International Journal of Dynamics and Control (2021) 9:818–827
https://doi.org/10.1007/s40435-020-00665-4

A review of PID control, tuning methods and applications

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Received: 11 June 2020 / Revised: 18 June 2020 / Accepted: 2 July 2020 / Published online: 17 July 2020

Abstract
This article provides a study of modern and classical approaches used for PID tuning and its applications in various domains. Most of the control systems that are implemented to date with the use of PID control because of its simple structure, ease of implementation, and active research in tuning the PID for a long time. The techniques reviewed in the paper are in the order from classical to modern optimization rules used for the PID tuning. This paper attempts to address the literature review of PID control in an era of control system and bio-medical applications. The development of classical PID to the integration of intelligent control to it, has been surveyed by consideration of various application domains. The primary purpose of this document is to provide a detailed point of information for the people to understand the command of PID in different application areas.

Keywords PID · Optimal PID control · Auto-tuning · Robotic manipulator · Process control · Electrical drives · Mechanical systems

1 Introduction

PID controller has a long history in the domain of automatic control. James Watt's developed steam engine and governor in 1769 and it was accepted as a first negative feedback device [1–3]. In 1868, J. C. Maxwell formulates a mathematical model for a governor control of the steam engine [1–3]. Maxwell listed the governors into two categories: moderators and genuine governors. According to modern terminologies, he defines the moderators as controllers with proportional control action only, whereas genuine governors as controllers with both proportional and integral control actions. Subsequently, Nicolas Minorsky provided a theoretical analysis for the derivative of error, its current rate of change [2]. The contribution from Minorsky, which was initially rejected by naval operators due to staff opposition, was support for the subsequent emergence of modern PID controllers. Elmer Sperry had developed first PID controller in 1911 for the US Navy [3,4]. In 1939, however, the Taylor Instrument Companies released a fully revised version of their "Fulscope" pneumatic controller [5]. This new device developed an action called "pre-act" along with proportional and reset control actions. Similarly, the Foxboro Instrument Company put forward the term "Hyper-reset" with proportional and reset action while introducing their pneumatic controller called "Stabilog" in the same year. Both " Pre-act and "Hyper-reset" delivered a control that is commensurate to the derivative of the error signal. correspondingly, reset (also known as "floating") offers action that is commensurate to the integral of the error signal [4,5]. The outcome of these two activities was that both the controllers were offered PID control. After a few years, the problem of steady-state error in the proportional controller was minimized by adjusting the point to some arbitrary value until the error gets zero. This resetting "integrated" the error and became known as the proportional-Integral controller [4,5]. The first pneumatic controller with a derivative action was developed by Taylor instrument companies in 1940, which minimized overshooting problems. But

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the engineers were not able to identify the appropriate PID controllers' parameters until 1942 when Zieglers and Nichols tuning regulations were implemented. And, automatic PID controllers were commonly used for industrial use during the mid-1950s [5]. In later stages, researchers have more focused on Tuning of the PID control which includes self-tuning and Auto-tuning [6–14], Genetic tuning of PID [15], Robust and Optimal tuning [16] etc. Also, Intelligent PID and PID based control startegies are introduced in [17–20], fuzzy PID in [21–23], Optimal PID controller design in [13,24–27], daptive PID contol [28] and Fractional order PID [29–32] are proposed.

As shown in Fig. 1 PID control employs three modes algorithm, i.e., proportional, integral and derivative. The proportional term incorporates appropriate proportional changes for error (which is the difference between the setpoint and process variable) to the control output.

The integral term examines the process variable over time and it corrects the output by reducing the offset from process variable. Derivative control mode monitors the rate of change of the process variable and therefore changes the output when there are unusual variations. The user adjusts each parameter of the three control functions to obtain the desired performance from the process. Due to their simple structure, easy implementation and maintenance, PID controllers are the most extensively used controllers in the motion control, process control, power electronics, hydraulics, pneumatics, and manufacturing industries etc. [33]. PID controller delivers good performance with a cost / benefit ratio which is difficult for other types of controllers. They are also prevalent in modern applications, like self-driving cars, Unmanned aircraft vehicle, and autonomous robots, for the same purpose [34]. In most of the control system applications 90-95 % of control loops are of PID form.

