

## **International co-operation in control engineering education using online experiments**

JIM HENRY\*† and HERBERT M. SCHAEDEL‡

†College of Engineering and Computer Science, University of Tennessee at Chattanooga,  
Chattanooga, TN 37403, USA

‡University of Applied Sciences Koeln, Faculty of Information, Media and Electrical Engineering,  
Betzdorfer Str. 2, 50769 Koeln, Germany

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This paper describes the international co-operation experience in teaching control engineering with laboratories being conducted remotely by students via the Internet. This paper describes how the students ran the experiments and their personal experiences with the laboratory. A tool for process identification and controller tuning based on spreadsheets like MS-Excel is outlined. Process identification and modelling can be carried out for the open- and closed-loop control circuit. Controller tuning is done according to the criterion of cascaded damping ratios. The design is based on a direct relation between the parameters of the process and the controller. Tuning for optimal set-point control as well as disturbance rejection is provided.

*Keywords:*

### **1. Introduction**

Web browsers and spreadsheet programs are installed on nearly every PC or laptop. At the University of Tennessee at Chattanooga web site, experiments on real equipment can be conducted remotely for engineering controls systems. Students at the University of Applied Sciences Koeln have conducted laboratory experiments (remotely) in the USA. At the completion of the experiments, the students retrieve the data which they analyse for system identification. A tool has been developed for process identification, controller tuning and control circuit simulation. The tool is based on Microsoft Excel.

The following sections describe the students' access to the experiments, the process identification tools used in the spreadsheet, controller tuning and our conclusions.

### **2. Access to the experiments**

Providing hands-on, or learn-by-doing, experiences for engineering students is often complicated by either a lack of equipment or technician support, or both. Yet many topics in controls

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\*Corresponding author. Email: jim-henry@utc.edu

engineering are learned best via a learn-by-doing approach. Computer simulations have been used in lieu of a truly hands-on experience, but these are often lacking in the fullness of detail that real systems provide. With the advent of high-speed Internet communications an alternative approach to providing hands-on experiences has become possible – remote operation of real equipment. Such remote operation experiences are fully learn-by-doing with nearly all the positive and negative aspects of true hands-on laboratory work.

Remote operation of actual equipment for experimental purposes was provided via an Internet connection to the Resource Centre for Engineering Laboratories on the Web (<http://chem.engr.utc.edu>) at the University of Tennessee at Chattanooga (UTC). The students in the control class at Koeln used the site at UTC. That site provides a pool of typical plants of process engineering that can be used via the Internet for measurement and control. Over a 2 year period, an online workshop was organized within the practical control course for the students of the fourth semester of the Faculty of Information Technology in Koeln. Two groups of 10 students were introduced into the online lab at UTC and investigated a flow-control and a speed-control process. Via the Internet, step responses of the plants were taken. The data were transmitted to the control lab in Koeln, where the students evaluated the data in order to make parameter estimation and controller tuning, based on the methods developed at Koeln. The students then transferred the controller tuning to the plant at UTC and tested the control circuit behaviour for changes in reference (set-point) and disturbance signals.

## 2.1 *The hardware*

There are seven stations for controls systems experiments. Some of these are single-input, single-output systems. All are inherently stable systems when run in open-loop configuration. That is, if you specify a fixed input value, the system will reach a constant steady-state condition. More complete descriptions of these have been given before (Henry 1993, 1995). A complete description of the controls systems experiments was given by Henry (1998).

The lab equipment at UTC is available 24 h a day, 7 days a week for students to operate remotely in conducting experiments for controls engineering. In addition to step response tests, ramp response, frequency response, pulse response and relay-feedback tests can be conducted for system identification. Proportional and proportional-integral feedback controllers can be run on all of the systems. Some systems have full proportional-integral-derivative (PID) feedback control capabilities.

## 2.2 *The experiences*

The results were extremely encouraging. Students were fascinated by the opportunities of this type of education and were very motivated, although there were some problems with the Internet connection during some of the experiments. Most of them repeated some of the experiments for the evaluation of the test results and discussed them in their reports. In the future, this co-operation will be extended.

