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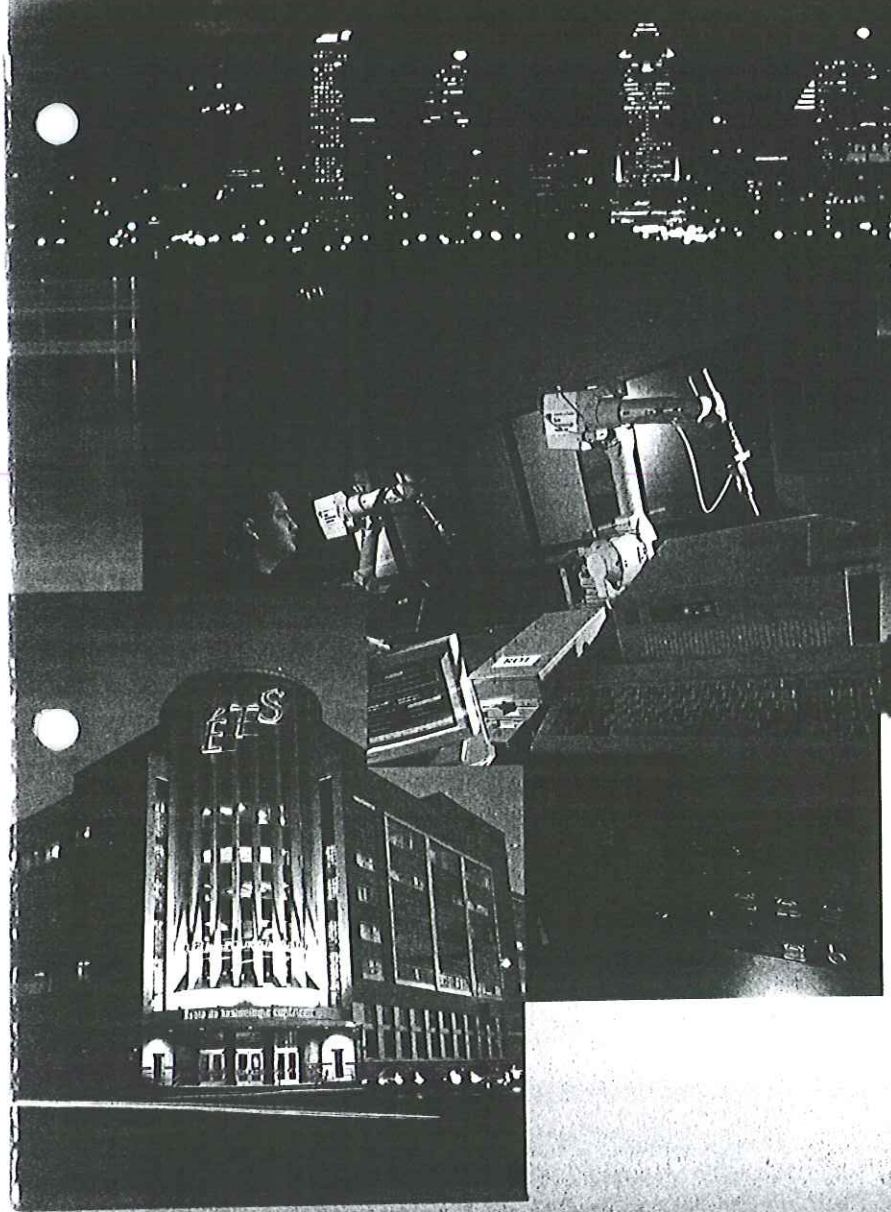
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OPTIMAL PID CONTROL OF A CHEMICAL BATCH REACTOR

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Abstract

RaPID (Robust Advanced PID Control) is a new and original design methodology for optimal PID controllers. It consists of a process modeling step with linear identification, followed by an optimal PID control design step based on engineering specifications. The design methodology is applied to a chemical continuously stirred tank reactor.

1. Introduction

PID controllers are the typical controllers at the lowest local level in industrial distributed control systems. Estimates indicate that more than 90 % of all controllers in the industry are PID. However in spite of the "lookup" tuning rules that have been around for more then 40 years [1,2] and the recent auto-tuning methods [3,4] a fraction of about 80 % is badly tuned and operates inappropriately or at least not optimally [5,6,7].

We believe this surprising fact originates in the typical limitations of auto-tuners and tuning rule control design strategies. These methods indeed break down for three major reasons: 1. The experiments are typically limited to simple step-like, open-loop experiments. 2. Through graphical inspection, a two or three parameter model is then obtained. These simple experiments and models are often too limited to capture all relevant dynamics of the process. 3. The control design based on these limited parameter models are straightforward strategies which allow no flexibility in the engineering specifications and present no alternative when they lead to unsatisfactory (unstable !) results.

