RaPID, Robust advanced PID control.

PID tuning based on engineering specifications

Introduction

The unquestionable importance of the PID controllers in the process industry is explained by its capacity to stabilize and control around 90% of the existing processes. This importance is often shadowed by its lack of performance in some applications. Many authors had reported that a significant percentage of the installed PIDs are operated in manual mode and 65% of the loops operating in automatic mode generate more variance in closed loop [1][2]. This lack of performance is in many cases the result of a poorly tuned set of parameters. The poor tuning is explained by different factors:

- Lack of knowledge of the operators and commissioning personal.
- Tuning methods are too generic and based on ad-hoc criteria, which does not match specific process needs.
- Difficulties to tackle the real cause of the poor behavior of the loop (valve problems, sensor failures, or poor controller tuning).
- The large variety of parameter denomination and representation introduces errors during the application of tuning rules.

These challenges motivated the development of a software package to tune PID controllers. The software is a very intuitive tool with different levels of complexity that can be accessed according to the knowledge of the person commissioning the loop.

This article describes this software tool and provides an insight on the methods and algorithms used to make the tuning of the PID loops. The structure of this article reflects the phases that are followed during a tuning exercise using the tool.

Project Description

This is the first step of the project and it is very important because it defines the main elements of the project. The user must provide the basic information about the control loop such as sampling time, ranges, units, names and descriptions of the setpoint, the controlled variable and the manipulated variable. These definitions are very important because they help to interpret sampled data in a correct way and define already the limits of the variables providing the constraints of the problem and a correct scaling.

Two other important elements are defined in this phase of the project. The objective that must be achieved once the PID is tuned (either disturbance rejection or setpoint tracking) and the template of the controller. The template of the controller contains the information of the parameters of several commercial PID controllers available as stand-alone units or integrated in DCS (Distributed Control Systems) units. The templates are from the most common manufacturers such as Siemens, Emerson, Omron, Honeywell, etc. The use of the templates brings a couple of advantages. The first advantage is related to the exact knowledge of the structure of the controller allowing the tool to squeeze the maximum potential of the real controller. The second advantage is the elimination of manual calculation of the controller parameters from the traditional *Kp, Ti*, and, *Td* into the parameters used by the manufacturer. The elimination of this phase reduces the chances of errors during the conversion, scaling and typing of the parameters and allows the user to work along the project in engineering units and not in scaled values.

Collection of Process Data

Once the elements of the project have been decided, RaPID requires the execution of an input-output experiment in order to identify the dynamics of the plant. Experiments are costly because they demand the interruption of the normal operation of the plant, for this reason RaPID integrates a complete set of inputs which can be customized according to the conditions of the process by adjusting parameters such as amplitude and DC content. Also the user can create its own input signal. The predefined input signals available in the product include step-like (step, block, polynomial step and saturated ramp), impulse input, sine wave (including single sine, swept sine and multi-sine) and noisy inputs of two types random Gaussian and PRBNS (Pseudo Random Binary Noise Sequence). The use of each type of signal present some advantages and disadvantages discussed in Table 1.

The signals from the experiment can be loaded in the program via files or using an OPC connection to the process computer. The OPC connection allows a reading and writing connection: the MV signal for the experiment can be designed in RaPID and send to the DCS/controller via OPC. The CV signal is then read back and used for the identification.

Identification

RaPID includes a powerful algorithm for system identification [3][4] complemented with a very intuitive user interface (see Figure 1). Once the signals from the experiment are acquired, RaPID sweeps over a set of different structures where different delays and numbers of poles and zeros are tested. The model with the best fit is automatically selected. The algorithm is capable of detecting integral effects on the dynamics. The algorithm applies an automatic preprocessing where the offset of the signals is automatically removed.

More elaborated options include the filtering of the signals using low pass, high pass, band pass and band stop filters. The filters can be configured by selecting the cut-off frequencies (described in hertz) and the order of the filter. All changes can be previewed before being applied.

Other parameters that can be set are the maximum delay, maximum number of poles and zeros. In many cases the operator has a good idea of the DC gain of the process; such prior knowledge can be integrated by imposing some limits on the DC gain of the model. Other options include the presence of resonant poles and anti-resonant zeros and non-minimal phase zeros. The user can test different models using a single click and the model can be evaluated in different ways, graphically by comparing the simulated response with the real response, and numerically using an error index in percentage, which measures the portions of the output signal which are not correctly explained by the model.

The models are identified as discrete time models; however the results are shown in a continuous representation because the continuous transfer function is more informative.

Control Design

Traditionally the tuning of PIDs has been performed using methods that already prescribe the shape of the closed loop step response; once the method was applied a process of trial and error was applied in order to achieve the desired response very often sacrificing the robustness provided by the original parameters proposed by the method.

RaPID reformulates the problem of control design as a constrained optimization problem. This reformulation brings as a benefit a controller designed to fulfill a desired time response while the robustness is still guarantee. As in any constrained optimization three elements must be defined:

1. Objective and structure
2. Cost function
3. Constraints

These elements are described in the following sections and they are defined as: Control objective and control structure, optimization criteria, and constraints. The selection of the criteria, control objectives, and constraints can be done via the user interface as shown in Figure 3 and Figure 4. The flexibility of the user interface allows an interactive design of the controller where any reformulation of the objectives and constraints is only one click away.

Control Objective and Control Structure

The control objective is decided by the user according to the application. There are two different objectives that can be pursued with the controller tuning:

1. accurately follow a reference signal, the so called *tracking* of a reference
2. keep as constant as possible the output of the system and recover as quickly as possible from load and disturbance changes, the so called *variance control*.

In order to achieve these objectives RaPID will optimize the parameters of the PID: K_P, K_I, K_D, K_{DD} and the parameters of the feed-forward action α, β and γ; where the representation of the controller is given by the formula (1.1) and a scheme is shown in Figure 2

$$\begin{aligned} U(s) &= K_P(\alpha R(s) - Y(s)) + \frac{K_I}{s}(R(s) - Y(s)) \\ &\quad + K_D \frac{s}{s+p_d}(\beta R(s) - Y(s)) + K_{DD}\frac{s^2}{\left(s+p_d\right)^2}(\gamma R(s) - Y(s)) \\ &\quad + \text{manual reset.} \end{aligned} \tag{1.1}$$

According to the control objective, the elements of the controller can be tuned to achieve the objective. Table 2 shows the function of each of the elements of the controller for the different control objectives. For instance, if the control objective is tracking, both the feedback and the feedforward parameters will be optimized to achieve a good tracking. On the other hand if the objective is to achieve at the same time tracking and variance rejection, the feedback parameters will focus on the variance rejection meanwhile the feed forward parameters will aim the tracking objective.

Optimization Criteria

The control objective and the structure (template) of the controller have already been selected. The next step is the selection of the criteria to evaluate the controllers along the optimization. There are two types of criteria, time defined criteria and overall error criteria. The time defined criteria attempt the minimization of the time needed to reach a given point of the step response. RaPID includes the following time defined criteria:

- **Settling time**: RaPID will find a set of parameters such that the settling time of the closed loop system with a step reference is minimized.
- **Rise time:** RaPID will find a set of parameters such that the rise time of the closed loop system with a step reference is minimized.

