2000-01-01

Time delayed process model parameter estimation: a classification of techniques

Aidan O'Dwyer
Technological University Dublin, aidan.odwyer@tudublin.ie

TIME DELAYED PROCESS MODEL PARAMETER ESTIMATION: A CLASSIFICATION OF TECHNIQUES

A.O'Dwyer

School of Control Systems and Electrical Engineering, Dublin Institute of Technology, Kevin St., Dublin 8, Ireland.

Keywords: Delay, parameter estimation.

Abstract: An extensive though scattered literature exists on the estimation of the model parameters of time delayed processes. However, it is possible to identify themes that are common to many of the proposed techniques. The intention of this paper is to provide a framework against which the literature may be viewed.

1. Introduction

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, dead times or time lags; they arise in physical, chemical, biological and economic systems, as well as in the process of measurement and computation. For brevity reasons, this paper will consider only those applications where the delay is estimated in the presence of other process parameters.

The purpose of the identification determines the type of process model required. Newell and Lee [1] suggest that the model complexity that may be reasonably identified from experimental data depends on the data quality available and the analysis technique used. The authors suggest that a cautious approach is to identify a first order lag plus delay (FOLPD) model from the experimental data and that an optimistic approach is to identify a second order system plus delay (SOSPD) model from the data. Appropriate modelling methods for real processes are also considered by other authors [2, 3]. A broad conclusion from these and other papers is that even if the process has no physical delay, it is possible to model such a (possibly high order) process by a low order time delayed model; the delay estimated may be a combination of an actual delay and contributions due to high order dynamic terms in the process transfer function. It is also reasonable that either a FOLPD or SOSPD model should be estimated, as either of these approximate process models is sufficiently accurate for many applications. However, if *a priori* information on the process is available (such as the process order), the estimation of the full order time delayed model may be indicated.

Estimation methods for time delayed processes may be broadly classified into time domain and frequency domain techniques; these techniques may be either off-line or on-line, with on-line estimation requiring recursive estimation in a closed loop environment. Time domain estimation methods will be treated first. A number of off-line estimation techniques are documented, for single input, single output (SISO) and multi-input, multi-output (MIMO) model structures, in open loop and closed loop. A discussion of multiple model estimation techniques will then be carried out. A number of on-line estimation techniques will subsequently be treated, followed by a discussion of gradient methods for parameter estimation; the latter methods may be implemented in either open loop or closed loop, and in either an off-line or on-line manner. Frequency domain estimation techniques may be classified in a similar manner to time domain estimation methods. The use of the frequency domain, as a means of estimating the time delayed model parameters, has a certain intuitive appeal, since the delay contributes to just the phase term of the frequency response. Other possibilities for estimation are subsequently detailed. In each section, conclusions as to the applicability of various classes of methods will be drawn, as appropriate. General conclusions from the literature review will subsequently be drawn. For space reasons, not all relevant references can be included in the paper; such references will be available from the author at the conference.

2. Time domain methods for parameter and delay estimation

2.1 Off-line estimation methods

2.1.1 Experimental open loop methods

One of the first such methods was described by Ziegler and Nichols [4], in which the time constant and time delay of a FOLPD model are obtained by constructing a tangent to the experimental open loop step response at its point of inflection. The tangent intersection with the time axis at the step origin provides a time delay estimate; the time constant is estimated by calculating the tangent intersection with the steady state output value divided by the model gain. Similar tangent methods may also be used to determine SOSPD model parameters [5-7]. The major disadvantage of all these methods is the difficulty of determining the point of inflection in practice.

Some methods that eliminate this disadvantage use two or more points on the process step response to estimate FOLPD model parameters [8, 9] or use two, three or more points on the process step or pulse response to estimate SOSPD model parameters [10-14]. An alternative experimental method involves calculating appropriate model parameters from the area under the step response output curve [15-17]. Other methods are also of interest [18].

Experimental open loop tests have the advantage of simplicity. However, the parameters identified may vary with process operating conditions and the step change size and direction. In addition, the process must be sufficiently disturbed by the change, to obtain reasonably accurate dynamic information, with the possibility that the process may be forced outside the region of linear behaviour. There is also a reluctance among plant management to permit such disturbances to be introduced for parameter estimation purposes. The process time scale must also be known in advance in order to determine when the transient response has been completed.

2.1.2 Experimental closed loop methods

These methods typically involve the analytical calculation of the model parameters from unity feedback, proportionally controlled, closed loop experimental step response output measurements. The delay is often approximated by a rational polynomial in the continuous time domain [19-23], though this is not absolutely necessary [24]. Other authors calculate the ultimate gain and frequency of a unity feedback, proportionally controlled, closed loop system from the experimental step response, and subsequently determine the time delayed model parameters [25-28]. A combination of the methods may also be used to determine the best time delayed model [29]. Identification strategies in a unity feedback, PI, PID or dead-time compensated, closed loop system may also be used [3, 29-34].