The design method presented in this paper, which we call RaPID[1] solves these problems in a very elegant way. It differs from the classical auto-tuning methods in the following two major ways: 1. Instead of using simple, graphical methods based on step response data, we suggest to use state of the art identification algorithms to derive process models. These algorithms allow for input excitations different from steps, which again allows for shorter testing times. On top of that more detailed dynamic information can be extracted from the system with the modeling technique described in this paper. 2. We believe an efficient control design method should be able to capture the essence of the control design problem at hand. We propose to determine the PID control parameters based on engineering criteria such as overshoot, rise-time, settling time, load and/or disturbance rejection, energy consumption, robustness, maximal input signals, etc. Unlike the solutions offered by tuning rules, the final solution of RaPID is not based on heuristics but takes into account these engineering specifications through the solution of optimization problems.

Finally, an efficient design method should be applicable to a wide range of systems. We have applied the new PID tuning method proposed in this paper with succes in the chemical and petro-chemical industry, the metallurgy and pulp & paper industry where typically first order systems with dead time result as process models. We however applied the method also to fast and oscillatory processes in mechanical, electronic, mechatronic, hydraulic and pneumatic areas.

[1] RaPID stands for Robust Advanced PID control.

2. Theory

In this section we explain the theory behind the PID design methodology RaPID. As almost all design methodologies, it consists of a characterization of the process dynamics followed by an optimal control design step. In Section 2.1 we review the process modeling, while in Section 2.2 the control design method is explained.

2.1 Process Modeling

The process modeling step represents an important part of the RaPID design methodology. In the framework of PID design, this step is typically performed through eyeball methods or methods of moments, both based on step responses [4]. These models typically consist of two or three parameters, for instance the dead time, the time constant and the ultimate gain.

When using a simple look-up tuning rule, or another sim-

ple design method, these simplified models probably suffice. However, when the design of the controllers includes more sophisticated objectives (see Section 2.2), a more detailed model is needed.

Data processing
Before you can use the measured input-output data for *linear* identification, they have to be pre-processed. This step is needed, to make the data as *linear* as possible (since you want to identify a linear model). The pre-processing transforms the raw data into pre-processed data:

Integrator When you known in advance that the system contains an integrator (positioning systems, level controls), it is advisable to remove the effect of the integrator from the data before identifying the model.

Filtering In the next pre-processing step you can filter the data to get rid of unwanted disturbances in the data (noise, low frequency disturbances).

Ranging After the derivation and filtering, you should remove unwanted initial and end effects in your data.

Detrending In the final pre-processing step, you determine which point you want to dynamically linearize your process around. Basically you should use the working point of your process (the nominal values of input and output).

Model structure selection and optimization
Once the data is suitably pre-processed, a model should be identified. Important steps are the model structure selection and the model computation. We suggest to use the following discrete model structure:

$$K\, z^{-nd}\, \frac{(1 - z_1 z^{-1}).(1 - z_2 z^{-1}) \ldots (1 - z_{n_z} z^{-1})}{(1 - p_1 z^{-1}).(1 - p_2 z^{-1}) \ldots (1 - p_{n_p} z^{-1})} \quad , \quad (1)$$

with z^{-1} the backward shift operator: $z^{-1}u_k = u_{k-1}$, K the gain, n_d the number of samples delay, $z_1, z_2, \ldots, z_{n_z}$ the zeros and n_z the number of zeros and $p_1, p_2, \ldots, p_{n_p}$ the poles and n_p the number of poles.
As in classical system identification [8], the output error between the measured output (y_k) and the simulated output (y_k^s) using model (1) is minimized:

$$\min_{\mathcal{P}, y_O} \sum_{k=1}^{N} \left(y_k - y_O - y_k^s(\mathcal{P})\right)^2 \quad , \quad (2)$$

where $\mathcal{P}$ denotes the free model parameters $K, z_1, \ldots, z_{n_z}$, $p_1, \ldots, p_{n_p}$ and y_O denotes an additional constant offset on y_k to compensate for slight errors in the detrending.
Important issues for this optimization problem are:

- The initial model should be accurate to ensure fast convergence. The subspace methods described in [9] deliver such models.
- The number of poles n_p, zeros n_z and delays n_d such be chosen carefully.
- By choosing the poles and zeros as optimization parameters (1), the following constraints become easy to impose: the number of resonant poles and/or zeros, the stability of the model, the number of non-minimum phase zeros.
- To make the model acceptable in industry, as much as possible a-priori information should be included in the constraints of the identification problem.