This review work initially focused on basics of PID and PID tuning methods introduced in previous literature. Then, in further stages of the paper, different domains where the explicitly used PID controller is discussed along with the PID control strategies used in the respective domains. The latest advancement in PID is discussed in this paper which makes it an intelligent one. And finally, the future research direction of PID control techniques has been presented.

2 PID controller structure and tuning methods

2.1 Structures of PID controllers

Commonly used structures for PID controllers are of parallel and series type:

– Parallel Type: In this form, Proportional P, integral I or derivative D action occurs in separate equation terms, and with their combined effect the sum is produced. In this type each parameter is independent of others and the corresponding control law is represented as:

$$u(t) = K_c\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right) \quad (1)$$

where, the proportional gain is $K_p = K_c$, integral time is T_i and $k_i = \frac{K_c}{T_i}$, derivative time is T_d and $k_d = K_c T_d$. This is also known as an ideal representation.

– Series Type: Series or interactive equation derives mainly from the pneumatic and analog electronic circuit characteristics. Just as an ideal PID equation the change in K_c impacts all the three actions, but both derivative and integral constants have the influence on proportional action. This type has the following control law:

$$e_1(t) = e(t) + T_d\frac{de(t)}{dt}$$
$$u(t) = K_c\left(e_1(t) + \frac{1}{T_i}\int e(t)dt\right) \quad (2)$$

Here, gain K_c affects all three portions of the PID structure. On the other hand, the values of the integral and derivative tuning parameters T_d and T_i also affects the proportional term. Therefore modifying T_d tends to impact D and P actions, modifying T_i impact on both the I and P actions, and modifying K_c impacts on all three actions. Most commercial controllers use a series algorithm only, mainly with the non-interactive form (ideal) and some use the interactive form. It is usually difficult to find a perfect model in the practical world. The manipulation and trial and error are therefore still very useful procedures. For instance, if a loop is too aggressive and oscillating too much, naturally the gain should be decreased. This will results in slow down the response and robustness is added to the loop. In the series algorithm this way of thought only works. The decreased gain also raises the controller phase in the parallel algorithm, which may lead to more oscillations and instability depending on the overall tuning. Thus it is easier to grasp the PID behavior intuitively with the the series algorithm, whereas it is far more complex with the ideal algorithm. In the latter, both raising or lowering the gains may generate instability, whereas in series algorithms, lowering the gain would often result in greater stability for self-regulating processes.

