Research Trends for PID Controllers

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Abstract

This paper analyses the most significant issues that have been recently been addressed by researchers in the field of Proportional-Integral-Derivative (PID) controllers. In particular, the most recent techniques proposed for tuning and designing PID-based control structures are briefly reviewed, together with methods for assessing their performance. Finally, fractional-order and event-based PID controllers are presented among the most significant developments in the field.

Keywords: PID controllers, design, tuning, control structures.

1 Introduction

Despite the new results in control theory that have been achieved by researchers year-by-year all over the world, Proportional-Integral-Derivative (PID) controllers are still the most widely-used controllers in industry. This is because it is really very difficult to improve their cost/benefit ratio, which is obviously a major concern in industry. PID controllers are still a very active field of research, because it is recognized that they are often poorly tuned in industrial applications, and the performance that is achieved can be improved many times by using a more effective design technique for the PID-based control system. A great impulse for research on PID controllers was provided by a workshop dedicated to them organized in Terrassa (Spain) in 2000, sponsored by the International Federation of Automatic Control (IFAC). The success of the meeting is witnessed not only by the number of participants but also by the large number of papers and books published in the last ten years specifically on this topic (see, e.g. [3, 15, 23, 45, 46, 52, 55]). In order to further outline the current state-of-the-art and the future perspectives from an academic and also from an industrial viewpoint, another IFAC conference dedicated to PID controllers was held in Brescia (Italy) in March 2012. This paper describes many significant results achieved recently in the field of PID controllers, and reviews in particular those related to tuning and designing PID-based control structures, determining the stabilizing region of the PID parameters, and performance assessment issues. Finally, new control concepts applied to PID controllers, namely fractional and event-based PID controllers, will be highlighted.

2 Generalities

A PID controller is typically employed in a unity-feedback control system like that shown in Figure 1, where P is the process, y is the process variable, r is the set-point signal and d is the load disturbance. In its basic form, the PID controller can be described by the following transfer function

$$C(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s \right), \qquad (1)$$

where K_p is the proportional gain, T_i is the integral time constant and T_d is the derivative time constant. Expression (1) is usually known as the ideal form. Other forms (usually called series and parallel forms) can also be employed [3]. In order to be effectively employed in practical cases, additional functionalities also have to be implemented. The most important functionalities can be summarized as follows (details can be found in [52]).

- The derivative action has to be filtered in order to make the controller proper and to filter the (high frequency) measurement noise; in addition, the derivative action is often applied directly to the process variable instead of to the control error in order to avoid the so-called derivative kick when a step signal is applied to the set-point. The derivative filter has to be taken into consideration in the overall design of the controller [13, 17].

- The set-point value for the proportional action can be weighted in order to obtain a two-degree-of-freedom controller, i.e. in order to reduce the overshoot in the set-point step response when the controller is tuned in order to increase the bandwidth of the system with the aim of increasing the load disturbance rejection performance. In this case a suitable choice of the value of the set-point weight (or the application of a more sophisticated techniques [47]) can yield a significant increment of the control performance.

- Suitable techniques (see, e.g. [48]) should be implemented properly in order to avoid the windup effect
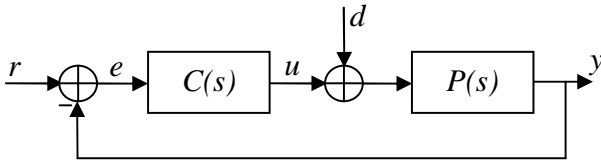
Figure 1: The unity feedback control scheme.

of the integral action which has a detrimental effect when large set-point changes are applied.

3 Tuning and automatic tuning techniques

Many tuning rules for PID controllers have been proposed in the last century [23], and new rules have also been proposed recently (for self-regulating, integral and unstable processes). Among these new rules, it is worth mentioning the SIMC tuning rules [9, 34] which have been proven to provide very good results despite their simplicity, and the AMIGO tuning rules, which are capable of giving high performance for a wide range of processes [2].

When a new technique is investigated, the following points should be considered. First, the parameters related to the additional functionalities mentioned in Section 2 should be explicitly taken into account. Other important issues, e.g. the robustness of the controller to modelling uncertainties, should also be considered [43]. Finally, the availability of more and more advanced identification techniques calls for procedures to select the most suitable identification strategy for a given application and for a general model-based design strategy [8, 18]. This is clearly more relevant when automatic tuning techniques are implemented. Obviously, each design methodology should yield an optimal PID controller, i.e. it should minimize some significant performance index (e.g. the integrated absolute error when a set-point or load disturbance step signal is applied) subject to constraints usually represented by the robustness of the control system of the control effort.

