Modern Applied Mathematical Techniques in Circuits, Systems and Control, World Scientific and Engineering Society Press, ISBN: 960-8052-05-X, July 1999, pp. 187-198.

A classification of techniques for the compensation of time delayed processes. Part 2. Structurally optimised controllers.

AIDAN O'DWYER,
School of Control Systems and Electrical Engineering,
Dublin Institute of Technology,
Kevin St., Dublin 8,
IRELAND.
E-mail: aidan.odwyer@dit.ie
Web address: http://www.dit.ie/eng/csee/aodwyer.html

JOHN RINGWOOD,
School of Electronic Engineering,
Dublin City University, Dublin 9,
IRELAND.
E-mail: ringwoodj@eeng.dcu.ie
Web address: http://www.eeng.dcu.ie/~csg/index.html

Abstract:- Following on from Part 1, Part 2 of the paper considers the use of structurally optimised controllers to compensate time delayed processes.

Keywords:- Time delay, compensation, PID, dead-time compensators.

1 Introduction

Structurally optimised controllers are those in which the controller structure and parameters are adapted optimally to the structure and parameters of the process model [1, 2]. A classification of such controllers for time delay processes is provided.

2 The Smith predictor

The Smith predictor [280] involves effectively removing the delay from the control loop; a 'primary' controller may then be designed for the delay free portion of the process. The applicability of the Smith predictor, especially compared to the PI/PID controller, has been discussed [20, 281-288]; Seborg *et al.* [20], for instance, quote studies stating that the Smith predictor performance for servo applications is up to 30% better than the use of a PID controller, tuned by minimising an integral squared error (ISE) criterion.

The Smith predictor is the optimal controller for a delayed process for servo applications, or for a step disturbance, if the optimal controller is designed using a constrained minimum output variance control law. If the disturbance is not of step form, then the optimal controller may be specified for regulator applications by the inclusion of an appropriate dynamic element in the feedback path of the Smith predictor structure [289-299]. The Smith predictor may also be related to other delay compensator strategies [14, 182, 300-304].

The Smith predictor has been investigated in many simulation and implementation studies [133, 305-309]; Singh and McEwan [305], for instance, consider the implementation of the predictor, realised in continuous time, in a laboratory case study. A modification of the Smith predictor, labelled the predictive PI controller by Hagglund [310], has also been discussed [16, 59, 310-317]. Other contributions are also of interest [318-322].

In real applications, it is inevitable that the model will not be a perfect representation of the process, perhaps because the process and model are of different structure or because the process parameters change in an unknown way with operating conditions. The presence of such mismatch means that perfect delay compensation using the Smith predictor is not possible. In these circumstances, the model parameters in the Smith predictor could be adaptively updated as the process parameters vary [288, 323-334]. The difficulty with many adaptive approaches is that the closed loop system may be unstable as a result of the mismatch, before the model parameters are updated to the process parameters. Therefore, a fundamental requirement is that the Smith predictor should be stable in the presence of mismatch; the performance of the resulting compensated system is also of interest. The conditions for stability in the presence of mismatch may be calculated using numerical techniques in both the time and frequency domains, though knowledge of the process parameters is required. An alternative is to specify robust stability and performance requirements for the Smith predictor implementation in the presence of mismatch [13, 136, 182, 288, 297, 335-345]; the internal model control (IMC) strategy is sometimes used in the analysis. Laughlin *et al.* [337], for instance, define a single multiplicative perturbation to represent the uncertainty in several process parameters; the authors subsequently derive analytical conditions for robust stability and robust performance of the Smith predictor. The IMC procedure is used to formulate the primary controller. Other applications of the IMC strategy have also been recorded [20, 346-349]. Interestingly, some authors consider creating a deliberate mismatch between the process and model parameters to improve stability or performance [350-354].

The Smith predictor is designed with servo applications in mind. Modifications of the Smith predictor have been discussed to improve the regulator properties of the compensated system and/or the performance of the compensated system in the presence of measurement noise and process parameter variations [11, 68, 136, 288, 295, 313, 324, 355-375]; Watanabe and Ito [295], for example, modify the Smith predictor by including a lead-lag compensator in the feedback path of the major loop to improve the regulator properties of the compensated system.

Smith predictors are often implemented in discrete time, as it is more straightforward to implement a delay in this domain than in the continuous time domain (at least if the delay is an integer multiple of the sample period). Analytical procedures to investigate the robustness of the predictor, operating under process-model mismatch conditions in discrete time, have been developed [376, 377]. It is common to estimate the model parameters before designing the primary compensator; the delay may be estimated explicitly or the model may be overparameterised, without an explicit estimation of the delay [378-385]. Modifications of the Smith predictor have also been considered [302, 386-402]. A closely related structure is the analytical predictor [18, 20, 59, 80, 282, 360, 403, 404] and generalised analytical predictor [20, 360, 405, 406], which include a disturbance filter in the feedback path; these algorithms combine good regulation behaviour with delay compensation. The IMC methodology may also be implemented in the discrete time domain [20, 348, 407-411].

Generalised continuous time and discrete time Smith predictors have been proposed to control delayed MIMO processes [290, 294, 412-424]. The robustness of these predictors is also discussed [425-428]; Feng [428], for example, derives a sufficient condition for compensator stability. Compensation of delayed MIMO processes, using the IMC approach, is also described [125, 336, 429-431].

