Model-Based Tuning Methods for PID Controllers

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KEYWORDS

PID, Controller Design, Controller Tuning, Dynamic Modeling, Process Data, Software

ABSTRACT

The manner in which a measured process variable responds over time to changes in the controller output signal is fundamental to the design and tuning of a PID controller. The best way to learn about the dynamic behavior of a process is to perform experiments, commonly referred to as “bump tests.” Critical to success is that the process data generated by the bump test be descriptive of actual process behavior. Discussed are the qualities required for “good” dynamic data and methods for modeling the dynamic data for controller design. Parameters from the dynamic model are not only used in correlations to compute tuning values, but also provide insight into controller design parameters such as loop sample time and whether dead time presents a performance challenge. It is becoming increasingly common for dynamic studies to be performed with the controller in automatic (closed loop). For closed loop studies, the dynamic data is generated by bumping the set point. The method for using closed loop data is illustrated. Concepts in this work are illustrated using a level control simulation.

FORM OF THE CONTROLLER

The methods discussed here apply to the complete family of PID algorithms. Examples presented will explore the most popular controller of the PID family, the Proportional-Integral (PI) controller:

$$u(t) = u_{\text{bias}} + K_C\, e(t) + \frac{K_C}{\tau_I}\int e(t)\, dt \qquad (1)$$

In this controller, $u(t)$ is the controller output and u_{bias} is the controller bias. The tuning parameters are controller gain, K_C, and reset time, τ_I. Because τ_I is in the denominator, smaller values of reset time provide a larger weight to (increase the influence of) the integral term.

CONTROLLER DESIGN PROCEDURE

Designing any controller from the family of PID algorithms entails the following steps:

- specifying the design level of operation,
- collecting dynamic process data as near as practical to this design level,
- fitting a first order plus dead time (FOPDT) model to the process data, and
- using the resulting model parameters in a correlation to obtain initial controller tuning values.

The form of the FOPDT dynamic model is:

$$\tau_P \frac{dy(t)}{dt} + y(t) = K_P \, u(t - \theta_P) \tag{2}$$

where $y(t)$ is the measured process variable and $u(t)$ is the controller output signal. When Eq. 2 is fit to the test data, the all-important parameters that describe the dynamic behavior of the process result:

- Steady State Process Gain, K_P
- Overall Process Time Constant, τ_P
- Apparent Dead Time, θ_P

These three model parameters are important because they are used in correlations to compute initial tuning values for a variety of controllers [1]. The model parameters are also important because:

- the sign of K_P indicates the sense of the controller ($+K_P \rightarrow$ reverse acting; $-K_P \rightarrow$ direct acting)
- the size of τ_P indicates the maximum desirable loop sample time (be sure sample time $T \leq 0.1\tau_P$)
- the ratio θ_P/τ_P indicates whether a Smith predictor would show benefit (useful if $\theta_P > \tau_P$)
- the dynamic model itself can be employed within the architecture of feed forward, Smith predictor, decoupling and other model-based controller strategies.

DEFINING GOOD PROCESS TEST DATA

As discussed above, the collection and analysis of dynamic process data are critical steps in controller design and tuning. A “good” set of data contains controller output to measured process variable data that is descriptive of the dynamic character of the process. To obtain such a data set, the answer to all of these questions about your data should be "yes" [1]. Ultimately, it is your responsibility to consider these steps to ensure success.

1. Was the process at steady state before data collection started?

Suppose a controller output change forces a dynamic response in a process, but the data file only shows the tail end of the response without showing the actual controller output change that caused the dynamics in the first place. Popular modeling tools will indeed fit a model to this data, but it will skew the fit in an attempt to account for an unseen "invisible force." This model will not be descriptive of your

actual process and hence of little value for control. To avoid this problem, it is important that data collection begin only after the process has settled out. The modeling tool can then properly account for all process variations when fitting the model.