4 PID-based control structures

Many different PID-based control structures have been considered as an effective means for obtaining high performance while retaining simple implementation of the control system. In this context it is worth highlighting (in addition to the above-mentioned decoupling strategies) structures and tuning techniques for dead time compensation schemes [22], for cascade [41] and ratio control systems [50, 51] and methods for designing feedforward control actions (both for the set-point following task [28, 49, 53] and for the load disturbance rejection task

[11, 27, 44]). It should be stressed that the challenging issue in a PID-based control system is to achieve a suitable combination of the block scheme design and the tuning of the controller parameters.

5 PID control for MIMO processes

As it is recognized that many processes are multivariable by their nature, the design of PID controllers for application in multi-input-multi-output (MIMO) systems is also a very interesting and relevant topic. In particular, the tuning of decentralized or multivariable PID controllers poses new challenges to be solved because of the coupling effects in the process [35, 54]. Further, effective decoupling strategies are needed where the best trade-off between ease of implementation and obtained performance is achieved [7, 19, 21, 29].

6 Stabilizing PID controllers

Great advances have been made in recent years on the more theoretical issue of determining the complete set of stabilizing PID controllers for a given process [33]. For example, if a first-order-plus-dead-time (FOPDT) process

$$P(s) = \frac{K}{Ts + 1} e^{-Ls} \qquad (2)$$

is considered, the stabilizing PID parameters can be computed by solving fairly simple equations (numerically) [32]. Similar procedures can also be employed for integral processes [25]. It should be stressed that knowledge of the set of stabilizing controllers provides information related to the robustness and/or fragility of the controller, and can also be employed for implementing advanced tuning techniques.

7 Performance assessment and retuning

In many practical cases, PID controllers are poorly tuned because of lack of time and lack of skill of the operator. As there are hundreds of control loops in large plants, it is almost impossible for operators to monitor each of them manually. It is therefore important to have automatic tools that are first able to assess the performance of a control system and, in the event that it is not satisfactory, to suggest a way to solve the problem (for example, if bad controller tuning is detected, new appropriate controller parameter values are determined). Many performance assessment methodologies have been proposed in the literature and have been applied successfully in industrial settings [14]. They are generally divided in two categories *stochastic performance monitoring* in which the ability of the control

system to cope with stochastic disturbances is of main concern (works that fall into this class mainly rely on the concept of minimum variance control), and *deterministic performance monitoring* in which performances related to more traditional design specifications, e.g. set-point and load rejection disturbance step response parameters, are taken into account. Restricting the analysis to the tuning assessment of PID controllers, methods for determining the minimum variance PID controller have been proposed in [16, 42]. Regarding deterministic performance monitoring, a practical approach has been proposed in [38, 39, 40]. It is based on a process parameter estimation procedure which uses the set-point step response (i.e. routine operation data). Its rationale relies in the so-called "half rule", which states that the largest neglected (denominator) time constant is distributed evenly to the effective dead time and the smallest retained time constant. Then, the performance that is obtained is evaluated by comparing the integrated absolute error with the error that would have been obtained by applying the SIMC tuning rule, which is considered as a benchmark, i.e.

$$IAE = 2AL, \qquad (3)$$

where A is the amplitude of the set-point step signal. In particular, for a FOPDT process (2), the gain is estimated as

$$K = A \frac{T_i}{K_p \int_0^\infty e(t)dt}. \qquad (4)$$

Then, the sum of the time constant and the dead time can be determined as

$$L + T = \frac{\lim_{t \to +\infty} \int_0^t e_u(v)dv}{A} \qquad (5)$$

where

$$e_u(t) = Ku(t) - y(t). \qquad (6)$$

Because the apparent dead time L can be determined by considering the time interval from the application of the step signal to the set-point and the time instant when the process output attains 2% of the new set-point value A (a suitable noise band can be employed in practical cases to cope with measurement noise), the value of T can easily be determined from 5.

