PID Control System Analysis, Design, and Technology

Kiam Heong Ang, Gregory Chong, *Student Member, IEEE*, and Yun Li, *Member, IEEE*

***Abstract*—Designing and tuning a proportional-integral-derivative (PID) controller appears to be conceptually intuitive, but can be hard in practice, if multiple (and often conflicting) objectives such as short transient and high stability are to be achieved. Usually, initial designs obtained by all means need to be adjusted repeatedly through computer simulations until the closed-loop system performs or compromises as desired. This stimulates the development of "intelligent" tools that can assist engineers to achieve the best overall PID control for the entire operating envelope. This development has further led to the incorporation of some advanced tuning algorithms into PID hardware modules. Corresponding to these developments, this paper presents a modern overview of functionalities and tuning methods in patents, software packages and commercial hardware modules. It is seen that many PID variants have been developed in order to improve transient performance, but standardising and modularising PID control are desired, although challenging. The inclusion of system identification and "intelligent" techniques in software based PID systems helps automate the entire design and tuning process to a useful degree. This should also assist future development of "plug-and-play" PID controllers that are widely applicable and can be set up easily and operate optimally for enhanced productivity, improved quality and reduced maintenance requirements.**

***Index Terms*—Patents, proportional-integral-derivative (PID) control, PID hardware, PID software, PID tuning.**

I. Introduction

With its three-term functionality covering treatment to both transient and steady-state responses, proportional-integral-derivative (PID) control offers the simplest and yet most efficient solution to many real-world control problems. Since the invention of PID control in 1910 (largely owning to Elmer Sperry's ship autopilot), and the Ziegler–Nichols' (Z-N) straightforward tuning methods in 1942 [34], the popularity of PID control has grown tremendously. With advances in digital technology, the science of automatic control now offers a wide spectrum of choices for control schemes. However, more than 90% of industrial controllers are still implemented based around PID algorithms, particularly at lowest levels [5], as no other controllers match the simplicity, clear functionality, applicability, and ease of use offered by the PID controller [32]. Its wide application has stimulated and sustained the development of various PID tuning techniques, sophisticated software packages, and hardware modules.

The success and longevity of PID controllers were characterized in a recent IFAC workshop, where over 90 papers dedicated to PID research were presented [28]. With much of academic research in this area maturing and entering the region of "diminishing returns," the trend in present research and development (R&D) of PID technology appears to be focused on the integration of available methods in the form of software so as to get the best out of PID control [21]. A number of software-based techniques have also been realized in hardware modules to perform "on-demand tuning," while the search still goes on to find the next key technology for PID tuning [24].

This paper endeavours to provide an overview on modern PID technology including PID software packages, commercial PID hardware modules and patented PID tuning rules. To begin, Section II highlights PID fundamentals and crucial issues. Section III moves to focus on patented PID tuning rules. A survey on available PID software packages is provided in Section IV. In Section V, PID hardware and tuning methods used by process control vendors are discussed. Finally, conclusions are drawn in Section VI, where some differences between academic research and industrial practice are highlighted.

Manuscript received September 8, 2003; revised August 15, 2004. Manuscript received in final form January 4, 2005. Recommended by Associate Editor D. W. Repperger. This work was supported in part by Universities U.K. and in part by University of Glasgow Scholarships.

K. H. Ang is with Yokogawa Engineering Asia Pte Ltd., Singapore 469270, Singapore (e-mail: KiamHeong.Ang@sg.yokogawa.com).

G. Chong and Y. Li are with the Intelligent Systems Group, Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8LT, U.K. (e-mail: g.chong@elec.gla.ac.uk; y.li@elec.gla.ac.uk).

Digital Object Identifier 10.1109/TCST.2005.847331

II. Three-Term Functionality, Design and Tuning

A. Three-Term Functionality and the Parallel Structure

A PID controller may be considered as an extreme form of a phase lead-lag compensator with one pole at the origin and the other at infinity. Similarly, its cousins, the PI and the PD controllers, can also be regarded as extreme forms of phase-lag and phase-lead compensators, respectively. A standard PID controller is also known as the "three-term" controller, whose transfer function is generally written in the "parallel form" given by (1) or the "ideal form" given by (2)

$$G(s) = K_P + K_I \frac{1}{s} + K_D s \tag{1}$$

$$= K_P \left(1 + \frac{1}{T_I s} + T_D s\right) \tag{2}$$

where K_P is the proportional gain, K_I the integral gain, K_D the derivative gain, T_I the integral time constant and, T_D the derivative time constant. The "three-term" functionalities are highlighted by the following.

- The proportional term—providing an overall control action proportional to the error signal through the all-pass gain factor.

- The integral term—reducing steady-state errors through low-frequency compensation by an integrator.
- The derivative term—improving transient response through high-frequency compensation by a differentiator.

The individual effects of these three terms on the closed-loop performance are summarized in Table I. Note that this table serves as a first guide for stable open-loop plants only. For optimum performance, K_P, K_I (or T_I) and K_D (or T_D) are mutually dependent in tuning.

The message that increasing the derivative gain, K_D, will lead to improved stability is commonly conveyed from academia to industry. However, practitioners have often found that the derivative term can behave against such anticipation particularly when there exists a transport delay [23], [28]. Frustration in tuning K_D has hence made many practitioners switch off or even exclude the derivative term. This matter has now reached the point that requires clarification, which will be discussed in Section II-E.

TABLE I
EFFECTS OF INDEPENDENT P, I, AND D TUNING

Closed-Loop Response	Rise Time	Overshoot	Settling Time	Steady-State Error	Stability
Increasing K_P	Decrease	Increase	Small Increase	Decrease	Degrade
Increasing K_I	Small Decrease	Increase	Increase	Large Decrease	Degrade
Increasing K_D	Small Decrease	Decrease	Decrease	Minor Change	Improve

B. Series Structure

A PID controller may also be realized in the "series form" if both zeros are real, i.e., if $T_I \geq 4T_D$. In this case, (2) can be implemented as a cascade of a PD and a PI controller in the form [23]

$$G(s) = K_P(\alpha + T_D s) \cdot \left(1 + \frac{1}{\alpha T_I s}\right) \tag{3}$$

where

$$\alpha = \frac{1 \pm \sqrt{1 - \frac{4T_D}{T_I}}}{2} > 0. \tag{4}$$

C. Effect of the Integral Term on Stability

Refer to (2) or (3) for $T_I \neq 0$ and $T_D = 0$. It can be seen that, adding an integral term to a pure proportional term will increase the gain by a factor of

$$\left|1 + \frac{1}{j\omega T_I}\right| = \sqrt{1 + \frac{1}{\omega^2 T_I^2}} > 1, \quad \forall\omega \tag{5}$$

and will increase the phase-lag at the same time since

$$\angle\left(1 + \frac{1}{j\omega T_I}\right) = \tan^{-1}\left(\frac{-\frac{1}{\omega T_I}}{1}\right) < 0, \quad \forall\omega. \tag{6}$$

Hence, both stability gain margin (GM) and phase margin (PM) will be reduced, i.e., the closed-loop system will become more oscillatory or potentially unstable.

D. Integrator Windup and Remedies

If an actuator that realizes the control action has an effective range limit, then the integrator may saturate and future correction will be ignored until the saturation is offset. This causes low-frequency oscillations and may lead to instability. A usual measure taken to counteract this effect is "anti-windup" [4], [8], [29]. This is realized by inner negative feedback of some excess amount of the integral action to the integrator such that saturation will be taken out. Nearly all software packages and hardware modules have implemented some form of integrator anti-windup protection.

As most modern PID controllers are implemented in digital processors, they can accommodate more mathematical functions and modifications to the standard three terms shown in (1) to (3). A simple and most widely adopted anti-windup scheme can be realized in software or firmware by modifying the integral action to

$$U_I'(s) = \frac{1}{T_I s}\left[K_P E(s) - \frac{U(s) - \widetilde{U}(s)}{\gamma}\right] \tag{7}$$

where $\widetilde{U}(s)$ represents the saturated control action and γ is a correcting factor. It is found that the range of [0.1,1.0] for γ results in extremely good performance if PID coefficients are tuned reasonably [23].

It is also reported that, in the "series form," the PI part may be implemented to counter actuator saturation without the need for a separate anti-windup action, as shown in Fig. 1 [4], [29]. When there is no saturation, the feedforward-path transfer is unity and the overall transfer from $U_{\mathrm{PD}}(s)$ to $U(s)$ is the same as the last factor in (3).

E. Effect of the Derivative Term on Stability

Generally, derivative action is valuable as it provides useful phase lead to offset phase lag caused by integration. It is also particularly helpful in shortening the period of the loop and thereby hastening its recovery from disturbances. It can have a more dramatic effect on the behavior of second-order plants that have no significant dead-time than first-order plants [29].

However, the derivative term is often misunderstood and misused. For example, it has been widely perceived in the control community that adding a derivative term will improve stability. It will be shown here that this perception is not always valid. In general, adding a derivative term to a pure proportional term will reduce phase lags by

$$\angle(1 + j\omega T_D) = \tan^{-1}\frac{\omega T_D}{1} \in \left[0, \frac{\pi}{2}\right], \quad \forall\omega \tag{8}$$

which alone tends to increase the PM. In the meantime, however, the gain will be increased by a factor of

$$|1 + j\omega T_D| = \sqrt{1 + \omega^2 T_D^2} > 1, \quad \forall\omega \tag{9}$$

and, hence, the overall stability may be improved or degraded.

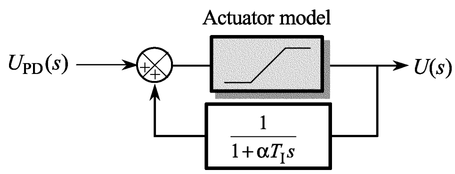


Fig. 1. Anti-windup PI part of a "series form."

