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Patents, Software, and Hardware for PID Control

AN OVERVIEW AND ANALYSIS OF THE CURRENT ART

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By YUN LI, KIAM HEONG ANG, and GREGORY C.Y. CHONG

Proportional-integral-derivative (PID) control provides simplicity, clear functionality, and ease of use. Since the invention of PID control in 1910 (largely owing to Elmer Sperry's ship autopilot) and the straightforward Ziegler-Nichols (Z-N) tuning rule in 1942 [1], the popularity of PID control has grown tremendously. Today, PID is used in more than 90% of practical control systems, ranging from consumer electronics such as cameras to industrial processes such as chemical processes [2]–[5].

The wide application of PID control has stimulated and sustained the development and patenting of various tuning and associated system identification techniques. For example, sophisticated software packages and ready-made hardware modules are developed to facilitate on-demand tuning and to "get the best out of PID" [5]. However, to achieve optimal transient performance, tuning methods vary, and at present there exists no standardization of PID structures. This article provides an overview and analysis of PID patents, commercial software packages, and hardware modules. We also highlight differences between academic research and

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industrial practice so as to motivate new research directions in PID technology.

PID PATENTS

Patents Filed

In this section, we provide an overview of patented PID tuning and associated system identification methods. A large number of patents are studied and analyzed, as chronologically listed in Table 1. Among them, 64 patents are filed in the United States, 11 in Japan (denoted by JP in Table 1), two in Korea (denoted by KR in Table 1), and two by the World Intellectual Property Organization (denoted by WO in Table 1). Note that a Korean patent is not included in the following discussions since it is not available in English.

Identification Methods for Tuning

Although patented tuning methods rely on identification (denoted by ID in Table 1) of plant dynamics, a simple model often suffices. System ID is usually performed using an excitation (denoted by E in Table 1) or nonexcitation (denoted by NE in Table 1) type of method, in which the excitation type is either a time- or frequency-domain method.

Excitation is used during plant setup and commissioning to set initial PID parameters. Time-domain excitation includes a step or pseudorandom binary sequence (PRBS) applied in an open-loop fashion for model-based tuning. Frequency-domain excitation uses a relay-like method, where the plant undergoes a controlled self-oscillation. This type of identification does not normally require a parametric model for tuning a PID controller, which is currently the main advantage over time-domain-based identification. However, nonparametric identification can also be performed in the time domain to model a linear or nonlinear plant and to tune a linear or nonlinear controller. An example of time-domain nonparametric models is the Volterra series, whose kernels up to the third order can be measured through excitation with a PRBS-like M-sequence [6].

Nonexcitation-type identification, which does not upset the plant, is preferred by industry for safety reasons, particularly during normal operations. The number of patents on NE identification is increasing, as shown in Figure 1.

Tuning Methods Patented

Most patented identification and tuning methods are process-engineering oriented and appear ad hoc. Table 1 lists patents and their type of method. Figure 2 confirms that formula-based (denoted by F in Table 1) tuning methods are the most actively developed. Formula-based tuning methods first employ identified characteristics of the plant and then perform a mapping (as in the ABB formula; see [9, Table 2]). These methods are typically used in on-demand tuning for responsiveness. Rule-based (denoted by R in Table 1) methods are used in adaptive control but can be quite complex and ad hoc. Recently, these methods have expanded to expert systems, including those using heuristics and fuzzy logic rules. All neural-network-based (denoted by NN in Table 1) methods require an optimization mechanism such as gradient guidance. Optimization-based (denoted by O in Table 1) designs often involve a numerical method such as

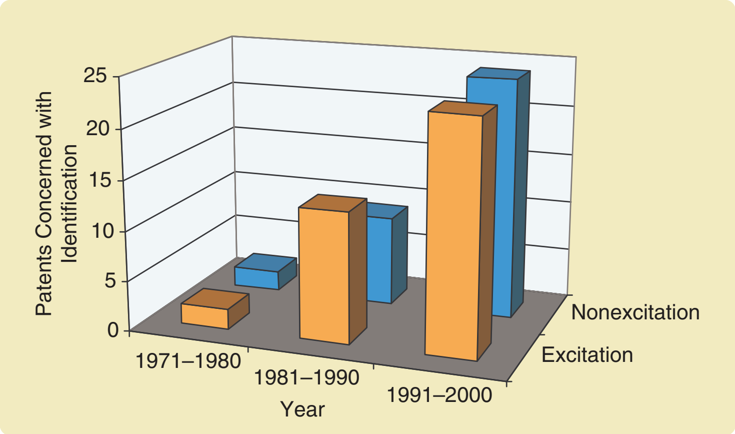

FIGURE 1 Number of excitation and nonexcitation identification methods filed in PID patents. Time-domain excitations are usually a step or pseudorandom binary sequence applied in an open-loop fashion, while frequency-domain excitations usually use a relay-like method, where the plant undergoes a controlled self-oscillation. Nonexcitation methods are becoming more and more popular due to safety reasons, particularly during normal operations, since this approach does not upset the plant.

