory. An obvious case is the specifications of speed of response and stability [6]. High speed of response can be achieved only at the cost of stability and vice versa. Quite often in process industry applications, the requirements are not very rigidly expressed, but are better expressed by control engineer's perceptions like 'good accuracy' and 'moderate stability'; 'moderate response time' and 'very good stability'. Therefore, flexibility is an essential feature for specifying requirements in certain control applications. Soft computing techniques offer great help in implementing flexibility. However, their use is presently limited to optimization of performance functions for computing controller parameters [7], [8], [9].

In today's changing manufacturing environment, where priority changes rapidly due to market forces, *flexibility* is a vital requirement in all activities concerned with production. In this context, bringing flexibility into controller configuration and tuning activity, in accordance with changing performance objectives, is important. Hence, techno-diversity, priority conflicts, less staff support and scope for cost and quality advantage all urge the need of a proper support environment for PID control performance improvement; an environment that will help to *know*, *diagnose* and *act* faster.

This paper proposes a fuzzy based decision support system implementing methods for performance assessment, diagnostics and controller tuning to support the control engineer in the activities pertaining to PID control performance improvement. Lambda-tuned [3],[10] values are taken as the initial values for controller parameters and are further fine tuned using fuzzy inference. The control system is then simulated with the fine-tuned optimal values of the control parameters and checked with performance specifications. MATLAB™ GUIDE environment and technical computing functions are used for DSS development and control loop simulation.

The remaining part of the paper has the following sections: section 2 gives a tutorial on PID control loop, section 3 briefs the existing techniques for their performance assessment, diagnostics and tuning, section 4 provides a framework for developing a DSS, section 5 applies the system to a heating process and section 6 concludes the work.

2. Pid Control - Functional Description

A schematic representation of a typical PID control loop is shown in Fig. 1. As shown in the figure a

PID-Controller consists of three elements: P for Proportional control, I for Integral control and D for Derivative control. For this reason the PID controller is sometimes called as three-term controller. The PID control can be implemented to meet

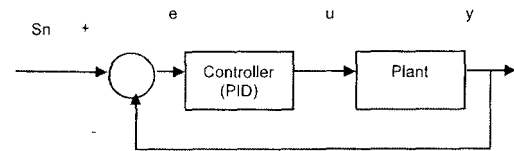


Fig. 1 Block Diagram of a PID Control Loop

various design specifications of the system. For proper understanding of the operation of a PID feedback controller, the above three terms are required to be considered separately.

- Proportional Control:** Proportional control is pure gain adjustment acting on the error signal to provide the driving input to the process. The P term in the PID controller is used to adjust the *speed* of the system.
- Integral Control:** Integral control is implemented through the introduction of an integrator. Integral control is used to provide the required accuracy for the control system.
- Derivative Control:** Derivative action is normally introduced to increase the damping in the system. The derivative term also amplifies the existing noise, which can cause problems including instability.

The input output relationship of a closed loop PID control system is given by:

$$H(s) = K_c [1 + 1/T_i s + T_d s] \quad \text{----- (1)}$$

where

K_c is the proportional gain,
 T_i is the integral time and
 T_d is the derivative time.

Optimization of a PID controller is the task of assigning optimal values for K_c , T_i and T_d depending on the control objectives. In a regulatory control, the parameters are adjusted to minimize error due to disturbance occurring at the process. This disturbance gets added to the controller output at 'u'. In servo control, parameters are assigned for tracking setpoint changes.

3. Methods for Pid Control Performance Assessment, Diagnostics and Tuning

As the task of performance improvement consists of performance assessment, diagnostics for cause finding of performance problems and corrective actions such as controller tuning, the existing methods are overviewed before drawing a framework for the proposed DSS.

