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PID compensation of time delayed processes 1998-2002: a survey

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ABSTRACT

A time delay may be defined as the time interval between the start of an event at one point in a system and its resulting action at another point in the system. Delays are also known as transport lags or dead times; they arise in physical, chemical, biological and economic systems, as well as in the process of measurement and computation. Methods for the compensation of time delayed processes may be broadly divided into proportional integral derivative (PID) based controllers, in which the controller parameters are adapted to the controller structure, and structurally optimised controllers, in which the controller structure and parameters are adapted optimally to the structure and parameters of the process model. The purpose of this paper is to extract the essence of the developments in design, tuning and implementation of PID controllers for delayed processes over the five years 1998-2002, concentrating on journal publications. The paper will provide a framework against which the literature may be viewed.

1. INTRODUCTION

The use of the PID controller is ubiquitous in industry; it has been stated, for example, that in process control applications, more than 95% of the controllers are of PID type (Astrom and Hagglund 1995). Despite the development of a large number of alternative control algorithms over the past four decades, and the fact that PID controllers have been used widely in industry for almost sixty years, their popularity is growing; eighty-three publications on the control of delayed processes using PID controllers have been recorded by the author in the year 2000, for example (O’Dwyer 2003a). However, Ender (1993) maintains that, in his testing of thousands of control loops in hundreds of plants, it has been found that more than 30% of installed controllers are operating in manual mode and 65% of loops operating in automatic mode produce less variance in manual than in automatic (i.e. the automatic controllers are poorly tuned); this is rather sobering, considering the wealth of information available in the literature for determining controller parameters. Table 1 is instructive in this regard.

Due to space considerations, this paper will provide an overview of continuous time PID compensation techniques, proposed since 1998, for SISO processes with time delay. Other reviews are recommended to the interested reader (Seborg et al. 1986; Bueno et al. 1991; Fisher 1991; Koivo and Tanttu 1991; Astrom et al. 1993; Astrom et al. 1995; Astrom 1996; Chen 1996; Unar et al. 1996; Gorez 1997; Tan et al. 1999; Astrom and Hagglund 2000a; Lelic and Gajic 2000; Cominos and Munro 2002; Hang et al. 2002; O’Dwyer 2003a,b).

Table 1: Control of delayed processes using PID controllers: publications by date (O’Dwyer, 2003a)

Year	Journal articles	Total publications
1942-1952	4	4
1953-1962	4	5
1963-1972	13	16
1973-1982	7	14
1983-1992	61	111
1993-2002	229	384
1993-1997	100	159
1998-2002	129	225

The PID controller may be implemented in continuous or discrete time, in a number of controller structures. The ideal continuous time PID controller is expressed in Laplace form as follows:

$$G_c(s) = K_c(1 + \frac{1}{T_i s} + T_d s) \tag{1}$$

with K_c = proportional gain, T_i = integral time constant and T_d = derivative time constant. If $T_i = \infty$ and $T_d = 0$ (i.e. P control), then the closed loop measured value will always be less than the desired value for processes without an integrator term, as a positive error is necessary to keep the measured value constant, and less than the desired value. The introduction of integral action facilitates the achievement of equality between the measured value and the desired value, as a constant error produces an increasing controller output. The introduction of derivative action means that changes in the desired value may be anticipated, and thus an appropriate correction may be added prior to the actual change. Thus, in simplified terms, the PID controller allows contributions from present, past and future controller inputs.

In many cases, the design of PID controllers for delayed processes are based on methods that were originally used for the controller design of delay-free processes.

However, there is general agreement that PID controllers are not well suited for the control of dominant delay processes. It has been suggested that the PID implementation is recommended for the control of processes of low to medium order, with small delays, when controller parameter setting must be done using tuning rules and when controller synthesis may be performed a number of times (Isermann 1989).

2. THE SPECIFICATION OF PI OR PID CONTROLLER PARAMETERS

2.1 Iterative Methods

The choice of appropriate compensator parameters may be achieved experimentally e.g. by manual tuning. However, such an approach is time consuming and the process typically has to be driven to its stability limit. Alternatively, a graphical or analytical approach to controller tuning may be done in either the time or frequency domains. The time domain design is done using root locus diagrams; it is, however, questionable that a delayed process would be sufficiently well modelled by the necessary second order model. The frequency domain design is typically done using Bode plots to achieve a desired phase margin. Iterative methods for controller design provide a first approximation to desirable controller parameters.