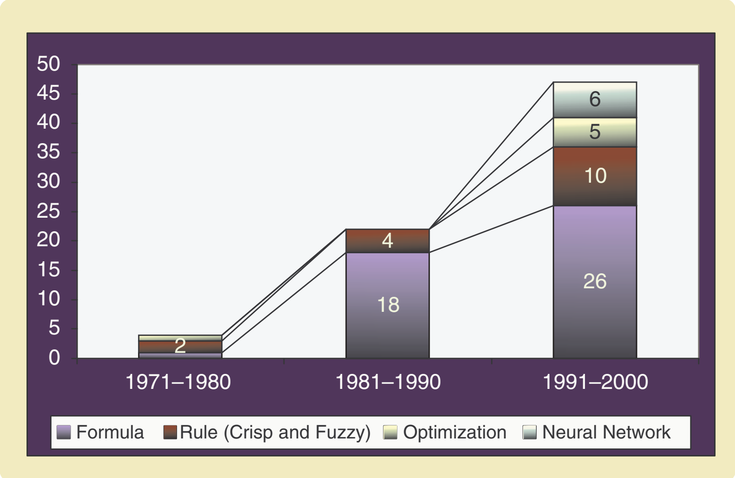

FIGURE 2 Types of tuning methods discussed in PID patents. Formula-based methods are the most popular in on-demand tuning for responsiveness. Recently, rule-based methods have expanded to expert systems, including those using heuristics and fuzzy logic rules. Note that all neural-network-based methods require an optimization or self-learning mechanism. Optimization, intelligent, and other modern methods are gaining momentum to supplement traditional methods originating from Ziegler and Nichols's work.

TABLE 1 **Complete listing of PID patents, the majority of which can be found at http://www.uspto.gov/patft/. System identification (ID) methods adopted in these patents are charted in Figure 1, and tuning methods are listed in Figure 2 for trend analysis.**

Year	Patent Number	Assignee/Title	ID	Tuning
1970	U.S. 3532862	International Business Machines Corporation (Armonk, NY) “Method for adjusting controller gain to control a process”	E	F
1973	U.S. 3727035	Phillips Petroleum Company (Bartlesville, OK) “Pulse test of digital control system”	E	F
1974	U.S. 3798426	The Foxboro Company (Foxboro, MA) “Pattern evaluation method and apparatus for adaptive control”	NE	R
1974	U.S. 3826887	Phillips Petroleum Company (Bartlesville, OK) “Simplified procedure for tuning PID controllers”	NE	R
1980	U.S. 4214300	K.R. Jones (Liverpool, England) “Three term (PID) controllers”	E	O
1982	U.S. 4346433	Phillips Petroleum Company (Bartlesville, OK) “Process control”	E	F
1983	U.S. 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	U.S. 4441151	Toyo Systems Ltd. (Tokyo) “Apparatus for tuning PID controllers in process control systems”	E	F
1984	U.S. 4451878	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, Japan) “Process control apparatus”	E	F
1984	U.S. 4466054	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, Japan) “Improved proportional integral-derivative control apparatus”	NE	F
1985	U.S. 4539633	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, Japan) “Digital PID process control apparatus”	E	F
1985	U.S. 4549123	NAF Controls AB (Solna, SE) “Method and an apparatus in tuning a PID-regulator”		
1986	U.S. 4563734	Tokyo Shibaura Denki Kabushiki Kaisha (Kawasaki, Japan) “Multivariable proportional-integral-derivative process control apparatus”	E E	F F
1986	U.S. 4602326	The Foxboro Company (Foxboro, MA) “Pattern-recognizing self-tuning controller”		
1987	U.S. 4669040	Eurotherm Corporation (Reston, VA) “Self-tuning controller”	NE	R
1988	U.S. 4754391	Yamatake-Honeywell Co. Ltd. (Tokyo) “Method of determining PID parameters and an automatic tuning controller using the method”	E E	F F
1988	U.S. 4758943	Hightech Network AB (Malmo, SE) “Method and an apparatus for automatically tuning a process regulator”	E	F
1988	U.S. 4768143	The Babcock & Wilcox Company (New Orleans, LA) “Apparatus and method using adaptive gain scheduling algorithm”	NE	F
1989	U.S. 4814968	Fischer & Porter Company (Warminster, PA) “Self-tuning process controller”		
1989	U.S. 4855674	Yamatake-Honeywell Company Limited (Tokyo) “Method and a process control system using the method for minimizing hunting”	NE E	F F
1989	U.S. 4864490	Mitsubishi Denki Kabushiki Kaisha (Tokyo) “Auto-tuning controller using fuzzy reasoning to obtain optimum control parameters”	NE	R
1989	U.S. 4881160	Yokogawa Electric Corporation (Tokyo) “Self-tuning controller”		
1989	U.S. 4882526	Kabushiki Kaisha Toshiba (Kawasaki) “Adaptive process control system”	NE	F
1990	U.S. RE33267	The Foxboro Company (Foxboro, MA) “Pattern-recognizing self-tuning controller”	E	F
1990	U.S. 4903192	Hitachi Ltd. (Tokyo) “PID controller system”	NE	R
1991	U.S. 5043862	Hitachi Ltd. (Tokyo) “Method and apparatus of automatically setting PID constants”	NE	R
1992	U.S. 5126933	Charles A. White III (Stamford, CT) “Self-learning memory unit for process controller and self-updating function generator”	NE NE	R NN
1992	U.S. 5153807	Hitachi Ltd. (Tokyo) “Self-tuning controller apparatus and process control system”		
1992	U.S. 5159547	Rockwell International Corporation (Seal Beach, CA) “Self-monitoring tuner for feed back controller”	NE NE	R R
1992	U.S. 5166873	Yokogawa Electric Corporation (Tokyo) “Process control device”		
1992	U.S. 5170341	Honeywell Inc. (Minneapolis, MN) “Adaptive controller in a process control system and a method therefor”	E E	F F
1993	U.S. 5223778	Allen-Bradley Company Inc. (Milwaukee, WI) “Automatic tuning apparatus for PID controllers”	E	F
1993	U.S. 5229699	Industrial Technology Research Institute (Chutung, TW) “Method and an apparatus for PID controller tuning”	E	F
1993	U.S. 5268835	Hitachi Ltd. (Tokyo) “Process controller for controlling a process to a target state”		
1993	U.S. 5272621	Nippon Denki Garasu Kabushiki Kaisha (Shiga, Japan) “Method and apparatus using fuzzy logic for controlling a process having dead time”	NE NE	F R
1994	U.S. 5283729	Fisher-Rosemount Systems, Inc. (Austin, TX) “Tuning arrangement for turning the control parameters of a controller”	E	F
1994	U.S. 5295061	Sanyo Electric Co. Ltd. (Osaka, Japan) “Control parameter tuning unit and a method of tuning parameters for a control unit”	NE	R
1994	U.S. 5311421	Hitachi Ltd. (Tokyo) “Process control method and system for performing control of a controlled system by use of a neural network”	NE	NN

Continued...