2. Did the test dynamics clearly dominate the process noise?

When generating dynamic process data, it is important that the change in controller output cause a response in the process that clearly dominates the measurement noise. A rule of thumb is to define a noise band of ±3 standard deviations of the random error around the process variable during steady operation. Then, when during data collection, the change in controller output should force the process variable to move at least ten times this noise band (the signal to noise ratio should be greater than ten). If you meet or exceed this requirement, the resulting process data set will be rich in the dynamic information needed for controller design.

3. Were the disturbances quiet during the dynamic test?

It is essential that the test data contain process variable dynamics that have been clearly (and in the ideal world exclusively) forced by changes in the controller output as discussed in step 2. Dynamics caused by unmeasured disturbances can seriously degrade the accuracy of an analysis because the modeling tool will model those behaviors as if they were the result of changes in the controller output signal. In fact, a model fit can look perfect, yet a disturbance that occurred during data collection can cause the model fit to be nonsense. If you suspect that a disturbance event has corrupted test data, it is conservative to rerun the test.

4. Did the model fit appear to visually approximate the data plot?

It is important that the modeling tool display a plot that shows the model fit on top of the data. If the two lines don't look similar, then the model fit is suspect. Of course, as discussed in step 3, if the data has been corrupted by unmeasured disturbances, the model fit can look great yet the usefulness of the analysis can be compromised.

NOISE BAND AND SIGNAL TO NOISE RATIO

When generating dynamic process data, it is important that the change in the controller output signal causes a response in the measured process variable that clearly dominates the measurement noise. One way to quantify the amount of noise in the measured process variable is with a *noise band*.

As illustrated in Fig. 1, a noise band is based on the standard deviation of the random error in the measurement signal when the controller output is constant and the process is at steady state. Here the noise band is defined as ±3 standard deviations of the measurement noise around the steady state of the measured process variable (99.7% of the signal trace is contained within the noise band). While other definitions of the noise band have been proposed, this definition is conservative when used for controller design.

When generating dynamic process data, the change in controller output should cause the measured process variable to move at least ten times the size of the noise band. Expressed concisely, the *signal to noise ratio should be greater than ten*. In Fig. 1, the noise band is 0.25°C. Hence, the controller output should be moved far and fast enough during a test to cause the measured exit temperature to move at least 2.5°C. This is a minimum specification. In practice it is conservative to exceed this value.

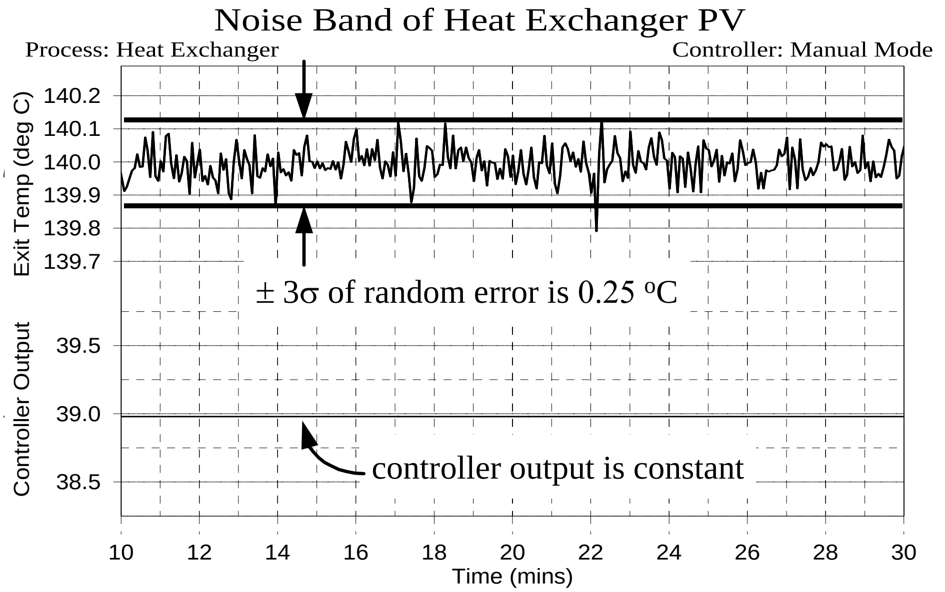

Figure 1 - Noise Band Encompasses ± 3 Standard Deviations Of The Measurement Noise

CONTROLLER TUNING FROM CORRELATIONS

The recommended tuning correlations for controllers from the PID family are the Internal Model Control (IMC) relations [1]. These are an extension of the popular *lambda* tuning correlations and include the added sophistication of directly accounting for dead time in the tuning computations.