Refinements to the published algorithms are possible; however, the robustness of many of the estimation methods to noise on the process response is questionable. This comment does not apply to the characteristic areas method [15], in which the area under the closed loop step response output curve is used to calculate the model parameters.

2.1.3 Multiple model estimation methods

These methods are based on estimating a number of different process models, for different delay and (often) model order values. The model parameters chosen minimise a cost function that depends on the difference between the process and model outputs. The model order, parameters and delay index (which is the integer value of the delay divided by the sample time) may be estimated [35-38]. Some authors concentrate on estimating the delay and process parameters only [39-46].

The attraction of multiple model estimation methods is that the grid searching used will facilitate the estimation of parameters corresponding to the global minimum of the cost function, even in the presence of local minima, provided enough models are estimated. However, the methods are computationally intensive.

2.2 On-line estimation methods

The delay may be approximated by a rational polynomial in the continuous time domain and the resulting model parameters estimated recursively, from which the delay may be deduced [44, 47, 48].

Alternatively, the method of overparameterisation may be used, which involves subsuming the delay term into an extended z domain numerator polynomial. The parameters are estimated recursively, and the delay is calculated based on the numerator parameters identified; for a noise free system, all numerator parameters whose indices are smaller than the delay index should be identified as zero. Only delay values that are integer multiples of the sample period are directly estimated by the method. The delay portion that is a fraction of the sample period may be calculated from the numerator parameters identified [49]; however, the robustness of the calculation method in the presence of noise is questionable. An overparameterisation method example is described by Kurz and Goedecke [50], who define a robust method for estimating the SISO model parameters that is equivalent to determining the best match between the impulse response of the overparameterised model and the impulse response of a non-overparameterised model with a pure delay; however, the method is computationally intensive. Other methods offer various trade-offs between robustness and computational load [44, 51-55]; the most promising method is defined by Teng and Sirisena [54], because of its relative computational simplicity. A recursive method to estimate the parameters, order and delay index for both a stochastic and deterministic system, using an overparameterised method to estimate the delay, is also described [56]. Some authors identify time delayed MIMO process models using the method of overparameterisation [57, 58].

The method of overparameterisation is a natural extension of methods used in delay-free identification applications. However, the computational burden of the identification algorithm increases with the square of the number of estimated parameters, the persistent excitation condition is more difficult to satisfy for overparameterised models and the high order numerator polynomial increases the likelihood of common factors in the numerator and denominator polynomials in the estimation model, rendering identification more difficult. A high-order correlation approach is an alternative to the overparameterisation method [59].

2.3 Gradient methods of parameter and delay estimation

Gradient methods of parameter estimation are based on updating the parameter vector (which includes the delay) by a vector that depends on information about the cost function to be minimised. The gradient algorithms normally involve expanding the cost function as a second order Taylor's expansion around the estimated parameter vector. Typical gradient algorithms are the Newton-Raphson, the Gauss-Newton and the steepest descent algorithms, which differ in their updating vectors. The choice of gradient algorithm for an application depends on the desired speed of tracking and the computational resources available. It is important that the error surface in the direction of the delay (and indeed the other parameters) should be unimodal if a gradient algorithm is to be used successfully. However, the error surface is often non-unimodal. In these circumstances, strategies for locating global minima may involve multiple optimisation runs, each initiated at a different starting point with the starting points selected by sampling from a uniform distribution. The global minimum is then the local minimum with the lowest cost function value among all the local minima identified.

Gradient algorithms based on the Newton-Raphson method have been defined; Liu [60], for example, describes a parameter updating scheme for a general order time delayed model based on the algorithm. The Gauss-Newton algorithm has been used to estimate FOLPD model parameters, in a Smith predictor structure [61]. A number of modifications of the approach have also been considered [62, 63]. The Gauss-Newton algorithm has also been used in an open loop application [64, 65] to estimate FOLPD model parameters. Other such approaches are also described [66]. The straightforward nature of the steepest descent algorithm has motivated its application to the estimation of process parameters; Elnagger *et al*. [67], for example, estimate the delay using the algorithm and estimate the non-delay parameters recursively. Other gradient algorithms have also been used for parameter estimation [68-71]; Gawthrop *et al*. [68], for example, update the delay based on the partial derivative of the error squared with respect to the delay. The most popular gradient algorithm is the Gauss-Newton algorithm, as it combines good tracking speed and moderate computational intensity.