To prove that adding a differentiator could actually destabilise the closed-loop system, consider without loss of generality a common first-order lag plus delay plant as described by

$$G(s) = \frac{K}{1+Ts}e^{-Ls} \tag{10}$$

where K is the process gain; T is the process time-constant; and L is the process dead-time or transport delay. Suppose that it is controlled by a proportional controller with gain K_P and now a derivative term is added. This results in a combined PD controller as given by

$$G_{PD}(s) = K_P(1+T_D s). \tag{11}$$

The overall open-loop feedforward-path transfer function becomes

$$G(j\omega)G_{\mathrm{PD}}(j\omega) = KK_P\frac{1+jT_D\omega}{1+jT\omega}e^{-jL\omega} \tag{12}$$

with gain becoming

$$\begin{aligned} |G(j\omega)G_{\mathrm{PD}}(j\omega)| &= KK_P\sqrt{\frac{1+T_D^2\omega^2}{1+T^2\omega^2}} \\ &\geq KK_P \min\left(1, \frac{T_D}{T}\right) \end{aligned} \tag{13}$$

where the inequality has been obtained because $\sqrt{(1+T_D^2\omega^2)/(1+T^2\omega^2)}$ is monotonic with ω. This implies that the gain is not less than 0 dB if $T_D \leq T$ and $KK_P \leq 1$ or $T_D \geq T$ and

$$T_D \geq \frac{T}{KK_P}. \tag{14}$$

In these cases, the 0 dB gain crossover frequency ω_c is at infinite, where the phase

$$\begin{aligned} \angle G(j\omega_c)G_{\mathrm{PD}}(j\omega_c) &= \tan^{-1}\frac{T_D\omega_c}{1} - \tan^{-1}\frac{T\omega_c}{1} - L\omega_c \\ &= \frac{\pi}{2} - \frac{\pi}{2} - \infty \quad < -\pi. \end{aligned} \tag{15}$$

Hence, by Bode or Nyquist criterion, there exist no stability margins and the closed-loop system will be unstable.

This phenomenon could have contributed to the difficulties in the design of a full PID controller and also to the reason that 80% of PID controllers in use have the derivative part omitted or switched off [21]. This means that the functionality and potential of a PID controller is not fully exploited. Nonetheless, it is shown that the use of a derivative term can increase stability robustness and can help maximize integral gain so as to achieve the best performance [7]. However, care must be taken, as it is difficult to tune the differentiator properly. An example is given in Figs. 2 and 3 for plant (10) with $K = 10$, $T = 1$ s and $L = 0.1$ s, which is initially controlled by a PI controller with $K_P = 0.644$ and $T_I = 1.03$ s. It can be seen that if a differentiator is added with $T_D = 0.0303$ s, both the GM and the PM will be maximized while the transient response improves to the best. However, if T_D is increased further to 0.1 s, the GM and transient response will deteriorate. The closed-loop system can even be destabilised if the derivative gain is increased to 20% of the proportional gain. Hence, the derivative term should be tuned and used properly.

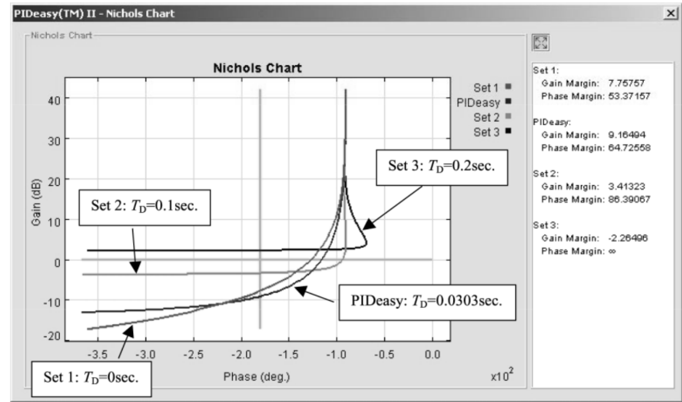


Fig. 2. Increasing derivative gain could decrease stability margins and destabilise the closed-loop system.

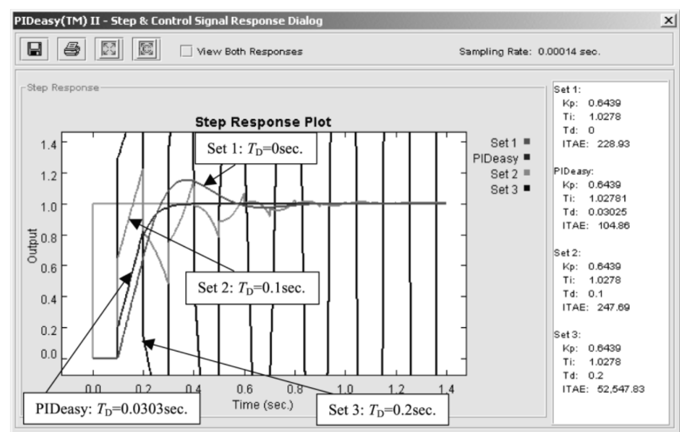


Fig. 3. Time-domain effect of an increasing gain on the closed-loop performance.

F. Remedies on Singular Derivative Action

A pure differentiator is not "casual." It does not restrict high-frequency gains, as shown in (9) and demonstrated in Fig. 2. Hence, it will results in a theoretically infinite high control signal when a step change of the reference or disturbance occurs. To combat this, most PID software packages and hardware modules perform some forms of filtering on the differentiator.

1) Averaging Through a Linear Low-Pass Filter: A common remedy is to cascade the differentiator with a low-pass filter, i.e., to modify it to

$$G'_D(s) = \frac{T_D s}{1 + \frac{T_D}{\beta} s}. \tag{16}$$

Most industrial PID hardware provides a β setting from 1 to 33 and the majority falls between 8 and 16 [72]. A second-order Butterworth filter is recommended in [17] for further attenuation of the high-frequency gains.

2) Modified Structure: The issue of improving transient performance has recently become such a crucial one that attention of the fundamental unity negative feedback structure has been proposed in the R&D of PID control [4]. In cascade control applications, the inner-loop often needs to be less sensitive to set-point changes than the outer-loop. For the inner-loop, a variant to the standard PID structure may be adopted, which uses the process variable (PV) instead of the error signal, for the derivative term [40], i.e.

$$u(t) = K_P\, e(t) + K_I \int_0^t e(\tau)d\tau - K_D \frac{d}{dt} y(t) \tag{17}$$

where $y(t)$ is the PV, $e(t) = r(t) - y(t)$ and $r(t)$ is the reference signal or set-point. It is also proposed that, in order to further reduce sensitivity to set-point changes, the proportional term may also be changed to act upon the PV, instead of the error signal, i.e., [40]

$$u(t) = -K_P\, y(t) + K_I \int_0^t e(\tau)d\tau - K_D \frac{d}{dt} y(t). \tag{18}$$

Structure (17) is sometimes referred to as "Type B" (or PI-D) control and structure (18) as "Type C" (or I-PD) control, while structures (1) to (3) as "Type A" PID control. Note that, Types B and C alter the foundations of conventional feedback control and can make the PID schemes more difficult to analyze with standard techniques on stability and robustness, etc. For set-point tracking applications, however, one alternative to using Type B or C is perhaps a set-point filter that has a critically-damped dynamics so as to achieve soft-start and smooth control [13]. Nevertheless, the ideal, parallel, series and modified forms of PID structures can all be found in present software packages and hardware modules. Readers may refer to Techmation's Applications Manual [72] for a list documenting the structures employed in some of the industrial PID controllers.

3) Removal of Singular Action Through a Nonlinear Median Filter: Another method is to use a median filter, which is nonlinear and widely applied in image processing. It compares several neighboring data points around the current one and selects their median for a "nonsingular" action. This way, unusual or unwanted spikes resulting from a step command or disturbance, for example, will be filtered out completely. Pseudocode of a three-point median filter is illustrated in Fig. 4 [23]. The main benefit of this method is that no extra parameter is needed, though it is not very suitable for use in under-damped processes.

```
derivative = (error ñ previous_error) / sampling_period;
if (derivative > max_d)
        new_derivative = max_d;              // median
else if (derivative < min_d)
        new_derivative = min_d;              // median
else
        new_derivative = derivative;         // median

if (derivative > previous_derivative) {
        max_d = derivative;
        min_d = previous_derivative;
} else {
        max_d = previous_derivative;
        min_d = derivative;
}
previous_derivative = derivative;
```

Fig. 4. Three-point median filter to eliminate singular derivative action.

G. Tuning Objectives and Existing Methods

Preselection of a controller structure can pose a challenge in applying PID control. As vendors often recommend their own designs of controller structures, their tuning rules for a specific controller structure does not necessarily perform well with other structures. One solution seen is to provide support for individual structures in software. Readers may refer to [16] and [22] for detailed discussions on the use of various PID structures. Nonetheless, controller parameters are tuned such that the closed-loop control system would be stable and would meet given objectives associated with the following:

- stability robustness;
- set-point following and tracking performance at transient, including rise-time, overshoot, and settling time;
- regulation performance at steady-state, including load disturbance rejection;
- robustness against plant modeling uncertainty;
- noise attenuation and robustness against environmental uncertainty.

With given objectives, tuning methods for PID controllers can be grouped according to their nature and usage, as follow [4], [13], [23].

- Analytical methods—PID parameters are calculated from analytical or algebraic relations between a plant model and an objective (such as internal model control (IMC) or lambda tuning). These can lead to an easy-to-use formula and can be suitable for use with online tuning, but the objective needs to be in an analytical form and the model must be accurate.
- Heuristic methods—These are evolved from practical experience in manual tuning (such as the Z-N tuning rule) and from artificial intelligence (including expert systems, fuzzy logic and neural networks). Again, these can serve in the form of a formula or a rule base for online use, often with tradeoff design objectives.
- Frequency response methods—Frequency characteristics of the controlled process are used to tune the PID controller (such as loop-shaping). These are often offline and academic methods, where the main concern of design is stability robustness.

- Optimization methods—These can be regarded as a special type of optimal control, where PID parameters are obtained *ad hoc* using an offline numerical optimization method for a single composite objective or using computerised heuristics or an evolutionary algorithm for multiple design objectives. These are often time-domain methods and mostly applied offline.
- Adaptive tuning methods—These are for automated online tuning, using one or a combination of the previous methods based on real-time identification.

The previous classification does not set an artificial boundary and some methods applied in practice may belong to more than one category. An excellent summary on PID tuning methods can be found in [4], [18], [26], and [28]. However, no tuning method so far can replace the simple Z-N method in terms of familiarity and ease of use to start with. Further, there exists a lack of methods that are generic and can be quickly applied to the design of onboard or onchip controllers for a wide range of consumer electronics, domestic appliances, mechatronic systems and microelectromechanical systems (MEMS). Over the past half century, search goes on to find the next key technology for PID tuning and modular realization [24].

H. PIDeasy—A Software-Based Approach

During the past decade, the Intelligent Systems research group at University of Glasgow has attempted to solve the PID design problem systematically, using modern computational intelligence technology. As a result, a design solution has been obtained in the form of software, PIDeasy [23]. For simplicity and reliability in PID applications, effort is made to maintain the controller structure in the "standard form," while allowing optimal augmentation with simple and effective differentiator filtering and integrator anti-windup. High-performance particularly that of transient response is offered through setting the controller parameters optimally in a fraction of a millisecond, as soon as changes in process dynamics are detected. The optimality is multiobjective and is achieved by addressing existing problems at the roots using modern computational intelligence techniques.