The first step in using the IMC (lambda) tuning correlations is to compute, τ_C, the closed loop time constant. All time constants describe the speed or quickness of a response. The closed loop time constant describes the desired speed or quickness of a controller in responding to a set point change. Hence, a small τ_C (a short response time) implies an aggressive or quickly responding controller. The closed loop time constants are computed as:

Aggressive Tuning: τ_C is the larger of $0.1\,\tau_P$ or $0.8\,\theta_P$
Moderate Tuning: τ_C is the larger of $1.0\,\tau_P$ or $8.0\,\theta_P$
Conservative Tuning: τ_C is the larger of $10\,\tau_P$ or $80.0\,\theta_P$

With τ_C computed, the PI correlations for IMC tuning are:

$$K_C = \frac{1}{K_P}\frac{\tau_P}{(\theta_P + \tau_C)} \qquad \tau_I = \tau_P \tag{3}$$

Final tuning is verified on-line and may require tweaking. If the process is responding sluggishly to disturbances and changes in the set point, the controller gain is too small and/or the reset time is too large. Conversely, if the process is responding quickly and is oscillating to a degree that makes you uncomfortable, the controller gain is too large and/or the reset time is too small.

EXAMPLE: SET POINT TRACKING IN GRAVITY DRAINED TANKS

The gravity drained tanks process, shown in Fig. 2, is two non-interacting tanks stacked one above the other. Liquid drains freely through a hole in the bottom of each tank. As shown, the measured process variable is liquid level in the lower tank. To maintain level, the controller manipulates the flow rate of liquid entering the top tank. The disturbance variable is a secondary flow out of the lower tank from a positive displacement pump. Thus, the disturbance flow is independent of liquid level.

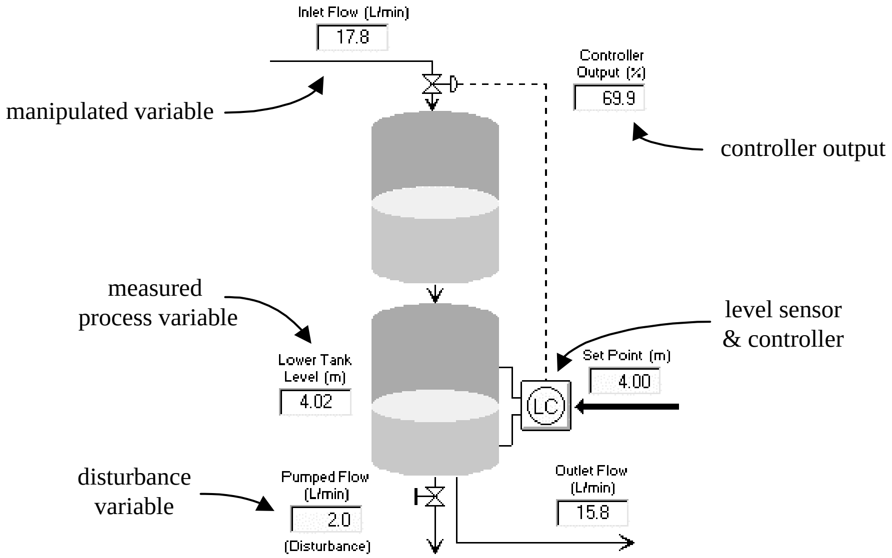

Figure 2 - Gravity Drained Tanks Process

The design level of operation for this study is a measured level in the lower tank of 2.4 m while the pumped flow disturbance is at its expected value of 2.0 L/min. The control objective is to track set point steps in the range of 2.0 to 2.8 m. The process is currently under P-Only control and operations personnel will not open

the loop for controller design experiments. Hence, closed loop set point steps are used to generate dynamic process data.