The above comments are based on the experiences of 20 students, 10 each year for 2000 and 2001, in Koeln. The data are anecdotal and qualitative; further quantitative surveys are being developed. Very similar comments can be made based on other remote-equipment-sharing students from Australia (about 50 students on one occasion), Indonesia (about 100 students in each year of 2001 and 2002) and several locations in the USA (Henry and Zollars 2003).

The next sections show simple and effective methods for parameter estimation and controller design with examples that can be used for a theoretical training of the students.

### 3. Process identification

Process identification and modelling can be carried out for the open- and closed-loop control circuit. The values of the input and output signals of the plant are represented in ASCII format in the data files from the remote experiments at UTC.

#### 3.1 Least squares approximation using the solver function of Excel

For the open loop the step response of the plant is approximated by a second-order system plus dead-time (represented by this Laplace-domain transfer function)

$$G_P(s) = \frac{K_P e^{-sT_t}}{(1 + s\tau_1)(1 + s\tau_2)} \quad (1)$$

with least squares fitting between the step response of the plant and the model using the solver function of Excel. From this the characteristic frequency parameters of the plant follow as

Sum of time constants:

$$T_1 = \tau_1 + \tau_2 + T_t. \quad (2)$$

Product sum of time constants:

$$T_2^2 = \tau_1 \tau_2 + (\tau_1 + \tau_2) T_t + 0.5 T_t^2. \quad (3)$$

Figure 1 shows the step response of a flow process that is provided by the online lab of J. Henry at UTC (<http://chem.engr.utc.edu>). The results of the process identification are given as

$$\begin{aligned} K_p &= 0.514 \text{ lb min}^{-1} \%^{-1} \\ \tau_1 &= 0.233 \text{ s} & T_1 &= 0.866 \text{ s} \\ \tau_2 &= 0.233 \text{ s} & T_2^2 &= 0.321 \text{ s}^2 \\ T_t &= 0.400 \text{ s.} \end{aligned}$$

The fit is for the time window of 12–20 s as shown in figure 1. The full experiment may well have start-up transients before it reaches its initial steady-state condition. These are not shown in figure 1 and do not contribute to the parameter estimation in the system identification. These parameters are used for controller tuning according to the criterion of cascaded damping ratios. Figure 1 also shows the second-order plus dead-time model for these parameters. There is very good agreement between the model and the experimental data.

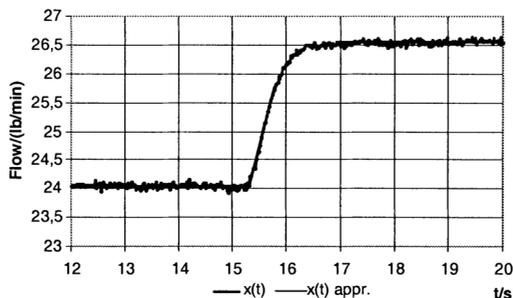


Figure 1. Step response of a flow process and approximation by a SOPDT-model.

### 3.2 Method of inflection tangent

Another method of parameter estimation is provided on the basis of the inflection tangent applied to the step response (Schaedel 2003a,b). Ziegler and Nichols (1942) have demonstrated that information obtained from the inflection tangent can be used for controller tuning. Their investigations were based on plants with first-order lag plus dead-time (FOPDT). It is obvious that for the same values of dead-time  $T_u$  and build-up time  $T_g$  one can find numerous configurations of different lag orders with and without dead-time (figure 2). The FOPDT-approximation with identical values of  $T_u$  and  $T_g$  proves to be insufficient. In order to locate the specific response function within the family of curves an additional parameter is needed.

The problem has to be looked at from the angle of process identification. A controller design is possible only if process identification can be carried out on the basis of parameters obtained by the inflection tangent. With this background a controller design can then be accomplished. Process identification does not have to be highly accurate because PID-controllers are rather robust against deviations of the plant parameters (Smith and Corripio 1997).

Figure 3 shows the normalized characteristic time constant  $T_1/T_g$  as a function of the normalized lag-time  $\mu = T_u/T_g$  for typical processes in table 1.