The overall error criteria evaluate the error signal (reference minus output) over a period of time (N samples), while a step signal is applied to the reference (see Figure 5). The idea is to consolidate in one number the total deviation between the reference and the output of the system. The indicators used by RaPID are:

- **Integrated absolute error** (IAE). This criterion calculates the integral of the absolute value of the error. Since the calculations are discrete the integral is transformed into a sum that cumulates over N samples the absolute value of the error

$$IAE = \sum_{k=1}^{N} \left| e_k \right|.$$

- **Energy**. This criterion calculates the sum of the squared error. Observe that squaring the error means that large values of error will be more amplified. Therefore the impact of applying this criterion will be a limitation of the large error components.

$$Energy = \sum_{k=1}^{N} e_k^2.$$

- **Integrated time multiplied by the absolute value of error** (ITAE) This criterion focuses mainly on the minimization of the steady state error since the penalty for deviating increases as time progress. The discrete representation of this criterion calculated over N samples is:

$$ITAE = \sum_{k=1}^{N} k \left| e_k \right|.$$

Optimization Constraints

Optimizing the parameters of the controller using only the optimization criteria will result in a controller that performs very well for the given model of the plant, but probably will be a non realistic controller that will violate the saturation limits of the actuator, probably will not be robust and will be sensitive to measurement noise. Additionally the user can be interested in limiting the overshoot of the step response of the closed-loop system. All these elements motivate the inclusion of a set of constraints in order to obtain a reliable set of parameters for the controller. These constraints are summarized in the next lines:

Overshoot

This constraint represents the maximum overshoot that is allowed when a reference signal is changed. This constraint is evaluated only for tracking purposes.

Saturation

Actuators are physically limited (e.g. valve openings are limited between 0 % and 100 %) and in the same way the output of the controller must be limited. Including this constraint will restrict the actions of the controller to the real limits avoiding the triggering of anti-windup mechanisms, which result in poor performance and risk of instability.

High Frequency Gain

This constraint aims to limit the impact of the high frequency measurement noise in the actuator. This can be done by limiting the high frequency gain of the controller (see Figure 6).

In order to illustrate the impact of the high frequency gain (HF-Gain) of the controller, let us assume an example of a room heating. The goal is to maintain the room temperature at 20°C. The temperature measurement has 0.2°C of measurement noise. The actuator, in this case is the heater, which is operated between 0% and 100%. In wintertime the heater is operating at 60% to maintain 20°C. Assuming a HF-Gain of 100 and since the measurement noise has a 0.2°C amplitude, then the controller output due to the noise will be (maximally) 0.2 °C * 100 = 20 %. This means that the actuator will be changing from 40% till 80% just because of the measurement noise. If the HF-Gain were 200 then this would result in a 40% action, which force your actuator from 60%-40% = 20% till 60% + 40% = 100%. The actuator will be driven into saturation only by the

noise. This is of course an undesired effect, since the measurement noise is not a real variation in temperature. Although the variation is not real, the heater acts 100%!
If the HF-Gain is 1, then the same measurement noise will result in only 0.2% heating variation (instead of 100% in the previous case!). In this case the controller action is far less sensitive to the noise.

The selection of the maximum HF-Gain is a trade-off between the speed of the controller and its sensitivity to the noise. If the HF-Gain is selected too small the controller will react slowly in tracking and variance control. So for improvement of the controller speed, the HF-Gain should be as large as possible, which is the opposite trend of what one would do to reduce the noise sensitivity.

Robustness

Another constraint is robustness. A controller is called robust if its performance does not degrade if the system itself is slightly altered. Robustness can also be interpreted as a measure for how well the controller performance is maintained despite modeling errors.

RaPID uses the identified model for calculations of the PID-controller. However, this linear model is only an approximation of the real plant. If the model has significant deviations from the real plant, the performance of the controller designed on this approximated model, is not guaranteed on the real plant. Only when the controller, calculated on this approximated model is robust, the optimized PID-values will not only be functional on this approximation but also on the real plant.

Once more there is a trade-off between robustness and controller speed. Robustness is expressed as a percentage: 0% means a critical stable controller, and 100% means an extremely robust but slow controller.

RaPID uses the robustness as a constraint in the optimization. This means that the computed parameters will correspond to a controller with the required robustness or even higher.

Different measures of robustness exist. Well-known measures are Gain Margin and Phase Margin. Another measure of robustness can be read from the Nyquist plot. This kind of robustness is used in RaPID. The Nyquist plot shows the transfer function in the complex plane, for frequencies varying from 0 till infinity. Since all continuous systems have gain 0 at an infinite frequency, the end point of the Nyquist curve lies always at the origin. In order to guarantee stability the Nyquist curve must not encircle the point -1 in the complex plane (for stable systems). The distance of the Nyquist curve to the point -1, is proportional to the robustness. For a distance equal to zero, the Nyquist curve passes through -1, which corresponds with a marginally stable system (0%).

The maximal distance from the point -1 is 1 since the Nyquist curve always ends up in 0. This corresponds with an extremely robust controller (100%). During the optimization the Nyquist curve is pushed away from the -1 point. In fact it should remain outside a circle with a radius corresponding with the desired robustness.

In RaPID a parabola replaces this circle, such that the Nyquist curve (if it remains outside this parabola) can never encircle the -1 point. An example of the Nyquist curve and the parabolic constraint is shown in Figure 7. This constraint guarantees that RaPID will never find an unstable PID-controller.

Example of an Industrial Application:

Tuning a Furnace Outlet Temperature Controller with RaPID

RaPID allows the user to perform system identification and PID tuning based on engineering specifications in a very intuitive and consistent way. Here the system identification and optimal tuning with RaPID of a furnace outlet temperature (FOT) PID controller is described. The furnace is a part of the reformer unit of the refinery plant of BRC (Belgian Refining Company) in Antwerp Belgium. First the reformer process is briefly discussed. Subsequently the different steps performed in RaPID for the tuning of the FOT are described. Finally, the significant improvement of the control performance after tuning the FOT controller with RaPID is illustrated.

Process Description

The objective of the reformer unit is to increase the octane number of the feed. At the same time the reformer produces hydrogen for other units of the refinery. The main reformer reaction is the catalytic dehydrogenation of naphtenes in the feed into aromates. This conversion is performed in the reactor section of the unit which consists of three preheat furnaces and reformer reactors in series as depicted in Figure 8. Accurate control of the FOT is crucial to obtain stable conversion, avoid undesired side reactions (hydrocracking) and optimize the lifetime of the reformer catalyst.

Project Definition

A simplified control scheme of the furnace is depicted in Figure 9. The FOT controller (TC) acts as a master controller for a fuel-gas flow controller (FC).

In the project definition stage of RaPID the correct loop settings (units, ranges), sampling time and controller template are selected (Figure 10). The control of the reformer unit is implemented on a Yokogawa CS3000 DCS system, therefore the corresponding controller template is selected to obtain directly the PID parameters in the correct format for the DCS. The main objective for the FOT controller is the reduction of variance around the setpoint caused by disturbances.

Data Acquisition

Before the tuning of the FOT controller, the fuel-gas flow controller was tuned with RaPID to obtain optimal tracking performance: the objective of this fuel-gas flow controller is to follow the changing setpoint, dictated by the FOT master controller, as accurate as possible. With this fast acting slave controller cascaded to the FOT, the FOT was put on manual mode and the output of the FOT controller was stepped. The signals of this open loop step response of the FOT were acquired online in RaPID by means of an OPC connection (Figure 11).

The data preprocessing tools provided in RaPID allow the user to modify the raw test-data before the system model is identified. Filtering of the signals, removing and replacing bad slices in the dataset and other preprocessing actions can be performed by the user in RaPID to improve the quality of the test-data if required.

Identification

Based on the acquired test data RaPID automatically identifies the system model that describes the dynamic and static behavior of the FOT open loop (Figure 12). RaPID selected a model with 2 poles and 20 seconds delay for the FOT open loop system.

Control Design

Once the system model is identified, this model will be used in the control design stage to find the optimal PID parameters for the FOT controller. Disturbance rejection was defined as the main controller objective for the FOT controller. Changes of the feed to the furnace and density changes of the fuel-gas are the main cause of disturbances for the FOT control loop. These disturbances are taken into account when RaPID performs the optimization of the PID parameters. In this case a step-like disturbance is defined by the user in order to simulate the effect of a sudden feed change or change of fuel-gas density (Figure 13).