It is not possible to compensate unstable delayed processes with a Smith predictor, as the poles of the compensated closed loop system always contain those of the unstable process [432]. A modified Smith predictor for the control of an unstable delayed process with one unstable pole has been detailed [433]. Other such compensation strategies for unstable SISO delayed processes are also proposed [355, 434, 435].

3 Direct synthesis methods

Typically, in the continuous time application of direct synthesis methods, the desired closed loop transfer function must include a delay greater than the process delay. The resulting controller has a delay compensator structure [20]. Other direct synthesis methods are also proposed, for delayed SISO [238, 436-440] and delayed MIMO [441-443] applications.

Sampled data controllers may also be designed; Dahlin [444], for instance, derives a controller by assuming that the desired closed loop transfer function is the discrete equivalent of a continuous first order lag plus delay (FOLPD) model. The desired time constant may be adjusted to give more sluggish control if the process parameters are not known accurately. This approach and its variations have been discussed elsewhere [12, 20, 59, 205, 296, 297, 304, 407, 445-453]. A pole placement design approach may also be used, when the process is in delayed SISO or MIMO form [1, 2, 17, 42, 284, 454-465]; the compensator may be designed by including the delay in an overparameterised process model [12, 381, 466-472], though the order of the resulting polynomial increases as the delay increases, making the method unattractive for the design of compensators for processes with large delays [12]. Alternatively, the compensator for stable delay

Modern Applied Mathematical Techniques in Circuits, Systems and Control, World Scientific and Engineering Society Press, ISBN: 960-8052-05-X, July 1999, pp. 187-198.

processes [473-475] and unstable delay processes [473] may be designed by approximating the delay by a rational polynomial. State-space design approaches have also been considered [1, 476-478]. Other pole placement controllers to compensate delayed MIMO processes have been developed [479, 480]. Adaptive pole placement controllers have been discussed for the compensation of delayed SISO processes in continuous time [481] and particularly in discrete time [482-487]. The design of such a controller for a delayed MIMO process is also described [488].

An alternative direct synthesis method is the finite spectrum assignment approach, which involves designing a feedback law based on pole assignment in either the time or frequency domains. The method may be used to compensate stable delayed processes [432, 489-501] and unstable delayed processes [432, 491, 493, 501, 502].

The advantages of the direct synthesis controller are that it may be detuned to avoid excessive control action, it provides delay compensation and it facilitates the control of processes with variable delay [12].

4 Optimal controller design methods

The controller is synthesised to minimise a criterion such as the variance of the controlled variable (minimum variance strategy) or the expected value of the square of the controlled variable plus a multiple times the square of the control signal (the linear quadratic strategy). The compensation of delayed SISO processes [136, 293, 326, 503-512] and delayed MIMO processes [326] in continuous time has been discussed. It is more common to consider delay compensator designs in discrete time; input-output model design approaches to compensate delayed SISO processes [2, 12, 14, 42, 292, 299, 378, 456, 484, 513-529] and delayed MIMO processes [416, 530-541] have been discussed. Alternatively, a state-space design approach may be used to specify the delay compensator in the SISO environment [542-545] or MIMO environment [414, 546-548]. Other optimisation strategies, such as the time optimal controller design approach, are also of interest [326, 549-558].

The minimum variance controller may be interpreted as a Smith predictor with a PI or PID primary controller, when the process is in FOLPD form or second order system plus delay (SOSPD) form, respectively [559]; it may also be interpreted as a Dahlin direct synthesis controller for a general process model with delay [297, 452, 559]. Generally speaking, however, a minimum variance controller is not suitable for the control of delayed processes, because the delay is likely to be a non-integer multiple of the sample period, which may result in the process model being in non-minimum phase form. The resulting closed loop system may be destabilised, as the implementation of the compensator involves the inversion of the model numerator polynomial. Therefore, if stable compensation is to be achieved, the delay used in the minimum variance controller design must be larger than the actual process delay, which results in a non-optimal controller. In a similar manner, varying delays also cause problems for the design of a minimum variance controller [12, 456].

5 Predictive controllers

Predictive controllers calculate a future controller output sequence so that the predicted process output is close to the desired output. The controller is designed by minimising a cost function, with appropriate constraints. One such controller is the unified predictive controller [303]; the controller action involves calculating the future set point sequence at any sampling instant, predicting the controlled variable, minimising the cost function to provide the suggested control sequence, implementing the first element of the control sequence and then repeating the calculations. Good tutorial introductions exist to predictive control strategies, together with their industrial applications [560-562].

The generalised predictive control (GPC) algorithm is a special case of the unified predictive control algorithm and has attracted a lot of interest for the design of delay compensators [13, 42, 449, 451, 452, 484, 562-571]; Camacho and Bourdons [566], for instance, provide simple formulae to calculate the tuning parameters of the GPC controller, when the process is modelled in FOLPD form. Other predictive controller strategies have also been discussed [572-592].

6 Other compensation strategies

Feedforward-feedback control may be used to compensate a delayed SISO process; typically the feedforward element is specified after the feedback controller is designed [2, 19, 182, 311, 359, 384, 406, 509, 593-597]. A disadvantage of feedforward control is that accurate knowledge of the process is required, though this may be overcome by using an adaptive feedforward-feedback controller implementation, in which the model parameters are continuously updated [2]. Feedforward-feedback controllers may also be used to compensated delayed MIMO processes [535, 536, 591].