3.1 Performance Assessment

A variety of standards have been proposed over the past one decade to assess the quality of process control performance; see [12], [13] for review. They explicitly or implicitly involve a comparison of the current quality of control to a pre-defined standard performance. A very brief overview of the PID performance indexes is given below:

3.1.1 Performance Index based on Minimum Variance (Harris Index)

The ratio of the controller variance to that of a minimum variance controller is termed as the Harris index [14], and is given by equation (2).

$$I_h = \frac{\sigma_y^2}{\sigma_{mv}^2} \quad \text{----- (2)}$$

where I_h is the Harris index, σ_y^2 is the variance of the process variable with the given controller and σ_{mv}^2 is the variance that would be produced by an MVC controller.

This approach was welcomed by the process industry as it was easy to implement, easy to interpret (ideally, one), non-invasive (does not disturb process) and required only modest knowledge of the process.

3.1.2 PID Optimal Performance Index

The Harris index is useful only for stochastic control. However, in practice regulatory control loops constitute around 97% of process control [1]. Therefore, it is required to have pragmatic indices, which relate to regulatory and servo control. Eriksson and Isaksson [11] proposed such a performance index on the closed loop transfer function of the control loop with the input / output disturbance models.

3.1.3 PID Best Performance Index

A more sensible index of controller performance is to determine comparatively how the current control structure (P, PI, PID etc.) performs compared to the

achievable performance of the current control structure. This index could also be used for comparing various control structures and then deciding on the best control structure for a particular application [11].

The performance index 'I' for a PI control structure is given by :

$$I_{PI} = \frac{\sigma_y^2}{\sigma_{PI}^2} \quad \text{----- (3)}$$

where σ_y^2 is the actual process variance and σ_{PI}^2 is the achievable variance from the existing control structure by optimization of control parameters K_c and T_i .

$$\sigma_y^2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} |He^{j\omega}|^2 d\omega \quad \text{----- (4)}$$

$$\sigma_{PI}^2 = \min_{K_c, T_i} \frac{1}{2\pi} \int_{-\pi}^{\pi} |He^{j\omega}|^2 d\omega \quad \text{----- (5)}$$

where H is the z transform of the transfer function of the control loop from setpoint to output or disturbance input from output depending on whether the control is servo or regulatory type respectively. This index is more useful as it indicates how much the output variability can be decreased using the current control structure.

3.2 Diagnostics

Control loop behavioural problems are often characterized by either sluggishness or oscillation. Root causes for this kind of behaviour could be inappropriate controller tuning, control valve stiction, etc. Systematic methods have been suggested for detecting sluggishness through an *idle index* [15] and oscillation [16], [17].

3.3 Controller Tuning

Poor or conservative controller tuning can result both in oscillatory and sluggish behaviour of a PID control loop. This increases variability in process control leading to product quality violations, wastages and even losses due to high control valve running costs. Therefore tuning of the controller is crucial to achieve good process control performance. Research

into PID controller tuning methods has been an active area and remains open for improvement. A recent survey of various methods is given in [18].

4. A Framework for Fuzzy Logic based decision support system for Pid Control

Fig. 2 depicts a framework for the proposed DSS, which integrates various tools, and functionalities to systematically assess, diagnose and correct PID control loops for best

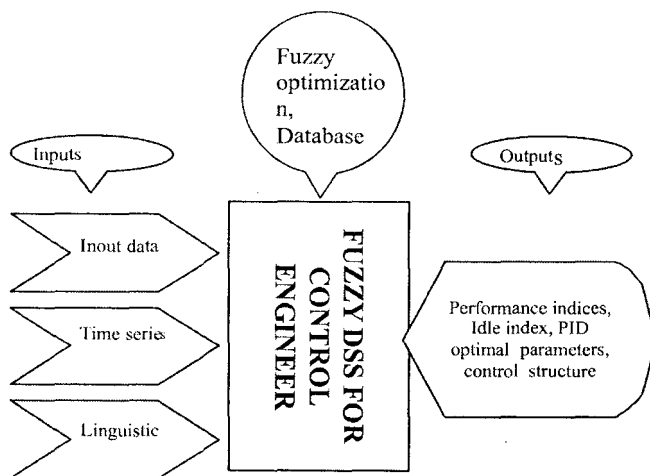


Fig. 2 : A framework of the proposed decision support system

performance. The resulting models, performance indices and controller parameters from each analysis are stored in a core database to facilitate query of historical data for data-centric and model based decision support.