TABLE 1 ***Continued***

Year	Patent Number	Assignee/Title	ID	Tuning
1994	U.S. 5331541	Omron Corporation (Kyoto, Japan) “PID control unit”		
1994	U.S. 5335164	Universal Dynamics Limited (CA) “Method and apparatus for adaptive control”	E	F
1994	U.S. 5355305	Johnson Service Company (Milwaukee, WI) “Pattern recognition adaptive controller”	NE	F
1995	U.S. 5394322	The Foxboro Company (Foxboro, MA) “Self-tuning controller that extracts process model characteristics”	NE E	F F
1995	U.S. 5406474	The Foxboro Company (Foxboro, MA) “Self-tuning controller”		
1995	U.S. 5453925	Fisher Controls International, Inc. (Clayton, MO) “System and method for automatically tuning a process controller”	NE E	R F
1996	U.S. 5535117	Kabushiki Kaisha Toshiba (Kawasaki, Japan) “Method and apparatus for controlling a process having a control loop using feedback control”	E	F
1996	U.S. 5568377	Johnson Service Company (Milwaukee, WI) “Fast automatic tuning of a feedback controller”	E	F
1996	U.S. 5587896	The Foxboro Company (Foxboro, MA) “Self-tuning controller”		
1997	U.S. 5625552	A.K. Mathur and T. Samad (Minneapolis, MN) “Closed loop neural network automatic tuner”	NE E	R NN
1997	U.S. 5649062	Motorola Inc. (Schaumburg, IL) “Auto-tuning controller and method of use therefore”		
1997	U.S. 5691615	Fanuc Ltd. (Yamanashi, Japan) “Adaptive PI control method”	NE	O
1997	U.S. 5691896	Rosemount Inc. (Eden Prairie, MN) “Field based process control system with auto-tuning”	NE E	F F
1998	U.S. 5742503	National Science Council (Taipei, TW) “Use of saturation relay feedback in PID controller tuning”	E	F
1998	U.S. 5796608	Hartmann & Braun A.G. (Frankfurt, DE) “Self controllable regulator device”		
1998	U.S. 5805447	Motorola Inc. (Schaumburg, IL) “Cascade tuning controller and method of use therefore”	NE NE	F O
1998	U.S. 5818714	Rosemount Inc. (Eden Prairie, MN) “Process control system with asymptotic auto-tuning”	E	F
1998	U.S. 5847952	Honeywell Inc. (Minneapolis, MN) “Nonlinear-approximator-based automatic tuner”		
1999	U.S. 5971579	Samsung Electronics Co. Ltd. (Seoul, Korea) “Unit and method for determining gains of a PID controller using genetic algorithm”	NE NE	NN O (EA)
1999	U.S. 5974434	Ralph E. Rose (San Jose, CA) “Method and apparatus for automatically tuning the parameters of a feedback control system”	NE	O
2000	U.S. 6076951	National University of Singapore (Singapore) “Frequency-domain adaptive controller”	E	F
2000	U.S. 6081751	National Instruments Corporation (Austin, TX) “System and method for closed loop autotuning of PID controllers”	E	F
2000	U.S. 6128541	Fisher Controls International Inc. (Clayton, MO) “Optimal auto-tuner for use in a process control network”	E	O
2001	U.S. 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	U.S. 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	NN
2002	U.S. 6438431	National University of Singapore (Singapore) “Apparatus for relay based multiple point process frequency response estimation and control tuning”	E	F
1984	JP 59069807	Fuji Denki Seizo KK (Japan) “Auto-tuning system for parameter of PID adjustor”		
1984	JP 59153202	Fuji Denki Seizo KK (Japan) “Auto-tuning system of parameter of PID adjustor”	E	F
1991	JP 3118606	Yokogawa Electric Corp (Japan) “Adaptive controller”	E	F
1991	JP 3265902	Yokogawa Electric Corp (Japan) “Process controller”	NE	NN
1992	JP 4076702	Sanyo Electric Co. Ltd. (Japan) “Automatic tuning PID control device”	NE	ARMA & NN
1992	JP 4346102	Hitachi Ltd (Japan) “PID parameter automatic tuning method”	NE	R
1993	JP 5073104	Hitachi Ltd (Japan) “Method for automatically tuning PID parameter”	E	F
1994	JP 6095702	Hitachi Ltd (Japan) “Auto-tuning PID controller”	E	F
1995	JP 7168604	Matsushita Electric Works Ltd (Japan) “Automatic tuning system for PID parameter”	E	F
1998	JP 10333704	Toshiba Corp (Japan) “Method and device for PID tuning”	E	F
1999	JP 11161301	Yaskawa Electric Corp (JP) “PID controller with automatic tuning function”	NE	F
1994	KR 9407530	Korea Electronics Telecomm (Korea) “Tuning method of PID controller”	NE	R
1997	KR 9705554	Samsung Aerospace Ltd. (Korea) “Method of gain control using puzzy technique”	–	–
1998	WO9812611	The University of Newcastle Research Associates Limited (Australia) “Method and apparatus for automated tuning of PID controllers”	E E	R F
2001	WO0198845	Fisher Rosemount Systems, Inc. (United States) “Adaptive feedback/feedforward PID controller”	NE	F

Notes:

E: excitation; NE: nonexcitation; F: formula based; R: rule based; NN: neural network based, O: optimization based; EA: evolutionary algorithm based least squares, while evolutionary-algorithm (EA-) based a posteriori learning and multipoint search techniques are increasingly used for global, structural, and multiobjective designs [7], [8].