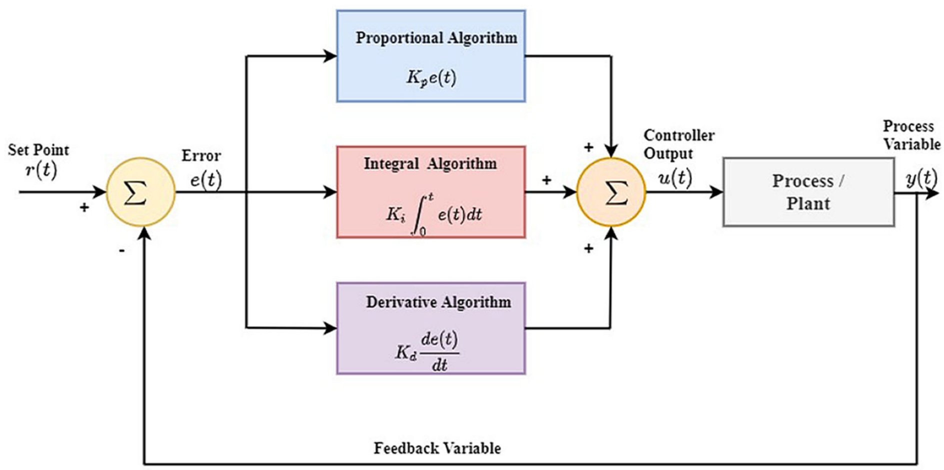

Fig. 1 Block diagram of process control using PID

2.2 Tuning methods

2.2.1 Classical tuning methods

Classical methods for PID controller tuning found in the literature include Trial and Error Method, Ziegler–Nichols Step Response Method (1941 and 1942 at Taylor Instrument Company, USA), Ziegler–Nichols Frequency Response Method [35] , Relay Tuning Method [36] and Cohen-Coon Method (1953). In addition, Weng Khuen Ho et al. (1996) addressed the efficiency and robustness of well-known PID formulas (Ziegler-Nichols, Cohen-Coon, and tuning formulas) for the processes with deadtime to time constant ratio between 0.1 and 1 [37]. It has been observed that Approximately 1.5 gain margins achieved with Ziegler-Nichols and optimized tuning formulas for calculating Integral Absolute Error (IAE), Integral Square Error (ISE) and Integral time Absolute Error (ITAE) for load disturbances. As the process deadtime to time constant ratio increases from 0.1 to 1 the phase margins increases from about 30 to 60°. Also, Gain margin appropriately 2 and phase margin of about 65° observed with the tuning formulas that optimizes the set-point response. To cancel the process poles these formulas mostly utilizes the PID controller zeroes. Classical tuning methods make certain assumptions about the plant and the desired output, and attempt to obtain some analytical or graphical feature of the process that is then used to determine the controller settings.These methods are simple to implement and has a very fast computation. These methods are good at the initial phase and do not give the desired results all the way due to assumptions made and further tuning is needed.

2.2.2 Intelligent tuning methods

The intricate systems and performance demands of the controller designer necessitate the introduction of new tuning design techniques following the emergence of classic PID controller tuning techniques. Throughout the years, several useful findings were obtained for PID tuning methods for more performance-specific criteria and to deal with more complicated systems. Earlier the classical tuning methods were only applicable to FOPDT (first-order plus dead-time) and SOPDT (second-order plus dead-time) models only. This is one of the demerit of classical tuning methods of PID control. In 1988, Fong-Chwee et al. introduced self-tuning PID controllers by pole assignment technique. Three types of self-tuning PID controllers have been discussed in it which can provide better control over dead time processes of different natures. Similarly, A. Besharati Rad et al. in [7] proposed a new self-tuning method (An option to ZN technique for auto-tuning).This tuning method is faster and is used to tune PID controllers that do not have an auto-tuning mode. Also, A. Besharati et al. proposed a Newton–Raphson search method which is found to be easy and it eliminates the complex root-solving procedures of the characteristic equation. Koivo and Tanttu in [38] carried out a survey of various tuning methods of a PID controller for SISO (Single Input Single Output) and MIMO (Multiple Input Multiple Output) technique. The different approaches for unknown plants are analyzed in his multi-variable case [38], and the findings have been generalized to time-delay systems and distributed parameter systems. In 1992, some researchers have contributed in designing the tuning methods such as auto-tuning [39], genetic algorithm approach [15] and model matching approach [40]. A novel PID Tuning technique based on model matching has been proposed in [40]. The important aspects of this method are: (i) plant transfer function is assumed to be known (ii) reference model match by cont rolled system while PID tracking (iii) the PID parameters are obtained solving a set of linear equations. The algorithm developed for controller design by LA Aguirre in [40] based on pade coefficients matching and Markov parameters.

LA Aguirre has proposed a simple controller structure, $C(s)$: $C(jw)G(jw)/[1 + C(jw)G(jw] \simeq H(jw)$, which can be found from plant transfer function $G(s)$, and $H(s)$ as a reference model. This type of representation can be used in tuning of a tracking PID controller. Brian Porter and AH Jones in [15] have proposed the techniques for genetic algorithms as an alternate way of tuning digital PID controllers. This genetic algorithm is very appealing, since even for digital PID controllers for complex multivariable plants with highly interactive dynamics, the same basic approach can still easily be employed. Also, J. C. Shen in [35] proposed new tuning method and performace assessment formula based on genetic algorithm. Ruano et al. in [39] have proposed a connectionist approach to PID autotuning which is to determine the required PID parameter values with the utilization of integral measures of the step response as the input to neural networks.