The default criterion, integrated absolute error (IAE), is used for the optimization of the PID parameters. The HF gain was selected by the user in such a way that the amplification of noise on the temperature signal to the actuator (in this case the setpoint of the fuel-gas controller) is still acceptable (0.5 %/deg). A noise signal was added to the FOT (controlled variable) signal to make the closed loop simulation more realistic.

The load of the furnace can change significantly over time. To assure good control performance in such circumstances, a relatively high robustness (94%) was selected by the user to obtain a robust control design.

The performance of the original PID settings and the RaPID tuning for the FOT controller can be compared easily in RaPID with closed loop simulations. Figure 14 clearly indicates that the response of the original PID controller is significantly more sluggish than the tuning obtained with RaPID.

Validation of Control Performance

After implementing the tuning settings obtained with RaPID on the DCS the significant improvement of the control performance of the FOT is confirmed on the real plant data. Figure 15 illustrates this significant variance reduction of the FOT after the tuning with RaPID.

Comparable variance reduction is achieved for the FOT controllers of the other furnaces resulting in more stable operation of the reformer reaction section, which allows higher average octane numbers for the product flows and increasing hydrogen yields without faster degradation of reformer catalyst.

Conclusions

RaPID is a tool that has been applied to hundreds of PID loops ranging from mechanical systems to process control loops and embedded applications. Power plants, refineries, chemical plants, food and beverages plants are just to mention some of the companies that benefit with the use of this methodology for PID tuning.

Among the benefits brought by the use of RaPID are the increase in stability and safety in the plant with a direct impact on productivity. The robustness of the calculated controllers is the most likely explanation for the success of the applied solutions. Reduction in down times due to actuator failures has also been observed, this improvement is explained by the limitation of the impact of the sensor noise in the control actions, thanks to the limits on the HF-Gain of the controller. Energy savings and increments in production have been reported and they are explained by the variance reduction.

The current user interface of RaPID reflects the feedback provided by operators and engineers along many projects make of RaPID a product that is ready to use.

References

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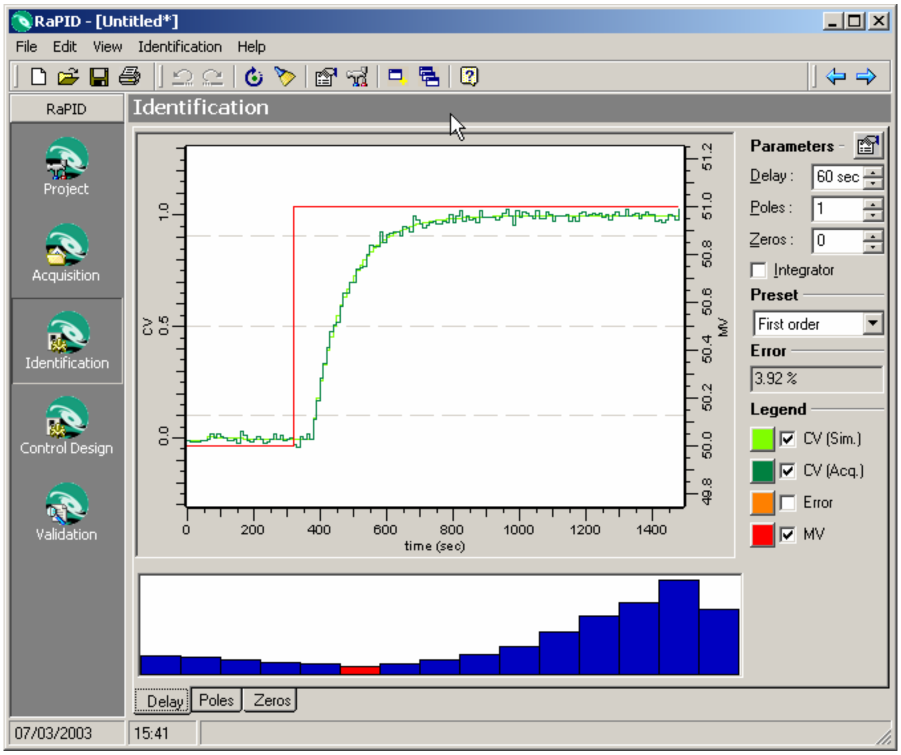
Table 1 Advantages and Disadvantages of the different types of excitation signal.

Signal Type	**Advantages**	**Disadvantages**
Step-like	• Easy to apply • Provides a visual delay detection • Provides a visual idea of the order and dynamics	• Limited frequency content • A non zero DC mean • Bad S/N ratio for some frequencies
Impulse input	• Broad spectrum • Provides a visual delay detection • Provides a visual idea of the order and dynamics	• Poor S/N ratio
Sine wave (including single sine, swept sine and multi-sine)	• Broad spectrum • Signal has zero DC mean	• Not easy visual detection of delay and systems order
Noisy inputs	• Broad spectrum • Signal has zero DC mean • Easy to apply	• Not easy visual detection of delay and system order

Table 2 Function of the sections of the controller in order to achieve the control objective.

	Controller Objective		
	Tracking	Variance	Variance+Tracking
Feedback	T	V	V
Feedforward	T		T

Function:
T: Tracking action
V: Variance action



Parameters

Delay : 60 sec

Poles : 1

Zeros : 0

☐ Integrator

Preset

First order

Error

3.92 %

Legend

🟩 ☑ CV (Sim.)

🟩 ☑ CV (Acq.)

🟧 ☐ Error

🟥 ☑ MV

Figure 1 Identification panel of RaPID. The dark green signal is the measured signal (output), the light green signal is the identified model and the red line is the manipulated variable (input).