As shown in Fig. 3, the P-Only controller being used has a K_C = 40 %/m and a bias value of 55.2% (determined as the value of the controller output that, in open loop, causes the measured level in the lower tank to steady at the design value of 2.4 m when the pumped flow disturbance is at its expected value of 2.0 L/min). With data being saved to file, the dynamic testing experiment begins. Specifically, the set point is stepped up to 2.8 m, then down to 2.0 m, and finally back to the design level of 2.4 m (set point sequences of other sizes and durations would be equally reasonable).

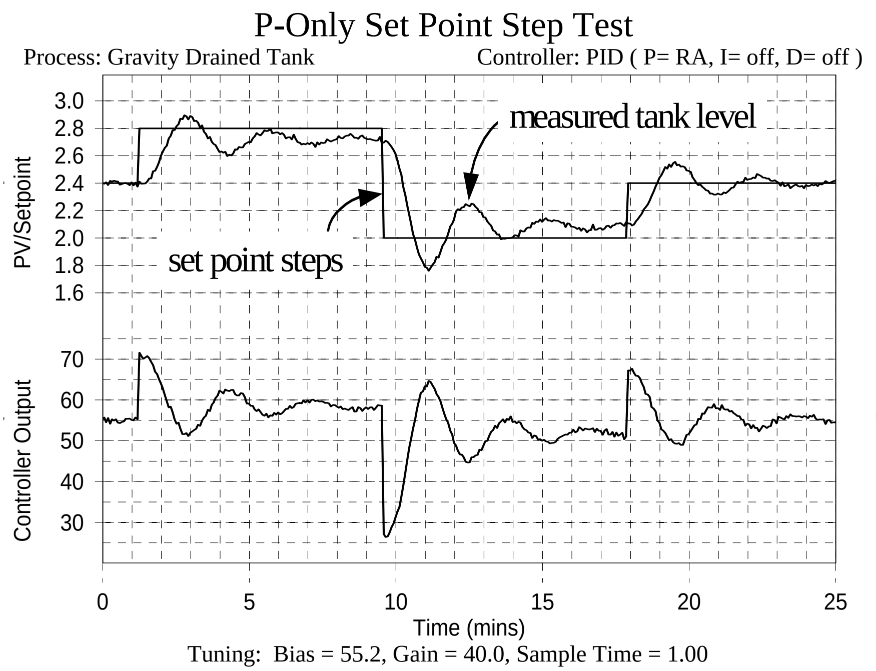

Figure 3 – Set point step tests on gravity drained tanks under P-Only control

Visual inspection of Fig. 3 confirms that the closed loop dynamic event is set point driven (as opposed to disturbance driven). Also, control action appears energetic enough such that the response of the measured process variable clearly dominates the noise.