3. Frequency domain methods for parameter and delay estimation

Typically, the process frequency response must be estimated before model parameters are estimated. Methods for estimating the process frequency response include correlation analysis, spectral analysis and methods based on the ratio of Fourier transforms [63].

The process frequency response may be used to *graphically* estimate FOLPD and SOSPD model parameters [72, 73] and the parameters of higher order delayed models [74]. The disadvantages of the method are the tediousness of the procedure and the introduction of errors in fitting model parameters using a trial and error approach; in addition, the identification of more general transfer function models is difficult using the method. The process frequency response may also be used to *analytically* estimate FOLPD and SOSPD model parameters [5, 75, 76] and the parameters of higher order delayed models [76, 77].

Alternatively, the model parameters may be estimated by minimising the squared error between the process and model frequency responses. For an arbitrary order time delayed model, many of the techniques available require a continuous time delay approximation, using an appropriate rational polynomial; the delay itself is not identified [78]. However, Dos Santos and De Carvalho [79] explicitly estimate the parameters of a general order time delayed model by determining the model order and the pole and zero value estimates iteratively from the delay, with the delay estimate calculated based on a least squares procedure from the phase plot. An alternative multiple model estimation method involves selecting the delay iteratively and determining the remaining model parameters in a least squares sense [73]. Other least squares methods have also been proposed [76, 80]. It is also possible to fit a low order delayed model to the process response, in a least squares sense [73, 81-85].

The time delayed model parameters may also be determined from the identification of one or more points on the process frequency response obtained when a relay is switched into the closed loop compensated system [17, 55, 86-104]. Indeed, further work in this area is possible, as it is more common to use such relay techniques for PI/PID autotuning rather than for model parameter estimation.

4. Other methods of process parameter and delay estimation

The identification of time delayed processes using neural networks is a subject of recent research. Bhat and McAvoy [105], for instance, propose a method to strip a back propagation neural network to its essential weights and nodes; the stripping algorithm is capable of identifying the delay and order of a FOLPD process (in the discrete time domain). More recent contributions have also been made [106, 107].

Process order estimation strategies may also be used to estimate the process delay (in the discrete time domain), since the delay appears as an increase in the numerator transfer function model order. Delay estimation using these strategies would depend on *a priori* knowledge of the order of the non-delay part of the process.

It is also possible to estimate the time delayed process parameters using the delta operator rather than the z (or shift) operator. Keviczky and Banyasz [108], in an analogue of a method defined by these authors in the z domain [53], identify the delay index using overparameterisation in the delta domain. There is further scope to estimate the delay and other model parameters in the delta domain, using techniques similar to those used in the z domain.

Finally, the use of genetic algorithms for process identification is beginning to attract interest. Genetic algorithms search from a population of points, use information about the cost function (rather than its derivative or other auxiliary knowledge used by gradient algorithms) and have a random component, quantified as a mutation rate, that helps drive the model parameters towards values corresponding to the global minimum of a possibly non-unimodal cost function; such cost functions often arise in the identification of delayed processes. Genetic algorithms are considered to be one extreme solution to the exploitation-exploration trade-off; the algorithms trade-off large computation time, and poor accuracy of the global minimum, with reliability in calculating the global minimum. Yang *et al.* [109], for example, use a genetic algorithm to estimate the denominator parameters and delay of a reduced order process model, while using the less computationally intensive least squares algorithm to subsequently determine the numerator model parameters (which is a linear problem).

5. Conclusions

This paper has considered a wide variety of methods for time delayed model parameter estimation, in both the continuous time and discrete time domains. It is clear that gradient techniques, both in the frequency and time domains, have the potential to rapidly estimate the model parameters [63]. The use of other methods, such as multiple model estimation methods or genetic algorithms, in combination with gradient methods, may be one way of determining the global minimum of the cost function with more certainty.

It remains true to declare that the choice of identification method (and indeed compensation method) for a process with delay depends on the application. There is still a lot of interest in the identification of FOLPD and/or SOSPD process models, using, for example, experimental closed loop methods or by analysing the process output when a relay is switched into the closed loop compensated system in place of the controller. This is due to the low computational intensity involved in identifying such models, to concerns about how complex a model may reasonably be identified from experimental data and to the subsequent use of PI or PID controllers for compensation purposes. There is scope to apply some of the identification methods in question to the estimation of the parameters of delayed MIMO process models.

The identification of higher order time delayed models is still conditioned on *a priori* information on the process; few applications exist in which the parameters of such higher order models are identified in a black box manner from process input and output data. In addition, few unified approaches to the estimation problem have emerged.