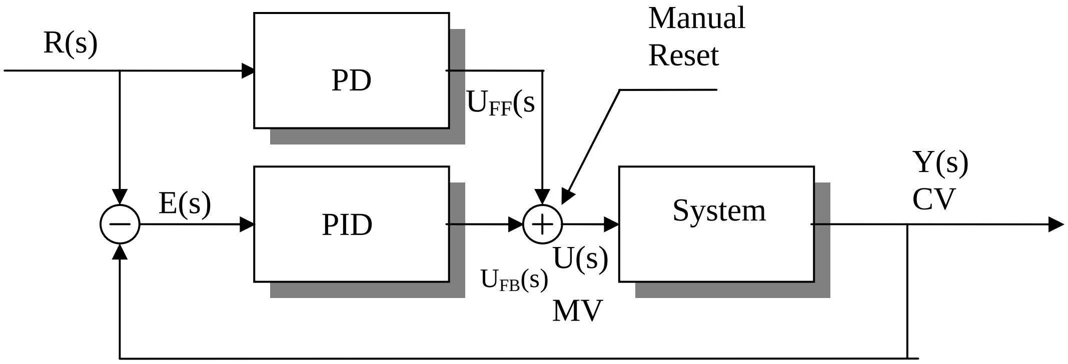
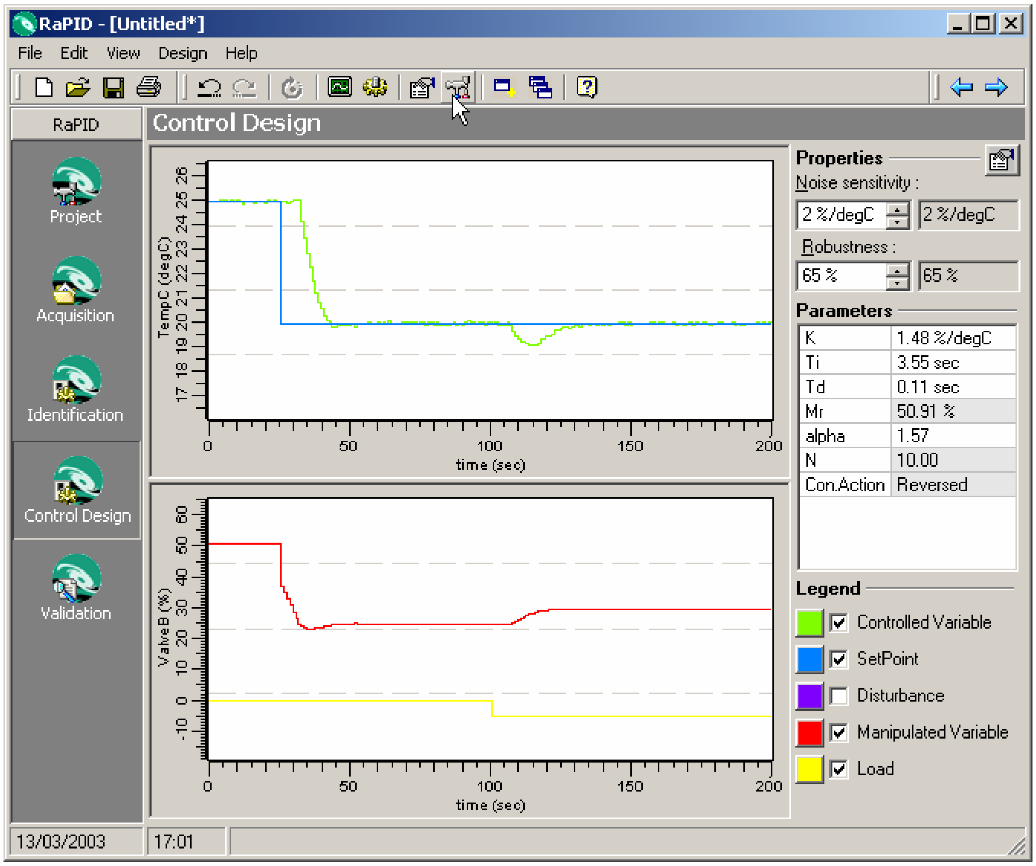


Figure 2 General PID-control with feedforward PDD-action and Manual Reset.



Properties

Noise sensitivity : 2 %/degC 2 %/degC

Robustness : 65 % 65 %

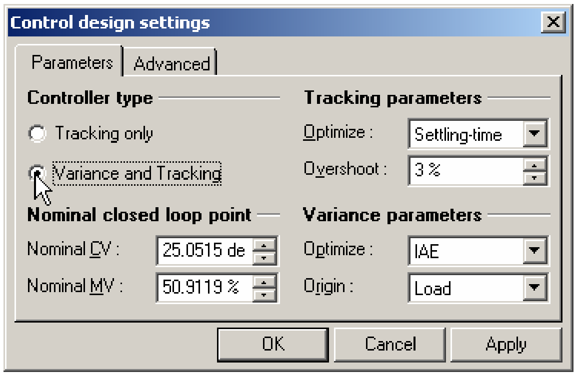
Parameters

K	1.48 %/degC
Ti	3.55 sec
Td	0.11 sec
Mr	50.91 %
alpha	1.57
N	10.00
Con.Action	Reversed

Legend

- 🟩 ☑ Controlled Variable
- 🟦 ☑ SetPoint
- 🟪 ☐ Disturbance
- 🟥 ☑ Manipulated Variable
- 🟨 ☑ Load

Figure 3 User interface for controller optimization. Observe that under properties the user can define the constraints on HF-gain or noise sensitivity and on robustness.



Controller type

○ Tracking only

● Variance and Tracking

Tracking parameters

Optimize : Settling-time

Overshoot : 3 %

Nominal closed loop point

Nominal CV : 25.0515 de

Nominal MV : 50.9119 %

Variance parameters

Optimize : IAE

Origin : Load

Figure 4 User interface for controller optimization. This window defines the control objectives, the cost function and the overshoot constraints.

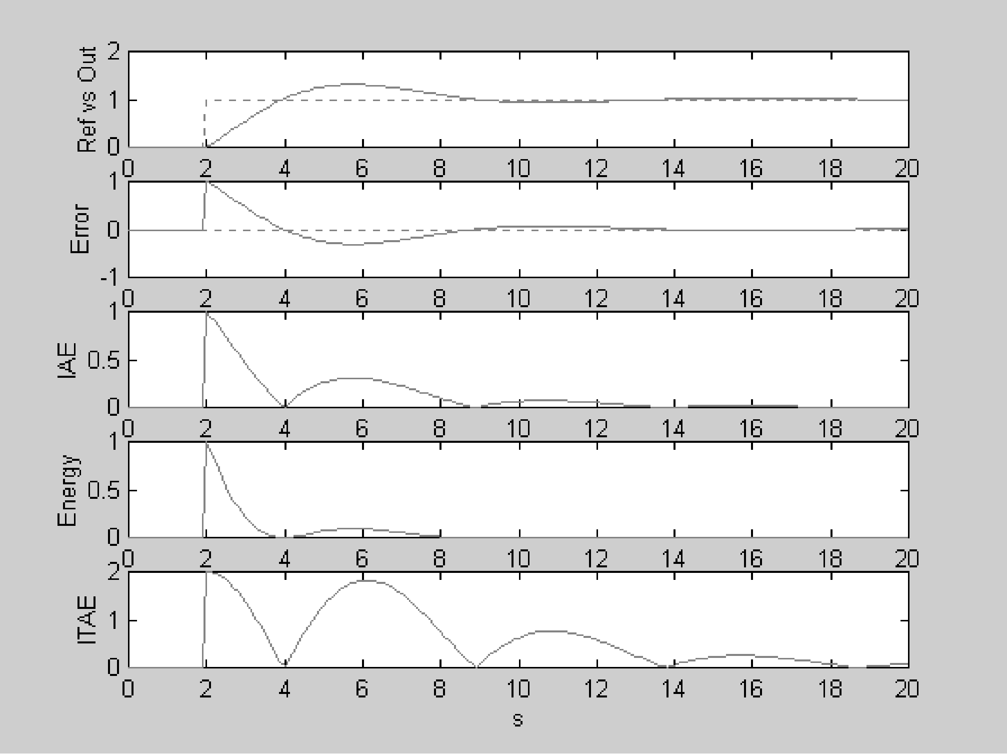


Figure 5 Error based optimization criteria.

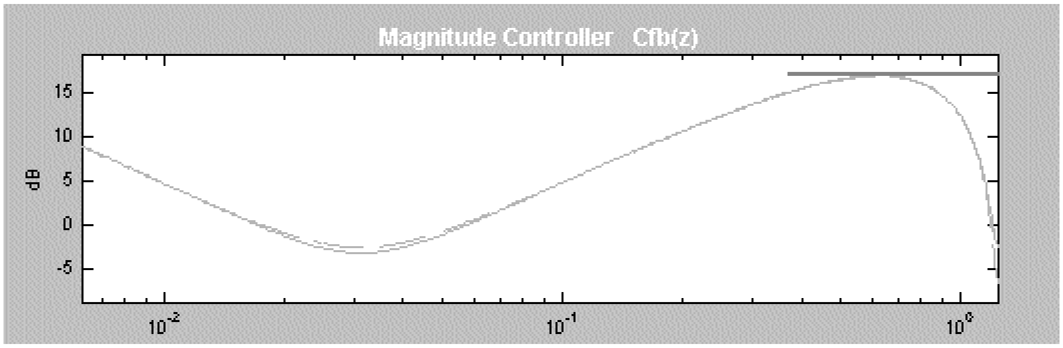


Figure 6 Bode Plot and the constraint on the controller for high frequency gain.