Other strategies compensate delayed processes in a robust manner; Chou *et al*. [598], for example, design a feedback controller to robustly stabilise an uncertain, saturating delay process. Other robust methods have also been described [599-611]. Other authors consider fuzzy logic techniques [612, 613], neural network methods [614-617], variable structure controllers [618, 619], sliding mode controllers [620-623] or expert system approaches [624].

7 Conclusions

PI/PID controllers are appropriate for the compensation of non-dominant delay processes, with structurally optimised controllers being appropriate for the compensation of dominant delay processes. Overall, the Smith predictor is the optimal (or a component of the optimal) controller for dominant delay processes. An alternative perspective is that the Smith predictor may be used to reduce the dominance of the delay term, and thus facilitate the conversion of the compensation problem to the control of a non-dominant delay process. However, model based delay controllers are, in general, less robust than PID controllers, and are particularly sensitive to variations in process gain and delay, which are the process parameters most likely to change [59]. The use of predictive controller strategies appear to be the compensation methods that are attracting increasing attention from the applications community; for instance, a review paper [560] reports hundreds of such applications in real installation examples. This is significant, in view of the well known and often well founded reluctance of applications engineers to implement controllers other than the PID controller.

References [280-624]:

[280] Smith, O.J.M., Closer control of loops with dead time, *Chemical Engineering Progress*, Vol. 53, 1957, pp. 217-219.

[281] Meyer, C., Seborg, D.E. and Wood, R.K., A comparison of the Smith predictor and conventional feedback control, *Chemical Engineering Science*, Vol. 31, 1976, pp. 775-778.

[282] Meyer, C., Seborg, D.E. and Wood, R.K., An experimental application of time delay compensation techniques to distillation column control, *Industrial and Engineering Chemistry Process Design and Development*, Vol. 17, No. 1, 1978, pp. 62-67.

[283] Hang, C.C., Tan, C.H. and Chan, W.P., A performance study of control systems with dead time, *IEEE Transactions on Industrial Electronics and Control Instrumentation*, Vol. IECI-27, No. 3, 1980, pp. 234-241.

[284] Astrom, K.J. and Zhou, Z.-Y., *Self-tuners with automatic adjustment of the sampling period for processes with time delays*, Report for Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, 1981.

[285] Horowitz, I., Some properties of delayed control (Smith regulator), *International Journal of Control*, Vol. 38, 1983, pp. 977-990.

[286] Hill, A.G. and Kanpittaya, S., Optimum tuning of the Smith dead time controller, Proceedings of the *ISA/89 International Conference and Exhibition. Advances in Instrumentation and Control*, Philadelphia, Pa., U.S.A., Vol. 44(1), 1989, pp. 35-49.

[287] Waggoner, R.C. and Witt, S.D., Tuning parameters for the commercial dead time compensator, Proceedings of the *ISA/89 International Conference and Exhibition. Advances in Instrumentation and Control*, Philadelphia, Pa., U.S.A., Vol. 44(1), 1989, pp. 79-102.

[288] Palmor, Z.J. and Blau, M., An auto-tuner for Smith dead time compensator, *International Journal of Control*, Vol. 60, 1994, pp. 117-135.

[289] Kleinmann, D.L., Optimal control of linear systems with time-delay and observation noise, *IEEE Transactions on Automatic Control*, October, 1969, pp. 524-526.

[290] Donoghue, J.F., A comparison of the Smith predictor and optimal design approaches for systems with delay in the controls, *IEEE Transactions on Industrial Electronics and Control Instrumentation*, Vol. IECI-24, 1977, pp. 109-117.

[291] Cook, G. and Price, M.G., Comments on "A comparison of the Smith predictor and optimal design approaches for systems with delay in the control", *IEEE Transactions on Industrial Electronics and Control Instrumentation*, Vol. IECI-25, 1978, pp. 180-181.

[292] Palmor, Z.J. and Shinnar, R., Design of sampled data controllers, *Industrial Engineering Chemistry Process Design and Development*, Vol. 18, No. 1, 1979, pp. 8-30.

[293] Grimble, M.J., Solution of the stochastic optimal control problem in the s domain for systems with time delay, Proceedings of the *Institution of Electrical Engineers Control and Science*, Vol. 126, 1979, pp. 697-703.

[294] Hammerstrom, L.G. and Waller, K.V., On optimal control of systems with delay in the control, *IEEE Transactions on Industrial Electronics and Control Instrumentation*, Vol. IECI-27, 1980, pp. 301-309.

[295] Watanabe, K. and Ito, M., A process model control for linear systems with delays, *IEEE Transactions on Automatic Control*, Vol. AC-26, 1981, pp. 1261-1269.

[296] Harris, T.J., MacGregor, J.F. and Wright, J.D., An overview of discrete stochastic controllers: generalised PID algorithms with dead-time compensation, *The Canadian Journal of Chemical Engineering*, Vol. 60, 1982, pp. 425-432.

[297] Palmor, Z.J., Properties of optimal stochastic control systems with dead-time, *Automatica*, Vol. 18, 1982, pp. 107-116.