6. References

1 NEWELL, R.B. and LEE, P.L.: ‘Applied process control - a case study’ (Prentice-Hall, 1989).

2 BIALKOWSKI, W.L.: ‘Control of the pulp and paper making process’, *The Control Handbook*, Editor: W.S. Levine, CRC/IEEE Press, 1996, pp. 1219-1242.

3 TOH, K.-A. and DEVANATHAN, R.: ‘Pattern-based identification for process control applications’, *IEEE Transactions on Control Systems Technology*, 1996, **4**, pp. 641-648.

4 ZIEGLER, J.G. and NICHOLS, N.B.: ‘Optimum settings for automatic controllers’, *Transactions of the ASME*, 1942, **64**, pp. 759-768.

5 SUNDARESAN, K.R., PRASAD, C. C. and KRISHNASWAMY, P.R.: ‘Evaluating parameters from process transients’, *Industrial and Engineering Chemistry Process Design and Development*, 1978, **17**, pp. 237-241.

6 HUANG, C.-T. and CLEMENTS, W.C.: ‘Parameter estimation for the second-order-plus-deadtime-model’, *Industrial Engineering Chemistry Process Design and Development*, 1982, **21**, pp. 601-603.

7 ASTROM, K.J. and HAGGLUND, T.: ‘PID Controllers: Theory, Design and Tuning’ (Second Edition, Instrument Society of America, 1995).

8 SUNDARESAN, K.R. and KRISHNASWAMY, P.R.: ‘Estimation of time delay, time constant parameters in time, frequency and Laplace domains’, *The Canadian Journal of Chemical Engineering*, 1978, **56**, pp. 257-262.

9 BI, Q., CAI, W.-J., LEE, E.-L., WANG, Q.-G., HANG, C.-C. and ZHANG, Y.: ‘Robust identification of first-order plus dead-time model from step response’, *Control Engineering Practice*, 1999, **7**, 1, pp. 71-77.

10 HUANG, C.-T. and HUANG, M.-F.: ‘Estimation of the second order parameters from the process transient by simple calculation’, *Industrial and Engineering Chemistry Research*, 1993, **32**, pp. 228-230.

11 HUANG, C.-T. and CHOU, C.-J.: ‘Estimation of the underdamped second-order parameters from the system transient’, *Industrial and Engineering Chemistry Research*, 1994, **33**, pp. 174-176.

12 RANGAIAH, G.P. and KRISHNASWAMY, P.R.: ‘Estimating second-order dead time parameters from underdamped process transients’, *Chemical Engineering Science*, 1996, **51**, pp. 1149-1155.

13 JAHANMIRI, A. and FALLAHI, H.R.: ‘New methods for process identification and design of feedback controller’, *Transactions of the Institute of Chemical Engineers*, 1997, **75**, A, July, pp. 519-522.

14 HAM, T.W. and KIM, Y.H.: ‘Process identification using pulse response and proportional-integral-derivative controller tuning with combined guidelines’, *Industrial Engineering Chemistry Research*, 1998, **37**, pp. 482-488.

15 NISHIKAWA, Y., SANNOMIYA, N., OHTA, T. and TANAKA, H.: ‘A method for auto-tuning of PID control parameters’, *Automatica*, 1984, **20**, pp. 321-332.

16 ABDELZAHAR, T.F.A. and SHEIRAH, M.A.: ‘Identification algorithm for multicapacity systems with dead time’, Proceedings of the *2nd IASTED Conference on Computer Applications in Industry*, 1992, **1**, pp. 376-379.

17 ASTROM, K.J., HAGGLUND, T., HANG, C.C. and HO, W.K.: ‘Automatic tuning and adaptation for PID controllers - a survey’, *Control Engineering Practice*, 1993, **1**, pp. 699-714.

18 CHUNG, K.J., KWAK, H.J., SUNG, S.W., LEE, I.-B. and PARK, J.Y.: ‘A direct estimation method of second order plus time delay model parameters for PID controller autotuning’, *Journal of Chemical Engineering of Japan*, 1999, **32**, 3, pp. 288-294.

19 YUWANA, M. and SEBORG, D.E.: ‘A new method for on line controller tuning’, *AIChE Journal*, 1982, **28**, pp. 434-440.

20 JUTAN, A. and RODRIGUEZ, E.S.: ‘Extension of a new method for on-line controller tuning’, *The Canadian Journal of Chemical Engineering*, 1984, **62**, pp. 802-807.

21 LEE, J.: ‘On-line PID controller tuning from a single, closed-loop test’, *AIChE Journal*, 1989, **35**, pp. 329-331.

22 PARK, H.I., SUNG, S.W., LEE, I.-B. and LEE, J.: ‘A simple autotuning method using proportional controller’, *Chemical Engineering Communications*, 1997, **161**, pp. 163-184.