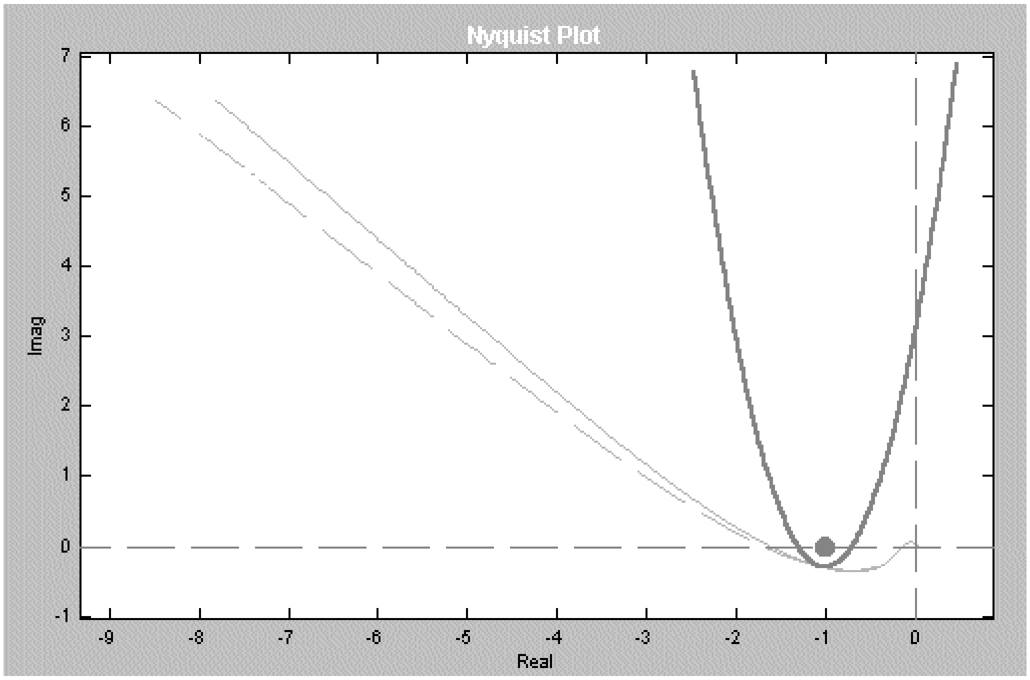


Figure 7 Nyquist plot and the parabolic robustness constraint.

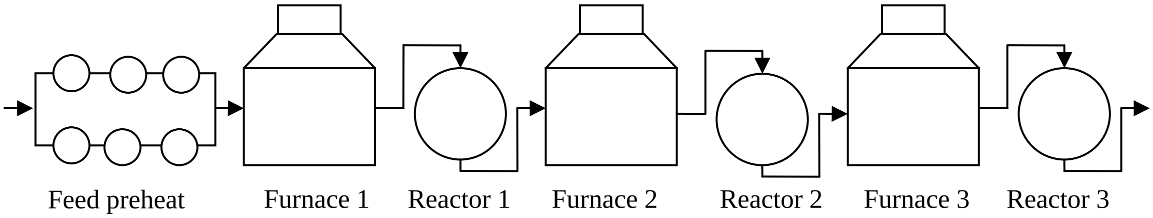


Figure 8 Flow scheme of the reaction section of a reformer unit.

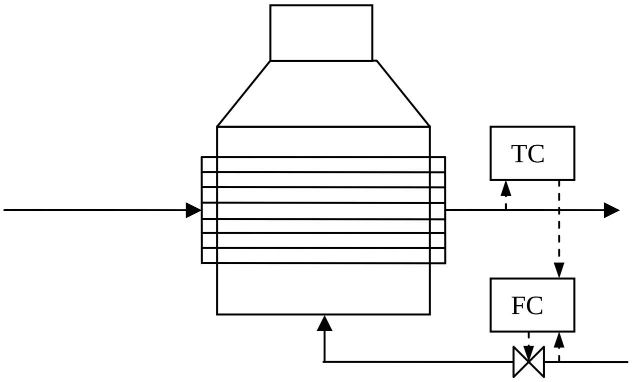
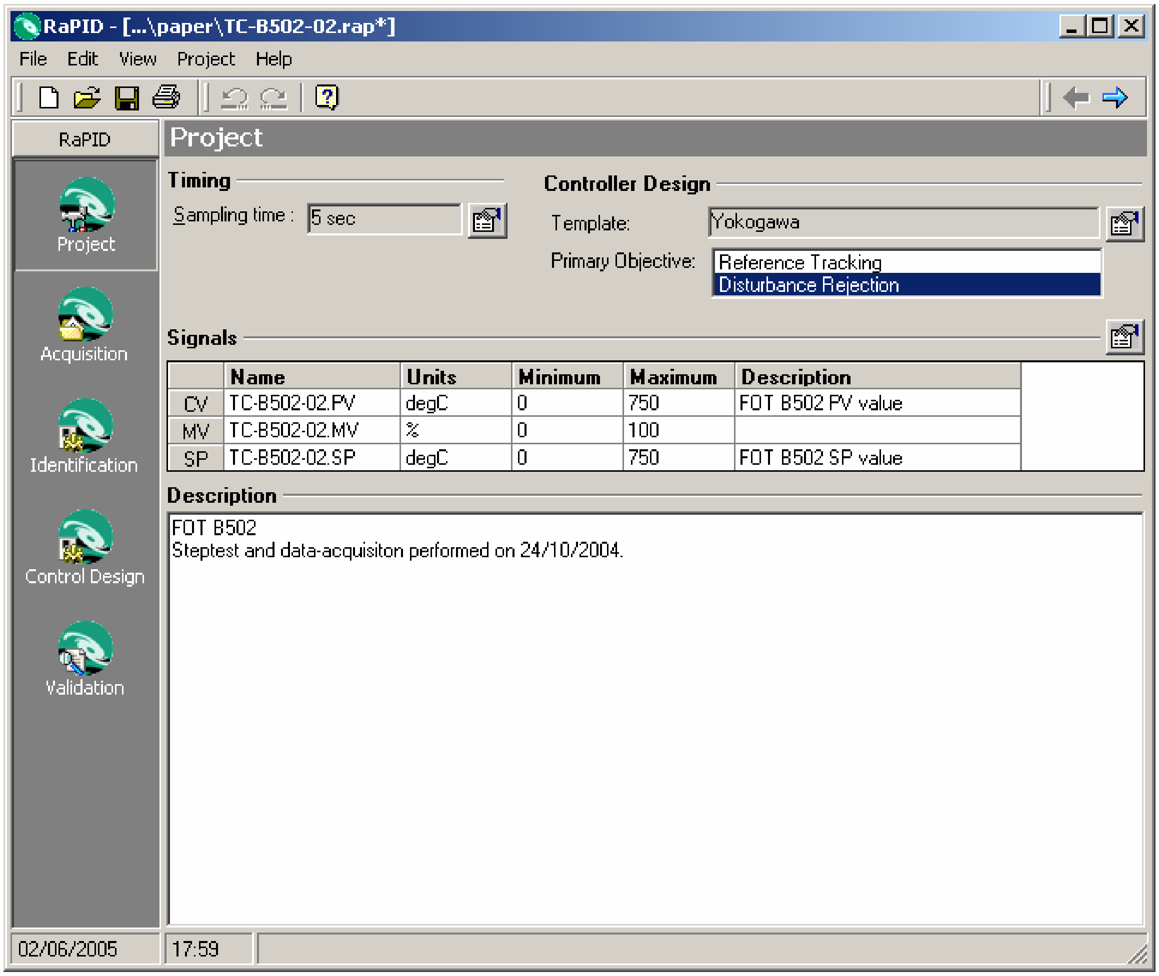


Figure 9 Simplified control scheme of the second reformer furnace. The furnace outlet temperature controller (TC) is master of the fuel-gas flow controller (FC).