With knowledge of the process parameters, the performance can be assessed by considering the following performance index (see (3))

$$J = \frac{2AL}{\int_0^\infty |e(t)|dt}, \qquad (7)$$

and, in the event that the performance is not satisfactory (in principle, it should be $J = 1$, but from a practical point of view $J > 0.6$ can be considered as acceptable), the PID controller can be retuned by applying the SIMC tuning rule (or some other suitable rule).

For an integral processes, the procedure is similar. The process model is

$$P(s) = \frac{K}{s(Ts + 1)} e^{-Ls} \qquad (8)$$

and the sum of the lags and of the dead time of the process can be determined as

$$L + T = \frac{\lim_{t \to +\infty} \int_0^t e_u(v)dv}{A}, \qquad (9)$$

where

$$e_u(t) := K \int_0^t u(v)dv - y(t) \qquad (10)$$

The process gain K can be determined as

$$K = A \frac{T_i}{K_p \int_0^\infty \int_0^t e(v)dvdt}. \qquad (11)$$

If the set-point following task is of concern and a PID controller is employed, the performance index becomes

$$J = \frac{3.45AL}{\int_0^\infty |e(t)|dt}. \qquad (12)$$

It is worth noting that this methodology can also be applied, with appropriate modifications, when a load disturbance step response is available.

8 Fractional-order PID controllers

A topic which continues to be the subject of many investigations is fractional-order PID (FOPID) controllers, which can be considered a generalization of standard integer-order PID controllers, where the orders of integration and differentiation are not necessary integer [20, 36]. The typical formulation of a FOPID controller is

$$C(s) = K_p \left(1 + \frac{1}{T_i s^\lambda} + T_d s^\mu \right), \qquad (13)$$

where λ and μ are the noninteger orders of the integral and derivative terms respectively. An alternative form (which includes the filter of the derivative term) is

$$C(s) = K_p \frac{T_i s^\lambda + 1}{T_i s^\lambda} \frac{T_d s^\mu + 1}{\frac{T_d}{N} s + 1}. \qquad (14)$$

FOPID controllers have the great advantages of providing more flexibility in their design, as the user can also tune also the order of integration and differentiation in addition to the proportional gain and the integral and derivative time constants. This implies that the frequency response of the open-loop system can be shaped with more degrees-of-freedom, thus allowing the user to meet more control requirements. For example, the iso-damping property can be pursued, namely the

capability of the control system to achieve the same phase margin (i.e.that is, the same overshoot in the set-point step response) independently from (moderate) variations of the process gain [4]. Further, the minimum integrated absolute error when a step signal is applied to the set-point or to the load disturbance can be decreased with respect to standard PID controllers [24, 26].

However, FOPID controllers are more difficult to implement (the fractional controller has to be approximated by a usually high-order integer-order controller) and, in spite of the theoretical results that have been recently achieved, there is still much work to be done before they are ready for widespread use in industrial settings. In particular, the effectiveness of the tuning rules that have been devised needs to be fully demonstrated and the substitution of classical PID controllers with FOPID controllers in control structures (see Section 4) still has to be addressed, as has the presence of the additional functionalities mentioned above (e.g. set-point weight, anti-windup, feedforward action, etc.) which makes standard industrial controllers successful in practical applications.

9 Event-based PID controllers

The recent introduction of wireless transmitters and wireless actuators in the process industry has motivated new interest in PID modifications that allow effective control using nonperiodic information updates. Indeed, the underlying assumption in process control has always been that control is executed on a periodic basis, and that a new measurement value is available each execution. However, it is well known that in some processes a small stationary control error or smooth oscillations of the process output around the set-point may not constitute hard design constraints, but a reduction in the information exchanged between the agents that take part in the control loop (sensors, controllers, actuators) can be one of the tightest requirements. In fact, when wireless sensors and actuators are involved, reduction of the information flow implies a decrement of computing operations and transmissions, and thus longer lifetime of batteries. With these demands, one of the most convenient strategies is to use event-based sampling and control approaches. In particular, in order to minimize power consumption, a wireless transmitter may transmit a new measurement only if the measurement has changed by a significant amount or, in general, when a logical condition becomes true. In the process control field, the logical condition is usually a composition of Boolean operations, where the variables are the signals (or a function of them such as an estimation, the derivative, the integration, etc.) that the sensor receives from the process or the control action produced by a controller [1, 31, 37]. In general, in event-based control strategies, the controller can be divided into four logical blocks as shown in Figure 2: the sensor unit (SU), the control unit (CU), the actuator

unit (AU) and a governor (G). The units and their tasks can be described as follows:

- The sensor unit is composed of the sensor and its on-board intelligence. Its task is to measure the process output and to calculate the error between the measured signal and a constant set-point value received from the governor.