The PIDeasy technology is targeted toward wider applications than the Z-N based and other techniques currently available, so as to offer the following:

- optimal PID designs directly from offline or online plant response;
- generic and widest application to any first-order (and higher order) delayed plants;
- "off-the-computer" digital controller code in C++ and Java languages;
- no need for any follow-up refinements; and
- "plug-and-play" integration of an entire process of data acquisition, system identification, design, digital code implementation and online testing.

Time-domain performance of PIDeasy is seem much better than existing methods, in all five criteria listed in Section II-G, with or without actuator saturation [23]. A simple example has been shown in Figs. 2 and 3. To verify the robustness, PIDeasy is tested against an L/T ratio ranging from 0.001 to 1000.0. The resulting GMs and PMs are shown in Fig. 5, which confirms that this tuning method is stable and robust with margins almost uniformly around those that practitioners prefer. While in the time-domain, fast response, no overshoot and no steady-state error are achieved.

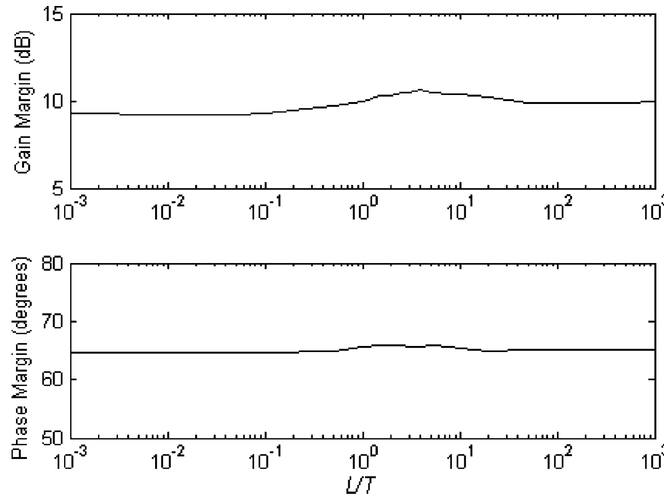


Fig. 5. Gain and phase margins resulting from PIDeasy designs.

TABLE II
GAIN AND PHASE MARGINS OF PIDEASY ON TEST EXAMPLES

	GM (dB)	PM (degrees)	K_P	T_I (sec)	T_D (sec)
$G_1(s)$, α=1	Infinity	102	92.1	1.0	0.00217
$G_1(s)$, α=2	Infinity	62.4	1.95	1.61	0.14
$G_1(s)$, α=3	26.8	60.7	1.12	2.13	0.28
$G_1(s)$, α=4	13.9	61	0.83	2.61	0.43
$G_1(s)$, α=8	9.05	58.9	0.50	4.31	1.01
$G_2(s)$, α=0.1	52.8	68.7	5.53	1.03	0.04
$G_2(s)$, α=0.2	38.6	66.3	2.87	1.08	0.07
$G_2(s)$, α=0.5	19.1	62.6	1.19	1.36	0.17
$G_3(s)$, α=0.1	19.4	61.2	1.03	2.15	0.31
$G_3(s)$, α=0.2	16.6	61.6	0.96	2.18	0.33
$G_3(s)$, α=0.5	13	62.4	0.79	2.23	0.39
$G_3(s)$, α=1	7.52	50.9	0.63	2.30	0.47
$G_3(s)$, α=2	7.45	58.6	0.48	2.39	0.57
$G_3(s)$, α=5	2.69	40.4	0.36	2.58	0.72
$G_4(s)$, α=0.1	10.4	66	0.23	0.43	0.12
$G_4(s)$, α=0.2	10.4	65.8	0.30	0.59	0.17
$G_4(s)$, α=0.5	10.5	65.6	0.49	1.07	0.26
$G_4(s)$, α=2	15	62.4	1.04	3.49	0.49
$G_4(s)$, α=5	24.2	62.1	1.42	8.32	0.92
$G_4(s)$, α=10	32.8	62.1	1.65	16.35	1.59

To further validate this software-based tuning method and to provide a lookup table of parameter sets for many typical plants, a batch of higher order plants proposed in [6] are tested

$$G_1(s) = \frac{1}{(s+1)^{\alpha}}, \quad \alpha = 1, 2, 3, 4, 8 \tag{19}$$

$$G_2(s) = \frac{1}{(s+1)(1+\alpha s)(1+\alpha^2 s)(1+\alpha^3 s)} \quad \alpha = 0.1, 0.2, 0.5 \tag{20}$$

$$G_3(s) = \frac{1-\alpha s}{(s+1)^3}, \quad \alpha = 0.1, 0.2, 0.5, 1, 2, 5 \tag{21}$$

$$G_4(s) = \frac{1}{(1+s\alpha)^2} e^{-s}, \quad \alpha = 0.1, 0.2, 0.5, 2, 5, 10. \tag{22}$$

TABLE III
PATENTS ON PID TUNING

Year	Patent Number	Assignee / Title	ID Method	Tuning Method
1970	US 3532862	International Business Machines Corporation (Armonk, NY) "Method for adjusting controller gain to control a process"	E	F
1973	US 3727035	Phillips Petroleum Company (Bartlesville, Okla.) "Pulse test of digital control system"	E	F
1974	US 3798426	The Foxboro Company (Foxboro, MA) "Pattern evaluation method and apparatus for adaptive control"	NE	R
1974	US 3826887	Phillips Petroleum Company (Bartlesville, Okla.) "Simplified procedure for tuning PID controllers"	NE	R
1980	US 4214300	K.R. Jones (Liverpool, England) "Three term (PID) controllers"	E	O
1982	US 4346433	Phillips Petroleum Company (Bartlesville, OK) "Process control"	E	F
1983	US 4407013	Leeds & Northrup Company (North Wales, PA) "Self tuning of P-I-D controller by conversion of discrete time model identification parameters"	NE	F
1984	US 4441151	Toyo Systems Ltd. (Tokyo, JP) "Apparatus for tuning PID controllers in process control systems"	E	F
1984	US 4451878	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, JP) "Process control apparatus"	E	F
1984	US 4466054	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, JP) "Improved proportional integral-derivative control apparatus"	NE	F
1985	US 4539633	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, JP) "Digital PID process control apparatus"	E	F
1985	US 4549123	NAF Controls AB (Solna, SE) "Method and an apparatus in tuning a PID-regulator"	E	F
1986	US 4563734	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, JP) "Multivariable proportional-integral-derivative process control apparatus"	E	F
1986	US 4602326	The Foxboro Company (Foxboro, MA) "Pattern-recognizing self-tuning controller"	NE	R
1987	US 4669040	Eurotherm Corporation (Reston, VA) "Self-tuning controller"	E	F
1988	US 4754391	Yamatake-Honeywell Co. Ltd. (Tokyo, JP) "Method of determining PID parameters and an automatic tuning controller using the method"	E	F
1988	US 4758943	Hightech Network AB (Malmo, SE) "Method and an apparatus for automatically tuning a process regulator"	E	F
1988	US 4768143	The Babcock & Wilcox Company (New Orleans, LA) "Apparatus and method using adaptive gain scheduling algorithm"	NE	F
1989	US 4814968	Fischer & Porter Company (Warminster, PA) "Self-tuning process controller"	NE	F
1989	US 4855674	Yamatake-Honeywell Company Limited (Tokyo, JP) "Method and a process control system using the method for minimizing hunting"	E	F
1989	US 4864490	Mitsubishi Denki Kabushiki Kaisha (Tokyo, JP) "Auto-tuning controller using fuzzy reasoning to obtain optimum control parameters"	NE	R
1989	US 4881160	Yokogawa Electric Corporation (Tokyo, JP) "Self-tuning controller"	NE	F
1989	US 4882526	Kabushiki Kaisha Toshiba (Kawasaki, JP) "Adaptive process control system"	E	F
1990	US RE33267	The Foxboro Company (Foxboro, MA) "Pattern-recognizing self-tuning controller"	NE	R
1990	US 4903192	Hitachi Ltd. (Tokyo, JP) "PID Controller System"	NE	R
1991	US 5043862	Hitachi Ltd. (Tokyo, JP) "Method and apparatus of automatically setting PID constants"	NE	R
1992	US 5126933	Charles A. White III (Stamford CT) "Self-learning memory unit for process controller and self-updating function generator"	NE	Self-learning memory unit
1992	US 5153807	Hitachi Ltd. (Tokyo, JP) "Self-tuning controller apparatus and process control system"	NE	R
1992	US 5159547	Rockwell International Corporation (Seal Beach, CA) "Self-monitoring tuner for feedback controller"	NE	R
1992	US 5166873	Yokogawa Electric Corporation (Tokyo, JP) "Process control device"	E	F
1992	US 5170341	Honeywell Inc. (Minneapolis, MN) "Adaptive controller in a process control system and a method therefor"	E	F
1993	US 5223778	Allen-Bradley Company Inc. (Milwaukee, WI) "Automatic tuning apparatus for PID controllers"	E	F