[298] Clark, D.W., *Self-tuning and adaptive control: theory and applications*, Edited by C.J. Harris and S.A. Billings, IEE Control Engineering Series 15, Peter Peregrinus Ltd, 1985.

[299] Durbin, L.D., Deadtime approximations with adaptive deadtime compensation, Proceedings of the *American Control Conference*, Vol. 3, 1985, pp. 1707-1712.

[300] Blevins, T.L., Modifying the Smith predictor for an applications software package, Proceedings of the *ISA Conference and Exhibition 1979. Advances in Instrumentation*, Chicago, IL., U.S.A., Vol. 34(2), 1979, pp. 121-129.

[301] Middleton, R.H. and Goodwin, G.C., *Digital control and estimation: a unified approach*, Prentice-Hall Inc., 1990.

[302] Landau, I.D., Robust digital control of systems with time delay (the Smith predictor revisited), *International Journal of Control*, Vol. 62, 1995, pp. 325-347.

[303] Soeterboek, R., *Predictive control - a unified approach*, Prentice-Hall Inc., 1992.

[304] Zhang, W.-D., Sun, Y.-X. and Xu, X.-M., Robust digital controller design for processes with dead times: new results, *IEE Proceedings - Control Theory and Applications*, Vol. 145, 1998, pp. 159-164.

[305] Singh, A. and McEwan, D.H., The control of a process having appreciable transport lag - a laboratory case study, *IEEE Transactions on Industrial Electronics and Control Instrumentation*, Vol. IECI-22, 1976, pp. 396-401.

[306] Parrish, J.R. and Brosilow, C.B., Inferential control applications, *Automatica*, Vol. 21, 1985, pp. 527-538.

[307] Papageorgiou, M. and Messner, A., Flow control of a long river stretch, *Automatica*, Vol. 25, 1989, pp. 177-183.

[308] Foss, B.A. and Wasbo, S.O., Benchmark IFAC 93: Adaptive predictive PI-control of an unknown plant, *Automatica*, Vol. 30, 1994, pp. 593-598.

[309] Lin, F.J., Liaw, C.M., Shieh, Y.S., Guey, R.J. and Hwang, M.S., Robust two-degrees-of-freedom control for induction motor servodrive, *IEE Proceedings - Electrical Power Applications*, Vol. 142, No. 2, 1995, pp. 79-86.

[310] Hagglund, T., A predictive PI controller for processes with long dead times, *IEEE Control Systems Magazine*, February, 1992, pp. 57-60.

[311] Shinskey, F.G., How good are our controllers in absolute performance and robustness?, *Measurement and Control*, Vol. 23, 1990, pp. 114-121.

[312] Shinskey, F.G., Putting controllers to the test, *Chemical Engineering*, December, 1990, 96-106.

[313] Matausek, M.R. and Micic, A.D., A modified Smith predictor for controlling a process with an integrator and long dead-time, *IEEE Transactions on Automatic Control*, Vol. 41, 1996, pp. 1199-1203.

[314] Normey-Rico, J.E., Bordons, C. and Camacho, E.F., Improving the robustness of dead-time compensating PI controllers, *Control Engineering Practice*, Vol. 5, 1997, pp. 801-810.

[315] Rad, A.B., Tsang, K.M. and Lo, W.L., Adaptive control of dominant time delay systems via polynomial identification, *IEE Proceedings - Control Theory and Applications*, Vol. 142, 1995, pp. 433-438.

[316] Lo, W.L. and Rad, A.B., Comparison of two auto-tuning predictive PI controllers, *International Journal of Modelling and Simulation*, Vol. 15, No. 3, 1995, pp. 98-106.

[317] Hagglund, T., An industrial dead-time compensating PI controller, *Control Engineering Practice*, Vol. 4, 1996, pp. 749-756.

[318] Kravaris, C. and Wright, R.A., Deadtime compensation for nonlinear processes, *AIChE Journal*, Vol. 35, No. 9, 1989, pp. 1535-1542.

[319] Al-Sunni, F. and Al-Nemer, T., A Smith predictor FL-based controller for processes with long dead time, *International Journal of Systems Science*, Vol. 28, 1997, pp. 1251-1258.

[320] Tan, Y. and De Keyser, R., Auto-tuning PID control using neural predictor to compensate large time-delay, Proceedings of the *Third IEEE Conference on Control Applications*, Glasgow, U.K., Vol. 2, 1994, pp. 1429-1434.

[321] Tian, Y.-C. and Gao, F., Double-controller scheme for separating load rejection from set-point tracking, *Transactions of the Institute of Chemical Engineers*, Vol. 76, Part A, 1998, pp. 445-450.

[322] Tian, Y.-C. and Gao, F., Double-controller scheme for control of processes with dominant delay, *IEE Proceedings - Control Theory and Applications*, Vol. 145, No. 5, 1998, pp. 479-484.

[323] Chiang, H.S. and Durbin, L.D., Variable gain deadtime compensation for the second order time lag case, Proceedings of the *ISA Conference and Exhibition. Advances in Instrumentation*, Houston, Texas, USA, Vol. 35(1), 1980, pp. 57-68.

[324] Marshall, J.E., *Control of time-delay systems*, IEE Control Engineering Series 10. Peter Peregrinus Ltd., 1979.