- The control unit implements the control algorithm, which determines the control action by taking into account the last received sampled error and sends it to the actuator unit.

- The actuator unit receives the control action signal from the control unit and applies it to the actuator. The governor, which, in practice, can be implemented together with one of the previous two blocks, receives the desired set-point value from a user interface or from a hierarchically higher controller, and sends it to the sensor unit.

These blocks can be implemented in a unique machine or in two or more physical entities. In this last case, the data has to be sent from one to each of the others in a network. It is clear that communication between two entities implies more effort than exchanging the data into a single machine, especially when they are battery-powered. For this reason, it is recommended to use event-triggered data exchanging for all the signals sent between two machines and normal time-driven sampling for the data elaborated by a unique machine. This implies that the control system has to be designed to deal effectively with an asynchronous sampling rate, and this opens new challenges both from a theoretical viewpoint and from a practical viewpoint, as the timing of the events influences the system performance and limit cycles may arise. Further, in addition to the PID gains, there are in general other parameters (threshold values) employed in the control algorithm that have to be tuned, thus making the overall control design more complex. For reasons such as these, in recent years event-based sampling and control techniques have received special attention from several research groups, and various effective methodologies have been proposed. Among the various solutions, it is worth mentioning the PIDplus technique, which has already been applied successfully in industry [6]. It involves restructuring the PID controller to reflect the reset contribution for the expected process response since the last measurement update. The so-called symmetric send-on-delta (SSOD) PI controller has recently been presented [5]. The approach that is employed is based on quantization of the sampled signal by a quantity multiple of a given parameter Δ, so that the relationship between the input and output of the event-generator block is symmetric with respect to the origin. In this context, necessary and sufficient conditions on the controller parameters for the existence of equilibrium points without limit cycles
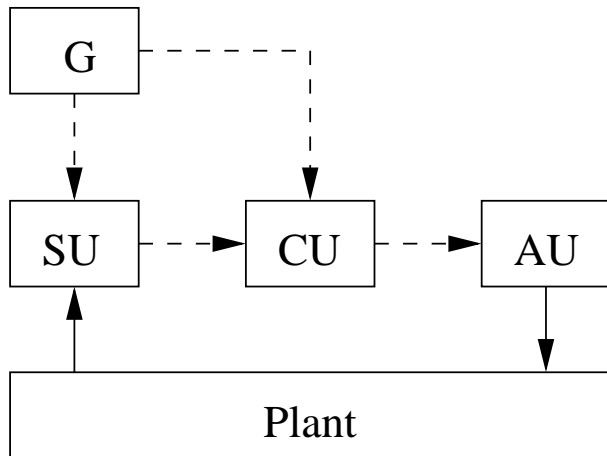
Figure 2: Scheme of a generic event based control strategy. The dashed arrows indicate the possibility of event-triggered data transmission.

can be determined, and this can be exploited to devise effective tuning rules. It is also shown that the choice of parameter Δ does not influence the stability of the system, and it can therefore be selected just in order to handle the trade-off between reducing the desired number of events and reducing the steady-state error.

10 CACSD tools

The availability of more and more sophisticated and high performance software tools has favored the realization of more and more effective Computed Aided Control System Design (CACSD) tools specifically designed for PID-based control systems [10, 12, 30]. CACSD tools surely contributes to the rapid dissemination of new methodologies through researchers and, most of all, makes their applicability much easier in industry, as theoretical issues can be made transparent to the user. Moreover, the user can often better understand the design procedure and the physical meaning of the design parameters. It is therefore recognized that each new proposed design methodology should also be made available in a suitable software tool.

11 Conclusions

Despite the long history of PID controller research and application, there are still many open issues and challenges related to many different aspects of the overall industrial control system design. Indeed, the need to keep improving the performance of control systems while keeping them as simple as possible, together with the need to satisfy technological requirements, calls for new methodologies to be applied in this field. A (surely not exhaustive) selection of relevant topics that are currently the subject of investigation has been presented

here, highlighting in particular the requirements that newly-devised methodologies should satisfy.

Acknowledgements

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