The system receives as input the controller input output data from proper excitation of the process through step tests, Pseudo Random Binary Sequence (PRBS) etc. The continuous process output data as time series is required for assessing existing performance of the process. The data is copied into the workspace of a Computer Aided Control Engineering (CACE) tool such as Matlab™ in ASCII .dat format. In addition, the user inputs his control requirements of stability and speed of response linguistically, which is quantified over a 0 to 10 scale.

4.1 Model Identification and Controller Parameters

A general First Order Plus Delay Time (FOPDT) model [3] is identified from the controller input

output data. The process model is then given by the transfer function $G(s)$:

$$G(s) = Ke^{T_d s} / \tau s + 1 \quad \text{----- (6)}$$

where

K is the process gain,
 T_d is the process time delay and
 τ is the time constant

Based on this model, tuning parameters can be determined using I-tuning method as follows:

$$K_c = \tau / K (T_d + \lambda), \quad T_i = \tau, \quad \lambda \in (\tau, 3\tau) \quad \text{----- (7)}$$

4.2 Performance Assessment & Diagnostics

For the purpose of a decision support system for PID control performance improvement, we shall make use of the PID specific performance indices given Section 3.1.2 and 3.1.3. This would help us in :

- Understanding the performance of any PID controller with respect to the existing PID parameters.
- Determination of optimal parameters for a particular control structure
- Deciding on how performance index can be improved by changing control structure

The user can visualize performance under various preferences, which shall be analyzed by a fuzzy logic module and will provide final parameters for the control structure. Having measured the performance of a control loop with reference to an index it could be compared against a user defined performance target and if the performance is below the target, the loop could be diagnosed to detect root causes for performance problems. The diagnostics leads to appropriate corrective action.

4.3 Fuzzy Controller Tuning

As discussed in Section 1.1 the optimal parameters for the PID controller for a particular application is a trade off among the various control requirements. The requirements are given by the control engineer or the expert of the application linguistically. λ -tuning provides an initial range of values for K_c and T_i given by equation (7) for good stability and fast response. Rules are formulated are:

- *Highly stable, but low performance controller, opt for λ -tune parameters for robustness*
- *High performance but low stability, opt for optimized control parameters for performance*

The above rules when defuzzified using the centroid method yield optimum of K_c and T_i . A few iterations for re-evaluation of stability indices like phase margin and gain margin and performance indices can establish whether we have got convincing values or not.

The DSS framework has been built with the following basic assumptions:

- The process is single input single output (SISO)
- λ -tuning method based on First Order Plus Delay Time (FOPDT), which is time tested and the most commonly used approach, applies to the process
- The application employs servo control or regulatory control with moderate time delay.
- PI control structure is assumed for initial parameter determination.

The MATLABTM code for performance improvement is given below:

```
%Variables

% K: Process gain, Td: Delay time, Tau: Process time
constant, theta: %process model in theta format, z:
controller input output data in

% Ts: sampling time, Kc_stability :  $\lambda$ -tuned gain for
good % stability, Kc_speed:  $\lambda$ -tuned gain for good
speed of response,

% Ti: Controller integral time, I: Controller optimal
index, Imin:

% User defined minimum acceptable performance,
Ii: Idle index

[K,Td,Tau,theta]=fopdt_id(z,Ts);
% identifies process FOPDT model
% from input output data

lambda=Tau;
Kc_stability=Tau / K* (Td+3*lambda);
% Computes lambda tune values
Kc_speed= Tau / K* (Td+lambda);
Ti=Tau;

I=pidoptimal_index(theta, Kc, Ti);
% Computes performance index

if I>Imin
[Ii,osc]=diagnostics;
% Diagnose for sluggishness and
% oscillation

if (Ii>0) || (osc==true)
[Kc,Ti]=fuzzy_tuner(Kc_stability, Kc_speed,Ti);
else helpdlg('Check other loop elements');
```

```
end
else helpdlg('The loop is okay');
end
```