Sampling time : 5 sec

Template: Yokogawa

Primary Objective: Reference Tracking / Disturbance Rejection

	Name	Units	Minimum	Maximum	Description
CV	TC-B502-02.PV	degC	0	750	FOT B502 PV value
MV	TC-B502-02.MV	%	0	100	
SP	TC-B502-02.SP	degC	0	750	FOT B502 SP value

FOT B502
Steptest and data-acquisiton performed on 24/10/2004.

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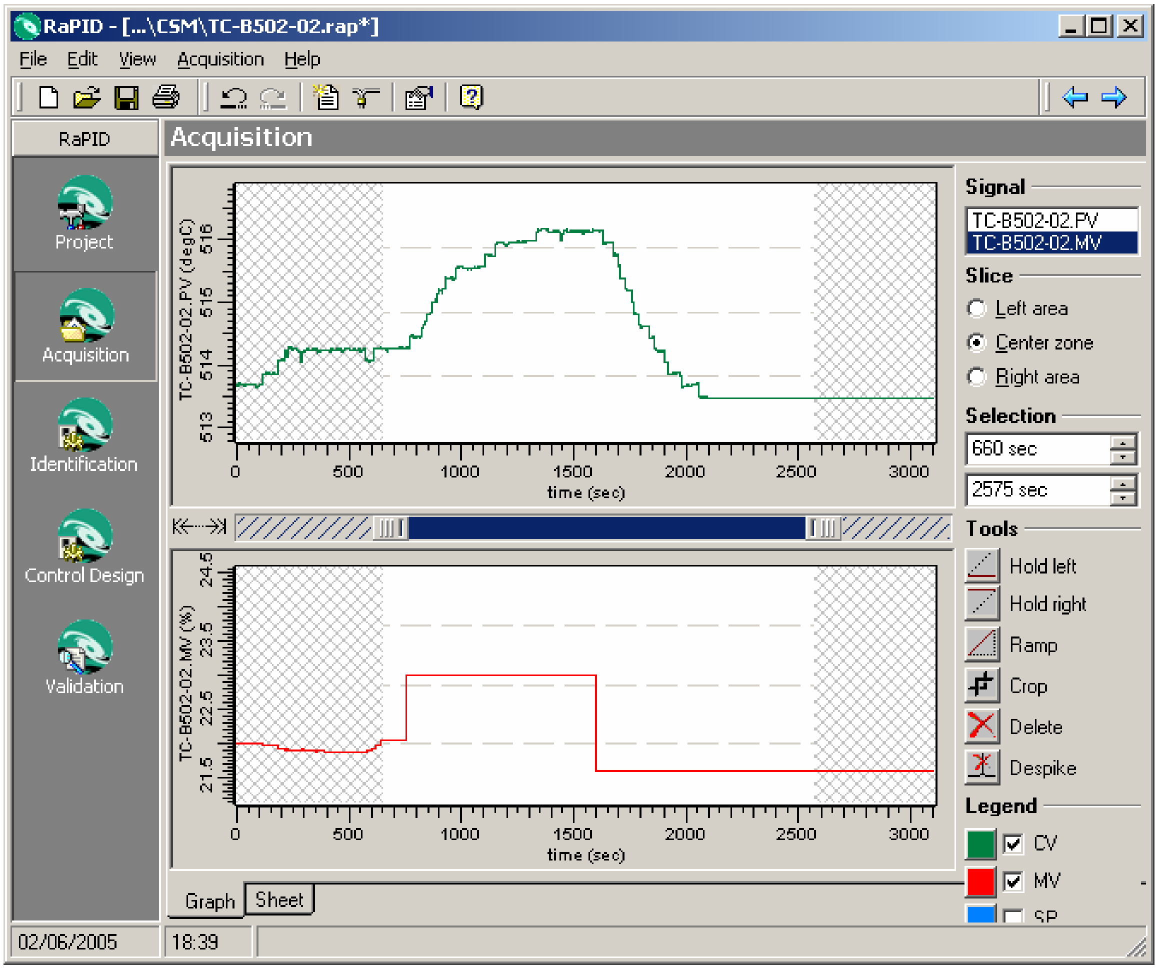
Figure 10: Project definition of the furnace outlet temperature controller (TC-B502-02).



Signal: TC-B502-02.PV, TC-B502-02.MV

○ Left area
● Center zone
○ Right area

Selection: 660 sec, 2575 sec

🟩 ☑ CV
🟥 ☑ MV
🟦 ☐ SP

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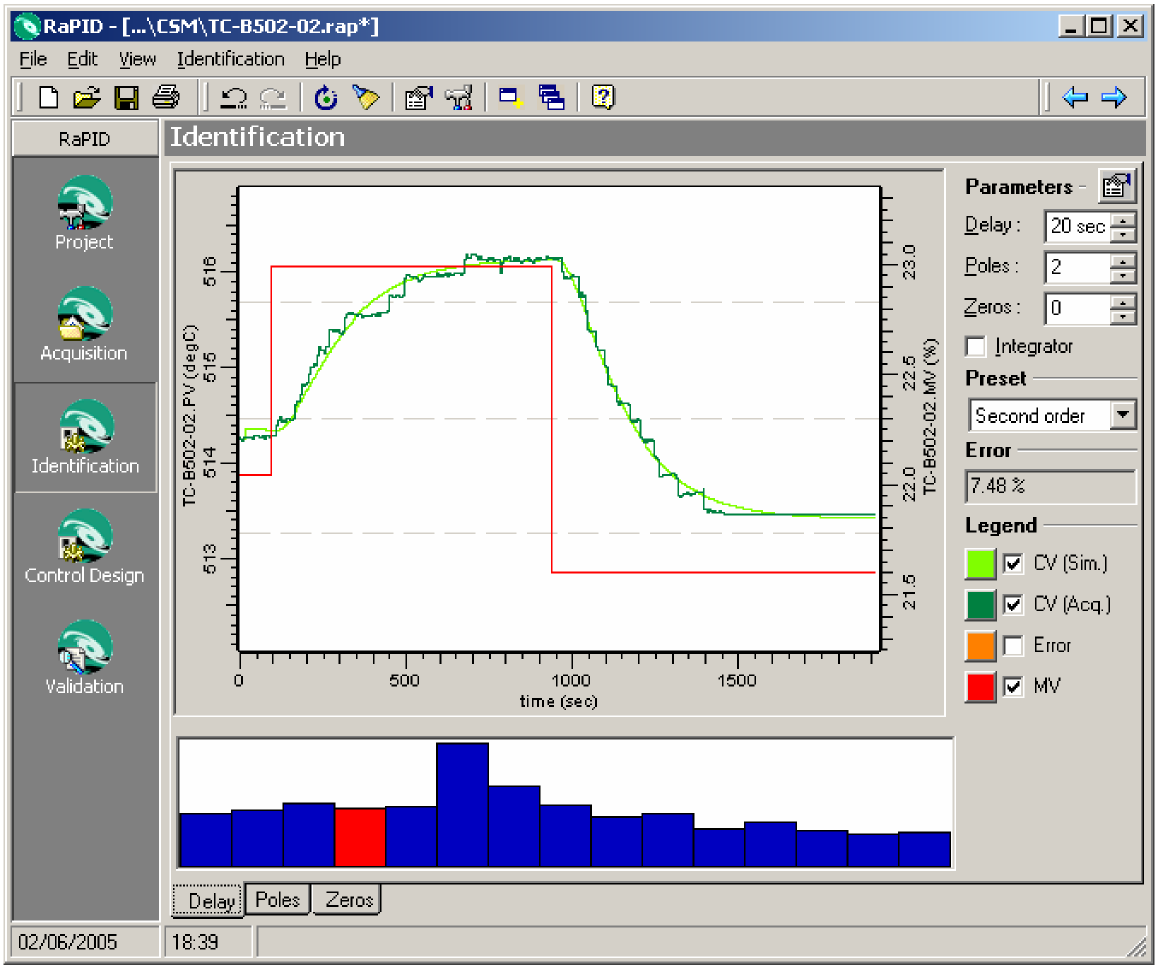
Figure 11 Step test data of the furnace outlet temperature acquired and preprocessed in RaPID.