2.2 Control Design

During the control design phase the following questions should be answered:

1. *Where will you implement your PID controller* (on which hardware platform) and *which type of controller will you implement* (a P, PI, PID, ..., with or without feedforward freedom) ? The answer to these two questions determines the structure of the PID controller and thus the freedom you have in designing the final controller.
2. *Which engineering criteria are important*: tracking or variance, rise time, settling time, energy, overshoot, robustness, ...
3. *Which reference, load and/or disturbance signals are involved* ?

The RaPID design methodology takes all of the above design constraints into account. We will not go into the details of the full controller design, however we will sketch the general lines here.

A first constrained optimization
We assume the controller structure has been determined and the free parameters to design the controller at hand have thus been identified. Typically, this set of parameters would consist of a proportional gain (K), an integral term (T_i) and a derivative term (T_d and N). On top of that, feedforward constants α and β could be included as follows:

$$U(s) = \underbrace{K\left[\alpha R(s) - Y(s)\right]}_{\text{Proportional}} + \underbrace{\frac{K}{T_i s}\left[R(s) - Y(s)\right]}_{\text{Integral}} + \underbrace{K T_d s\left[\beta R(s) - Y(s)\right]}_{\text{Derivative}} \quad (3)$$

In this first optimization step, we determine the maximal integrating action that can be tolerated in the loop, under a set of constraints. The idea of maximizing the integral contribution is not new and is due to Astrom and Hägglund [4]. One of the main motivations is that the integral of the error due to a load disturbance is inversely proportional to the integral gain $k_i = K/T_i$: $\int_0^\infty e(t) = \frac{1}{k_i}$. Maximizing k_i is thus equivalent to minimizing the integral error. There is however an implicit danger of maximizing the integral contribution, in a sense that the closed loop could become very oscillatory, positive and negative contributions could cancel). The following constraints are thus enforced during the optimization:

Robustness: The robustness constraint is enforced by keeping the Nyquist curve at a certain distance from the critical point -1. This corresponds to enforcing a guaranteed gain and phase margin [4] and thus the term "robustness".

High frequency gain: A second important constraint is the gain of the controller at high frequencies. This gain should typically be limited, since it determines the amplification of the noise at the process output towards the actuator input.

The optimization of k_i under the robustness constraint and high frequency constraint thus leads in this first step to a maximal integral action $k_i^{\max}$.

A second constrained optimization

It is not always the prime engineering objective to optimize the integral gain. So, in a second step, the following optimization problem is solved:

$$\min_{0 \le k_i \le k_i^{\max}} \mathcal{F}(k_i) \tag{4}$$

For the definition of $\mathcal{F}(k_i)$ assume for simplicity that the objective of the PID controller is to reject a load disturbance as "good" as possible. As a simple example, assume the load to be a step disturbance entering at the process input. The error at the output e_k due to this load disturbance is a function of the integral gain k_i and also of the remaining controller parameters K and K_d (3). We denote this error sequence with $e_k(K, K_d, k_i^*)$, where we replaced k_i with k_i^* to indicate the "fixed" nature of this parameter. We can now define $\mathcal{F}(k_i^*)$ in many different ways, of which we only give two examples here:

- When the Integral Time Absolute Error is important, the following definition of $\mathcal{F}(k_i^*)$ is relevant: $\mathcal{F}(k_i^*) = \min_{K,K_d} \sum_{k=0}^{\infty} |e_k(K, K_d, k_i^*)|$ where the minimum is computed under the robustness and HF gain constraints.
- When the overshoot when recovering from the load disturbance is important, the following definition of $\mathcal{F}(k_i^*)$ is relevant: $\mathcal{F}(k_i^*) =$ Overshoot of $e_k(K, K_d, k_i^*)$, where K and K_d are determined from the optimization problem: $\min_{K,K_d} \sum_{k=0}^{\infty} [e_k(K, K_d, k_i^*)]^2$ where the minimum is computed under the robustness and noise constraints.

These definition can be easily extended to settling time, rise time and other types of control relevant objectives.

3. Application to a Chemical Reactor

We illustrate the advantages of the RaPID design methodology with an application to a chemical batch reactor. The data of this batch reactor in the harbor of Antwerp has been scaled for reasons of secrecy. The PID controller has to move the reactor temperature of this exothermal reaction from 70 to 88 degrees. This is done with an actuator in split range: above 66 % the reactor is heated with steam, below 66 % the reactor is cooled with water.

In a first step, the temperature loop was taken manually and the reactor was excited by alternating between heating and cooling. Figure 1 shows the measured signals.