The above code shows model identification using user defined *fopdt_id* function, λ -tuning for initial value set for fuzzy tuner and performance index computing using user defined *pidoptimal_index* function. The programme calls diagnostics function if performance is below target and executes *fuzzy_tuner* in case of either sluggishness (Ii more than 1) or oscillation.

5. System Application Study of a Laboratory Heating Process¹

A prototype of the system was developed using MATLABTM 6p5. The various modules for FOPDT process identification, λ -tuning, computation of performance indices, stability parameters and Integrated Time multiplied Squared Error (ITSE) etc. are integrated with a graphical user interface.

The system was used to determine optimal controller parameters for the heating process of a laboratory hairdryer. The input output data for model estimation and validation are plotted in Fig.3.

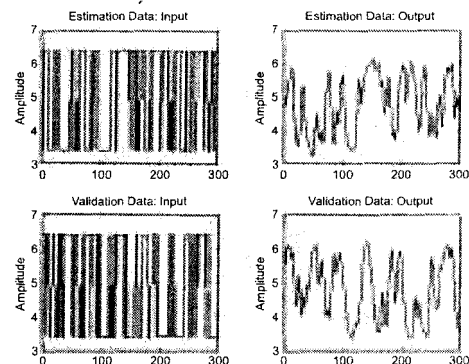


Fig. 3 : Input Output data used for model building and validation

The process works as follows: Air is fanned through a tube and heated at the inlet. The air temperature is measured by a thermocouple at the outlet. The input is the voltage over the heating device, which is just a mesh of resistor wires. The output is the outlet air temperature (or rather the voltage from the thermocouple). The input-output data collected contains 1000 measurements of voltage applied to the heater and temperature in the outlet air stream respectively. The input was generated

¹ This case and data are adopted from the "Build Simple Models" option under 'command line demos' of MATLABTM.

as a PRBS that switches from one level to the other with probability 0.2.

The system was implemented in windows platform using MATLABTM 6p5 and Microsoft AccessTM. GUI was developed in MATLABTM's development environment GUIDE. MATLABTM connects to Microsoft AccessTM through the database interface QUERYBUILDER. The functions used in the Matlab code given in Section 4.3 are implemented through *callback* functions and executed on command from the front end. Data is shared among the various windows using the windows handles structure available through the *guihandles* function of MATLABTM.

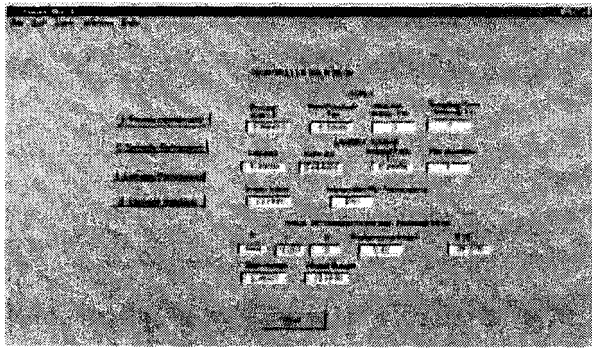


Fig. 4: The Controller Helpdesk Screen

5.1 Model Identification and λ -tune Parameters

Parameter identification of the process based on the input-output data was carried out using the "process identification" option in the main *Helpdesk* shown in Fig. 4. The following model resulted:

$$G(s) = 0.9974e^{-3s} / 5.4s + 1 \quad \text{----- (8)}$$

This yielded $K_c = 0.282$ and $T_i = 5.4$ for robust control and $K_c = 0.6445$ and $T_i = 5.4$ for tight control. The step response of the model developed is shown in Fig. 5.