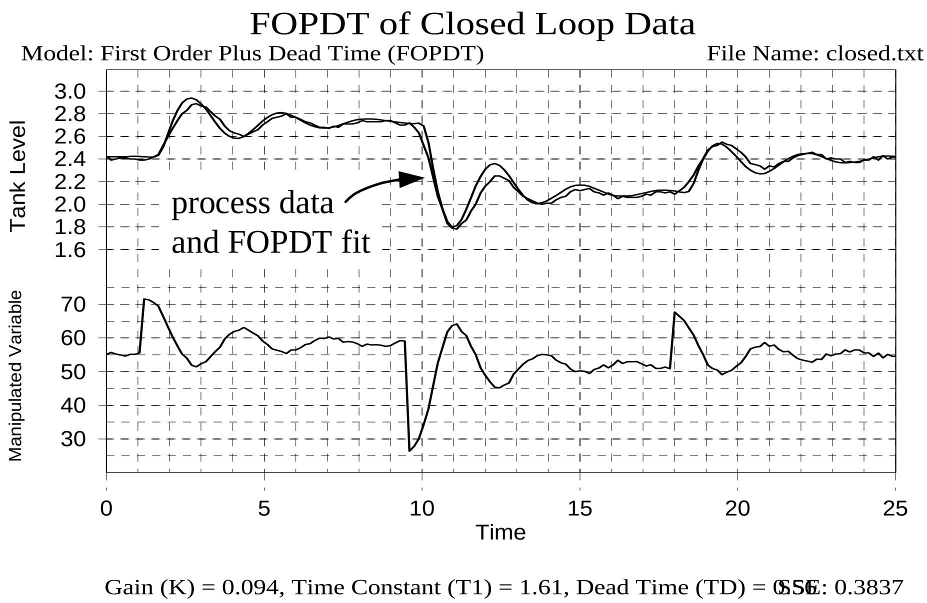

Figure 4 – FOPDT fit of closed loop dynamic data generated in Fig.8.5

The dynamic data of Fig. 3 is fit with a FOPDT model using Loop-Pro software by Control Station. A plot of the model and closed loop process data is shown in Fig. 4. The model appears to be reasonable and appropriate based on visual inspection, thus providing the design parameters:

Process Gain, $K_P = 0.094$ m/%
Time Constant, $\tau_P = 1.6$ min
Dead Time, $\theta_P = 0.56$ min

We first compute the closed loop time constant. Here we choose aggressive tuning, which is computed as:

$$\tau_C = \text{larger of } 0.1\tau_P \text{ or } 0.8\theta_P = \text{larger of } 0.1(1.6) \text{ or } 0.8(0.56) = 0.45 \text{ min.}$$

Substituting this closed loop time constant and the above FOPDT model parameters into the IMC tuning correlations of Eq. 3 yields the following tuning values:

$$K_C = \frac{1}{0.094}\left(\frac{1.6}{0.56+0.45}\right) = 16.9 \text{ \%/min} \qquad \tau_I = 1.6 \text{ min}$$

A reverse acting controller is required because K_C is positive. Because the PI controller has integral action, the bias value is not entered but is automatically initialized by our instrumentation to the current value of the controller output at the moment the loop is closed.

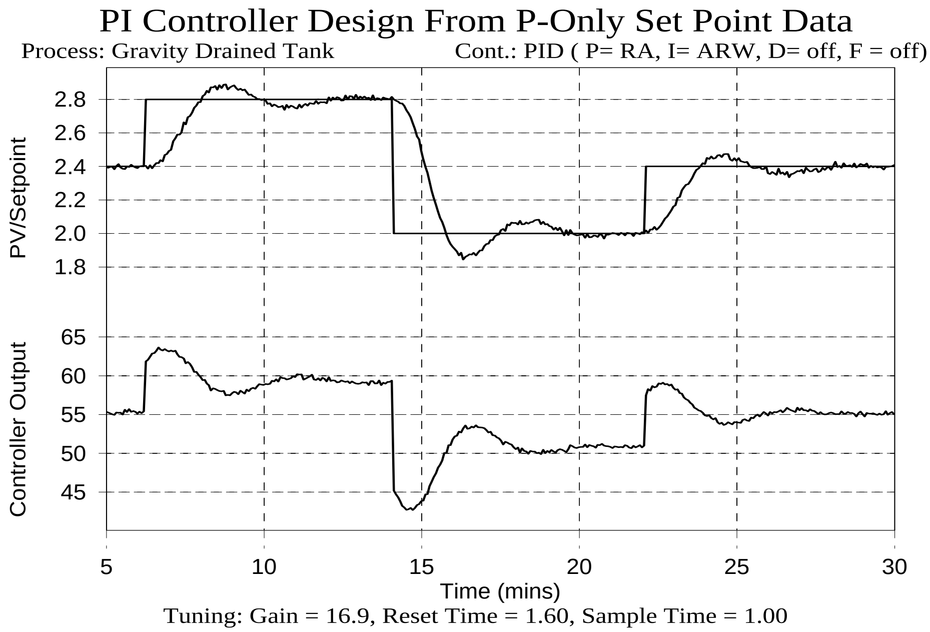

Figure 5 – Performance of PI controller in tracking set point steps

The performance of this controller in tracking set point changes is pictured in Fig. 5. Although good or best performance is decided based on the capabilities of the process, the goals of production, the impact on downstream units and the desires of management, Fig. 5 exhibits generally desirable performance. That is, the process responds quickly, shows modest overshoot, settles quickly, and displays no offset. Compare this to Fig. 3, that shows P-Only performance for the same control challenge.