23 SUNG, S.W., LEE, I.-B. and LEE, B.-K.: 'On-line process identification and automatic tuning method for PID controllers', *Chemical Engineering Science*, 1998, **53**, 10, pp. 1847-1859.

24 SUNG, S.J., PARK, H.J., LEE, I.-B. and YANG, D.R.: 'On-line process identification and autotuning using P-controller', *Proceedings of the Asian Control Conference*, Tokyo, Japan, 1994, pp. 411-414.

25 CHEN, C.-L.: 'A simple method for on-line identification and controller tuning', *AIChE Journal*, 1989, **35**, pp. 2037-2039.

26 LEE, J., CHO, W. and EDGAR, T.F.: 'An improved technique for PID controller tuning from closed loop tests', *AIChE Journal*, 1990, **36**, pp. 1891-1895.

27 TAIWO, O.: 'Comparison of four methods of on-line identification and controller tuning', *IEE Proceedings, Part D*, 1993, **140**, pp. 323-327.

28 KRISHNASWAMY, P.R. and RANGAIAH, G.P.: 'Closed-loop identification of second order dead time process models', *Transactions of the Institute of Chemical Engineers*, 1996, **74**, pp. 30-34.

29 HWANG, S.-H. and TSENG, T.-S.: 'Process identification and control based on dominant pole expansions', *Chemical Engineering Science*, 1994, **49**, pp. 1973-1983.

30 ITAKURA, H.: 'Parameter identification in a process-model control system', *IEEE Transactions on Automatic Control*, 1986, **AC-31**, 12, pp. 1173-1175.

31 HWANG, S.-H.: 'Closed-loop automatic tuning of single-input-single-output systems', *Industrial Engineering Chemistry Research*, 1995, **34**, pp. 2406-2417.

32 MAMAT, R. and FLEMING, P.J.: 'Method for on-line identification of a first order plus dead-time process model', *Electronics Letters*, 1995, **31**, 15, pp. 1297-1298.

33 ROTACH, V. Ya.: 'Automatic tuning of PID-controllers – expert and formal methods', *Thermal Engineering*, 1995, **42**, 10, 794-800.

34 SUGANDA, P., KRISHNASWAMY, P.R. and RANGAIAH, G.P.: 'On-line closed loop identification from closed loop tests under PI control', *Transactions of the Institute of Chemical Engineers*, 1998, **76**, Part A, pp. 451-457.

35 GABAY, E. and MERHAV, S.J.: 'Identification of linear systems with time-delay operating in a closed loop in the presence of noise', *IEEE Transactions on Automatic Control*, 1976, **AC-21**, pp. 711-716.

36 TURKEY, A.A.: 'An automatic algorithm using ESS modeling for parameters and structure estimation', *Control and Computers*, 1993, **21**, 3, pp. 69-76.

37 HANG, C.C., LEE, T.H. and HO, W.K.: 'Adaptive Control' (Instrument Society of America, 1993).

38 TUCH, J., FEUER, A. and PALMOR, Z.J.: 'Time delay estimation in continuous linear time invariant systems', *IEEE Transactions on Automatic Control*, 1994, **39**, pp. 823-827.

39 AGARWAL, M. and CANUDAS, C.: 'On line estimation of time delay and continuous-time process parameters', *International Journal of Control*, 1987, **46**, pp. 295-311.

40 UNBEHAUEN, H. and RAO, G.P.: 'Identification of continuous systems' (Volume 10, North Holland System and Control Series, Elsevier Science Publishers B.V., 1987).

41 ZHENG, W.-X. and FENG, C.-B.: 'Optimising search-based identification of stochastic time-delay systems', *International Journal of Systems Science*, 1991, **22**, 5, pp. 783-792.

42 CHEN, R. and LOPARO, K.A.: 'Identification of time delays in linear stochastic systems', *International Journal of Control*, 1993**, 57**, pp. 1273-1291.

43 LEVA, A., MAFFEZZONI, C. and SCATTOLINI, R.: 'Self-tuning PI-PID regulators for stable systems with varying delay', *Automatica*, 1994, **30**, pp. 1171-1183.

44 FERRETTI, G., MAFFEZZONI, C. and SCATTOLINI, R.: 'The recursive estimation of time delay in sampled-data control systems', *Control and Dynamic Systems. Advances in Theory and Applications*, C.T. Leondes (Ed.), 1995, Vol. 73, pp. 159-206, Academic Press Inc.