RaPID - [...\CSM\TC-B502-02.rap*]

Identification

Parameters

Delay : 20 sec

Poles : 2

Zeros : 0

☐ Integrator

Preset

Second order

Error

7.48 %

Legend

🟩 ☑ CV (Sim.)

🟩 ☑ CV (Acq.)

🟧 ☐ Error

🟥 ☑ MV

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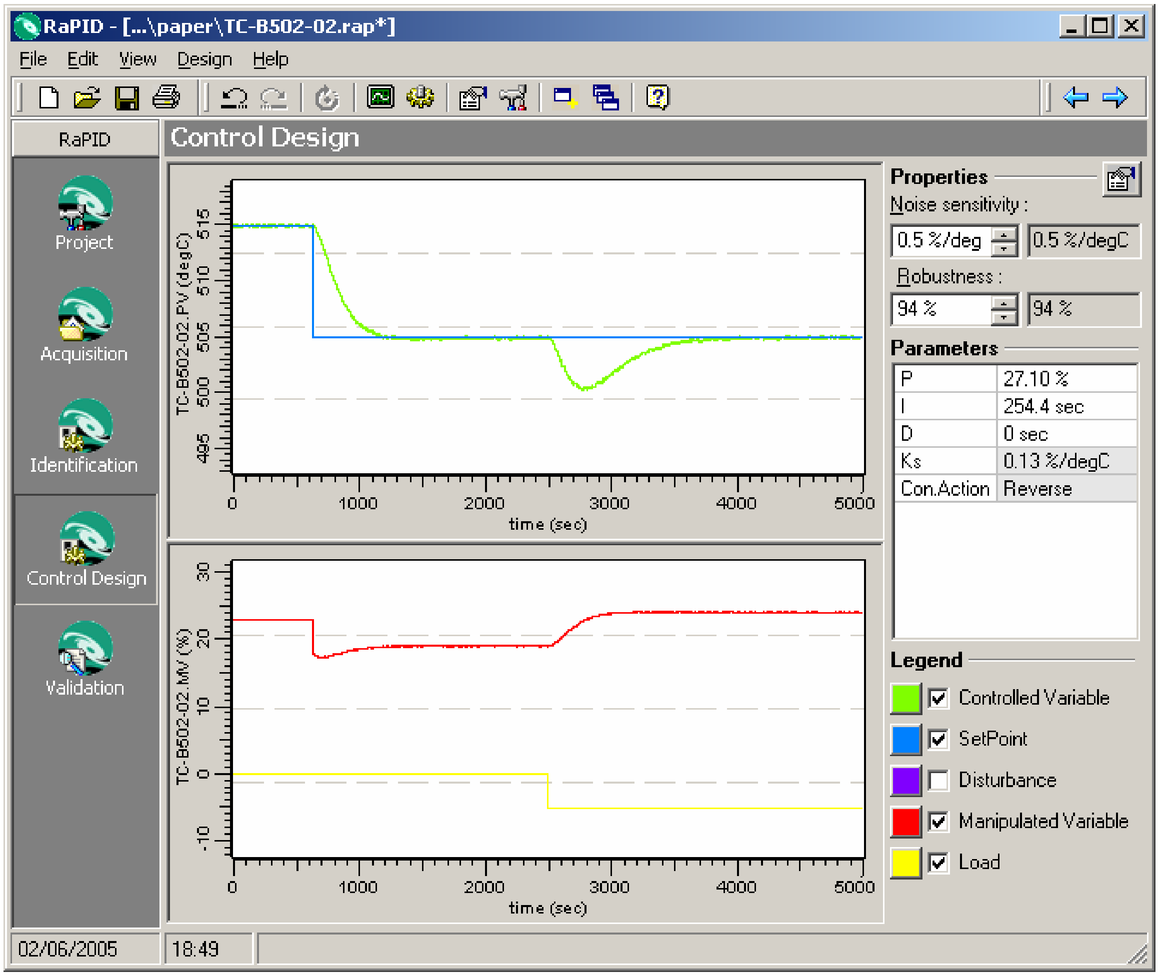
18:39

Figure 12: Identified model for the furnace outlet temperature loop based on the acquired and preprocessed step test data.



Properties

Noise sensitivity : 0.5 %/deg | 0.5 %/degC

Robustness : 94 % | 94 %

Parameters

P	27.10 %
I	254.4 sec
D	0 sec
Ks	0.13 %/degC
Con.Action	Reverse

Legend

🟩 ☑ Controlled Variable
🟦 ☑ SetPoint
🟪 ☐ Disturbance
🟥 ☑ Manipulated Variable
🟨 ☑ Load

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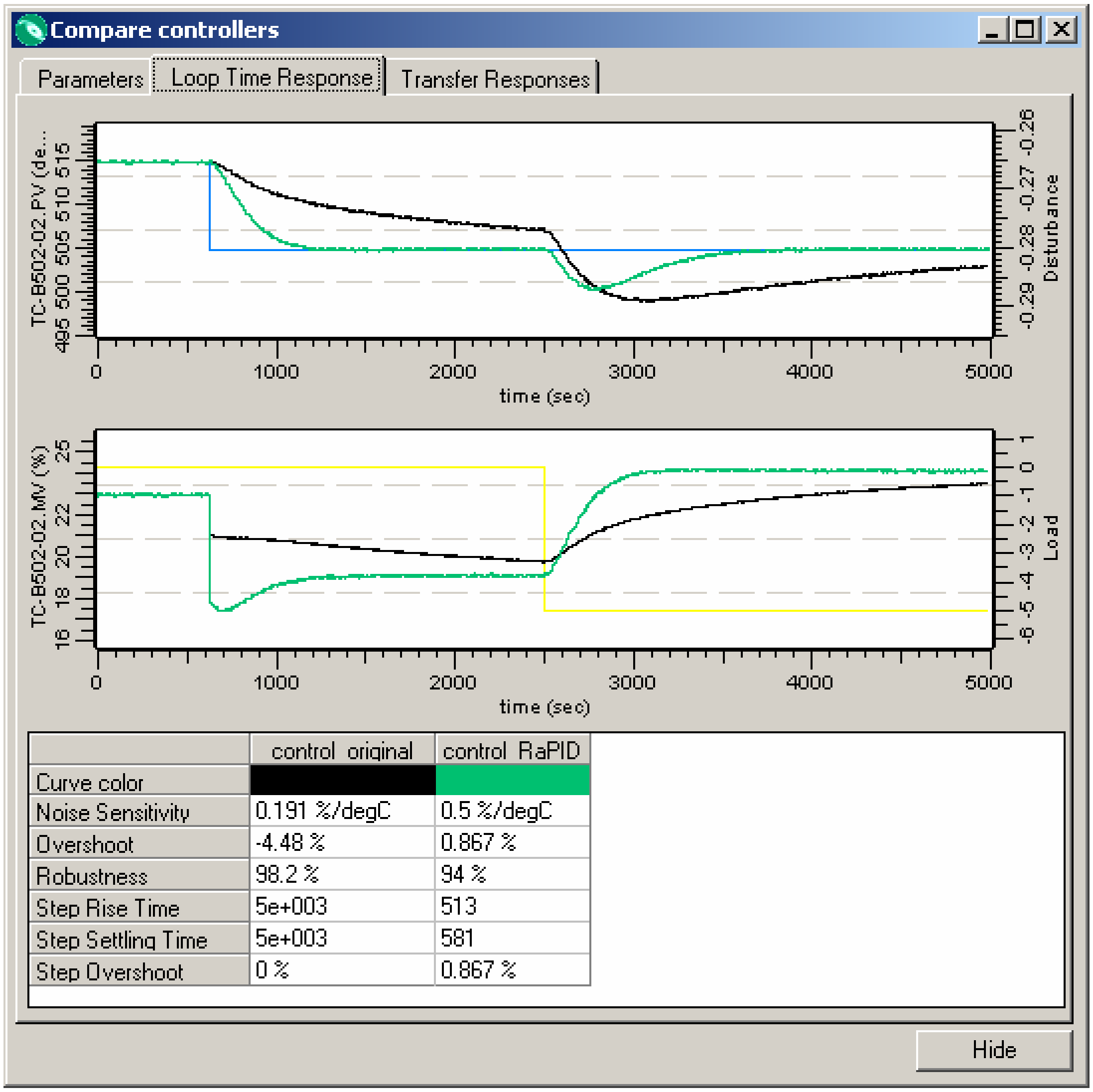
Figure 13 Closed loop response of the furnace outlet temperature loop with the optimized PID parameters. A setpoint (blue signal, upper plot) change is defined in the closed loop simulation at time 500 seconds. A load change (yellow signal, lower plot) is defined at time 2500 seconds.