[325] Mee, D.K., Asbury, W.L., Kaiser, K.W. and Orejuela, M., Variable dead time compensation and calculation of salt-acid concentration ratio improved evaporator control, Proceedings of the *ISA/86 International Conference and Exhibition. Advances in Instrumentation*, Houston, Texas, U.S.A., Vol. 41(2), 1986, pp. 765-779.

[326] Malik-Zafarei, M. and Jamshidi, M., *Time delay systems - analysis, optimisation and applications*, North Holland Systems and Control Series Volume 9, Elsevier Science Publishers B.V., 1987.

[327] Kaya, A. and Scheib, T.J., A self-tuning method for Smith predictor and PID controls, Proceedings of the *ISA International Conference and Exhibition*, Houston, Texas, U.S.A., 1984, pp. 843-855.

[328] Liu, G., Adaptive predictor control for slowly time-varying systems with variable time delay, *Advances in Modelling and Simulation*, Vol. 20, 1990, pp. 9-21.

[329] Hang, C.-C., Wang, Q.-G. and Cao, L.-S., A novel self-tuning technique for Smith predictors, Proceedings of the *Asian Control Conference*, Tokyo, Japan, 1994, pp. 327-330.

[330] Hang, C.-C., Wang, Q.-G. and Cao, L.-S., Self-tuning Smith predictors for processes with long dead time, *International Journal of Adaptive Control and Signal Processing*, Vol. 9, 1995, pp. 255-270.

[331] Jones, A.H. and De Moura Oliveira, P.B., Auto-tuning of PI Smith predictor controllers using genetic algorithms, Proceedings of the *UKACC International Conference on Control*, 1996, pp. 454-457.

[332] O'Dwyer, A., *The estimation and compensation of processes with time delays*, Ph.D. thesis, 1996, Dublin City University, Dublin 9, Ireland.

[333] Balestrino, A., Verona, F.B. and Landi, A., On-line process estimation by ANNs and Smith controller design, *IEE Proceedings - Control Theory and Applications*, Vol. 145, 1998, pp. 231-235.

[334] Tian, Y.-C. and Gao, F., Compensation of dominant and variable delay in process systems, *Industrial Engineering Chemistry Research*, Vol. 37, 1998, pp. 982-986.

[335] Palmor, Z.J., Stability properties of Smith dead-time compensator controllers, *International Journal of Control*, Vol. 32, 1980, pp. 937-949.

[336] Garcia, C.E. and Morari, M., Internal Model Control. 2. Design procedure for multivariable systems, *Industrial and Engineering Chemistry Process Design and Development*, Vol. 24, 1985, pp. 472-484.

[337] Laughlin, D.L., Rivera, D.E. and Morari, M., Smith predictor design for robust performance, *International Journal of Control*, Vol. 46, 1987, pp. 477-504.

[338] Yamanaka, K. and Shimemura, E., Effects of mismatched Smith controller on stability in systems with time-delay, *Automatica,* Vol. 23, 1987, pp. 787-791.

[339] Santacesaria, C. and Scattolini, R., Easy tuning of Smith predictor in presence of delay uncertainty, *Automatica*, Vol. 29, 1993, pp. 1595-1597.

[340] Wang, Z.-Q. and Skogestad, S., Robust control of time delay systems using the Smith predictor, *International Journal of Control*, Vol. 57, 1993, pp. 1405-1420.

[341] Shu, Z., Watanabe, K. and Yamade, K., Robust internal model control of time-delay system, Proceedings of the *Asian Control Conference*, Tokyo, Japan, 1994, pp. 1045-1048.

[342] Wang, Z.-Q., Lundstrom, P. and Skogestad, S., Representation of uncertain time delays in the H infinity framework, *International Journal of Control*, Vol. 59, 1994, pp. 627-638.

[343] Lee, T.H., Wang, Q.G. and Tan, K.K., Robust Smith-predictor controller for uncertain time delay systems, *AIChE Journal*, Vol. 42, 1996, pp. 1033-1040.

[344] De Moura Oliveira, P.B. and Jones, A.H., Robust co-evolutionary design of SISO Smith predictor PID controllers, Proceedings of the *2nd International Conference in engineering systems: innovations and applications (GALESIA '97)*, Glasgow, Scotland, 1997, pp. 504-509.

[345] Lee, D., Lee, M., Sung, S. and Lee, I., Robust PID tuning for Smith predictor in the presence of model uncertainty, *Journal of Process Control*, Vol. 9, 1999, pp. 79-85.

[346] Morari, M., Robust process control, *Chemical Engineering Research and Design*, Vol. 65, 1987, 462-479.

[347] Thompson, S., Internal model control and feedback systems, Proceedings of the *Irish Colloquium on DSP and Control*, University College Dublin, Dublin 4, Ireland, 1993, pp. 133-140.

[348] Vandeursen, J.M. and Peperstraete, J.A., Internal model control with improved disturbance rejection, *International Journal of Control*, Vol. 62, 1995, pp. 983-999.

[349] Datta, A. and Ochoa, J., Adaptive interval model control: design and stability analysis, *Automatica*, Vol. 32, 1996, pp. 261-266.

[350] Ioannides, A.C., Rodgers, G.J. and Latham, V., Stability limits of a Smith controller in simple systems containing a time delay, *International Journal of Control*, Vol. 29, 1979, pp. 557-563.