45 HALEVI, Y.: 'Reduced order models with delay', *International Journal of Control*, 1996, **64**, pp. 733-744.

46 SCHIER, J.: 'Estimation of transport delay using parallel recursive modified Gram-Schmidt algorithm', *International Journal of Adaptive Control and Signal Processing*, 1997, **11**, pp. 431-442.

47 ROY, S., MALIK, O.P. and HOPE, G.S.: 'Adaptive control of plants using all-zero model for dead-time identification', *IEE Proceedings Part D*, 1991, **138**, pp. 445-452.

48 RAD, A.B.: 'Self-tuning control of systems with unknown time delay: a continuous-time approach', *Control - Theory and Advanced Technology*, 1994, **10**, pp. 479-497.

49 THOMSON, M., CASSIDY, P.G. and SANDOZ, D.J.: 'Automatic tuning of PID controllers using a combined time- and frequency-domain method', *Transactions of the Institute of Measurement and Control*, 1989, **11**, pp. 40-47.

50 KURZ, H. and GOEDECKE, W.: 'Digital parameter-adaptive control of processes with unknown dead time', *Automatica*, 1981, **17**, pp. 245-252.

51 WONG, K.Y. and BAYOUMI, M.M.: 'A self-tuning control algorithm for systems with unknown time delay', Proceedings of the *IFAC Identification and System Parameter Estimation Conference*, Washington, D.C., U.S.A., 1982, pp. 1193-1198.

52 DE KEYSER, R.M.C.: 'Adaptive dead-time estimation', Proceedings of the *IFAC Adaptive Systems in Control and Signal Processing Conference*, Lund, Sweden, 1986, pp. 385-389.

53 KEVICZKY, L. and BANYASZ, CS.: 'A completely adaptive PID regulator', Proceedings of the IFAC *Identification and System Parameter Estimation Conference*, Beijing, China, 1988, pp. 89-95.

54 TENG, F.-C. and SIRISENA, H.R.: 'Self-tuning PID controllers for dead time processes', *IEEE Transactions on Industrial Electronics*, 1988, **35**, pp. 119-125.

55 LUNDH, M. and ASTROM, K.J.: 'Automatic initialisation of a robust self-tuning controller', *Automatica*, 1994, **30**, pp. 1649-1662.

56 CHEN, H.-F. and ZHANG, J.-F.: 'Identification and adaptive control for systems with unknown orders, delay and coefficients', *IEEE Transactions on Automatic Control*, 1990, **35**, pp. 866-877.

57 GURUBASAVARAJ, K.H. and BROGAN, W.L.: 'Identification of time delay in multiple input, multiple output discrete systems', Proceedings of the *American Control Conference*, 1983, pp. 1253-1254.

58 ZHANG, J.-F. and CHEN, H.-F.: 'Identification of coefficients, orders and time-delay for ARMAX systems', Proceedings of the *11th IFAC World Congress on Automatic Control*, Tallinn, Estonia, 1990, Vol. 3, pp. 129-134.

59 CHEN, J.-M. and CHEN, B.-S.: 'Identification of linear systems with unknown time delay and input-output noisy data: high-order correlation approach', *Control – Theory and Advanced Technology*, 1994, **10**, 3, 317-346.

60 LIU, G.: 'Adaptive predictor control for slowly time-varying systems with variable time delay', *Advances in Modelling and Simulation*, 1990, **20**, pp. 9-21.

61 MARSHALL, J.E.: 'Control of time-delay systems' (IEE Control Engineering Series 10. Peter Peregrinus Ltd., 1979).

62 ROMAGNOLI, J.A., KARIM, M.N., AGAMENNONI, O.E. and DESAGES, A.: 'Controller designs for model-plant parameter mismatch', *IEE Proceedings, Part D*, 1988, **135**, pp. 157-164.

63 O'DWYER, A.: 'The estimation and compensation of processes with time delays', *Ph.D. thesis*, 1996, Dublin City University, Dublin 9, Ireland.

64 DURBIN, L.D.: 'Deadtime approximations with adaptive deadtime compensation', Proceedings of the *American Control Conference*, 1985, Vol. 3, pp. 1707-1712.

65 O'DWYER, A.: 'Open loop time domain gradient methods for parameter and delay estimation', *Modern Applied Mathematical Techniques in Circuits, Systems and Control*, World Scientific and Engineering Society Press, ISBN: 960-8052-05-X, 1999, pp. 229-236.

66 BANYASZ, CS. and KEVICZKY, L.: 'Recursive time delay estimation method', *International Journal of System Science*, 1994, **25**, pp. 1857-1865.