1993	US 5229699	Industrial Technology Research Institute (Chutung, TW) "Method and an apparatus for PID controller tuning"	E	F
1993	US 5268835	Hitachi Ltd. (Tokyo, JP) "Process controller for controlling a process to a target state"	NE	F
1993	US 5272621	Nippon Denki Garasu Kabushiki Kaisha (Shiga, JP) "Method and apparatus using fuzzy logic for controlling a process having dead time"	NE	R
1994	US 5283729	Fisher-Rosemount Systems, Inc. (Austin, TX) "Tuning arrangement for turning the control parameters of a controller"	E	F
1994	US 5295061	Sanyo Electric Co. Ltd. (Osaka, JP) "Control parameter tuning unit and a method of tuning parameters for a control unit"	NE	R
1994	US 5311421	Hitachi Ltd. (Tokyo, JP) "Process control method and system for performing control of a controlled system by use of a neural network"	NE	Neural network
1994	US 5331541	Omron Corporation (Kyoto, JP) "PID control unit"	E	F
1994	US 5335164	Universal Dynamics Limited (CA) "Method and apparatus for adaptive control"	NE	F
1994	US 5355305	Johnson Service Company (Milwaukee, WI) "Pattern recognition adaptive controller"	NE	F
1995	US 5394322	The Foxboro Company (Foxboro, MA) "Self-tuning controller that extracts process model characteristics"	E	F
1995	US 5406474	The Foxboro Company (Foxboro, MA) "Self-tuning controller"	NE	R
1995	US 5453925	Fisher Controls International, Inc. (Clayton, MO) "System and method for automatically tuning a process controller"	E	F
1996	US 5535117	Kabushiki Kaisha Toshiba (Kawasaki, JP) "Method and apparatus for controlling a process having a control loop using feedback control"	E	F
1996	US 5568377	Johnson Service Company (Milwaukee, WI) "Fast automatic tuning of a feedback controller"	E	F
1996	US 5587896	The Foxboro Company (Foxboro, MA) "Self-tuning controller"	NE	R
1997	US 5625552	A.K. Mathur and T. Samad (Minneapolis, MN) "Closed loop neural network automatic tuner"	E	Neural network
1997	US 5649062	Motorola Inc. (Schaumburg, IL) "Auto-tuning controller and method of use therefor"	NE	O
1997	US 5691615	Fanuc Ltd. (Yamanashi, JP) "Adaptive PI control method"	NE	F
1997	US 5691896	Rosemount Inc. (Eden Prairie, MN) "Field based process control system with auto-tuning"	E	F
1998	US 5742503	National Science Council (Taipei, TW) "Use of saturation relay feedback in PID controller tuning"	E	F
1998	US 5796608	Hartmann & Braun A.G. (Frankfurt, DE) "Self controllable regulator device"	NE	F
1998	US 5805447	Motorola Inc. (Schaumburg, IL) "Cascade tuning controller and method of use therefor"	NE	O
1998	US 5818714	Rosemount Inc. (Eden Prairie, MN) "Process control system with asymptotic auto-tuning"	E	F
1998	US 5847952	Honeywell Inc. (Minneapolis, MN) "Nonlinear-approximator-based automatic tuner"	NE	Neural network
1999	US 5971579	Samsung Electronics Co. Ltd. (Seoul, KR) "Unit and method for determining gains of a PID controller using genetic algorithm"	NE	Genetic algorithm
1999	US 5974434	Ralph E. Rose (San Jose, CA) "Method and apparatus for automatically tuning the parameters of a feedback control system"	NE	O
2000	US 6076951	National University of Singapore (SG) "Frequency-domain adaptive controller"	E	F
2000	US 6081751	National Instruments Corporation (Austin, TX) "System and method for closed loop autotuning of PID controllers"	E	F
2000	US 6128541	Fisher Controls International Inc. (Clayton, MO) "Optimal auto-tuner for use in a process control network"	E	O
2001	US 6253113	Honeywell International Inc. (Morristown, NJ) "Controllers that determine optimal tuning parameters for use in process control systems and methods of operating the same"	E	O
2002	US 6353766	Siemens Aktiengesellschaft (Munich, DE) "Method for generating control parameters from a response signal of a controlled system and system for adaptive setting of a PID controller"	E	Neural network

2002	US 6438431	National University of Singapore (SG) "Apparatus for relay based multiple point process frequency response estimation and control tuning"	E	F
1984	JP 59069807	Fuji Denki Seizo KK (JP) "Auto-tuning system for parameter of PID adjustor"	E	F
1984	JP 59153202	Fuji Denki Seizo KK (JP) "Auto-tuning system of parameter of PID adjustor"	E	F
1991	JP 3118606	Yokogawa Electric Corp (JP) "Adaptive controller"	NE	Neural network
1991	JP 3265902	Yokogawa Electric Corp (JP) "Process controller"	NE	ARMA with neural network
1992	JP 4076702	Sanyo Electric Co. Ltd. (JP) "Automatic tuning PID control device"	NE	R
1992	JP 4346102	Hitachi Ltd (JP) "PID parameter automatic tuning method"	E	F
1993	JP 5073104	Hitachi Ltd (JP) "Method for automatically tuning PID parameter"	E	F
1994	JP 6095702	Hitachi Ltd (JP) "Auto-tuning PID controller"	E	F
1995	JP 7168604	Matsushita Electric Works Ltd (JP) "Automatic tuning system for PID parameter"	E	F
1998	JP 10333704	Toshiba Corp (JP) "Method and device for PID tuning"	NE	F
1999	JP 11161301	Yaskawa Electric Corp (JP) "PID controller with automatic tuning function"	NE	R
1994	KR 9407530	Korea Electronics Telecomm (KR) "Tuning method of PID controller"	—	—
1997	KR 9705554	Samsung Aerospace Ltd. (KR) "Method of gain control using puzzy technique"	E	R
1998	WO9812611	The University of Newcastle Research Associates Limited (AU) "Method and apparatus for automated tuning of PID controllers"	E	F
2001	WO0198845	Fisher Rosemount Systems, Inc. (US) "Adaptive feedback/feedforward PID controller"	NE	F

TABLE IV
PID SOFTWARE PACKAGES

	Product Name	(a)	(b)	(c)	(d)	(e)	(f)	Remarks
Analytical Methods	AdvaControl Loop Tuner [35]	—	—	✓	—	Microsoft Windows and Advant OCS system	Contact for pricing	Select fast, normal or damped closed-loop performance using Dominant Pole Placement method extended with Robustness Criteria (DPPM-RC)
	IMCTune [41]	×	×	×	—	Microsoft Windows and MATLAB	Freeware	Using IMC tuning
	Model ID & PID Tuning Software [43]	✓	✓	—	3.5	Microsoft Windows	US$ 699 for single user license	Using IMC tuning
	Robust PID Tuning [44]	?	—	×	—	Microsoft Windows	Contact for pricing	Select modified IMC/Lambda tuning or ratio of closed-loop to open-loop response time for non-integral process and closed-loop response time for integral process
	INTUNE [45]	✓	✓	✓	4.12	Microsoft Windows	Contact for pricing	Using advanced IMC based tuning
	Control Station [49]	✓	×	×	3.0.1	Microsoft Windows	US$ 895 per year for single user yearly maintenance license	Select regulating or tracking performance using Lambda tuning correlations
	DeltaV Tune [50]	✓	—	✓	5.1	DeltaV workstation and DeltaV controller running control software	Contact for pricing	Select performance ranging from no overshoot to very aggressive using either modified Z-N rules for PI, phase and gain margin rules for PID, Lambda tuning rules for PI, Lambda-Averaging Level for PI, Lambda-Smith Predictor or IMC tuning rule
	EnTech Toolkit Tuner Module [51]	✓	—	✓	—	Microsoft Windows	Contact for pricing	Using advanced Lambda tuning
	pIDtune [54]	✓	—	×	1.0.5	Microsoft Windows and MATLAB	Contact for pricing	Using IMC tuning
	ExperTune [55]	✓	✓	✓	—	Microsoft Windows	Contact for pricing	Select regulating or tracking performance, quarter amplitude damping, 10% overshoot and Lambda (standard or level)
	Easy PID Tuning [57]	✓	—	—	2.0	Microsoft Windows and MATLAB	Contact for pricing	Using pole placement method
	Tune Plus [58]	✓	—	✓	—	Microsoft Windows	Contact for pricing	Using Lambda/IMC tuning
	Control Loop Assistant [63]	✓	×	×	1.0c	Microsoft Windows	Contact for pricing	Using Lambda tuning
	TuneUp [64]	✓	—	✓	—	Microsoft Windows and MATLAB (optional)	Contact for pricing	Using Optimisation/Lambda tuning
	TuneWizard [66]	✓	✓	✓	2.5.2	Microsoft Windows	Contact for pricing	Select either regulating or tracking performance or IMC (Lambda) tuning or surge tank application

	RSTune [68]	✓	✓	✓	—	Microsoft Windows and Allen-Bradley PLC-5, SLC 500 or ControlLogix PLCs	Contact for pricing	Using ExperTune
	ProTuner 32 [72]	✓	×	✓	6.04.01	Microsoft Windows	Contact for pricing	Select fast, medium or slow response to either regulating or tracking performance using pole cancellation with gain and phase margin and closed loop damping factor
	Tune-a-Fish [73]	✓	✓	✓	—	Microsoft Windows and PROVOX Controllers	Contact for pricing	Using ExperTune
	EZYtune [74]	✓	✓	×	1.1.02	Microsoft Windows	US$ 199 per copy	Select performance based on closed-loop time constant and 10%-90% rise time
Optimisation Methods	PIDeasy [23]	✓	×	✓	1.0	Microsoft Windows	Contact for pricing	Using proprietary algorithm
	GRAPHIDOR [42]	✓	×	×	—	Microsoft Windows	Contact for pricing	Generate 3-D plot using P, I and error with objective to search for minimum error
	Profit PID [56]	✓	—	✓	—	Honeywell TPS/TDC	Contact for pricing	Using proprietary min-max algorithm
	Simple Analytical Tuning of Digital PI/PID Control for Fluid & Motion Systems [70]	✓	✓	—	—	Microsoft Windows	Contact for pricing	Using proprietary algorithm
	VisSim/OptimizePRO [75]	—	—	✓	4.0	Microsoft Windows and Professional VisSim 4.0	Contact for pricing	Using generalised, reduced gradient algorithm (GRG2)
Unknown Methods	TOPAS [36]	✓	✓	×	1.2	Microsoft Windows	€2000 for single user	Select regulating or tracking performance and tight and average level control
	WinREG-PID [37]	✓	✓	✓	—	Microsoft Windows and WinREG	Contact for pricing	—
	SimAxiom (Off-line tuning) [38]	✓	✓	×	—	Microsoft Windows	Contact for pricing	Select desired closed-loop response time
	DynAxiom (On-line tuning) [38]	✓	?	✓	—	—	Contact for pricing	—
	PITOPS [39]	✓	✓	×	—	Microsoft Windows	Contact for pricing	Select regulating or tracking performance
	BESTune [40]	✓	✓	×	4.4	Microsoft Windows and MATLAB	US$ 500 per copy	Select controller tightness
	CADET V12 [46]	—	—	✓	—	Microsoft Windows	Contact for pricing	—
	Universal Process Identification for Advanced Process Control (UPID) [47]	✓	—	—	—	Microsoft Windows	Contact for pricing	—
	PEWIN Pro [48]	✓	—	✓	2.0	Microsoft Windows	Contact for pricing	—
	Intelligent Tuner [52]	✓	—	✓	—	DEC OpenVMS VAX or OpenVMS AXP series; PROVOX or SRx controllers	Contact for pricing	—
	OvationTune [53]	—	—	✓	—	Westinghouse Process Control DCS	Contact for pricing	—
	RaPID [59]	✓	✓	✓	1.2	Microsoft Windows and MATLAB	€3300 for single user	Select regulating or tracking performance or both

	Commander Supervisory Software [60]	—	✓	✓	4.1.41	Microsoft Windows	Contact for pricing	—
	Control System Tuning Package (CSTP) [61]	✓	—	—	3.0	Microsoft Windows and MATLAB	Contact for pricing	—
	JC Systems Toolbox [62]	—	—	—	—	Microsoft Windows and LabVIEW	US$ 495 per copy	—
	LabVIEW PID Control Toolset for Windows [65]	—	—	✓	—	Microsoft Windows and LabVIEW	Contact for pricing	—
	PIDS [67]	×	×	×	—	Microsoft Windows	US$18 per copy	Select performance based on ITAE, ITSE, ISE or IAE
	PID Self-Tuner [69]	—	—	✓	5.0	Microsoft Windows and S7-300/400 station	Contact for pricing	—
	Controller Tuning 101 [71]	✓	×	×	3.0	Microsoft Windows	US$ 11 - Base price	—
	GeneX [76]	—	—	—	2.0	Microsoft Windows and MATLAB	Contact for pricing	—
	CtrlLAB [77]	×	×	×	3.0	Microsoft Windows and MATLAB	Freeware	Select performance based on ISE, ISTE, IST^{2}E or Gain/Phase margins

Notes:

(a) Model-based tuning. Indicate software that matches the open/closed loop plant response data to a specific model.