2.2 Tuning Rules

Process reaction curve tuning rules are based on calculating the controller parameters, from the model parameters determined from the open loop process step response. This method was originally suggested by Ziegler and Nichols (1942), who modelled the SISO process by a first order lag plus delay (FOLPD) model, estimated the model parameters using a tangent and point method and defined tuning parameters for P, PI and PID controllers. Other process reaction curve tuning rules of this type are also described, sometimes in graphical form, to control processes modelled by a FOLPD model (Shinskey 2001) or an integral plus delay (IPD) model (Hay 1998). The advantages of such tuning strategies are that only a single experimental test is necessary, a trial and error procedure is not required and the controller settings are easily calculated; however, it is difficult to calculate an accurate and parsimonious process model, load changes may occur during the test which may distort the test results and a large step input may be necessary to achieve a good signal to noise ratio.

Performance (or optimisation) criteria, such as the minimisation of the integral of absolute error in a closed loop environment, may be used to determine a unique set of controller parameter values. Tuning rules have been described, sometimes in graphical form, to optimise either the regulator response or the servo response, of a compensated SISO process, modelled in stable or unstable FOLPD form (Wilton 1999; Majhi and Atherton 2000; Visioli 2001a; Shen 2002), IPD form (Visioli 2001a), stable or unstable second order system plus delay (SOSPD) form (Wilton 1999; Kwak et al. 2000) or more general form (Shen 2000). Tuning rules to achieve specified servo and regulator responses simultaneously are also described (Tan et al. 1998; Yang and Shao 2000a).

Ultimate cycle tuning rules are calculated from the controller gain and oscillation period recorded at the ultimate frequency (i.e. the frequency at which marginal stability of the closed loop control system occurs). The first such tuning method was defined by Ziegler and Nichols (1942) for the tuning of P, PI and PID controller parameters of a process that may or may not include a delay. The tuning rules implicitly build an adequate frequency domain stability margin into the compensated system. Such tuning rules, to compensate delayed processes by either minimising a performance criterion, or achieving a specified gain and/or phase margin, are discussed when the SISO process is modelled in IPD form (Kookos et al. 1999), or stable or unstable SOSPD form (Luyben 2000). Alternatively, ultimate cycle tuning rules, and modifications of the rules in which the proportional gain is set up to give a closed loop transient response decay ratio of 0.25, or a phase lag of 135^0, may compensate general, possibly delayed, stable or unstable processes (Hay 1998; Tan et al. 1999; Yu 1999; Prashanti and Chidambaram 2000; Tan et al. 2001; Robbins, 2002a), sometimes to achieve either a specified gain and/or phase margin (Prashanti and Chidambaram 2000; Tan et al. 2001) or a specified closed loop response (Vrancic et al. 1999, 2001). The controller settings are easily calculated; however, the system must generally be destabilised under proportional control, the empirical nature of the method means that uniform performance is not achieved in general, several trials must typically be made to determine the ultimate gain, the resulting process upsets may be detrimental to product quality, there is a danger of misinterpreting a limit cycle as representing the stability limit and the amplitude of the process variable signal may be so great that the experiment may not be carried out for cost or safety considerations.

Direct synthesis tuning rules result in a controller that facilitates a specified closed loop response. These methods include pole placement strategies and frequency domain techniques, such as gain margin and/or phase margin specification methods. Pole placement strategies are described to compensate SISO processes modelled in stable or unstable FOLPD form (Bi et al. 1999; Chien et al. 1999; Huang et al. 2000; Zhang and Xu 2000; Mann et al. 2001b; Chen and Seborg, 2002), IPD form (Chen et al. 1999; Chien et al. 1999a; Chen and Seborg, 2002), first order lag plus integral plus delay (FOLIPD) form (Chen and Seborg, 2002) or SOSPD form (Wang et al. 1999a; Bi et al. 2000; Chen and Seborg, 2002). Frequency domain based tuning rules are also described, for processes modelled in stable or unstable FOLPD form (Ho et al. 1998; Ho and Xu 1998; Chen et al. 1999a; Wang and Cai 2002), stable or unstable SOSPD form (Ho and Xu 1998; Huang et al. 2000; Wang et al. 2001a), IPD form (Poulin and Pomerleau 1999; Cheng and Yu 2000; Kristiansson and Lennartson 2002), FOLIPD form (Kristiansson and Lennartson 2002; Wang and Cai 2002) or more general form (Yang and Shao 2000b, Kristiansson and Lennartson 2002; Tang et al. 2002).