INTERACTION OF PI TUNING PARAMETERS

One challenge of the PI controller is that there are two tuning parameters to adjust and difficulties can arise because these parameters interact with each other. Figure 6 shows a tuning map that illustrates how a typical set point response might vary as the two tuning parameters are changed.

The center of Fig. 6 shows a set point step response that is labeled as the base case performance. It is important to recognize that this base case plot will not be considered by some to be the "best" performance. What is best must be determined by the operator or engineer for each implementation. Some require no overshoot while others will tolerate some overshoot in exchange for a faster set point response. In any event, the grid shows how a set point step response changes as the two tuning parameters are doubled and halved from a base (here defined as desired) tuning.

PI Controller Tuning Map

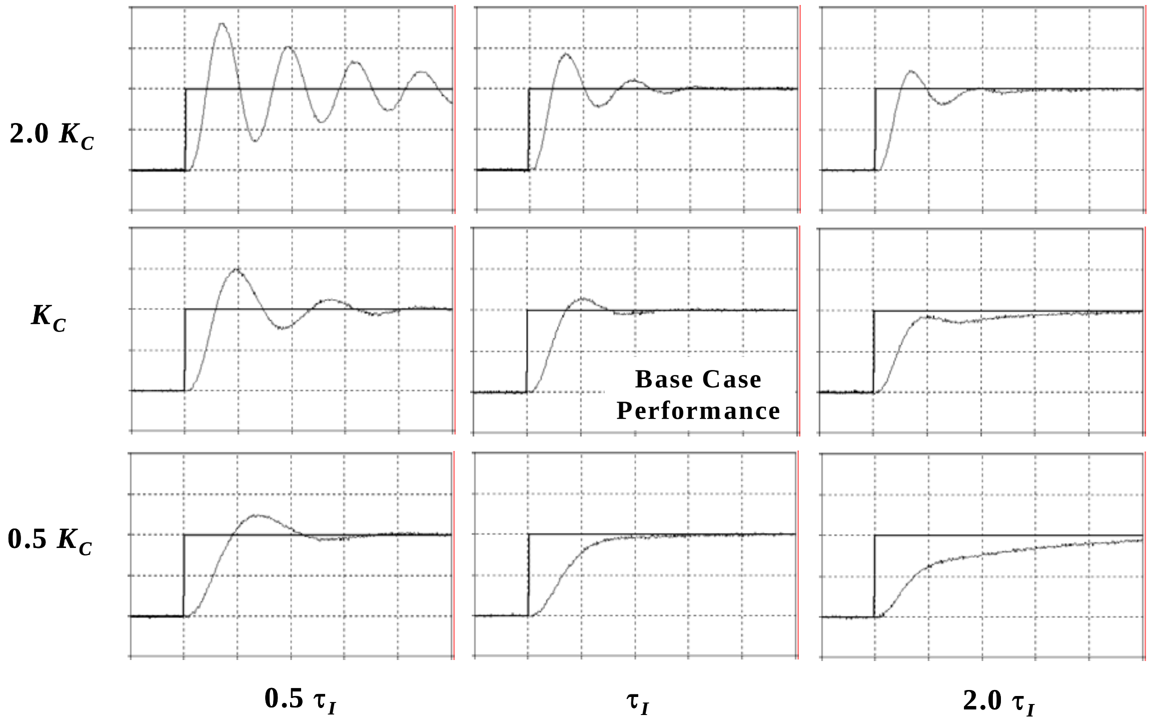

Figure 6 - How PI controller tuning parameters impact set point tracking performance

The plot in the upper left of the grid shows that when gain is doubled and reset time is halved, the controller produces large, slowly damping oscillations. Conversely, the plot in the lower right of the grid shows that when controller gain is halved and reset time is doubled, the response becomes sluggish. This chart is called a tuning map because, in general, if a controller is behaving poorly, you can match the performance you observe with the closest picture in Fig. 6 and obtain guidance as to the appropriate tuning adjustments required to move toward your desired performance.