[351] Vit, K., Smith-like predictor for control of parameter distributed processes, *International Journal of Control*, Vol. 31, 1979, pp. 179-193.

[352] Marshall, J.E. and Salehi, S.V., Improvement of system performance by the use of time-delay elements, *IEE Proceedings, Part D*, Vol. 129, 1982, pp. 177-181.

[353] Hocken, R.D., Salehi, S.V. and Marshall, J.E., Time-delay mismatch and the performance of predictor control schemes, *International Journal of Control*, Vol. 38, 1983, pp. 433-447.

[354] Tan, K.K., Wang, Q.G., Lee, T.H. and Bi, Q., New approach to analysis and design of Smith-predictor controllers, *AIChE Journal*, Vol. 42, 1996, pp. 1793-1797.

[355] Hang, C.C. and Wong, F.S., Modified Smith predictors for the control of processes with dead time, Proceedings of the *ISA Conference and Exhibition. Advances in Instrumentation and Control*, Chicago, IL., U.S.A., Vol. 34(2), 1979, pp. 33-44.

[356] Durbin, L.D., Second order plus deadtime observer with deadtime compensator, Proceedings of the *ISA Conference and Exhibition. Advances in Instrumentation*, Anaheim, CA., U.S.A., Vol. 36(2), 1981, pp. 315-326.

[357] Watanabe, K., Ishiyama, Y. and Ito, M., Modified Smith predictor control for multivariable systems with delays and unmeasurable step disturbances, *International Journal of Control*, Vol. 73, 1983, pp. 959-973.

[358] Kantor, J.C. and Andres, R.P., The analysis and design of Smith predictors using singular Nyquist arrays, *International Journal of Control*, Vol. 31, 1980, pp. 655-664.

[359] Palmor, Z.J. and Powers, D.V., Improved dead-time compensator controllers, *AIChE Journal*, Vol. 31, 1985, pp. 215-221.

[360] Wong, S.K.P. and Seborg, D.E., A theoretical analysis of Smith and analytical predictors, *AIChE Journal*, Vol. 32, 1986, pp. 1597-1603.

[361] Romagnoli, J.A., Karim, M.N., Agamennoni, O.E. and Desages, A., Controller designs for model-plant parameter mismatch, *IEE Proceedings, Part D*, Vol. 135, 1988, pp. 157-164.

[362] Huang, H.-P., Chen, C.-L., Chao, Y.-C. and Chen, P.-L., A modified Smith predictor with an approximate inverse of dead time, *AIChE Journal*, Vol. 36, 1990, pp. 1025-1031.

[363] Mitchell, R.J., Multi-microprocessor control of processes with pure time delay, *Transactions of the Institute of Measurement and Control*, Vol. 12, 1990, pp. 58-64.

[364] Astrom, K.J., Hang, C.C. and Lim, B.C., A new Smith predictor for controlling a process with an integrator and long dead time, *IEEE Transactions on Automatic Control*, Vol. 39, 1994, pp. 343-345.

[365] Zhang, W.D. and Sun, Y.X., Modified Smith predictor for controlling integrator/time delay processes, *Industrial Engineering Chemistry Research*, Vol. 35, 1996, pp. 2769-2772.

[366] Zhang, W.-D., Sun, Y.-X. and Xu, X.-M.,Two degree-of-freedom Smith predictor for processes with time delay, *Automatica*, Vol. 34, No. 10, 1998, pp. 1279-1282.

[367] Leonard, F., Tuning of a modified Smith predictor, Proceedings of the *IFAC Conference: System Structure and Control*, Nantes, France, 1998, pp. 571-574.

[368] Benouarets, M. and Atherton, D.P., Autotuning design method for a Smith predictor control scheme, Proceedings of the *IEE International Conference on Control*, 1994, pp. 795-800.

[369] Ferriera, A.M.P., Disturbance rejection dead time controller, Proceedings of the *3rd IEEE Conference on Control Applications*, Vol. 3, 1994, pp. 1777-1782.

[370] Dastych, J., Analysis and design of control loops with dead-times, *EURACO Workshop: Recent results in robust and adaptive control*, Florence, Italy, 1995, pp. 420-439.

[371] Ebach, U. and Graser, A., Design of an extended Smith controller with gain adaptation, *Control Engineering Practice*, Vol. 3, 1995, pp. 1467-1470.

[372] Palmor, Z.J., Time delay compensation - Smith predictor and its modifications, *The Control Handbook*, Editor: W.S. Levine, CRC/IEEE Press, 1996, pp. 224-237.

[373] Gorecki, R. and Jekielek, J., Simplifying controller for process control of systems with large dead time, Proceedings of the *ISA Tech/Expo Technology Update*, Anaheim, California, Vol. 1(5), 1997, pp. 113-120.

[374] Copp, D.G., Burnham, K.J. and Lockett, F.P., Model comparison for feedforward air/fuel ratio control, Proceedings of the *UKACC International Conference on Control '98*, Swansea, Wales, Vol. 1, 1998, pp. 670-675.

[375] Smith, L., A modified Smith predictor for extruded diameter control, Proceedings of the *InstMC Mini Symposium - Algorithms and Architectures for Industrial Controllers (in UKACC International Conference on Control '98)*, Swansea, Wales, 1998, Lecture 5.