PID SOFTWARE PACKAGES AND CHARACTERISTICS

Software Packages

The lack of a widely applicable mathematical method is compensated for by the development of easy-to-use PID tuning software that combines various design methods within a single package and hence allows a practitioner with control knowledge or plant information to tune a PID controller efficiently and optimally for various applications. These software tools can improve system performance, production quality, and efficiency without a major investment of time and human resources.

Table 2 summarizes commercial PID software packages, grouped by tuning methods. Some packages are dedicated to PID, while others, such as IMCTune and CtrlLAB, are general control system software with good PID capabilities. Some packages can interface directly with generic data-acquisition hardware for online control, such as the LabVIEW PID Control Toolset [23]. Note that AdvaControl Loop Tuner (Advant OCS system), DeltaV Tuner (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 associated hardware modules only. Note also that Tune-a-Fish has been discontinued since 2 April 2002; ExperTune, Inc., now handles support and upgrade.

Tuning Methods Adopted

Within the "Analytical Methods" group in Table 2, as noted in the "Remarks" column, the IMC or lambda tuning method is the most widely adopted tuning method in commercial PID software packages. Most of these packages require a time-domain plant model before the controller can be designed. The widely adopted plant model is the first order with delay given by

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

where K is the process gain, T is the process time constant, and L is the process dead time or transport delay. The pIDtune method by EngineSoft is the only method that uses an auto regressive with eXternal input (ARX) model instead of (1). The type C (or I-PD) structure [9] is strongly recommended in BESTune [24]. Note that ExperTune is embedded in RSTune and Tune-a-Fish.

So far, no commercial package claims the ability to deliver both optimal tracking response and optimal regulation with one tuning or one set of PID coefficients. Also, none can set the PID to satisfy design criteria with multiple objectives (as opposed to a preweighted composite objective). However, most packages studied in Table 2 provide a tunable parameter set for the user to determine an overall performance that is best suited to the application.

Operating Systems and Online Operation

Based on the information summarized in Table 2, Microsoft Windows is currently the most supported platform, while MATLAB is a popular software environment used in offline analysis. Many packages in Table 2 do not support online operations, such as real-time sampling of data and online tuning. The common nonvendor interfaces supported for online operations are Microsoft Windows dynamic data exchange (DDE) and OLE for Process Control (OPC) [25], 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 through the collaboration of several leading worldwide automation and hardware/software suppliers working in cooperation with Microsoft, Inc. OPC defines a method for exchanging real-time automation data among PC-based clients using Microsoft operating systems. Thus, the aim of OPC is to facilitate 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.

Modern Features

Remedial features such as differentiator filtering and integrator antiwindup are now mostly accommodated as standard features in PID software packages. Currently, development focuses on providing additional and supervisory features, including support for various controller structures, artificial intelligence, diagnostic analysis, user-friendly interfaces, and user-definable settings for determining PID parameters manually when necessary.

An example of comprehensive fault diagnosis features is highlighted by ExperTune, including valve wear analysis, robustness analysis, automatic loop report generation, multivariable loop analysis, power spectral density plotting, auto- and cross-correlations plotting, and shrink-swell (inverse-response) process optimization.

PID HARDWARE MODULES AND SYSTEMS

Hardware Types and Applications

Although analog-interfaced PID controllers exist, such as Stanford Research Systems' SIM960 analog PID controller [10], commercial hardware modules are mainly digital. These modules run on a dedicated computer, which can implement features found in PID software packages. General-purpose, data-acquisition modules that can be interfaced with dedicated PID software for online implementation are also available; one example is National Instruments' LabVIEW [23]. However, with the discontinuation of generic modules like Agilent's E1415A algorithmic closed-loop controller, PID hardware is now dominated by five major vendors—ABB, Emerson,

TABLE 2 PID software packages. Many of these packages incorporate multiple design methods. Some packages can interface with data-acquisition hardware for direct online use.