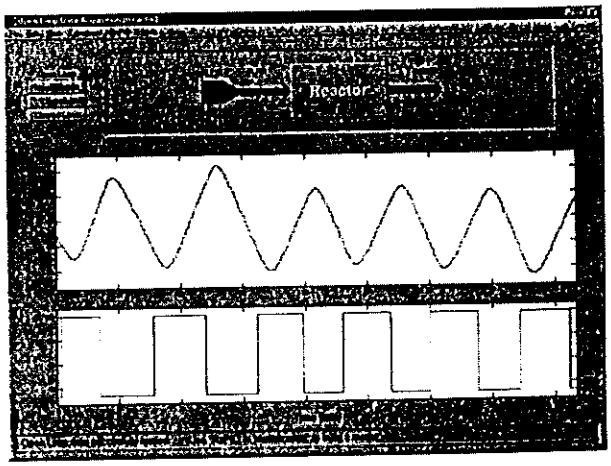


Figure 1: Measured signals on the chemical batch reactor.

In a second step, a linear model is built from the data in Figure 1. Note that classical graphical inspection modeling methods would fail on this type of data. Figure 2 shows the measured and simulated temperature using the methodology described in Section 2.1. The delay is set equal to 1 minute, while the number of poles is two and there are no zeros.

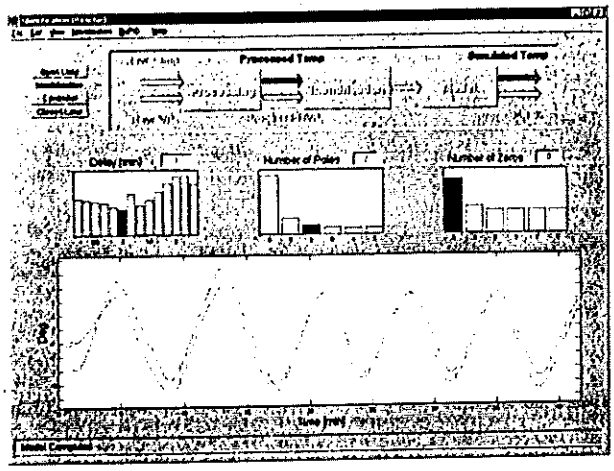


Figure 2: Process model for the reactor.

In a third step a the linear model is used to compute an optimal controller. In this case the controller had to move the reactor temperature from 70 to 88 degrees, with a minimal settling time and a maximal overshoot of 3 %. Furthermore was the robustness parameter M_s set to 1.3, which corresponds to a guaranteed phase margin of 45 degrees and a gain margin of 12 dB [4]. The high frequency gain, which determines the amplification of the output measurement noise was set to 6. With measurement noise of 0.1 degrees this led to a dither of 0.6 % on the valve, which was acceptable. Figure 3 show the resulting controller.

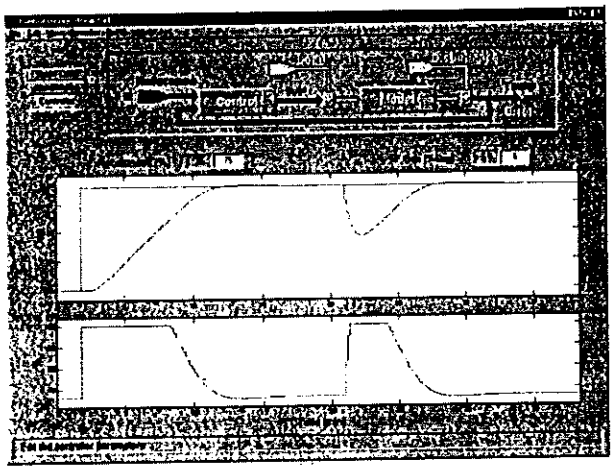


Figure 3: Designed controller using the linear model to simulate the responses. The top figure shows how the temperature reacts to a setpoint response from 70 to 88 degrees. Note how the overshoot is limited to 3 %. The second part of the signal shows how the system reacts to a load. The bottom figure shows the valve position.

The implementation of this controller on the reactor lead to a reduction in the temperature oscillations of 20 %. Which in its turn lead to a reduction in cooling and heating actions. Reduced energy and maintenance was the economical consequence.

4. Conclusions

In this paper we sketch a systematic way to optimize PID controllers. In a first step a process model is constructed from arbitrary input-output data of the process using state-of the art identification algorithms. In a second step, the PID design procedure is explained. It consists of a sequel of optimization problems, which allows to formulate the specification of the controller as engineering relevant objectives. Finally the applicability of the RaPID methodology has been illustrated on a chemical batch reactor, which has to be temperature controlled.

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