The dead-time term is replaced with a second-order Taylor series expansion according to  $e^{-sT_u} \approx 1/(1 + sT_u + 0.5s^2T_u^2)$ . A set of curves results, which is confined at the upper border by the first-order lag with time delay ( $G_{P1}$ ) and at the lower border by the  $n$ th order lag with equal time constants ( $G_{P4}$ ). The left border for low ratios  $T_u/T_g$  is confined by the transition from the first-order lag to the second-order lag with varying ratios of the two time constants ( $G_{P2}$ ). In order to determine the sum of time constants  $T_1$  for a given ratio  $\mu = T_u/T_g$ , additional information is needed. For practical applications this characteristic information has to be taken in a simple way from the step response. It is fairly obvious to take the value of the unit step response  $h_x$  for the time  $t_x = T_u + T_g$ . This build-up value  $h_x$  can be taken with rather good accuracy.

The simplest way of approximating the step response is a polygonal approach using the inflection tangent

$$G_P(s) \approx \frac{K_I}{s} e^{-sT_u} (1 - e^{-sT_g}) \quad \text{with} \quad K_I = \frac{K_P}{T_g}. \tag{4}$$

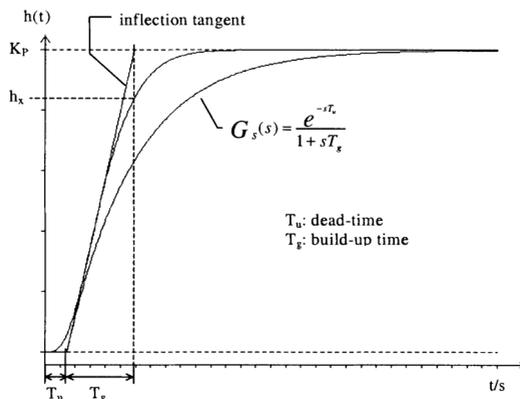


Figure 2. Step response of a lag process and first-order plus dead-time approximation (FOPDT) with identical  $T_u$  and  $T_g$ .

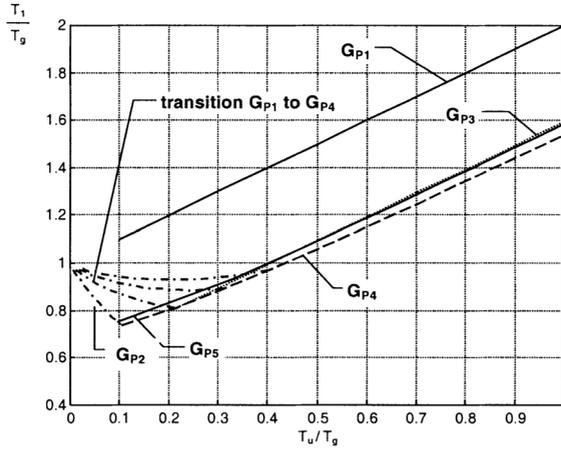


Figure 3. Step of time constants  $T_1$  as a function of  $\mu = T_u/T_g$ .

This is a superposition of two integrating terms with different delays  $T_u$  and  $T_t = T_u + T_g$ . This approach is modified by introducing a time lag into the integral term:

$$G_S(s) \approx \frac{K_I}{s} e^{-sT_u} - \frac{K_I}{s(1+s\tau)} e^{-sT_t}. \tag{5}$$

The parameters  $T_g$  and  $\tau$  have to be adjusted in such a manner that the unit step response function passes through the build-up value  $h_x = h(T_u + T_g)$ . From this, one finds the relation for time constant  $\tau$  as a function of the build-up value  $h_x$ . Using apparent dead-time  $T_u$ , build-up time  $T_g$  and build-up value  $h(T_u + T_g)$ , the characteristic time parameters  $T_1$  and  $T_2^2$  according to equations (2) and (3) may be estimated by

$$\begin{aligned} T_1 &= (\mu + A)T_g \\ T_2^2 &= \frac{1}{2} \frac{\mu}{\mu + 0.37A} T_1^2, \end{aligned} \tag{6}$$

where

$$H = e^{\left(1 - \frac{h_x}{K_P}\right)}, \quad A = 0.5(1 + H^2) \tag{7}$$

and  $T_u$  is lag-time (apparent dead-time),  $T_g$  is build-up time,  $\mu = T_u/T_g$  and  $h_x = h(T_u + T_g)$  is the build-up value.