Product Name	(a)	(b)	(c)	(d)	(e)	(f)	Remarks
Analytical Methods							
AdvaControl Loop Tuner [31]	—	—	✔	—	Microsoft Windows and Advant OCS system	Contact for pricing	Selects fast, normal, or damped closed-loop performance using dominant-pole placement method extended with robustness criteria
IMCTune [32]	✘	✘	✘	—	Microsoft Windows and MATLAB	Freeware	Uses IMC tuning
Model ID and PID Tuning Software [33]	✔	✔	—	3.5	Microsoft Windows	US$699 for single user license	Uses IMC tuning
Robust PID Tuning [34]	?	—	✘	—	Microsoft Windows	Contact for pricing	Selects modified IMC/Lambda tuning or ratio of closed-loop to open-loop response time for nonintegral process and closed-loop response time for integral process
INTUNE [35]	✔	✔	✔	4.12	Microsoft Windows	Contact for pricing	Uses advanced IMC based tuning
Control Station [36]	✔	✘	✘	3.0.1	Microsoft Windows	US$895 per year for single user yearly maintenance license	Selects regulating or tracking performance using Lambda tuning correlations
DeltaV Tune [28]	✔	—	✔	5.1	DeltaV workstation and DeltaV controller running control software	Contact for pricing	Selects 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 [27]	✔	—	✔	—	Microsoft Windows	Contact for pricing	Uses advanced Lambda tuning
pIDtune [37]	✔	—	✘	1.0.5	Microsoft Windows and MATLAB	Contact for pricing	Uses IMC tuning
ExperTune [38]	✔	✔	✔	—	Microsoft Windows	Contact for pricing	Selects regulating or tracking performance, quarter amplitude damping, 10% overshoot and Lambda (standard or level)
Easy PID Tuning [39]	✔	—	—	2.0	Microsoft Windows and MATLAB	Contact for pricing	Uses pole placement method
Tune Plus [40]	✔	—	✔	—	Microsoft Windows	Contact for pricing	Uses Lambda/IMC tuning
Control Loop Assistant [41]	✔	✘	✘	1.0c	Microsoft Windows	Contact for pricing	Uses Lambda tuning
TuneUp [42]	✔	—	✔	—	Microsoft Windows and MATLAB (optional—depends on edition)	Contact for pricing	Uses Lambda tuning and optimization
TuneWizard [43]	✔	✔	✔	2.5.2	Microsoft Windows	Contact for pricing	Selects either regulating or tracking performance or IMC (Lambda) tuning or surge tank application
RSTune [44]	✔	✔	✔	—	Microsoft Windows and Allen-Bradley PLC-5, SLC 500, or ControlLogix PLCs	Contact for pricing	Uses ExperTune
ProTuner 32 [45]	✔	✘	✔	6.04.01	Microsoft Windows	Contact for pricing	Selects 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 [46]	✔	✔	✔	—	Microsoft Windows and Fisher-Rosemount PROVOX Controllers	Contact for pricing	Uses an ExperTune engine

Continued...

TABLE 2 *Continued*

Product Name	(a)	(b)	(c)	(d)	(e)	(f)	Remarks
EZYtune [47]	✔	✔	✘	1.1.02	Microsoft Windows	US$199 per copy	Selects performance based on closed-loop time constant and 10–90% rise time
Optimization Methods							
PIDeasy [9]	✔	✘	✔	2.0	Microsoft Windows	Commercial version yet to develop, inquiries welcome	Intelligent methods, including F, R, and O means to set multioptimal PIDs instantly from a transfer function or offline or online step response for any operating point
GRAPHIDOR [48]	✔	✘	✘	—	Microsoft Windows	Contact for pricing	Generate 3-D plot using P, I, and error with objective to search for minimum error
Profit PID [29]	✔	—	✔	—	Honeywell TPS/TDC	Contact for pricing	Uses proprietary min-max algorithm
Simple Analytical Tuning of Digital PI/PID Control for Fluid & Motion Systems [49]	✔	✔	—	—	Microsoft Windows	Contact for pricing	Uses proprietary algorithm with optimization
VisSim/OptimizePRO [50]	—	—	✔	4.0	Microsoft Windows and Professional VisSim 4.0	Contact for pricing	Uses generalized, reduced gradient algorithm GRG2
TOPAS [51]	✔	✔	✘	1.2	Microsoft Windows	€2000 for single user	Uses first or second order and delay model; includes 20+ tuning methods; optimizes for regulating or tracking, but not both; can also minimize control resources
Unknown Methods							
WinREG-PID [52]	✔	✔	✔	—	Microsoft Windows and WinREG	Contact for pricing	—
SimAxiom (Offline tuning) [53]	✔	✔	✘	—	Microsoft Windows	Contact for pricing	Selects desired closed-loop response time
DynAxiom (Online tuning) [53]	✔	?	✔	—	—	Contact for pricing	—
PITOPS [54]	✔	✔	✘	—	Microsoft Windows	Contact for pricing	Selects regulating or tracking performance
BESTune [24]	✔	✔	✘	4.4	Microsoft Windows and MATLAB	US$500 per copy	Selects controller tightness
CADET V12 [55]	—	—	✔	—	Microsoft Windows	Contact for pricing	—
Universal Process Identification for Advanced Process Control (UPID) [56]	✔	—	—	—	Microsoft Windows	Contact for pricing	—
PEWIN Pro [57]	✔	—	✔	2.0	Microsoft Windows	Contact for pricing	—
Intelligent Tuner [58]	✔	—	✔	—	DEC OpenVMS VAX or OpenVMS AXP series and OpenVMS version 6.1 or later operating software; PROVOX 10-series, 20-series, 20-series SR90 controllers, or SRx controllers	Contact for pricing	—
OvationTune [59]	—	—	✔	—	Westinghouse Process Control DCS	Contact for pricing	—
RaPID [60]	✔	✔	✔	1.2	Microsoft Windows and MATLAB	€3300 for single user	Selects regulating or tracking performance or both
Commander Supervisory Software [61]	—	✔	✔	4.1.41	Microsoft Windows	Contact for pricing	—
Control System Tuning Package (CSTP) [62]	✔	—	—	3.0	Microsoft Windows and MATLAB	Contact for pricing	—
JC Systems Toolbox [63]	—	—	—	—	Microsoft Windows and LabVIEW	US$495 per copy	—

Continued...

TABLE 2 ***Continued***

Product Name	(a)	(b)	(c)	(d)	(e)	(f)	Remarks
LabVIEW PID Control Toolset for Windows [23]	—	—	✔	—	Microsoft Windows and LabVIEW	Contact for pricing	Can self-learn to meet key response specs, such as set-time, reset-time, and overshoots.
PIDS [64]	✘	✘	✘	—	Microsoft Windows	US$18 per copy	Can select performance based on ITAE, ITSE, ISE, or IAE
PID Self-Tuner [65]	—	—	✔	5.0	Microsoft Windows and S7-300/400 station; STEP 7 (≥ V3.2) and Standard PID Control V5 installed on programming device	Contact for pricing	—
Controller Tuning 101 [66]	✔	✘	✘	3.0	Microsoft Windows	US$11 base price	—
GeneX [67]	—	—	—	2.0	Microsoft Windows and MATLAB	Contact for pricing	—
CtrlLAB [68]	✘	✘	✘	3.0	Microsoft Windows and MATLAB	Freeware	Selects performance based on ISE, ISTE, IST^{2}E, or Gain/Phase margins

Legend:
✔ Support; ✘ Does not support; ? Probably support; —Information not available.