Alberto Leva, in 1993 have proposed a relay-based algorithm for automatic PID tuning to assume a process model structure and to achieve regulator tuning by defining one point of process frequency response [8]. The algorithm tends to give satisfactory performance and accuracy if the supposed process structure is close to reality. In 1993, Zhuang and Atherton evaluated the method needed to achieve the optimum settings for their PID-controller . This method is used later to obtain formulas to set the parameters of a controller for FOPDT (first-order plus dead-time) plant which is popular in process industries [9]. Also, in [41], Zhuang and Atherton described the auto-tuning procedure for determining the diagonal PID controller for the TITO (Two Input Two Output) system. This method considers two relay controllers used to achieve the critical frequency and gain of the process used in the tuning formulas. The parameters of the PID controller can then be determined using the generalized Ziegler–Nichols method or the characteristic loci method. In addition, PID tuning has also been investigated using an integral performance optimization mechanism for a TITO system.

Astrom et al. has reviewed various adaptive techniques such as gain scheduling, automatic tuning, adaptation system etc. in [10]. Later, Poulin and Pomerleau in [42] has focused on integrating and unstable processes. They have introduced a systemic PI and PID tuning method. This tuning method is based on a maximum peak-resonance specification which leads to simple expressions of the tuning parameters and is illustrated graphically by the Nichols chart. In 1998 W. Tan et al. [43] introduced PID tuning method by loop-shaping and H_∞ control for stable and integrating processes. While Q. G. Wang in 1999 [44] introduces a new method for PID tuning which achieves high performance for several linear self-regulating processes. It was based on the adaptation of the process frequency response to a specific SOPDT structure capable of modeling both the monotonous and the oscillatory features of the process. Here, closed-loop poles can be simply assigned using a classical root locus analysis method. This method tested experimentally for the laboratory set-up as well as industry application of Heating Ventilation and Air Conditioning System (HVAC).

In beginning of the 20^{th} century G. Mann in [45], Visioli and Antonio in [46] proposed new PID tuning rules such as time-domain based design analysis and fuzzy logic tuning rules respectively. Cominos and Munro in [47] noted that PID controllers are often improperly tuned, and attempts were carried out to tackle this problem systematically. A brief description of PID theory has been given in his contribution comprising PID tuning methods widely used and to explore a few latest efficient methods. An adaptive control scheme applicable to SISO system was proposed by Haung et al. [48] with the on-line tuning of PID controllers. In the suggested control structure [48] two adaptive loops has been considered . To guarantee the robust stability of the system the first loop evaluates and tunes the controller on-line without betting against nominal design performance. The second loop performs periodic on-line detection when modeling errors occur and retune the controller. After this, the system will treat as a newly configured system to provide effective control performance directly. In later part, Robust and optimal tuning of PI and PID controllers has been proposed in [16] by Birgitta Kristiansson and Bengt Lennartson. In addition, an evaluation procedure, an analytical design method and robust internal model control (RIMC) introduced in the [49]. For PI and PID, it is a slight change in IMC, in which the lambda (tuning factor) is substituted by specific tuning parameters relevant to crucial MF (medium frequency) and HF (high frequency) robustness characteristics. This proposed RIMC in [49] is found to be desirable.

3 PID applications

3.1 PID for process control

In process control, PID controllers are popularly used and are therefore listed in the majority of the automatic control textbooks. In 1977, E.M. Stafford have suggested a method as design aid for approximate PD and PID ON/OFF controllers [50]. Jacobs et al. in [51] emphasised on pH control of industrial process as a contribution towards modern control technology. Computer interface used from a full-scale production process for on-line effluent neutralisation. The analysis consisted of studies, some of which were extended using a computer to control neutralization according to various algorithms and to track performance and simulation studies. The algorithms comprises PID self-tuning control and optimal-k-step-ahead (O.K.) adaptive control. In 1983, Coppus et al. in [52] adapts the multi-variable, feedback-feedforward controller of Davison to control the binary distillation column. Experiments have shown that it is not possible to explicitly apply a robust controller to the non-linear design of the distillation column. The robust controller was implemented and tested in a masters loop, cascaded in series to the multiloop proportional controlled distillation column. The outcomes of this contribution were i) Better control of the distillation column was achieved with robust feedback and feedforward control cascaded to a simple proportional controller. ii)Excellent set-pot tracking and regulatory control performance has been achieved despite major upsets in process operating conditions. iii) The efforts required in tuning the controller are considerably less than tuning a PID controller on multiloop. Later, Thomas et al. in [53] contributed a short article which gives new desaturation strategy for digital PID controllers with a real time application of industrial batch reaction process.