CONCLUSIONS

Understanding the dynamic behavior of a process is essential to the proper design and tuning of a PID controller. The recommended design and tuning methodology is to:

- step, pulse or otherwise perturb the controller output near the design level of operation,
- record the controller output and measured process variable data as the process responds, and
- fit a first order plus dead time (FOPDT) dynamic model to this process data,
- use the dynamic model parameters in a correlation to compute P-Only, PI, PID and PID with Filter
- controller tuning values,
- test your controller to ensure satisfactory performance.

LITERATURE CITED

1. Cooper, Douglas, "Practical Process Control Using Control Station," Published by Control Station, Inc, Storrs, CT (2004).

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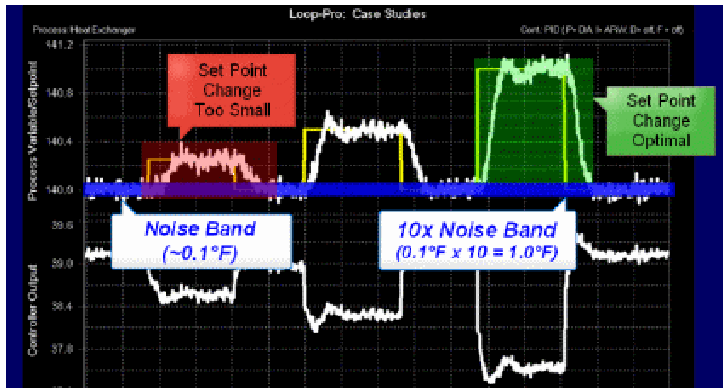

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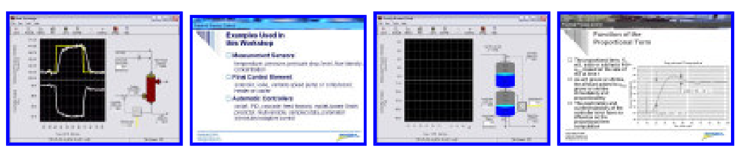

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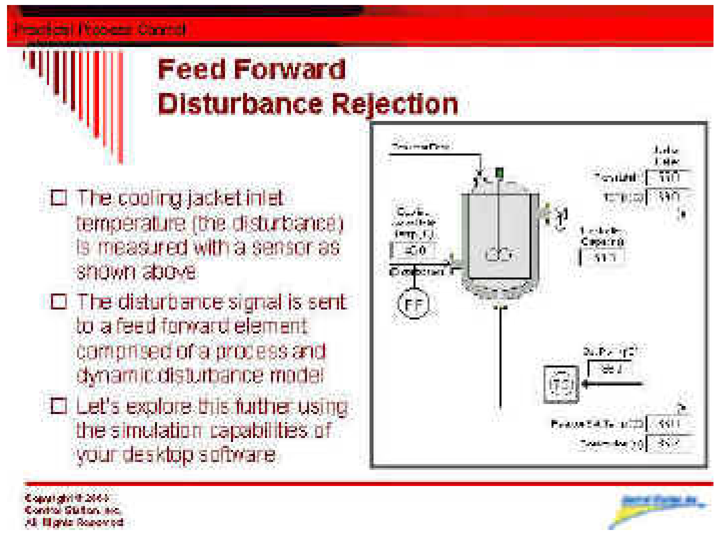

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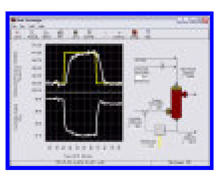

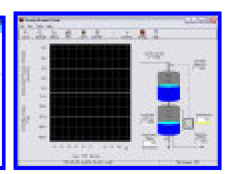
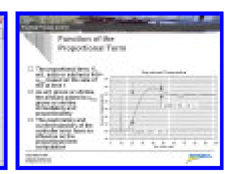

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changing PID parameters effect the process Take the guess work out of PID control tuning.