Notes:
(a) Model-based tuning. Indicates software that matches the open-/closed-loop plant response data for a specific model.
(b) Supports vendor-specific PID controller structures. Indicates software that explicitly supports vendor-specific PID controller structures rather than generic PID controller structures.
(c) Support online operation. Indicates software that supports online operation such as sampling of data and online tuning.
(d) Software version reviewed.
(e) Operating systems and hardware/software dependence.
(f) Prices. Please contact the manufacturer for updated prices on their products.

Foxboro (Invensys), Honeywell, and Yokogawa—as listed in Table 3. More information on commercial PID controllers is given in [11] and [12]–[17]. The hardware modules are often targeted to process applications, although PID control is widely seen in consumer electronics and mechatronic systems.

Based on a survey carried out by *Control Engineering* in 1998 [26], single-loop models account for 64% of the controllers, while multiloop models account for 36%. The survey 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 expected from a loop controller are, in order of importance, PID functionality, start-up self-tuning, online self-tuning, adaptive control, and fuzzy logic.

Tuning Methods in Hardware Modules

Many PID vendors provide facilities for easy controller tuning. As seen in PID patents and software packages, the majority of hardware systems employ a time-domain tuning method, while a minority rely on frequency-domain relay experiments. Some modules offer gain-scheduling capabilities, which can cover a large operating envelope [9], [12]. Some modules are more adaptive, using online model identification or rules inferred from online responses.

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

Tuning-on-demand with upset typically determines the PID controller parameters by introducing a controlled perturbation in the process and then using measurements of the process response to calculate appropriate controller parameters. Adaptive tuning aims to set PID parameters without inducing upsets. For adaptive tuning, a controller constantly monitors the process variable for oscillation around the setpoint; hence, closed-loop identification can be as effective as in tuning-on-demand. Adaptive tuning is ideal for processes in which load characteristics change drastically while the process is running. When oscillation occurs, the controller adjusts the PID parameters to eliminate the oscillation. However, adaptive tuning cannot be used effectively during steady state or if the process has externally induced upsets that cannot be tuned out.

ABB Controllers

Note that hardware brands from Elsag Bailey, Kent-Taylor Instruments, Hartmann & Braun, and Alfa Laval have been acquired by ABB. For nonoscillatory processes, ABB's Micro-DCI series uses a formula-based tuning method, termed Easy-Tune.

TABLE 3 Commercial digital PID hardware modules. While general-purpose data-acquisition modules are available for PID and other control applications, dedicated PID modules are dominated by five major vendors.

Vendor	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
Emerson	DeltaV PID Function Block (inc. Model 3244 MV)	✔	?	✔	✔	2002	Mainly integrated in Emerson's cascade structure, also as a DeltaV workstation running DeltaV Tune [28]
	Fisher-Rosemount PROVOX DCS Control System (legacy 20-serise and SRx series)	✔	?	✔	✔	2002	Sets gain, reset rate, and derivative time using Tune-a-Fish. Database module can transit to DeltaV. Can communicate via HDL over network.
	RS3 (legacy)	✔	?	✔	✔	2002	PID is tuned by DeltaV Tune. Database module can transit to DeltaV. Can operate from a DeltaV workstation.
Foxboro (Invensys)	716C	✔	✘	✔	✘	1996	1/16 DIN temperature controller
	718PL, 718PR	✔	✘	✔	✘	1996	1/8 DIN process controller with local setpoint (PL) and remote setpoint (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:

✔ Support; ✘ Does not support; ? Probably support; —Information not available.

The controller approximates the process with a first-order plus delay model, as shown in (1), using a typical step-response-based graphical method to estimate the gain, delay, and time constant. The identified parameters are then used to map the controller coefficients through preoptimized formulae [18] (see [9, Table 2]).

For oscillatory processes, ABB controllers provide two autotuning options, quarter-wave and minimal overshoot. A control efficiency monitor displays and measures six second-order-like "key performance" indicators labeled in Figure 3 [19], enabling the user to vary PID settings for oscillatory processes and fine-tune manually. Information on the tuning mechanism is not disclosed, although the technique may be similar to the Micro-DCI series based on a formula-based look-up table.

Emerson

Several brands have been acquired under Emerson Process Management Group: Brooks Instrument, Daniel, DeltaV, Fisher, Intellution, Micro Motion, PROVOX, Rosemount, RS3, and Westinghouse Process Control. Emerson's PID functionality is integrated in a cascade structure embedded in Emerson Process Management Systems, and their hardware does not appear to be marketed as an independent PID module [27]. However, Fisher-Rosemount Systems' DeltaV PID Function Block [28] is embedded in many Emerson process systems, such as the Rosemount Model 3244MV MultiVariable Temperature Transmitter. Legacy systems such as PROVOX and RS3 are now upgraded with product transition to PlantWeb architecture (version 7.2) by means of DeltaV, where users can expand their PROVOX or RS3 system with DeltaV.

DeltaV provides a STRUCTURE parameter, which allows switching between several options, including

- PID terms on error
- PI terms on error, D term on the process variable (PV)
- I term on error, PD term on PV
- PD terms on error
- P term on error, D term on PV
- ID terms on error
- I term on error, D term on PV
- two-degree-of-freedom PID.