Self-tuning PID controller has been implemented for level control of a lab scale water tank [11] and for Aluminum Rolling Mill [12]. Also, T. Yamamoto and S.L. Shah in [54] have proposed a new multivariable self-tuning PID controller design for level plus temperature control system . Further, P.J. Gawthrop in [55] has contributed by making a comparative evaluation of different adaptive control techniques for temperature control of industrial processes. It includes techniques that are based on a Z-N method, a waveform-analysis based, and least-square identification-based methods for self-tuning. Two industrial applications are used to control the temperature using these techniques: a plastic-on wire extrusion process and a laboratory furnace. Also the control strategies for temperature control of heating plant and Rapid Thermal Processing (RTP) were put forward in [56] (Robust nonlinear control) and [57](Conventional and auto-adaptive algorithm). Chen and Chang in [58] and Hodel, CE Hall in [59] proposed a Variable Structure PID Control. C-L Chen and F-Y Chang in [58] considered the application of the pH control in the neutralization process with the use of neural/fuzzy variable structural proportional-integral-derivative (neural/fuzzy VSPID) control method. This neural/fuzzy VSPID controller has an identical structure to that of the conventional PID. The PD mode in this controller used to speed up the response in case of large errors, while the PI mode is used to reduce the steady-state offset for small error conditions. Visioli in [60] presented optimal tuning formulas for PID controllers for integral and unstable processes. Also, Optimal PID tuning method usesg a direct search algorithms which has been proposed by Daley and Liu in [61]. These approaches can be used in various industrial applications, as well as those of high-order dynamics. The effectiveness of this approach has been demonstrated by the use of two industrial processes: one is a hydraulic system and combustor emission control with sluggish dynamics. The suggested tuning methodology in [61] is rely on the idea that the system and its controller works in a parallel fashion in real-time. An optimization algorithm will automatically adjust the parameters of the model controller. After that, these can be retrieved to the controller itself. The reference model for a simple second-order system is defined as:

$$Z(s) = \frac{\omega_n^2}{S^2 + 2\zeta\omega_n S + \omega_n^2} \tag{3}$$

Where ζ is damping factor and ωn is natural frequency of the system. It uses a direct search algorithm that can deal with both extreme non-linearities and discontinuities. The adaptive model is calculated with the help of parameters derived from the least square algorithm. The model form is

$$z_t = \alpha^T \phi_{t-1} \tag{4}$$

where $\alpha = [m_1, m_2, \ldots, m_n, n_0, n_1, \ldots, n_m]^T$

$$\phi_{t-1}=[-z_{t-1}, -z_{t-2}, \ldots, -z_{t-n}, c_{t-d}, c_{t-d-1}, \ldots, c_{t-d-m}]^T$$

c_t and z_t are the plant input and output respectively. m_i and n_i, are coefficients of a discrete transfer function and d is the plant delay.
The least squares algorithm is

$$\hat{\alpha}_t = \hat{\alpha}_{t-1} + P_t\phi_{t-1}(y_t - \hat{\alpha}^T\phi_{t-1}) \tag{5}$$

$$P_t = \lambda^{-1}(P_{t-1} - P_{t-1}\phi_{t-1}\phi_{t-1}^T(\lambda + \phi_{t-1}^T\phi_{t-1})^{-1}) \tag{6}$$

where $\lambda \in [0, 1]$ is a forgetting factor.