(b) Support vendor specific PID structures. Indicate software that explicitly support vendor specific PID structures and not those just support some different generic PID structures.

(c) Support online operation. Indicate software that supports online operation like sampling of data, online tuning etc.

(d) Software version reviewed.

(e) Operating Systems and Hardware/Software Dependence.

(f) Prices. Please contact the manufacturer for updated prices on their products.

Legend:

✓ Support; × Does not support; ? Probably support; — Information not available

TABLE V
COMMERCIAL PID CONTROLLER HARDWARE MODULES

Manufacturer	Product Model	(a)	(b)	(c)	(d)	(e)	Description
ABB	Bitric P	✓	×	×	×	2000	Compact Single Loop Controller
	Digitric 100	✓	×	×	×	2001	Versatile Single Loop Controller
	COMMANDER 100	✓	×	×	×	1999	1/8 DIN Universal Process Controller
	COMMANDER 250	✓	×	×	×	1999	1/4 DIN Compact Process Controller
	COMMANDER 310	✓	×	×	×	1999	Wall/Pipe-mount Universal Process Controller
	COMMANDER 351	✓	✓	×	×	2001	1/4 DIN Universal Process Controller
	COMMANDER 355	✓	✓	×	✓	2001	1/4 DIN Advanced Process Controller
	COMMANDER 505	✓	✓	×	✓	2000	6x3 format Advanced Process Controller
	COMMANDER V100	×	×	×	×	1999	1/8 DIN Motorized Valve Controller
	COMMANDER V250	×	×	×	×	1998	1/4 DIN Motorized Valve Controller
	ECA06	✓	×	×	×	2000	ECA Series – General Purpose Process Controller
	ECA60	✓	✓	×	✓	2000	ECA Series – General Purpose Process Controller
	ECA600	✓	✓	✓	✓	2000	ECA Series – General Purpose Process Controller
	MODCELL™ 2050R	✓	×	×	×	2001	Single Loop Controller
	53SL6000	✓	×	×	×	2001	Micro-DCI™ Instrumentation Single Loop Controller
Foxboro	716C	✓	×	✓	×	1996	1/16 DIN Temperature Controller
	718PL, 718PR	✓	×	✓	×	1996	1/8 DIN Process Controller with Local Set Point (PL) and Remote Set Point (PR)
	718TC, 718TS	✓	×	✓	×	1996	1/8 DIN Temperature Controller with mA Output (TC) and Servo Output (TS)
	731C	✓	×	✓	×	1996	1/4 DIN Digital Process Controller
	743C	✓	×	✓	×	1994	Field Station MICRO® Controller
	760C	✓	×	✓	×	1985	Single Station MICRO® Controller
	761C	✓	×	✓	×	1987	Single Station MICRO® Plus Controller
	762C	✓	×	✓	×	1996	Single Station MICRO® Controller
	T630C	✓	×	✓	×	2000	Process Controller
Honeywell	UDC100	×	×	×	×	1999	1/4 DIN Universal Digital Temperature Controller
	UDC700	✓	×	✓	×	1996	1/32 DIN Universal Digital Controller and Indicator
	UDC900	✓	×	✓	×	1997	1/16 DIN Universal Digital Temperature Controller
	UDC1000, UDC1500	✓	×	✓	×	2001	Micro-Pro Series – Universal Digital Controllers
	UDC2300	✓	×	✓	×	1999	1/4 DIN Universal Digital Controller
	UDC3300	✓	✓	✓	×	1999	1/4 DIN Universal Digital Controller
	UDC5000	✓	×	✓	×	1994	Ultra-Pro Universal Digital Controller
	UDC6300	✓	✓	✓	✓	1997	Stand-Alone Process Controller and Process Indicator
Yokogawa	US1000	✓	✓	×	✓	1998	Process Controllers
	UT320, UT350, UT420, UT450, UT520, UT550, UT750	✓	×	×	×	2000	Enhanced Green Series Temperature Controllers
	UP350, UP550, UP750	✓	×	×	×	2000	Enhanced Green Series Programmable Controllers
	YS150	✓	×	✓	✓	1991	High-Level Process Controllers
	YS170	✓	✓	✓	✓	1991	High-Level Process Controllers

Notes:
(a) On-Demand Auto Tune; (b) Gain-Scheduling; (c) Adaptive Control; (d) Feedforward Control; (e) Year of release

Legend:
Please refer to Table IV

Again, PIDeasy provides optimal parameters within a millisecond. The results on the GM and PM are shown in Table II, confirming the software-based PIDeasy approach is stable and robust against model variations. Therefore, this software-based approach has a wide applicability and should provide a useful engine for onboard or onchip controller design. It also provides an excellent starting point for higher order and nonlinear plants to swiftly tune a network of PID controllers *ad hoc* [10].

III. PID PATENTS

A. Patents Filed

This section focused on the currently patented tuning methods that are often adopted in industry for PID design tools and hardware modules. A range of patents on PID tuning are being studied and analyzed, which are chronologically listed in Table III. There are 64 such patents filed in the United States

(US), 11 in Japan (JP), 2 in Korea (KR) and 2 by the World Intellectual Property Organization (WO). Note that a Korean patent (KR 9 407 530) is not included in the following analysis as it is not available in English. Readers may refer to [12] and [30] for detailed information on each patent.

B. Identification Methods for Tuning

Most of the tuning methods patented rely on an identification of plant dynamics, using an excitation (E) or nonexcitation (NE) type of method. The excitation type can be broken down further into time- or frequency-domain method.

Excitation is often used during plant set-up and commissioning in order to set initial PID parameters. Time-domain excitations are usually a step or pseudorandom binary sequence (PRBS) applied in an open-loop fashion. This is a classical and the most widely practised method. It is often adopted for model-based tuning methods. Frequency-domain excitations usually use a relay-like method, where the plant will undergo a controlled self-oscillation. This type of identification does not normally require a parametric model in tuning a PID controller, which is the main advantage over time-domain based identification.

Generally, nonexcitation type of identification is preferred by industry due to safety reasons, particularly during normal operations, as this does not upset the plant. An increasing number of patents are now filed on nonexcitation identification, as seen in Fig. 6.

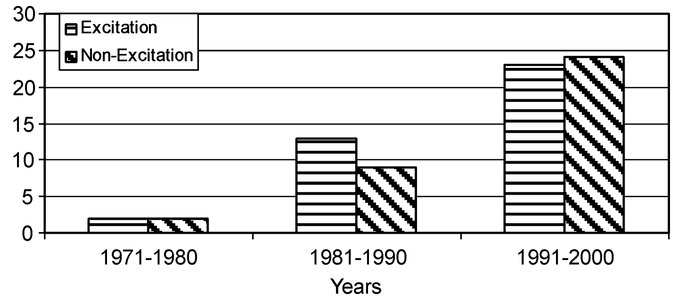


Fig. 6. Type of identifications used in patents from 1971 to 2000.

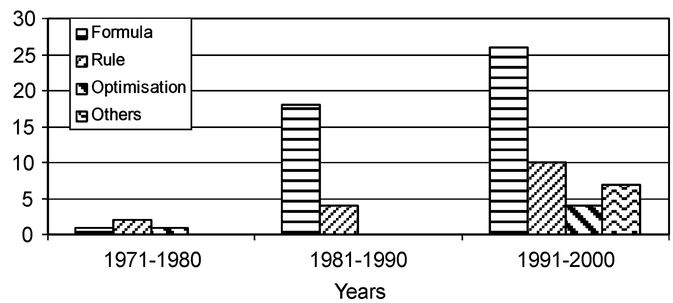


Fig. 7. Type of tuning methods used in patents from 1971 to 2000.

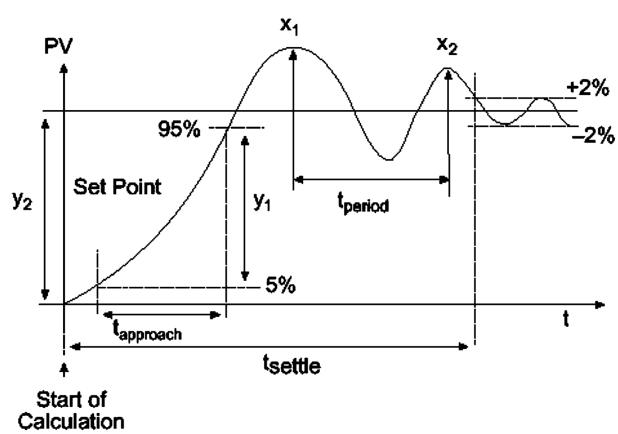


Fig. 8. ABB–CEM measurements [2].

C. Tuning Methods Patented

Most of the identification and tuning methods patented are process engineering oriented and appear rather *ad hoc*. Shown in Table III, patented tuning methods are mostly formula-based (F), rule-based (R), and optimization-based (O). Formula-based methods first identified the characteristics of the plant and then perform a mapping (similar to the Z-N formula). These are often used in on-demand tuning for responsiveness. Rule-based methods are often used in adaptive control, but can be quite complex and *ad hoc*. These can be expert systems, including simple heuristics and fuzzy logic rules. Optimization-based methods are often applied offline or on very slow processes, using a conventional (such as least mean squares) or an unconventional (such as genetic algorithms [13]) search method.

Fig. 7 shows that formula-based tuning methods are still the most actively developed, while other methods receive an increasing attention. However, most do not yield global or multi-objective optimal performance and their applicability is, hence, often limited.

IV. PID Software Packages

A. Software Packages

Due to the lack of a simple and widely applicable tuning method, a need for the development of easy to use PID tuning software has therefore arisen. This allows a practitioner with some control knowledge or plant information to be able to tune a PID controller efficiently and optimally for various applications. It is hoped that such software tools will increase the practising company's system performance and, hence, production quality and efficiency without needing to invest a vast amount of time and manpower in testing and adjusting control loops.