The two-degree-of-freedom PID shapes the setpoint response by adjusting the proportional and derivative action applied to the setpoint, while tuning a control loop for disturbance rejection. For full PID terms, Emerson recommends the standard parallel form for underdamped processes and the series form for simpler tuning. However, for both forms, a lowpass filter is used to smooth the derivative action and, hence, modifies the pure derivative term to

$$G_D(s) = K_P \frac{T_D s}{1 + \frac{T_D}{\beta} s}, \tag{2}$$

where K_P is the proportional gain, T_D is the derivative time constant, and β is fixed to ten in DeltaV. Unfortunately, no information on the tuning mechanism is disclosed by the vendor. Finally, Fisher-Rosemount Systems promotes fuzzy control as an "intelligent alternative to PID" [27].

Foxboro Series

Invensys Production Management Division consists of APV, Avantis, Esscor, Eurotherm, Foxboro, Pacific Simulation, Triconex, and Wonderware, where the Foxboro series is the most

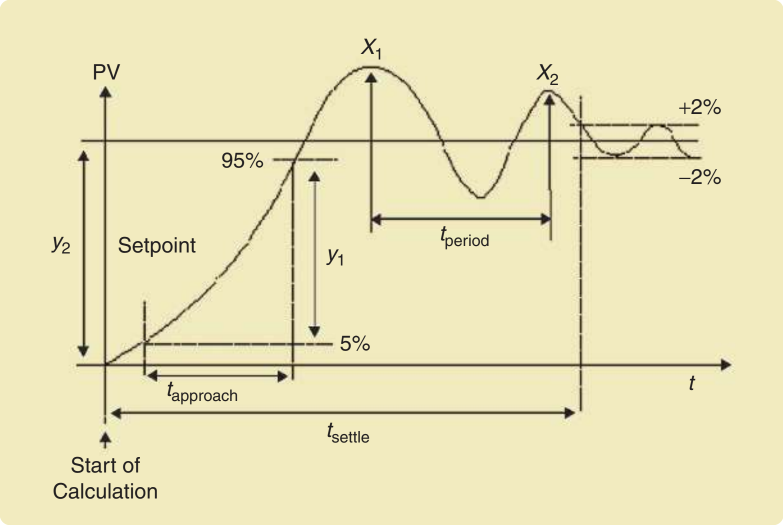

FIGURE 3 ABB's Control Efficiency Monitor [19]. This device measures six second-order-like "key-performance" indicators independently to set PIDs for oscillatory processes. Although $y_1 = 0.9 y_2$, the signal y_1 is nevertheless monitored to determine $t_{approach}$. (Reproduced with permission of ABB Ltd.)

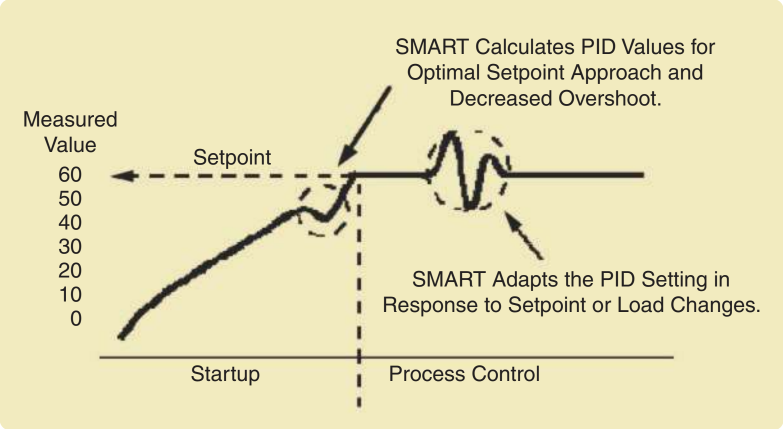

FIGURE 4 Foxboro's SMART self-adjusting mechanism [20]. During startup and control, SMART continuously monitors the process variable and automatically adjusts the PID parameters according to the response of the process variable, without injecting an artificial perturbation into the system. (Reproduced with permission of Invensys Process Systems.)

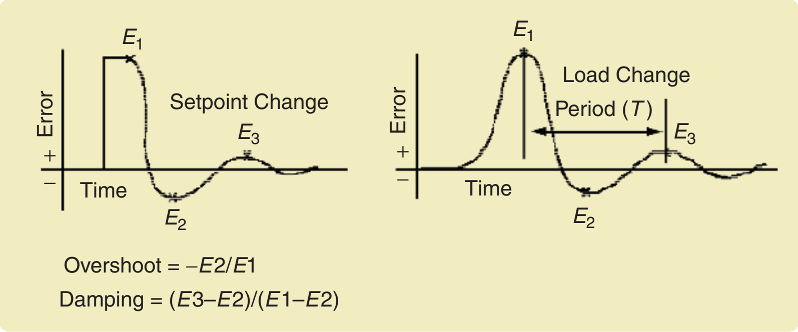

FIGURE 5 Foxboro's patterns with parameters for recognition [21]. The user can choose threshold levels for desired damping and overshoot-to-load changes once initial PID parameters are set. (Reproduced with permission of Invensys Process Systems.)

visible. Foxboro 716C, 718, and 731C series use a proprietary self-adjusting algorithm called SMART. During startup and control, SMART continuously monitors the process variable and automatically adjusts the PID parameters according to the response of the process variable, as shown in Figure 4 [20]. The advantage of SMART is its ability to operate without injecting any artificial upset into the system.