In 2000, Grassi and Tsakalis has proposed PID controller tuning by frequency loop-Shaping technique for the application to diffusion furnace temperature Control [62]. Also, Katebi and Moradi [63] have proposed design of predictive PID controllers with similar features to the model-based predictive controllers (MPC). Bernd-Markus Pfeiffer (Siemens) has introduced a new approach to control polymerization reactor which includes the feed-forward control with those of feedback control in a smart way [64]. An effective method of robust PID control proposed by Skoczowski et al. [65]. This can be conveniently implementable on controllers like PLC to the various applications in process industries. Similarly, some of researchers have put forward PID control startegies for various process control and industrial applications in [66–69] and in [70–73]. In [72] P. Teppa Garrán and G. Garcia introduces active disturbance rejection control (ADRC)for the design of an Optimal PID Controller for a coupled tanks system. In 2018, Eslami et al.[70] and Verma, Padhy [73] have proposed PID based intelligent control methods for water level control of canonical tank system and gas turbine respectively. Sina Razvarz et al. used the PID controller in [71] for fluid flow control in pipelines and proved that the PID controller is indeed the selection for process control applications. The PID controller 's stability is validated in the contribution which was not given attention in earlier research considering flow rate control. In addition, the technique of using the motor-pump arrangement with a torsional actuator is a completely new concept.

3.2 PID for robotic manipulator

Despite the progress of modern control theory, robot manipulator controllers still often use classical PD or PID algorithms, primarily due to their simplicity of concept and explicit tuning procedures. Y. Bestaoui propsed a method of robotic manipulator control based on decentralized pole-placement feedback deduced from the computed torque [74]. Also, Hong Zhang in [75] performs the optimal PID digitally implemented for the robotic manipulators. Later, Paolo Rocco in [76] and Dong Sun et al. in [77] proves the stability of PID control for industrial robot arms. PID control has been extended to nonlinear model of robot manipulators and also to the devices with similar dynamics [78]. Variable structure-based PID control schemes are proposed in [79,80].

Research related to PID controller which is applied to robotic manipulators are being categorized into three areas. The first area includes the tuning of PID gains by applying intelligent control such as fuzzy control [81–83], neural networks [84], or genetic methods [85]. The second area of research is targeted on the PID gain selection methods using control techniques such as optimal controls [86,87] or inverse dynamics controls [88]. The third type of research area comprises PID gain selection methods using a direct stability analysis using Lyapunov stability [89,90] and similarly, in [91] addresses the global asymptotic control of robot manipulators under input constraints, both with and without velocity measurements.

Chang et al. introduced a technique for gain selection of robust PID control for nonlinear Second-Order plants [92]. The technique used in [92] is easy and effective for tuning PID gains applicable to inaccurate models as well. Also, it provides an equivalence relationship between the PID control and TDC (Time delay control) in a discrete-time domain. In recent research work [93], Pradhan and Subudhi proposed a new nonlinear self-tuning PID controller (NSPIDC) to control a flexible-link manipulator (FLM) joint position and link deflection while it is subject to different payloads. Also, in [94] Shaban et al. proposed a new method for discrete time PID called PID+ applied to robotic manipulator.

3.3 PID for electric drives and power applications

The use of PID controllers is widespread in mechanical process automation where motor control is of concern. Also, PID control plays a vital role in power generation applications. CM Liaw et al. presents the quantitative design and deployment of a 2-degree PID Freedom Controller (2DOFC) for motor drives in [95]. KK Tan et al. in [96] tested the efficacy of a nonlinear PID controller enhanced with a learning technique when applied to piezoelectric actuator's precision motion control. Lin and Jan in [97,98] proposed a robust output tracking control design and genetic algorithm (GA)-based multi-objective PID control for a linear brushless DC motor with modelling uncertainties. The deployment of PID controls used to regulate dc motors has been experimentally shown by Kelly et al. in [99]. Zang et al. in [100] has developed an effective method for analysis and design for the two-inertia system. In [101] Angel and Viola introduces the design methods and analysis for PID controllers applicable to motor-generator system. Also, it Compares integer-order PID controller, the fractional-order PID controller, and the SIMC PID controller. New control strategies such as optimal control, adaptive control are presented in articles [102–104] contributed towards the control mechanism in DC Motor and motor drives. Particle swarm optimization, self-tuning PID controller, optimization of PID controller with genetic algorithm are used in automatic voltage regulator (AVR) system [105–107].