67 ELNAGGER, A., DUMONT, G.A. and ELSHAFEI, A.-L.: 'System identification and adaptive control based on a variable regression for systems having unknown delay', Proceedings of the *29th IEEE Conference on Decision and Control*, Honolulu, Hawaii, U.S.A., 1990, Vol. 3, pp. 1445-1450.

68 GAWTHROP, P.J., NIHTILA, M. and RAD, A.B.: 'Recursive parameter estimation of continuous-time systems with unknown time delay', *Control - Theory and Advanced Technology*, 1989, **5**, pp. 227-248.

69 PUPEIKIS, R.: 'Recursive estimation of the parameters of linear systems with time delay', Proceedings of the *IFAC Identification and System Parameter Estimation Conference*, York, U.K., 1985, pp. 787-792

70 NIHTILA, M., DAMAK, T. and BABARY, J.P.: 'On-line estimation of the time delay via orthogonal collocation', *Simulation Practice and Theory*, 1997, **5**, pp. 101-120.

71 BOER, E.R. and KENYON, R.V.: 'Estimation of time-varying delay time in nonstationary linear systems: an approach to monitor human operator adaptation in manual tracking tasks', *IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans*, 1998, **28**, pp. 89-99.

72 DESHPANDE, P.B. and ASH, R.H.: 'Elements of Computer Process Control with Advanced Control Applications' (Instrument Society of America, Prentice-Hall Inc., 1983).

73 SEBORG, D.E., EDGAR, T.F. and MELLICHAMP, D.A.: 'Process dynamics and control' (John Wiley and Sons, 1989).

74 LUYBEN, W.L.: 'Process modeling, simulation and control for chemical engineers' (McGraw-Hill, New York, 1983).

75 KOGANEZAWA, K.: 'On-line parameter identification of non-stationary continuous system with time-variant delay', Proceedings of the *1991 International Conference on Industrial Electronics*, Kobe, Japan , 1991, Vol. 3, pp. 1990-1993.

76 O'DWYER, A.: 'Estimation of delayed process model parameters in the frequency domain', *Progress in Simulation, Modeling, Analysis and Synthesis of Modern Electrical and Electronic Devices and Systems*, World Scientific and Engineering Society Press, ISBN: 960-8052-08-4, 1999, pp. 318-324.

77 ISERMANN, R., BAUR, U., BAMBERGER, W., KNEPPO, P. and SEIBERT, H.: 'Comparison of six on line identification and parameter estimation methods', *Automatica*, 1974, **10**, pp. 81-103.

78 LEVY, E.C.: 'Complex curve fitting', *IRE Transactions on Automatic Control*, 1959, **AC 4**, pp. 37-43.

79 DOS SANTOS, P.L. and DE CARVALHO, J.L.M.: 'Automatic transfer function synthesis from a Bode plot', Proceedings of the *29th Conference on Decision and Control*, Honolulu, Hawaii, U.S.A., 1990, pp. 1093-1098.

80 YOUNG, G.E., RAO, K.S.S and CHATUFALE, V.R.: 'Block-recursive identification of parameters and delay in the presence of noise', *Transactions of the ASME. Journal of Dynamic Systems, Measurement and Control*, 1995, **117**, pp. 600-607.

81 LILJA, M.: 'Least squares fitting to a rational transfer function with time delay', *IEE Control Conference*, 1988, pp. 143-146.

82 PALMOR, Z.J. and BLAU, M.: 'An auto-tuner for Smith dead time compensator', *International Journal of Control*, 1994**, 60**, pp. 117-135.

83 SUNG, S.W., LEE, I.-B. and LEE, J.: 'New process identification method for automatic design of PID controllers', *Automatica*, 1998, **34**, pp. 513-520.

84 PARK, J.H., PARK, H.I. and LEE, I.-B.: 'Closed-loop on-line process identification using a proportional controller', *Chemical Engineering Science*, 1998, **53**, pp. 1713-1724.

85 SUNG, S.W. and LEE, I.-B.: 'On-line process identification and PID controller autotuning', *Korean Journal of Chemical Engineering*, 1999, **16**, 1, 45-55.

86 LI, W., ESKINAT, E. and LUYBEN, W.L.: 'An improved autotune identification method', *Industrial and Engineering Chemistry Research*, 1991, **30**, pp. 1530-1541.

87 CHANG, R.-C., SHEN, S.-H. and YU, C.-C.: 'Derivation of transfer function from relay feedback system', *Industrial and Engineering Chemistry Research*, 1992, **31**, pp. 855-860.

88 LEE, J. and SUNG, S.W.: 'Comparison of two identification methods for PID controller tuning', *AIChE Journal*, 1993, **39**, pp. 695-697.