Foxboro 743C, 760C, 761C, 762C, and T630C controllers use an alternative patented self-tuning algorithm, expert adaptive controller tuning (EXACT). Instead of a parametric model, EXACT adjusts the controller based on pattern recognition allied to actual current process, as shown in Figure 5 [21]. Upon sensing a process upset, EXACT takes corrective action based on updated pattern recognition results. The user can choose threshold levels for desired damping and overshoot-to-load changes. To achieve satisfactory performance, EXACT needs to have a good initial PID parameter set to start with. To meet this need, the initial PID parameters are determined by applying a small perturbation to the process and using the resulting process reaction curve for identification. To start up the control system, the operator must determine an anticipated noise band and maximum wait time for the process. The noise band is a value representing the expected amplitude of the noise on the feedback signal. The maximum wait time is the maximum time that EXACT waits for a second peak in the feedback signal after detecting a first peak. These two settings are crucial for EXACT to deliver optimal performance, but they can be difficult to determine.

All Foxboro controllers discussed here are rule based, rather than model based, but do not support feedforward control. If these controllers supported setpoint scheduling [9], however, they would be effective for the entire operating envelope, since gain scheduling can be more useful than continuous adaptation in most situations [12].

Honeywell Tuners

Honeywell's tuning-on-demand controller, Autotune, offers no adaptive or continuous tuning. Honeywell also offers 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 tuner is Accutune II, which incorporates a fuzzy logic overshoot-suppression mechanism. Accutune II provides a plug-and-play tuning algorithm, which starts at the touch of a button or through a step-response data set to identify the process and then tune the controller for the identified process. The process can be an integrating process or a process with dead time. Plug-and-play tuning, which simplifies and speeds up the startup procedure, allows retuning at any setpoint in an automatic mode. The fuzzy logic overshoot-suppression function operates independently of Accutune tuning as an add on. Overshoot suppression does not change the PID parameters but temporarily modifies the control signal to suppress overshoot. Although this feature makes the control system more complex and difficult to analyze, overshoot suppression allows more aggressive action to coexist with smooth process output. The overshoot-suppression function can be disabled, depending on the application or user requirements, and should be unnecessary if the PID controller is set optimally [29].

Yokogawa Modules

Yokogawa introduced its Super Control module over a decade ago. The module consists of two main parts, namely, the setpoint modifier and the setpoint selector. Similar to Honeywell's Accutune II, Super Control uses a fuzzy-logic-based algorithm to eliminate overshoots, mimicking the control expertise of an experienced operator.

To deliver both a short rise time and low overshoot, the setpoint modifier first models the process and functions as an expert operator, bypassing PID control. The modifier then seeks a knowledge base about the process, its dynamics, and any nonlinearity of the process (including load changes) and thus leads the system into performing accurately by feeding artificial target setpoints into the PID block through the setpoint selector.

In particular, Super Control switches between three modes [30]. Mode 1 is designed for overshoot suppression when the process output approaches a new target setpoint by observing the rate of change and installing subsetpoints to ensure that overshoot does not occur. Mode 2 ensures high stability at the setpoint while sacrificing response time to a setpoint change. Mode 3 provides a faster response (than delivered by Mode 2) to a setpoint or load change with a compromise in stability when a new setpoint is entered and the process output approaches that change. If Mode 2 or 3 observes a phase-shift change from normal operating conditions, Super Control uses the process model, which is a first-order lag with gain model, to compute the calculated process variable (CPV) to suppress PV from hunting. It is unclear how switching is conducted between the three modes, but it would be advantageous if switching were scheduled automatically.

DISCUSSION AND CONCLUSIONS

Many PID patents focus on automatic tuning for process control, starting from conventional or intelligent system identification. With system identification included, the entire PID design and tuning process can be automated, and modular building blocks can be made available for timely online application and adaptation. The inclusion of system identification functionality is seen more in hardware modules, since software packages are mainly focused on offline design and hence have a different objective.

Many PID hardware vendors have made tremendous efforts to provide built-in tuning while incorporating their knowledge base into their tuning algorithms. Current PID control modules provide tuning-on-demand with upset or adaptive tuning or both, depending on the model and user settings. Both techniques have advantages and disadvantages. For example, when using tuning-on-demand only, the controller needs to be retuned periodically as well as whenever changes occur in the process dynamics. This tuning process can be tedious, and sometimes underperformance can be too late to be noticed. Therefore, tuning-on-demand coupled with setpoint scheduling may provide an advantage.

When relying on an adaptive tuner only, the range of changes that can be covered is limited, and a classical step-response model is needed to determine initial PID settings. Before normal operations can begin, these systems usually require a carefully supervised start-up and testing period. Furthermore, the more controller parameters the operator selects, the more difficult it is to tune and the longer it takes to prepare for the operation. Nevertheless, once the controller is correctly set up to run, the system can constantly monitor the process and automatically adjust the controller parameters to adapt to changes in the process. Without doubt, formulas (as well as rule bases), such as those used in ABB modules, yield the fastest tuning, although these formulae do not necessarily offer the best possible or multioptimal PIDs.

While automatic tuning is offered in many commercial PID products, multiobjectives and timeliness in design continue to pose a challenge. The major difficulty appears in delivering an optimal transient response, due to unexpected difficulties in setting an optimal derivative term [9]. Hence, to suppress overshoot, artificial intelligence is incorporated in software or onboard algorithms to augment simple PID structures. To meet multiple objectives, switching between different functional modes is necessary in PID hardware modules. However, these features are not commonly seen in commercial software packages.

While software and onboard algorithms offer flexibility in PID design and implementation, ad hoc patches can lead to local optimality as well as unnecessary complication and a steeper learning curve. Since PID control derives its success from simple and easy-to-understand operation, effort should be made to maintain such a consistent representation. At present, there exists no standardization of PID structures, which is particularly evident as analog PID controllers are replaced by digital ones. Modularization around standard structures should help improve cost effectiveness of PID control and maintenance. Since digital PIDs are widely used in consumer electronics and mechatronic systems, standardized code modules would be particularly suited to system-on-board or system-on-chip integration for future consumer electronics, microelectromechanical systems, and other embedded applications.

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