Table IV analyzes and summarizes currently available commercial PID software packages, grouped by the methods of their tuning engines whenever known. Note that Adva-Control Loop Tuner (Advant OCS system), DeltaV Tune (DeltaV workstation), Intelligent Tuner (Fisher-Rosemount PROVOX controller), OvationTune (Westinghouse DCS), Profit PID (Honeywell TPS/TDC system), PID Self-Tuner (Siemens SIMATIC S7/C7) and Tune-a-Fish (Fisher-Rosemount PROVOX controller) are for *ad hoc* systems. Note also that Tune-a-Fish has been discontinued since 2 April 2002 and ExperTune Inc. now handles support and upgrade. IMCTune and CtrlLAB are suitable for learning and testing of generic controller designs, they are also listed in Table IV for information.

TABLE VI
ABB—ITAE EFORMULA MAPPING

Mode	Action	Equation
P	K_P	$2.04K\left(\frac{L}{T}\right)^{1.084}$
	T_I (sec.)	0
	T_D (sec.)	0
PI	K_P	$1.164K\left(\frac{L}{T}\right)^{0.977}$
	T_I (sec.)	$\frac{T*60}{40.44}\left(\frac{L}{T}\right)^{0.68}$
	T_D (sec.)	0
PID	K_P	$0.7369K\left(\frac{L}{T}\right)^{0.947}$
	T_I (sec.)	$\frac{T*60}{51.02}\left(\frac{L}{T}\right)^{0.738}$
	T_D (sec.)	$\frac{T*60}{157.5}\left(\frac{L}{T}\right)^{0.995}$
PD†	K_P	$0.5438K\left(\frac{L}{T}\right)^{0.947}$
	T_I (sec.)	0
	T_D (sec.)	$\frac{T*60}{157.5}\left(\frac{L}{T}\right)^{0.995}$

† Empirical estimates not based on ITAE method

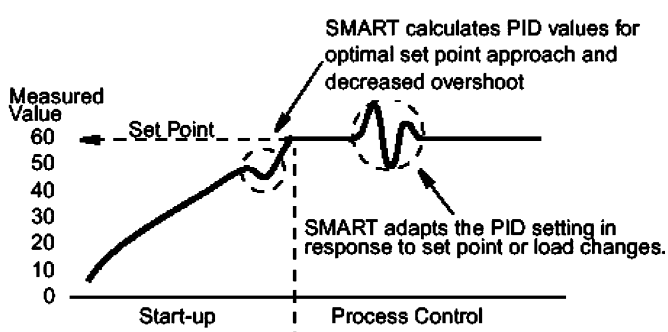


Fig. 9. Foxboro—SMART adaptive self-tuning [14].

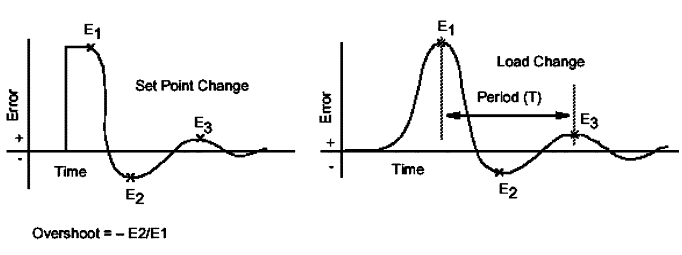


Fig. 10. Foxboro—pattern recognition characteristics [15].

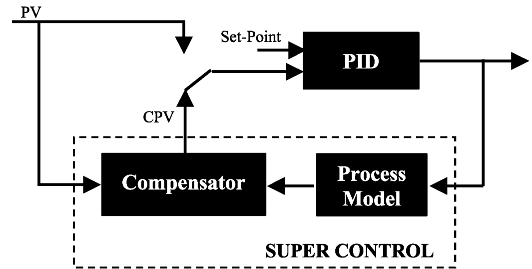


Fig. 11. Functional block diagram of Yokogawa SUPER CONTROL modes 2 and 3 [33].

B. Tuning Methods Adopted

Within the "Analytical Methods" group in Table IV, it is seen from the "Remarks" column that the IMC or lambda tuning method is the most widely adopted tuning method in commercial software packages. Almost all these packages require a time-domain model before the controller can be set. The adopted model is the one given by (10). The pIDtune method by EngineSoft is the only one that uses an ARX (Auto Regressive with eXternal input) model instead of the model given by (10). On design, "Type C" (or I-PD) structure is strongly recommended in BESTune [40]. Note that ExperTune is embedded in RSTune and Tune-a-Fish.

It is almost impossible to name a software package to be the best as there is no generic method to set the PID controller optimally to satisfy all design criteria and needs. However, most of the software packages studied in Table IV provide a tuneable parameter set for the user to determine an overall performance that is best suited to an *ad hoc* application.

C. Operating Systems and Online Operation

Based on the information summarized in Table IV, Microsoft Windows is currently the most supported platform. Meanwhile, MATLAB is a popular software environment used in offline analysis.

Quite a few software packages in Table IV do not support online operations, such as, real-time sampling of data, online tuning, etc. The common nonvendor specific interfaces supported for online operations are Microsoft Windows dynamic data exchange (DDE) and OLE for process control (OPC) [27] based on Microsoft object linking and embedding (OLE), component object model (COM) and distributed component object model (DCOM) technologies.

OPC is an industry standard created with the collaboration of a number of leading worldwide automation and hardware/software suppliers working in cooperation with Microsoft Inc. The standard defines a method for exchanging real-time automation data among PC-based clients using Microsoft operating systems. Thus the aim of OPC is to realize possible interoperability between automation and control applications, field systems and devices, and business and office applications. There are currently hundreds of OPC Data Access servers and clients available.

D. Modern Features

Remedial features such as differentiator filtering and integrator anti-windup are now mostly accommodated in a PID software package. Now the trend is to provide some additional features, such as diagnostic analysis, which prove to be very helpful in practice. An example is highlighted by ExperTune, which includes a wide range of fault diagnosis features, such as valve wear analysis, robustness analysis, automatic loop report generation, multivariable loop analysis, power spectral density plot, auto and cross correlations plot, and shrink-swell (inverse response) process optimization, etc. Other additional features seen in commercial PID packages include user-friendly interfaces, support of a variety of controller structures and allowing more user-defined settings in determining PID parameters when necessary.

V. PID Hardware Modules

A. Hardware and Auto-Tuning

Many PID software features are now incorporated in hardware modules, particularly those used in process control. A range of these are available from the four dominant vendors, namely, ABB, Foxboro, Honeywell and Yokogawa, as listed in Table V. Hardware brands from Elsag Bailey, Kent-Taylor Instruments, Hartmann & Braun and Alfa Laval have been acquired by ABB. The following brands have been acquired under Emerson Process Management Group, namely, Brooks Instrument, Daniel, DeltaV, Fisher, Intellution, Micro Motion, PROVOX, Rosemount, RS3 and Westinghouse Process Control. Invensys Production Management Division consists of APV, Avantis, Esscor, Eurotherm, Foxboro, Pacific Simulation, Triconex, and Wonderware. Readers may refer to [3], [4], [9], [19], [20], [25], and [31] for more information on commercial PID controllers.

Based on a survey carried out by *Control Engineering* in 1998 [11], single-loop models account for 64% of the controllers, while multiloop, 36%. It also reveals that 85% of the loop controllers are used for feedback control, 6% for feedforward control, and 9% for cascade control. The most important features that are expected from a loop controller are, in order of importance, PID function, start-up self-tuning, online self-tuning, adaptive control and fuzzy logic.

Many PID controller manufacturers provide various facilities in their products that allow easy tuning of the controller. As seen in PID patents and software packages, most of the hardware systems also adopt a time-domain tuning method, while a minority rely on open-loop relay experiments. Some modules offer gain-scheduling capabilities and, hence, can cover a large operation envelope. Some are more adaptive, using online model identification or rules inferred from online responses.

Automated tuning is mainly implemented through either "tuning on demand" with upset or "adaptive tuning." Some manufacturers refer 'tuning on demand' with upset as "self-tune," "auto-tune" or "pretune," while "adaptive tuning" is sometimes known as "self-tune," "auto-tune" or "adaptive tune." There exists no standardization in the terminology.

"Tuning on demand" with upset typically determines the PID parameters by inducing a controlled upset in the process. This allows measurements of the process response so as to calculate the appropriate controller parameters. "Adaptive tuning" aims to set the PID parameters without inducing upsets. When a controller is utilising this function, it constantly monitors the PV for any oscillation around the set-point and, hence, closed-loop identification can be as effective as in "tuning on demand." This type of tuning is ideal for processes where load characteristics change drastically while the process is running. If there is any oscillation, the controller adjusts the PID parameters in an attempt to eliminate them. It cannot be used effectively, however, if the process has externally induced upsets for which the control could not possibly be tuned out.

B. ABB Controllers

ABB controllers offer two auto-tuning options, namely, quarter-wave and minimal overshoot. They also come with a manual fine-tuning option called control efficiency monitor (CEM). As shown in Fig. 8, six "key-performance" parameters labeled are measured and displayed, allowing the user to vary the PID settings to match the process needs and to fine-tune manually.

ABB also offers another tuning algorithm for its Micro-DCI series, the Easy-Tune. The Easy-Tune algorithm approximates a process by a first-order plus delay model, as shown in (10). It uses a typical graphical method, where the step changes are applied so as to measure the gain, delay and rise-time and, hence, the time-constant. These are then used to map the controller parameters through formulae shown in Table VI [1], which are optimized for the integral of time-weighted absolute error (ITAE) performance index.

It is unclear, unfortunately, whether the three plant parameters are continuously identified so as to vary the PID parameters online. If they are, however, Micro-DCI series should be very powerful in dealing with changing plant dynamics through continuously scheduled optimal PID settings.

C. Foxboro Series

Foxboro 716C, 718, and 731C series use a proprietary self-tuning algorithm SMART. During start-up and control, SMART continuously monitors the PV and automatically adjusts the PID parameters according to the response of the PV, as shown in Fig. 9. The advantage of SMART is its ability to operate without injecting any artificial change into the system.

Foxboro 743C, 760C, 761C, 762C, and T630C controllers use another patented self-tuning algorithm, expert adaptive controller tuning (EXACT). EXACT does not use a parametric model, but adjusts the controller based on pattern recognition results of the actual current process. When it senses a process upset, it immediately takes corrective action for the pattern recognition. The user can choose the threshold levels of desired damping and overshoot-to-load changes, as shown in Fig. 10. EXACT needs to have a good initial PID parameter set to start with in order to achieve satisfactory performance. Thus, the initial PID parameters are determine by introducing a small perturbation to the process and use the resulting process reaction curve to calculate. To start up the control system, engineers must determine an anticipated noise-band and maximum wait-time of the process. The noise-band is a value representing expected amplitude of noise on the feedback signal. The maximum wait-time is the maximum time that EXACT algorithm will wait for a second peak in the feedback signal after detecting a first peak. These two settings are crucial in order for the EXACT algorithm to have optimal performance but can be quite tricky to determine.