Implementation of PID control for DC-DC converter carried out by Kapat and Krein in [108] and by Seo et al. in [109]. The usage of PID based control strategies are effectively introduced in power generation and power station processes [110–113].

3.4 PID for biomedical applications

Various PID based control approaches are proposed for the biomedical applications such as arterial blood pressure infusion/regulation, muscle relaxation in surgical patients, joint angle control in artificially stimulated muscle, liver transplantation, blood glucose control, control of propofol anesthesia.

In [114], Slate and Sheppard used a nonlinear digital PID controller to regulate arterial blood pressure by infusing sodium nitroprusside into the drug. It is used during open-heart surgery in the cardiac surgical intensive care unit to control high blood pressure. In [115], Satoru Isaka and Anthony V Sebald investigated the application of automatic control strategies for control of arterial blood pressure. A variety of control methods are used in [115], including PID control and its variations, optimum control, adaptive control, rule-based control including blurred control, and neural network control. Denai et al. [116] implemented self-tuning PID regulation of muscle relaxation caused by atracurium in surgical patients. In [117], Veltink et al. also presents the joint angle regulation system for the artificially stimulated muscle.

Expert PID control system and improved PID switching control for blood glucose regulation are proposed in

[118,119]. PID controller is used to model vecuronium pharmacokinetics and pharmacodynamics during liver transplantation by O' Hara et al. in [120]. Robust PID control is proposed by Van Heusden et al. to control of Propofol Anesthesia in Children [121].

3.5 PID for mechanical systems

In industry most of the mechanical systems are controlled by PID control techniques. Research carried out in PID control methods that are applicable to active magnetic bearing (AMB) rotor systems, milling process, quadrotor, constant tension control system, magnetic leviation systems, twin-rotor MIMO systems, pilot crane, gripper, etc.

In [122] Marttinen et al. introduces a simple root-locus method which was used to tune a cascade type of PID controller for the application of pilot crane. Homberg et al. has presented a PID control strategy for laser surface hardening of steel [123]. Juang et al. in [124] introduces a new method using evolutionary computational PID control to a non-linear multi-input multi-output (MIMO) system through a laboratory setup of MIMO twin rotor system (TRMS). In [125], Jose Romero et al. defined a group of mechanical systems (e.g. inertia wheel, cranes, spherical pendulum etc.) that can be stabilized globally using a linear PID. In [126], Chunsheng Wei and Dirk Söffker presents the algorithms and the corresponding results from the design of an AMB controller, including optimisation using a multi-objective genetic algorithm. Similarly, a new active control technique is proposed in [127] to reduce chatter noise in the milling process. Ortiz et al. in [128] introduces the methodology for designing and implementing a non-linear robust controller for the regulation of attitude in an experimental framework of a quadrotor unmanned aerial vehicle (UAV). PID based control strategies are introduced for magnetic leviation systems in [129,130]. A saturation-based tuning method for fuzzy PID controller is proposed to control gripper rotation [131]. Meng et al. in recent research work proposed optimal fractional fuzzy PID control [132] which is used for a constant tension control system.

4 Conclusion and future direction of reasearch

On extensive literature survey we can conclude that the PID controller has become the most widely used controller in various application domains because of its simple structure and easy implementation. The emerging features of automatic tuning have greatly simplified the use of PID control. Recently, fractional-order PID combined with the fuzzy logic system , IMC-PID controller design, optimal PID control, combination of PID-observer structure are gradually got attention. In the future, PID based control such as optimal fractional order PID, fractional fuzzy PID, self-tuning of PID can be extend it for numerical control systems applications. Also, it can be concluded that the PID can able to provide automatic tuning facility due to which it has received a more attention from the industrial users. The tuning of PID controllers would be a large research area.

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