[376] Palmor, Z.J. and Halevi, Y., Robustness properties of sampled-data systems with dead time compensators, *Automatica*, Vol. 26, 1990, pp. 637-640.

[377] Whalley, R. and Zeng, Z., Mismatch Smith predictors, *Transactions of the Institute of Measurement and Control*, Vol. 16, 1994, pp. 174-182.

[378] Chien, I.-L., Seborg, D.E. and Mellichamp, D.A., A self tuning controller for systems with unknown or time varying time delays, *International Journal of Control*, Vol. 42, 1985, pp. 949-964.

[379] Hang, C.C., Lee, T.H. and Tay, T.T., The use of recursive parameter estimation as an auto-tuning aid, Proceedings of the *ISA/85 International Conference and Exhibition. Advances in Instrumentation*, Philadelphia, Penn., U.S.A., Vol. 40(1), 1985, pp. 387-396.

[380] Batur, C., Stable sub-optimum controllers for the Smith dead-time compensation, Proceedings of the *American Control Conference*, Seattle, Washington, U.S.A., Vol. 2, 1986, pp. 1354-1357.

[381] Wang, F.-S., Adaptive root locus control for SISO processes with time delays, *Optimal Control Applications and Methods*, Vol. 11, 1990, pp. 211-221.

[382] Fujikawa, H. and Yamada, S.-I., A design method of self-tuning Smith predictor for unknown time-delay system, Proceedings of the *International Conference on Industrial Electronics - IECON '91*, Vol. 3, 1991, pp. 1801-1806.

[383] Guez, A. and Piovoso, M., Custom neurocontroller for a time delay process, Proceedings of the *American Control Conference*, Vol. 2, 1991, pp. 1592-1596.

[384] Mills, P.M., Lee, P.E. and McIntosh, P., A practical study of adaptive control of an alumina calciner, *Automatica*, Vol. 27, 1991, pp. 441-448.

[385] Behbehani, K., Delpasse, J.S. and Klein, K.W., A self-tuning controller with accommodation of time delay variations, *International Journal of Control*, Vol. 58, 1993, pp. 1215-1225.

[386] Batur, C., Self tuning controller for the Smith control scheme, Proceedings of the *ISA/85 International Conference and Exhibition*, Philadelphia, Penn., U.S.A., Vol. 40(1), 1985, pp. 637-642.

[387] Teng, F.-C., Investigation of the enlarged least-square estimator combined with a classical PID controller, *Transactions of the Institute of Measurement and Control*, Vol. 12, 1990, pp. 224-228.

[388] Chen, C.-L. and Jong, M.-J., Fuzzy predictive control for the time-delay system, Proceedings of the *Second IEEE International Conference on Fuzzy Systems*, San Francisco, California, U.S.A., 1993, pp. 236-240.

[389] Chotai, A. and Young, P.C., Pole-placement design for the time delay systems using a generalised, discrete time Smith predictor, Proceedings of the *IEE Control Conference*, 1985, pp. 218-223.

[390] Chotai, A. and Young, P.C., Pole-placement design for time delay systems using PIP control structure, Proceedings of the *IEE Colloquium on Control of Time Delay Systems*, London, U.K., 1987, Digest No. 1987/115, pp. 2/1-2/7.

[391] Walgama, K.S., Fisher, D.G. and Shah, S.L., Control of processes with noise and time delays, *AIChE Journal*, Vol. 35, 1989, pp. 213-222.

[392] Hang, C.C., Lim, K.W. and Chong, B.W., A dual-rate adaptive digital Smith predictor, *Automatica*, Vol. 25, 1989, pp. 1-16.

[393] Roffel, B. and Chin, P.A., Controlling processes with inverse response and dead time, *Hydrocarbon Processing*, December, 1987, pp. 40-42.

[394] Zhu, J.J-M. and Saucier, M., An IMC-based extended PID controller for sampled data systems, Proceedings of the *American Control Conference*, Chicago, Il., U.S.A., Vol. 1, 1992, pp. 601-606.

[395] De La Cruz, J.M., Dormido, S. and Velasco, F., Robust predictive PI controller, Proceedings of the *Conference on Systems, Man and Cybernetics*, 1993, pp. 63-68.

[396] Li, J., Yuan, D.C. and Jiang, C.H., A Smith predictive control structure for stochastic processes, Proceedings of the *Asian Control Conference*, Tokyo, Japan, 1994, pp. 209-212.

[397] Whalley, R. and Zeng, Z., A robust Smith predictor, *Transactions of the Institute of Chemical Engineers*, Vol. 74, Part A, 1996, pp. 21-29.

[398] Mulholland, M. and Fernandes, L.A.R., Combined Smith prediction and recursive filtering for observation of a polyethlene reactor, *Computers and Chemical Engineering*, Vol. 21, 1997, pp. 1283-1289.

[399] Yamamoto, T., Oki, T. and Kanada, M., Discrete-time advanced PID control systems for unknown time delay systems and their applications, *Electrical Engineering in Japan*, Vol. 118, No. 3, 1997, pp. 50-57.

[400] Taylor, J., Chotai, A. and Young, P., Proportional-integral-plus (PIP) control of time delay systems, Proceedings of the *Institute of Mechanical Engineers*, Vol. 212, 1998, pp. 37-48.