All Foxboro's controllers studied here are rule-based, instead of model-based but do not support feedforward control. If they support gain scheduling, however, they will be very effective for the entire operating envelope, as gain-scheduling can be more useful than continuous adaptation in most situations [3].

D. Honeywell Tuners

Honeywell offers a "tuning on demand" controller, Autotune, which is not adaptive or continuous. They also offer an adaptive tuner, Accutune, which uses a combination of frequency and time response analysis plus rule-based expert system techniques to identify the process continually. An enhanced version of this is, Accutune II, which incorporates a fuzzy logic overshoot suppression mechanism. It provides a "plug-and-play" tuning algorithm, which will starts at the touch of a button or through an input response data set identify and tune for any processes including integrating processes and those with a dead-time. This speeds up and simplifies the startup process and allows retuning at any set-point in an "automatic mode." The fuzzy logic overshoot suppression function operates independently from Accutune tuning as an add-on. It does not change the PID parameters, but temporarily modifies the control action to suppress overshoot. Although this makes the control system more complex and difficult to analyze, it allows more aggressive action to co-exist with smooth process output. It can be disabled, depending on the application or user requirements, and should be unnecessary if the PID controller is set adaptively optimally.

E. Yokogawa Modules

Yokogawa first introduced its SUPER CONTROL module over a decade ago. Similar to Honeywell's Accutune II, it also uses a fuzzy logic based algorithm to eliminate overshoots, mimicking control expertise of an experienced operator. It consists of two main parts, namely, the set-point modifier and the set-point selector.

The set-point modifier models the process and functions as an "expert operator" by first considering that a PID controller is difficult to tune to deliver both a short rise-time and a low overshoot. It thus seeks a knowledge base about the process, its dynamics, and any nonlinearity of the process (including load changes). Then it leads the system into performing perfectly by feeding artificial target set-points into the PID block through the set-point selector.

In particular, SUPER CONTROL operates on three modes. Mode 1 is designed for overshoot suppression by observing the rate of change when the process output approaches a new target set-point. It installs "subset points" as the process output approaches set-point to insure overshoot does not occur. Mode 2 is for ensuring high stability at the set-point while sacrificing some response time to a set-point change. Mode 3 is for a faster response than Mode 2 to a set-point or load change with some compromise in stability when a new set-point is entered and as the process output approaches that change. The process block is simply the first-order lag time with gain model and it simulates the PV without any inherent dead time. A functional block diagram for Modes 2 and 3 is shown in Fig. 11. If Mode 2 or 3 observes any phase shift that has changed from normal operating conditions, it uses the process model to compute a calculated process variable (CPV) and attempts to suppress PV from hunting. The compensation model switches between the measured PV and CPV while the control function block performs the normal PID computation. It is unclear how the three modes are switched between, but it would be advantageous if this is scheduled automatically.

F. Remarks

Many PID hardware vendors have made tremendous efforts to provide a built-in tuning facility. Owing to their vast experience on PID control, most manufacturers have incorporated their knowledge base into their algorithms. Current PID control modules provide "tuning on demand" with upset or "adaptive tuning" or both, depending on the model and user settings. Either technique has its advantages and disadvantages. For example, if using "tuning on demand" only, the controller needs to be retuned periodically and whenever changes occur in the process dynamics. This can be quite tedious and sometimes under-performance can be too late to notice. Therefore, "tuning on demand" coupled with "gain-scheduling" could provide an advantage.

If relying on an "adaptive tuner" only, the range of changes that can be covered is rather limited and a classical step-response model is still needed for determining initial PID settings. Before normal operations may begin, these systems generally require a carefully supervised start-up and testing period. Further, the more controller parameters the operator needs to select, the more difficult it is to adjust for optimal performance and the longer it takes to prepare for the operation. Nevertheless, once the controller is correctly configured, it can constantly monitor the process and automatically adjust the controller parameters to adapt to changes in the process.

The second effort made by many PID hardware vendors appears to be incorporating an overshoot suppression function in their onboard algorithms. In order to meet multiple objectives highlighted in Section II-G, they have also added other functions to a standard PID algorithm or allowed the user to switch between modes. However, these features are not commonly seen in commercial software packages (see Table IV).

VI. Conclusion

PID, a structurally simple and generally applicable control technique, stems it success largely from the fact that it just works very well with a simple and easy to understand structure. While a vast amount of research results are published in the literature, there exists a lack of information exchange and analysis. This can lead to some misunderstanding between academia and industry. For example, there exists no standardization of a generic PID structure for control engineering practice. This is particularly evident with analogue PID controllers being replaced by digital ones, where flexibility in software permits *ad hoc* patches for some local optimality. It has led to unnecessary complication and extra learning curve in tuning PID controllers. This problem becomes severe when there are multiple control loops and different brands or models of PID controllers involved in one application. These may explain why the argument exists that academically proposed tuning rules do not work well on industrial PID controllers, while it is desired that years of research results help industrial practice more for improved quality and profitability.

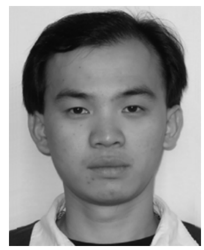
Many PID patents filed so far focus on automatic tuning for process control. This starts from conventional or "intelligent" system identification and is more resembled to hardware modules. Software packages are mainly focused on offline simulation and have thus a different objective. While automatic tuning is offered in many commercial PID products for multiple optimality, timeliness continues to pose a challenge. The major difficulty appears in delivering an optimal transient response, due to difficulties in setting an optimal derivative term. Hence, modifications to the easy-to-understand PID structure have been made through the use of artificial intelligence so as to suppress overshoots. In order to meet multiple objectives, switching between different functional modes has also been offered in PID hardware modules.

The present trend in tackling PID tuning problem is to be able to use the standard PID structure to meet multiple design objectives over a reasonably range of operations and systems. Standardization or modularization around this structure should also help improve cost-effectiveness of PID control and its maintenance. This way, robustly optimal tuning method can be developed, as evident in PIDeasy. With the inclusion of system identification techniques, the entire PID design and tuning process can be automated and modular building blocks can be made available for timely online application and adaptation. This would be particularly suited to "system-onboard" or "system-on-chip" integration for future consumer electronics and MEMS.

REFERENCES

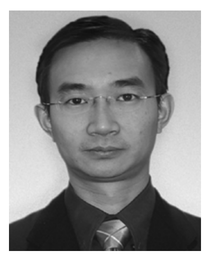
[1] ABB, Instruction Manual of MICRO-DC$^{\mathrm{ITM}}$ 53SL6000, 2001.
[2] ——, Specification DataFile of Commander 355, 2001.
[3] K. J. Åström, T. Hägglund, C. C. Hang, and W. K. Ho, "Automatic tuning and adaptation for PID controllers—a survey," *Control Eng. Pract.*, vol. 1, no. 4, pp. 699–714, 1993.
[4] K. J. Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*. Research Triangle Park, NC: Instrument Soc. Amer., 1995.
[5] ——, "PID Control," in *The Control Handbook*, W. S. Levine, Ed. Piscataway, NJ: IEEE Press, 1996, pp. 198–209.
[6] ——, Benchmark Systems for PID Control, pp. 165–166, 2000.
[7] ——, "The future of PID control," *Control Eng. Pract.*, vol. 9, no. 11, pp. 1163–1175, 2001.
[8] C. Bohn and D. P. Atherton, "An analysis package comparing PID antiwindup strategies," *IEEE Control Syst. Mag.*, vol. 15, no. 2, pp. 34–40, Apr. 1995.
[9] R. Cao and T. McAvoy, "Evaluation of a pattern recognition adaptive PID controller," *Automatica*, vol. 26, no. 4, pp. 797–801, Jul. 1990.
[10] G. Chong and Y. Li, "Trajectory controller network and its design automation through evolutionary computing," in *Proc. EvoWorkshops 2000: Real-World Applications of Evolutionary Computing*, Edinburgh, U.K., Apr., pp. 139–146.
[11] (1998, May) Control Engineering—Single-Loop Controllers Dominate Marketplace. [Online] http://www.manufacturing.net/ctl/article/CA189 397
[12] (2004, Jun.) B1—esp@cenet—Your Gateway to Patents. [Online] http://gb.espacenet.com
[13] W. Feng and Y. Li, "Performance indexes in evolutionary CACSD automation with application to batch PID generation," in *Proc. 10th IEEE Int. Symp. Computer Aided Control System*, Hawaii, Aug. 1999, pp. 486–491.
[14] Foxboro, Product Specifications of I/A Series 716C 1/16 DIN Temperature Controller, 1996.
[15] ——, Technical Information of EXACT Tuning With 762, 760, and 740 Series Controllers, Aug. 1995.
[16] J. P. Gerry, "A comparison of PID control algorithms," *Control Eng.*, vol. 34, no. 3, pp. 102–105, Mar. 1987.
[17] J. P. Gerry and F. G. Shinskey. (2004, May) PID Controller Specification (White Paper). [Online] http://www.expertune.com/PIDspec.htm
[18] R. Gorez, "A survey of PID auto-tuning methods," *J. A*, vol. 38, no. 1, pp. 3–10, 1997.
[19] T. Hägglund and K. J. Åström, "Industrial adaptive controllers based on frequency response techniques," *Automatica*, vol. 27, no. 4, pp. 599–609, Jul. 1991.
[20] C. C. Hang and K. K. Sin, "A comparative performance study of PID auto-tuners," *IEEE Control Syst. Mag.*, vol. 11, no. 5, pp. 41–47, Aug. 1991.
[21] "Getting the best out of PID in machine control," in *Proc. Dig. Inst. Elect. Eng. PG16 Colloquium (96/287)*, London, U.K., Oct. 24, 1996.
[22] A. Kaya and T. J. Scheib, "Tuning of PID controls of different structures," *Control Eng.*, vol. 35, no. 7, pp. 62–65, Jul. 1988.
[23] Y. Li, W. Feng, K. C. Tan, X. K. Zhu, X. Guan, and K. H. Ang, "PIDeasy and automated generation of optimal PID controllers," in *Proc. 3rd Asia-Pacific Conf. Control and Measurement*, Dunhuang, P.R. China, 1998, pp. 29–33.
[24] P. Marsh, "Turn on, tune in," *New Electron.*, vol. 31, no. 4, pp. 31–32, 1998.
[25] B. J. Minter and D. G. Fisher, "A comparison of adaptive controllers: academic vs industrial," in *Proc. Amer. Control Conf.*, Atlanta, GA, 1988, pp. 1653–1658.
[26] A. O'Dwyer, *Handbook of PI and PID Controller Tuning Rules*. London, U.K.: Imperial College Press, 2003.
[27] OPC Foundation. (2002, June) The OPC Foundation—Dedicated to Interoperability in Automation. [Online] http://www.opcfoundation.org
[28] "Digital control: past, present and future of PID control," in *Proc. IFAC Workshop*, J. Quevedo and T. Escobet, Eds., Terrassa, Spain, Apr. 5–7, 2000.
[29] F. G. Shinskey, *Feedback Controllers for the Process Industries*. New York: McGraw-Hill, 1994.
[30] (2004, Jun.) Patents—Patent Full-Text and Full-Page Image Databases. [Online] http://ww.uspto.gov/patft
[31] H. J. Versteeg, H. J. Jansma, and K. Turner, "Evaluation of commercially available adaptive controllers," *J. A*, vol. 27, no. 3, pp. 120–126, 1986.
[32] L. Wang, T. J. D. Barnes, and W. R. Cluett, "New frequency-domain design method for PID controllers," *Proc. Inst. Elect. Eng. D—Control Theory Appl.*, vol. 142, no. 4, pp. 265–271, 1995.
[33] C. Wilson and C. Callen. (2004, Jan.) Close Process Control Translates To Quality Heat Treated Parts. [Online] http://www.industrialheating.com/CDA/ArticleInformation/coverstory/BNPCoverStoryItem/0,2830,116383,00.html
[34] J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers," *Trans. ASME*, vol. 64, pp. 759–768, 1942.
[35] ABB. (2004, May) The ABB Group. [Online] http://www.abb.com
[36] ACT. (2004, May) ACT GmbH Homepage. [Online] http://www.act-control.com
[37] ADAPTECH. (2004, May) Adaptech—Identification and Advanced Control. [Online] http://www.adaptech.com/Ang/menu_a.html
[38] Algosys Inc. (2004, May) Algosys—Solutions & Technology. [Online] http://www.algosys.com/solutions/stdtech.asp
[39] Artcon Inc. (2004, May) Artcon Inc. [Online] http://artcon.com/artcon.html
[40] BESTune. (2004, May) PID Controller Tuning. [Online] http://bestune.50megs.com
[41] C. B. Brosilow. (2002, Jun.) Coleman Brosilow. [Online] http://www.cwru.edu/cse/eche/people/faculty/brosilow/brosilow.htm
[42] Communications & Systems. (2004, May) COTEMS. [Online] http://www.cotems.com/anglais/default.htm
[43] Control Arts Inc. (2004, May) Control Arts Inc: Process Control, Alarm Analysis, Abnormal Situation Management, Engineering Analysis and Operations Management Software. [Online] http://www.controlartsinc.com/index.html
[44] Control & Optimization Specialists. (2004, May) COSpecialists—Control & Optimization Specialists. [Online] http://www.cospecialists.com/index.html