It must be stressed that  $T_1$  represents the sum of time constants including the dead-time term of the process and  $T_2^2$  represents the product sum of time constants including the dead-time

Table 1. Laplace-domain transfer functions of typical processes.

$G_{P1}(s) = \frac{K}{1+s\tau}$	$G_{P2}(s) = \frac{K}{(1+s\tau_1)(1+s\alpha\tau_1)}$
$G_{P3}(s) = \frac{Ke^{-sT_t}}{(1+s\tau_1)(1+s\alpha\tau_1)^2}$	with $\alpha = 0, \dots, 1$
$G_{P4}(s) = \frac{K}{(1+s\tau)^n}$	$G_{P5}(s) = \frac{K}{\prod_{i=1}^n (1+s(\tau/i))^i}$

term of the process. Thus, it is not necessary to determine the exact value of the dead-time of the process for a controller tuning according the rule in section 4. The results of identification through the inflection tangent for the flow process under test in section 3.1 differ only slightly from those according to least squares approximation using the solver function of Excel.

### 3.3 Closed-loop identification

For the closed loop, the characteristic frequency parameters  $T_1$  and  $T_2^2$  of the process can be estimated from the plant input signals  $m(t)$  and plant output signals  $c(t)$  applying least squares approximation of the frequency response  $G_P(s)$  (Golubev and Horowitz 1982, Schaedel 2003a,b):

$$\int_0^\infty \left[ \frac{c(s)}{m(s)} - \frac{K_P}{1 + sT_1 + s^2T_2^2} \right]^2 ds = \min. \quad (8)$$

This leads to

$$\int_0^\infty [c(s)\{1 + sT_1 + s^2T_2^2\} - m(s)K_P]^2 ds = \min. \quad (9)$$

Using integration instead of differentiation (as is done in the determination of the inflection tangent), the method becomes much less sensitive to noise.

$$\int_0^\infty \left[ \frac{c(s)}{s^2} + T_1 \frac{c(s)}{s} + T_2^2 c(s) - K_P \frac{m(s)}{s^2} \right]^2 ds = \min. \quad (10)$$

Applying Parseval's theorem

$$\frac{1}{2\pi} \int_{-\infty}^{+\infty} |X(\omega)|^2 d\omega = \int_{-\infty}^{+\infty} x^2(t) dt \quad (11)$$

the problem is transferred into the time domain

$$\int_0^\infty [I^2(c) + T_1 I(c) + T_2^2 c(t) - K_P I^2(m)]^2 dt = \min, \quad (12)$$

where

$$\begin{aligned} I(c) &= \int_0^\infty c(t) dt & I^2(c) &= \int_0^\infty \int_0^t c(t') dt' dt \\ I(m) &= \int_0^\infty m(t) dt & I^2(m) &= \int_0^\infty \int_0^t m(t') dt' dt \end{aligned} \quad (13)$$

are the integrals of the input and output data of the plant. The discrete time version follows as

$$\sum_{k=0}^N [I^2(c_k) + T_1 I(c_k) + T_2^2 c_k - K_P I^2(m_k)]^2 = \sum_{k=0}^N e^2(k)$$

with

$$I(c_k) = I(c_{k-1}) + (c_k + c_{k-1}) \frac{T_0}{2} \quad (14)$$

using the trapezoidal rule for integration. Looking for least squares error by taking the differentials to the characteristic values  $K_P$ ,  $T_1$  and  $T_2^2$  leads to a matrix relation between input and

output data and frequency parameters (15) from which the characteristic frequency parameters of the plant can be determined by matrix inversion (16):