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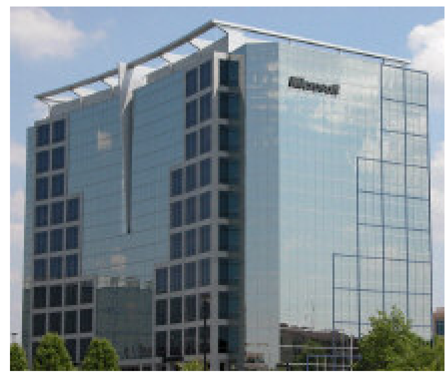
"*Control Station's 'case study' approach to teaching the subject was unique. Learning by doing helped me understand the topics as they were presented.*" Process Engineer - International Flavor & Fragrances

This more advanced seminar is part of Business Industrial Network's **Phase II Training** (Phase I training is our PLC Troubleshooting course), and is also offered as On-Site Training.

Both of these courses offer information your people will actually use out on the shop floor.

Course Location ...



The Microsoft Building

3 Cityplace Drive

Saint Louis, MO. 63141

Click picture online for location details >>

This seminar/workshop will be held in the state of the art training facility located in the Microsoft building next to Business Industrial Network's HQ offices.

Recommended Lodging ...

Drury Inn & Suites just 1/2 mile down the road at ...

11980 Olive Blvd, Creve Coeur, Missouri, 63141

Discount code provide after registration.

Saint Louis, MO.

Industrial Process Control Training

Saint Louis, MO. Schedule: Jan 18-19, 2007
All training workshops offered as On-Site Training too, contact us for details.

Seminar Fee ...

$1450 PID course per attendee. **Group discounts may apply. 10% discount** to AFE members! (*not to be used with other discounts*)

Registration Methods ...
1) **Online** (This page)
2) **Fax** (860) 875-1749
3) **Phone** (877) 566-7776
4) **Mail** this form to ...

Control Station, Inc.
One Technology Drive
Tolland, CT. 06084

5) **Email** all form information to

Training@bin95.com

Seminar Location ...

The Microsoft Building

3 Cityplace Drive,
Saint Louis, MO 63141

Located at our new state of the art training facility located in the Microsoft building 2nd floor, across the street from Business Industrial Network offices. www.BIN95.com

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Accommodations ...

Drury Inn & Suites
11980 Olive Blvd
Creve Coeur, Missouri, 63141
Hotel website link is online
Hotel Phone :
(314) 989-1100

Schedule ...

8:00am - Class Starts
12:00 - 1:00pm Lunch
4:30 - Class Ends

Authorizing Manager:

Name
Title: Email:
Company Name:
Address:
City: Zip: State/Prov:
Phone: Fax:

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2 Day Process Control (PID) Workshop Date: ◉ January 18-19, **2007** - ($1450)

Seminar Attendees:

Name: Title:
Name: Title:

** Group discount for 2 or more attendees **

Name: Title:
Name: Title:

Payment Method: Amount to be charged **per attendee - for** two or more attendees PID course will be **discounted** to $1250 per attendee! To Register online, see https://www.bin95.com/Saint_Louis_PID_registration.htm

Please enter your credit card information below before submitting this secure form. You will also need to submit this form with contact information above filled out when paying with Check.

☐ Visa ☐ MasterCard ☐ AMX ☐ Check Enclosed (pay to Control Station Inc.)

Card Number:
Expiration Date: Card Code?:
Name on Card:
Signature:

Group discount for PID course, is $200 off list price per attendee. Two or more attendees qualifies for the group discount. If AFE member, indicate so in name field. (US$1125, per AFE attendee) Cancellations may apply fees to other training classes.

Registrants may receive additional information and updates via their email address. Lunch and snacks provided! Seminar Ends 4:30 Friday, please book travel accordingly. (Sat. recommended) *All trademarks and trade names are property of their respective owners.*