[45] Control Soft Inc. (2004, May) Control Soft Inc.—The Company With Leading Control Technologies. [Online] http://www.controlsoftinc.com/index.shtml
[46] CP Engineering Systems Ltd. (2004, May) NF CADET V12 Page 1. [Online] http://www.cpengineering.com/exthtmnf/Nfcadetv12.html
[47] Cutler Johnston Corporation. (2004, May) Products. [Online] http://www.cutlerjohnston.com/Products.htm
[48] Delta Tau Data Systems Inc. (2004, May) PMAC Executive Pro Suite. [Online] http://www.deltatau.com/PMACExecutiveSuite.htm
[49] D. Cooper. (2004, May) Control Station is Software for Process Control Training, Tuning and Analysis. [Online] http://www.engr.uconn.edu/control/index.html
[50] DeltaV Tune. (2004, May) DeltaV/Product Data Sheet. [Online] http://www.easydeltav.com/productdata/pds/index.asp
[51] EnTech Toolkit Tuner Module. (2004, May) Emerson Process Management—EnTech—Tuner Module. [Online] http://www.emersonprocess.com/entechcontrol/products/tune/index.asp
[52] Intelligent Tuner. (2004, May) PROVOX/Product Data/Control. [Online] http://www.provox-secure.com/product/control.asp
[53] OvationTune. (2004, May) Westinghouse Process Control: Products: Ovation: Descriptions: Tuning Tools. [Online] http://www.westinghousepc.com/ovation/details-tuningtools.cfm
[54] EngineSoft. (2002, Jun.) pIDtune—Integrated System Identification and PID Controller Design. [Online] http://www.pidtune.com/index.html
[55] ExperTune Inc. (2004, May) Process Performance Monitoring & Optimization, Analysis, Simulation, and PID Tuning. [Online] http://www.expertune.com
[56] Honeywell International Inc. (2004, May) http://www.acs.Honeywell.com/ichome/rooms/DisplayPages/LayoutInitial. [Online] http://www.acs.honeywell.com
[57] Ingénierie Pour Slgnaux et Systèmes (IPSIS). (2004, May) Easy PID Tuning. [Online] http://www.ipsis.com/produits/Pidtuning/pidtuning.htm
[58] Tune Plus—PID Tuning Product, Innovention Industries Inc. (2004, May). *http://www.innovin.com/tuneplus.htm* [Online]
[59] IPCOS Netherlands/Belgium. (2004, May) IPCOS Creators in Control. [Online] http://www.ipcos.be/welcome.htm
[60] ISE Inc. (2004, May) Commander Software Data Sheet. [Online] http://instserv.com/commande.htm
[61] Israel Electric Corporation. (2004, May) Optimal PID Tuning Through Best Process Identification. [Online] http://www.geocities.com/ugf4aggnn/CSTPmain.htm
[62] JC Systems. (2004, May) Untitled Document. [Online] http://www.jcsystemsinc.com/html/tool_oview.html
[63] Lambda Controls. (2004, May) Lambda Controls: A Process Control Optimization Company. [Online] http://www.lambdacontrols.com
[64] Metso Automation Inc. (2004, May) Metso Automation—High Level Automation Solutions, Systems and Services. [Online] http://www.metsoautomation.com/automation/home.nsf/FR?ReadForm&ATL=/Automation/Epprod.nsf/WebWID/WTB-010 912-2256A-8C73F
[65] National Instruments. (2004, May) LabVIEW PID Control Toolset for Windows—Products and Services—National Instruments. [Online] http://sine.ni.com/apps/we/nioc.vp?cid=1394&lang=US
[66] Plant Automation Services Inc. (2004, May) PAS Home Page. [Online] http://www.tunewizard.com
[67] S. Raczynski. (2004, May) PID Controller Settings. [Online] http://www.raczynski.com/pn/pids.htm
[68] Rockwell Automation. (2004, May) RSTune—Overview. [Online] http://www.software.rockwell.com/rstune/
[69] Siemens. (2004, May) Siemens—SIMATIC Technology—PID Control. [Online] http://www.ad.siemens.de/simatic/regelsysteme/html_76/produkte/sbpidcontr2.htm
[70] SpecializedControl. (2002, Jun.) PID Control Tuning—Analytical PID Tuning Methods for Feedback Control Systems. [Online] http://www.specializedcontrol.com
[71] Straight-Line Control Co. Inc. (2004, May) Controller Tuning 101. [Online] http://members.aol.com/pidcontrol/software.html
[72] Techmation Inc. (2004, May) Techmation. [Online] http://protuner.com
[73] TiPS Inc. (2002, Oct.) TiPSWEB Tune-a-Fish Page. [Online] http://www.tipsweb.com/tuneafish.htm
[74] Matrikon Inc. (2004, May) Advanced Process Control—ProcessACT at Matrikon.com. [Online] http://www.matrikon.com/products/processact/index.asp
[75] Visual Solutions Inc. (2004, May) Visual Solutions, Inc.—VisSim, VisSim/Comm & VisSim/DSP Home Page. [Online] http://www.vissim.com/products/addons/optimize.html
[76] Xiera Technologies Inc. (2004, May) GeneX. [Online] http://www.xiera.com/genex.htm
[77] D. Xue. (2004, May) MATLAB Central File Exchange—CtrlLAB. [Online] http://www.mathworks.com/matlabcentral/fileexchange/Files.jsp?fileId=18



Kiam Heong Ang received the B.Eng. and Ph.D. degrees in electronics and electrical engineering from University of Glasgow, Glasgow, U.K., in 1996 and 2005, respectively.

From 1997 to 2000, he was a Software Engineer with Advanced Process Control Group, Yokogawa Engineering Asia Pte. Ltd., Singapore. Since 2005, within the same company, he has been working on process industry standardization and researching into new technologies for future Yokogawa products. His current research interests include evolutionary multi-objective learning, computational intelligence, control systems and engineering design optimization.



Gregory Chong (S'99) received the B.Eng. degree in electronics and electrical engineering from University of Glasgow, Glasgow, U.K., in 1999. He is currently working toward the Ph.D. degree at the same university.

His current research interests include evolutionary multiobjective and intelligent control for nonlinear systems.

Yun Li (S'87–M'90) received the B.Sc. degree in radio electronics science from Sichuan University, Chengdu, China, in 1984, the M.Sc. degree in electronic engineering from University of Electronic Science and Technology of China (UESTC), Chengdu, in 1987, and the Ph.D. degree in computing and control engineering from University of Strathclyde, Glasgow, U.K., in 1990.

From 1989 to 1990, he worked at the U.K. National Engineering Laboratory and for Industrial Systems and Control Limited, Glasgow, U.K. He became a Lecturer at the University of Glasgow in 1991. In 2002, he served as a Visiting Professor at Kumamoto University, Japan. He is currently a Senior Lecturer at University of Glasgow and a Visiting Professor at UESTC. In 1996, he independently invented the "indefinite scattering matrix" theory, which opened up a ground-breaking way for microwave feedback circuit design. From 1987 to 1991, he carried out leading work in parallel processing for recursive filtering and feedback control. In 1992, he achieved first symbolic computing for circuit design power electronic, without needing to invert any matrix, complex-numbered or not. Since 1992, he has pioneered into design automation of control systems and discovery of novel engineering systems using evolutionary learning and search techniques. He has produced 11 Ph.D. degrees in this area and has over 130 publications.

Dr. Li is a Chartered Engineer and a Member of the Institution of Electrical Engineers. He established the IEEE CACSD Evolutionary Computation Working Group and the European Network of Excellence in Evolutionary Computing (EvoNet) Workgroup on Systems, Control, and Drives in 1998.