89 LEVA, A.: 'PID autotuning algorithm based on relay feedback', *IEE Proceedings, Part D*, 1993, **140**, pp. 328-338.

90 ASTROM, K.J., LEE, T.H., TAN, K.K. and JOHANSSON, K.H.: 'Recent advances in relay feedback methods - a survey', Proceedings of the *IEEE International Conference on Systems, Man and Cybernetics*, 1995, Vol. 3, pp. 2616-2621.

91 LEE, T.H., WANG, Q.G., TAN, K.K. and NUNGAM, S.: 'A knowledge based approach to dead-time estimation for process control', *International Journal of Control*, 1995, **61**, pp. 1045-1072.

92 HUANG, H.P., CHEN, C.-L., LAI, C.-W. and WANG, G.-B.: 'Autotuning for model-based PID controllers', *AIChE Journal*, 1996, **42**, pp. 2687-2691.

93 TAN, K.K., LEE, T.H. and WANG, Q.G.: 'Enhanced automatic tuning procedure for process control of PI/PID controller', *AIChE Journal*, 1996, **42**, pp. 2555-2562.

94 HO, W.K., FENG, E.B. and GAN, O.P.: 'A novel relay auto-tuning technique for processes with integration', *Control Engineering Practice*, 1996, **4**, 7, 923-928.

95 WANG, Q.-G., HANG, C.-C. and BI, Q.: 'Process frequency response estimation from relay feedback', *Control Engineering Practice*, 1997, **5**, 1293-1302.

96 LUO, R., QIN, S.J. and CHEN, D.: 'A new approach to closed-loop autotuning for proportional-integral-derivative controllers', *Industrial Engineering Chemistry Research*, 1998, **37**, pp. 2462-2468.

97 TAN, K.K, WANG, Q.-G., LEE, T.H. and GAN, C.H.: 'Automatic tuning of gain-scheduled control for asymmetrical processes', *Control Engineering Practice*, 1998, **6**, pp. 1353-1363.

98 TSANG, K.M., LO, W.L. and RAD, A.B.: 'Adaptive delay compensated PID controller by phase margin design', *ISA Transactions*, 1998, **37**, 177-187.

99 KAYA, I. and ATHERTON, D.P.: 'An improved parameter estimation method using limit cycle data', Proceedings of the *UKACC International Conference on Control '98*, Swansea, Wales, 1998, **1**, pp. 682-687.

100 WANG, Q.-G., LEE, T.-H., FUNG, H.-W., BI, Q. and ZHANG, Y.: 'PID tuning for improved performance', *IEEE Transactions on Control Systems Technology*, 1999, **7**, 4, pp. 457-465.

101 WANG, Q.-G., HANG, C.-C. and BI, Q.: 'A technique for frequency response identification from relay feedback', *IEEE Transactions on Control Systems Technology*, 1999, **7**, 1, pp. 122-128.

102 SCALI, C., MARCHETTI, G. and SEMINO, D.: 'Relay with additional delay for identification and autotuning of completely unknown processes', *Industrial Engineering Chemistry Research*, 1999, **38**, 5, pp. 1987-1997.

103 WANG, Q.-G., HANG, C.-C., ZHU, S.-A. and BI, Q.: 'Implementation and testing of an advanced relay auto-tuner', *Journal of Process Control*, 1999, **9**, 4, 291-300.

104 WANG, L., DESARMO, M.L. and CLUETT, W.R.: 'Real-time estimation of process frequency response and step response from relay feedback experiments', *Automatica*, 1999, **35**, pp. 1427-1436.

105 BHAT, N.V. and McAVOY, T.J.: 'Determining model structures for neural models by network stripping', *Computers and Chemical Engineering*, 1992, **16**, pp. 271-281.

106 LEVA, A. and PIRODDI, L.: 'Model-specific autotuning of classical regulators; a neural approach to structural identification', *Control Engineering Practice*, 1996, **4**, pp. 1381-1391.

107 BALESTRINO, A., VERONA, F.B. and LANDI, A.: 'On-line process estimation by ANNs and Smith controller design', *IEE Proceedings - Control Theory and Applications*, 1998, **145**, pp. 231-235.

108 KEVICZKY, L. and BANYASZ, CS.: 'An adaptive PID regulator based on time delay estimation', Proceedings of the *31st conference on Decision and Control*, Tucson, Arizona, U.S.A., 1992, pp. 3243-3248.

109 YANG, Z.-J., HACHINO, T. and TSUJI, T.: 'On-line identification of continuous time-delay systems combining least-squares techniques with a genetic algorithm', *International Journal of Control*, 1997, **66**, pp. 23-42.