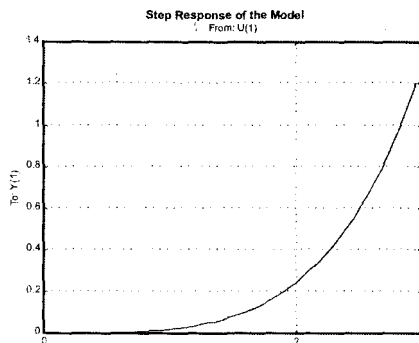


Fig. 5: Step response of the model developed

5.2 Performance Assessment

The Helpdesk facilitates computation of indices for performance specifications. The results of the experiment are tabulated in Table 1. When tuned for good stability, the gain margin (Gm) and phase margin (Pm) improved at the cost of performance index (PI). Similarly when tuned for good performance control, performance index improves but at the cost of stability.

Table 1: Hairdryer Heating Process PID Controller Tuning Results

Experiment	Kc	Ti	ITSE	PI	Gm	Pm
λ -Tune for good stability	0.282	5.4	95.59	12.843	11.89	82.49
λ -Tune for good performance	0.6445	5.4	21.279	6.51	5.2	72.87
Fuzzy Fine-Tuner results for [5,10]	0.422	5.4	44.629	9.076	7.9473	78.77

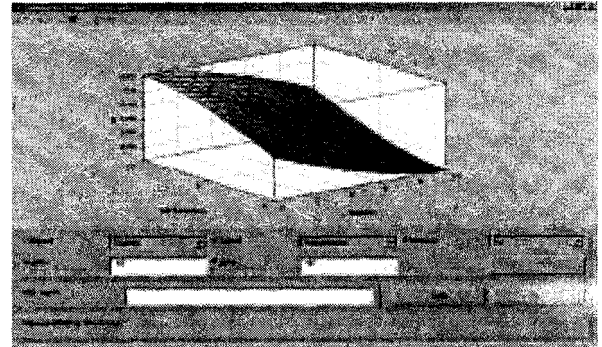


Fig. 6: MATLABTM surface plot showing stability, performance and controller gain relationship

5.3 Fuzzy Fine-tuning

Finally, parameters were determined by the Fuzzy Tuner which when simulated gives performance index and stability parameters proportional to the user demand. MATLABTM surface plot for performance, stability and K_c is given in Fig.6. In this application, the objective was to determine optimal parameters for K_c and T_i based on the requirement that "the controller should be very stable but moderately performing". The results of the analysis are given in row 4 of Table 1.

The figures for gain margin, phase margin and performance indices recomputed with the K_c and T_i values determined by the fuzzy tuner show a good

trade off between stability and performance according to the user requirement.

The system provides a very good support to the control engineer in performance related issues of control loops. However, the following limitations were observed:

- The system cannot accommodate processes, which are highly non-linear and regulatory processes with long time delay
- The system applies only to SISO systems
- The assessment of control structure based performance indices require disturbance of the process for obtaining input output data for model identification.

6. Conclusion

A fuzzy based decision support system was presented which provides basic support to a process control engineer for decision making on PID control performance related issues. Information pertaining to various performance parameters such as performance index, stability, idle index, presence of oscillation etc. are made available to the engineer to decide on measures for performance improvement. A fuzzy logic based tool for fine-tuning of control parameters translates application objectives into parameter values. The present work is limited only to SISO systems for servo applications. Further improvement is possible by extending the system for regulatory and multi input multi output (MIMO) systems. An intelligent database support to the system will further equip the user with historic trends that may be used to set alarm limits for performance and schedules of control loops for predictive and preventive maintenance.

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