$$\begin{aligned}\frac{\partial}{\partial K_P} \sum_{k=0}^N e_k^2 &= -2 \sum_{k=0}^N [I^2(c_k) + T_1 I(c_k) + T_2^2 c_k - K_P I^2(m_k)] \cdot I^2(m_k) = 0 \\ \frac{\partial}{\partial T_1} \sum_{k=0}^N e_k^2 &= 2 \sum_{k=0}^N [I^2(c_k) + T_1 I(c_k) + T_2^2 c_k - K_P I^2(m_k)] \cdot I(c_k) = 0 \\ \frac{\partial}{\partial T_2^2} \sum_{k=0}^N e_k^2 &= 2 \sum_{k=0}^N [I^2(c_k) + T_1 I(c_k) + T_2^2 c_k - K_P I^2(m_k)] \cdot c_k = 0\end{aligned}\quad (15)$$

$$\begin{aligned}& \begin{bmatrix} \sum_{k=0}^N [I^2(c_k)]^2 & - \sum_{k=0}^N I(m_k) \cdot I^2(c_k) & - \sum_{k=0}^N m_k \cdot I^2(c_k) \\ \sum_{k=0}^N [I^2(c_k) \cdot I(m_k)] & - \sum_{k=0}^N [I(m_k)]^2 & - \sum_{k=0}^N m_k \cdot I(m_k) \\ \sum_{k=0}^N [I^2(c_k)] \cdot m_k & - \sum_{k=0}^N I(m_k) \cdot m_k & - \sum_{k=0}^N [m_k]^2 \end{bmatrix} \begin{bmatrix} K_P \\ T_1 \\ T_2^2 \end{bmatrix} \\ &= \begin{bmatrix} \sum_{k=0}^N I^2(m_k) \cdot I^2(c_k) \\ \sum_{k=0}^N I^2(m_k) \cdot I(m_k) \\ \sum_{k=0}^N I^2(m_k) \cdot m_k \end{bmatrix} \cdot\end{aligned}\quad (16)$$

Figure 4 shows the results from the remote UTC lab for a PI-controlled flow process with poor tuning.

Parameter estimation based on input and output data gives the characteristics of the plant

$$K_P = 0.5 \text{ lb min}^{-1} \%^{-1}, \quad T_1 = 0.826 \text{ s}, \quad T_2^2 = 0.246 \text{ s}.$$

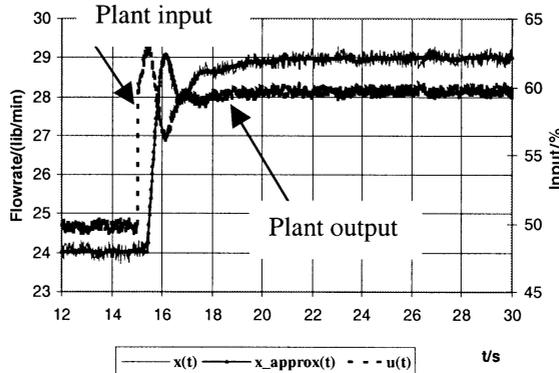


Figure 4. Step response of a PI-controlled flow process with poor parameter tuning.

In order to compare the response of the real process with the result of the identification, a first-order plus dead-time (FOPDT) model for the plant may be calculated from the data above by

$$\tau = \sqrt{T_1^2 - 2T_2^2} \quad \text{and} \quad T_t = T_1 - \tau$$

resulting in

$$K_P = 0.5 \text{ lb min}^{-1} \%^{-1}, \quad T_t = 0.39 \text{ s}, \quad \tau = 0.436 \text{ s}.$$

The reduced dead-time  $\mu = T_t/\tau$  is varied for optimal fitting manually. Figure 4 shows excellent agreement between the approximating model and the real plant.

#### 4. Controller tuning

Controller tuning is done according to the criterion of cascaded damping ratios (Schaedel 1997a,b, 1998). The design is based on a direct relation between the parameters of the process and the controller and enables the use of classical filter design (e.g. Butterworth, Tschebyscheff) and standard forms (e.g. ITAE, IAE). A design for optimal set-point control as well as optimal disturbance rejection is provided. Tables 2 and 3 give tuning rules for the parameters of the PI-controller proportional gain  $K_C$  and reset time  $T_r$ . The tuning rules for optimal set-point control may be applied to processes with arbitrary dead-time and lag-order.