The presence of unmodelled process dynamics demands a robust design approach. The Internal Model Control (IMC) design procedure, which allows uncertainty on the process parameters to be specified, may be used to design appropriate PI and PID controllers; other robust strategies may also be used to design such controllers. Processes may be modelled in stable or unstable FOLPD form (Alvarez-Ramirez et al. 1998; Lee et al. 1998; Chen et al. 1999b; Chun et al. 1999; Isaksson and Graebe 1999; Lee et al. 2000; Leva and Colombo 2000; Rivera and Jun 2000; Marchetti and Scali 2000; Ho et al. 2001; Luyben 2001; Zhong and Li 2002; Huang et al. 2002), IPD form (Alvarez-Ramirez et al. 1998; Zhang et al. 1999; Rivera and Jun 2000; Zhong and Li 2002) or stable and unstable SOSPD form (Lee et al. 1998; Chen et al. 1999b; Rivera and Jun 2000; Zhong and Li 2002; Zhang and Xu 2002).

Tuning rules are easy to use, even in the absence of an accurate process model. These design methods are suitable for the achievement of a simple performance specification, for a compensated process with a non-dominant delay. Comprehensive summaries of the tuning rule formulae are available (O’Dwyer 2003b). A summary of tuning rules published by year and medium is provided in Table 2; as this table shows, interest in the development of tuning rules is growing.

Table 2: Tuning rules - publications by date (O’Dwyer, 2003a)

Year	Journal articles	Total publications
1942-1952	4	4
1953-1962	4	4
1963-1972	7	9
1973-1982	5	8
1983-1992	21	38
1992-2002	99	160
1992-1997	46	72
1998-2002	53	88

2.3 Analytical Techniques

Controller parameters may be determined using analytical techniques. Some methods minimise an appropriate performance index (Astrom et al. 1998; Ham and Kim 1998; Kookos et al. 1999; Liu and Daley 1999; Leva and Colombo 1999; He et al. 2000; Howell and Best 2000; Tan et al. 2000; Wang and Cluett 2000; Leva and Colombo 2001; Campi et al. 2002; Panagopoulos et al. 2002; Hwang and Hsiao 2002; Robbins, 2002b; Sung et al. 2002; Tan et al. 2002; Yang et al. 2002a). Alternatively, a direct synthesis strategy may be used to determine the controller parameters. Such strategies may be defined in the time domain, possibly by using pole placement (Atherton 1999; Daley and Liu 1999; Jung et al. 1999a, 1999b; Majhi and Atherton 1999; Jaguste and Agnihotri 2002) or in the frequency domain, possibly by specifying a desired gain and/or phase margin (Fung et al. 1998; Wang et al. 1999b, 1999c; Grassi et al. 2001; Seki et al. 2001; Crowe and Johnson 2002; Yang et al. 2002b).

Robust methods may be used to design analytically an appropriate PID controller (Huang and Wang 2001; Wang et al. 2001b; Ge et al. 2002). Finally, alternative design methods may be used to determine the controller parameters, such as fuzzy logic (Bandyopadhyay and Patranabis 1998, 2001; Blanchett et al. 2000; Xu et al. 1998, 2000; Li and Tso 1999, 2000; Mudi and Pal 1999; Visioli 1999, 2001b; Wang et al. 1999d; Tao and Taur 2000; Mann et al. 2001a), genetic algorithms (Cheng and Hwang 1998; Wang et al. 1999d) or neural networks (Huang et al. 1999; Sbarbaro et al. 2000; Shu and Pi 2000).

Analytical methods are suitable for the design of PI/PID controllers for non-dominant delay processes where there are well-defined performance requirements to be achieved.

CONCLUSIONS

Control academics and practitioners remain interested in the use of the PID controller to compensate processes with time delay. This paper provides a comprehensive summary of such compensation techniques that have appeared in relevant journals since 1998. It is the hope of the author that the paper will provide a convenient reference for application work. The work demonstrates that new design techniques have been accumulating, each claiming that it is the best suited for the application. In general, there is a lack of comparative analysis with other design techniques; associated with this is the lack of benchmark examples, at least until the recent suggestions of Astrom and Hagglund (2000b), for testing the different methods. The main priority for future research should be a critical analysis of available design techniques.

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