	control original	control RaPID
Curve color	■	🟩
Noise Sensitivity	0.191 %/degC	0.5 %/degC
Overshoot	-4.48 %	0.867 %
Robustness	98.2 %	94 %
Step Rise Time	5e+003	513
Step Settling Time	5e+003	581
Step Overshoot	0 %	0.867 %

Figure 14 Comparing the closed loop simulation response of the FOT controller with the original PID settings (black) and the PID settings obtained with RaPID (green).

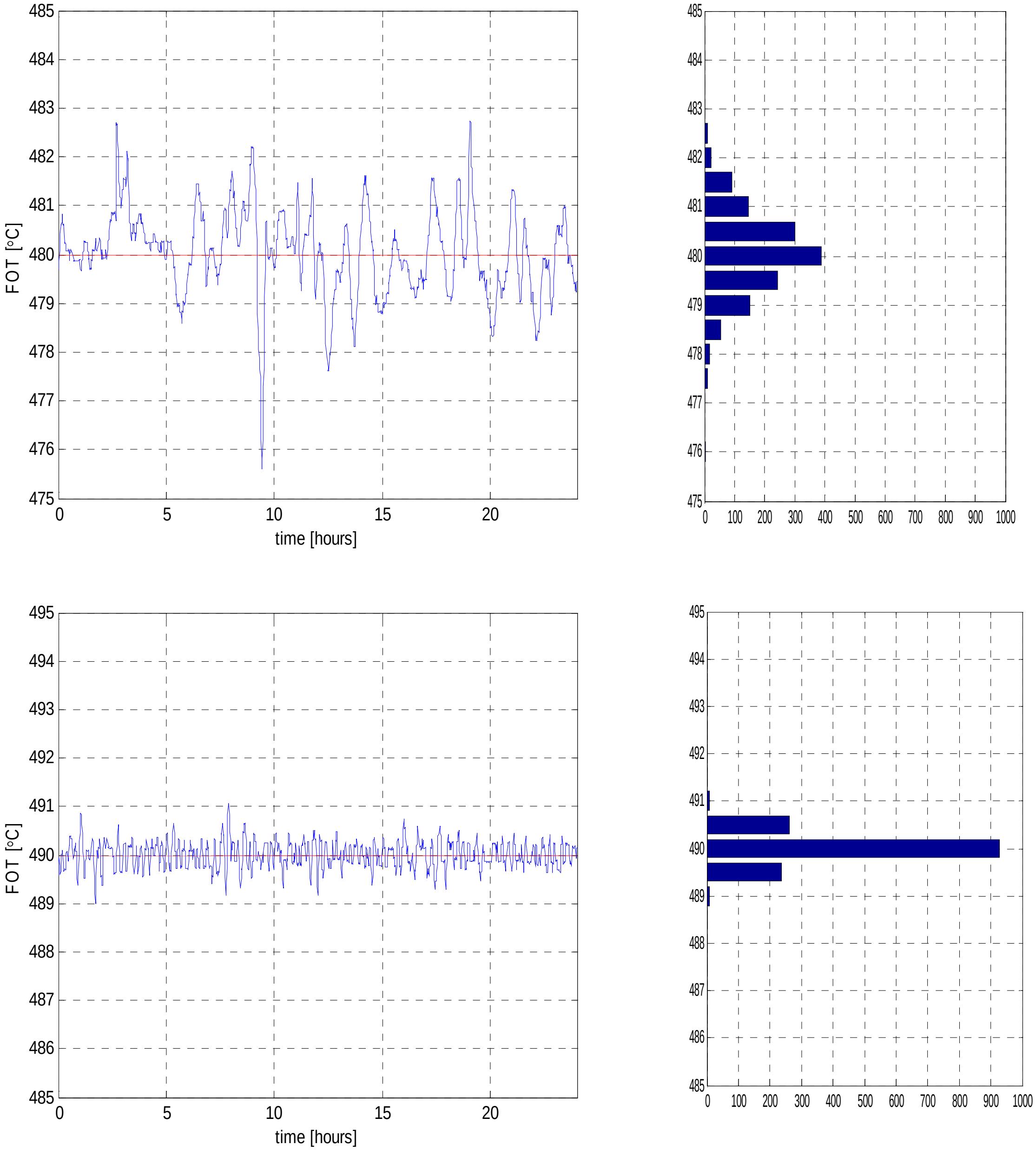


Figure 15 Comparing the real control performance of the FOT controller with the original PID settings (upper plot) and with the RaPID PID settings (lower plot). The graphs on the right side show the histograms of the deviations from the setpoint.

Jairo J. Espinosa Oviedo obtained his electronics engineering degree from the Universidad Distrital de Bogotá and a Master (Cum laude) and a Ph.D. (Magna Cum Laude) degrees in Electrical Engineering from the Katholieke Universiteit Leuven.

At this moment he is working as Research and Development Engineer for the company IPCOS N.V. in Belgium where he makes research in advanced control systems for processes. He combines his work at IPCOS with teaching assignments at the Universidad de Ibagué in Colombia. He has been involved in the creation of products to construct inferential sensors, nonlinear model based predictive controllers and process optimization. He has hands on experience in many industrial areas including oil, polymers, petrochemicals, automotive, power generation and iron production were he has applied many of his developments. His research interests are intelligent control, nonlinear modeling, model based predictive control, inferential sensors and model reduction techniques.

Tom Boelen Received his MSc in Agriculture Engineering in 1997 from the Katholieke Universiteit Leuven. He was a researcher in the field of biological process technology at the same university. He joined ISMC in 1998 and is a project engineer for the projects in chemical and petrochemical industry.

Peter Van Overschee Received his Msc in Aplied Sciences in 1989 at the Katholieke Universiteit Leuven, Belgium. In 1990 he received his MSc in Electrical Engineering at Stanford University, California, USA. At the Katholieke Universiteit Leuven, he obtained his doctoral degree with the work "Subspace Identification: Theory - Implementation - Applications" in 1995. This PhD was promoted by Prof. Bart De Moor. In 1994, he won the biannual Belgian Siemens Award with the work entitled: "Graphical User Interface Software for System identification". In 1996 he won the Automatica Best Paper Award with the paper "N4SID : Subspace Algorithms for the Identification of Combined Deterministic-Stochastic Systems". He is one of the founders of ISMC. Currently, he is President of IPCOS Belgium and responsible for the projects in the oil exploration.