Table 2. PI-controller for optimal set-point control.

<i>Butterworth (normal design)</i>	
$K_C = \frac{0.5}{K_P} \frac{T_r}{T_1 - T_r}$	$T_r = \sqrt{T_1^2 - 2T_2^2}$
<i>Tschebyscheff 0.5 db (sharp design)</i>	
$K_C = \frac{0.375}{K_P} \frac{T_r}{T_1 - T_r}$	$T_r = T_1 - \frac{T_2^2}{T_1}$
<i>ITAE</i>	
$K_C = \frac{0.375}{K_P} \frac{T_r}{T_1 - T_r}$	$T_r = -0.64T_1 + 1.64T_1 \sqrt{1 - 1.2 \frac{T_2^2}{T_1^2}}$

Table 3. PI-controller for optimal disturbance rejection.

<i>Butterworth (normal design)</i>	
$K_C = \frac{1}{K_P} \left( \frac{1}{2} \frac{T_r^2}{T_2^2} - 1 \right)$	$T_r = 4 \frac{T_2^2}{T_1} \left( 1 - 2 \frac{T_2^2}{T_1^2} \right)$
<i>Tschebyscheff 0.1 db</i>	
$K_C = \frac{1}{K_P} \left( 0.7 \frac{T_r^2}{T_2^2} - 1 \right)$	$T_r = 3.11 \frac{T_2^2}{T_1} \left( 1 - 1.43 \frac{T_2^2}{T_1^2} \right)$
<i>ITAE</i>	
$K_C = \frac{1}{K_P} \left( 0.69 \frac{T_r^2}{T_2^2} - 1 \right)$	$T_r = 3.86 \frac{T_2^2}{T_1} \left( 1 - 1.46 \frac{T_2^2}{T_1^2} \right)$

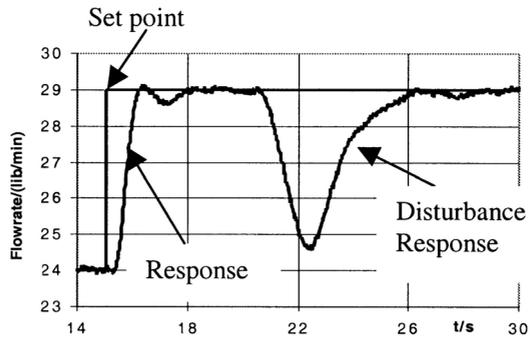


Figure 5. Response of the PI-controlled process to a set-point change and a disturbance change.

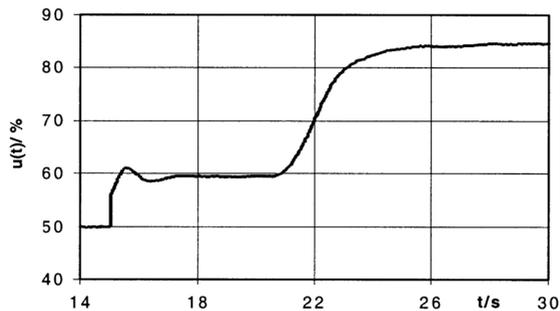


Figure 6. Plant input signal (manipulated variable) of the PI-controlled flow process.

The application of PI-tuning rules for optimal disturbance rejection is limited to processes of low orders up to about 3 and small dead-time respectively a ratio  $\mu = T_u/T_g < 0.2$ .

As pointed out in section 3.2  $T_1$  and  $T_2^2$  represent the sum of time constants and the product sum of time constants, both including the dead-time term of the process, respectively.

From parameter estimation in section 3.1, the tuning of the PI-controller of the sharp design is obtained for optimal reference control of the flow process as

$$K_C = 0.973\% / (\text{lb}/\text{min}) \text{ and } T_i = 0.495 \text{ s.}$$

Figures 5 and 6 show the response of the control circuit to a set-point change at 15 s and a change in disturbance at 20 s.

## 5. Concluding remarks

The use of remote experiments for obtaining plant data and designing feedback controllers was entirely successful. The spreadsheet control tool designed can be used in teaching as well as industrial applications. An extension of the tool may be done quite easily by adding sheets and introducing hyperlinks. The tool will be continuously extended and examples will be included for educational purposes in order to illustrate modern methods of control engineering for application in industry.

## References

- Golubev, B. and Horowitz, I., Plant rational transfer approximation from input–output data. *Int. J. Control*, 1982, **36**, 711–723.
- Henry, J., Engineering controls systems with LabVIEW, in *Scientific and Engineering Applications for Macintosh*, Woburn: MA, August, 1993. Available online at <http://chem.engr.utc.edu/Henry-Pub>
- Henry, J., LabVIEW applications in teaching controls systems laboratories, in *ASEE Annual Meeting, Anaheim: CA, June, 1995*. Available online at <http://chem.engr.utc.edu/Henry-Pub>
- Henry, J., Laboratory teaching via the World Wide Web, in *ASEE Southeast Annual Meeting, April, 1998*. Available online at <http://chem.engr.utc.edu/Henry-Pub>
- Henry, J. and Zollars, D., Assessment of remote experiments and local simulations: student experiences, satisfaction and suggestions, in *ASEE Annual Meeting, June, 2003*. Available online at <http://chem.engr.utc.edu/Henry-Pub>
- Schaedel, H.M., Parameterschätzung über die Wendetangente und direkter Reglerentwurf in den CAE-Werkzeugen SimTool und SIMID. 2. VDI/VDE Aussprachetag Rechnergestützter Entwurf von Regelsystemen, Kassel, 16–17 September, 1997a, GMA-Bericht 32, pp. 9–18.
- Schaedel, H.M., A new method of direct PID controller design based on the principle of cascaded damping ratios, in *Proceedings of the 4th European Control Conference, Brussels, Paper WE-A H4, BELWARE Information Technology, Waterloo, 1–4 July, 1997b*.
- Schaedel, H.M., Neue Prinzipien des direkten Entwurfs parameteroptimierter Regler für stabile, schwingungsfähige und instabile Strecken mit dem CAE-Werkzeug SimTool. GMA-Kongress '98 Mess- und Automatisierungstechnik, Ludwigsburg, VDI-Berichte 1397, pp. 103–110, 1998.
- Schaedel, H.M., Spreadsheet Control – Prozessidentifikation. Reglerentwurf und Regelkreissimulation mit MS – Excel. GMA-Kongress 2003. Automation und Information in Wirtschaft und Gesellschaft. Baden-Baden, VDI-Berichte 1756, pp. 723–730, 2003a.
- Schaedel, H.M., Processidentification, Controller Tuning and Control Circuit Simulation using MS Excel, in *Proceedings of 13th IFAC Symposium on System Identification Rotterdam, Netherlands, 27–29, August, Paper SWR 143 (on CD), 2003b*.
- Smith, C.A. and Corripio, A.B., *Principles and Practice of Automatic Process Control*, p. 304, 1997 (Wiley: Hoboken, NJ), .
- Ziegler, J.G. and Nichols, G.A., Optimum settings for automatic controllers. *Trans. ASME*, 1942, **64**, 759–768.

## About the authors

*Herbert M. Schaedel* has been Professor in controls engineering at the Faculty of Information, Media and Electrical of the University of Applied Sciences Cologne since 1971. He obtained his Doctorate from RWTH Aachen. He has industrial experience in electronics and controls engineering. His main interest is in controls and signal processing, and specifically in CAE-tools and design methods for engineering education and industrial applications in controls engineering. He has written more than 20 articles and conference papers concerning this latter field.

*Jim Henry (Dr)* is a professor in the area of chemical and environmental engineering at the University of Tennessee at Chattanooga. He received his PhD from Princeton University. He has been teaching engineering for 35 years. He is interested in laboratory development for improved learning. He has been developing web-based laboratories for engineering education since 1995 and has lectured internationally on his work in web-based laboratories.