[401] Taylor, J., Chotai, A. and Young, P., Multivariable proportional-integral-plus (PIP) control of time delay systems, Proceedings of the *Institute of Mechanical Engineers Seminar S576: Tuning-in to increase profit - developments in PID tuning*, London, U.K., 1998, Lecture 6.

[402] Daniel, P. and Cox, C.S., Time delay compensation: the PIP philosophy, *International Journal of Systems Science*, Vol. 26, No. 1, 1995, pp. 113-124.

[403] Deshpande, P.B., Gopalratnam, P.C. and Ash, R.H., Design and application of deadtime compensation algorithms, Proceedings of the *ISA Conference and Exhibition 1979. Advances in Instrumentation*, Chicago, IL., U.S.A., Vol. 34(2), 1979, pp. 131-163.

[404] Huang, H.-P. and You, H.-S., State analytical predictor for systems with multiple time delays, *International Journal of System Science*, Vol. 25, 1994, pp. 991-1014.

[405] Wellons, M.C. and Edgar, T.F., The generalised analytical predictor, *Industrial Engineering Chemistry Research*, Vol. 26, 1987, pp. 1523-1536.

[406] Peter, K. and Isermann, R., Predictive self-tuning control of a thermal process with unknown deadtimes, Proceedings of the *IFAC Adaptive Control of Chemical Processes Conference*, Copenhagen, Denmark, 1988, pp. 69-74.

[407] Zafiriou, E. and Morari, M., Digital controllers for SISO systems: a review and a new algorithm, *International Journal of Control*, Vol. 42, 1985, pp. 865-876.

[408] Shahrohki, M. and Naimpour, F., A feedback control scheme for SISO systems with time delays and constrained inputs, *Computers and Chemical Engineering*, Vol. 16, 1992, pp. 1073-1076.

[409] Peebles, S.M., Hunter, S.R. and Corripio, A.N., Implementation of a dynamically-compensated PID control algorithm, *Computers and Chemical Engineering*, Vol. 18, 1994, pp. 995-1000.

[410] Vandeursen, J.M. and Peperstraete, J.A., Model-based and PID controllers for disturbance rejection in processes with time delay: a comparison, *ISA Transactions*, Vol. 35, 1996, pp. 225-236.

[411] Jones, A.H. and Lin, Y.-C., Design of digital two steps internal model controller with simplified internal model, Proceedings of the *UKACC International Conference on Control '98*, Swansea, Wales, Vol. 2, 1998, pp. 1599-1604.

[412] Alevisakis, G. and Seborg, D.E., Control of multivariable systems containing time delays using a multivariable Smith predictor, *Chemical Engineering Science*, Vol. 29, 1974, pp. 373-380.

[413] Ogunnaike, B.A. and Ray, W.H., Multivariable controller design for linear systems having multiple time delays, *AIChE Journal*, Vol. 25, 1979, pp. 1043-1057.

[414] Ray, W.H., *Advanced process control*. McGraw-Hill, 1981.

[415] Watanabe, K. and Sato, M., A process model control for multivariable systems with multiple delays in inputs and outputs subject to unmeasurable disturbances, *International Journal of Control*, Vol. 39, 1984, pp. 1-17.

[416] Chien, I.-L., Mellichamp, D.A. and Seborg, D.E., Multivariable self-tuning controller with time delay compensation, Proceedings of the *IFAC Identification and System Parameter Estimation Conference*, York, U.K., 1985, pp. 1261-1266.

[417] Jerome, N.F. and Ray, W.H., High-performance multivariable control strategies for systems having time delays, *AIChE Journal*, Vol. 32, 1986, pp. 914-931.

[418] Ozturk, N. and Fardanesh, B., Multivariable control of the robot manipulator in the presence of time delay, Proceedings of the *International Conference on Industrial Electronics, Control and Instrumentation (IECON '91)*, Kobe, Japan, Vol. 2, 1991, pp. 1191-1193.

[419] Triantafyllou, M.S. and Grosenbaugh, M.A., Robust control for underwater vehicle systems with time delays, *IEEE Journal on Oceanic Engineering*, Vol. 16, 1991, pp. 146-151.

[420] Austin, P.C., Crawford, R.A. and Carter, M.R., A generalised multivariable Smith predictor arising from new pseudo-commutativity results, Proceedings of the *IFAC 12th World Congress*, Sydney, Australia, Vol. 2, 1993, pp. 223-226.

[421] Desbiens, A., Pomerleau, A. and Hodouin, D., Frequency based tuning of SISO controllers for two-by-two processes, *IEE Proceedings - Control Theory and Applications*, Vol. 143, 1996, pp. 49-56.

[422] Pandiscio, A.A. and Pearson, A.E., The reducing transformation and Smith predictor methods for stabilising plants with transport lag, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 499-503.

[423] Stankovski, M.J., Dimirovski, G.M., Gough, N.E. and Hanus, R., Industrial furnace control: an experiment in iterative identification and design, Proceedings of the *UKACC International Conference on Control '98*, Swansea, Wales, Vol. 1, 1998, pp. 946-951.

[424] Vlachos, C., Williams, D. and Gomm, J.B., Solution to the Shell standard control problem using genetic algorithms, Proceedings of the *UKACC International Conference on Control '98*, Swansea, Wales, Vol. 2, 1998, pp. 1587-1592.

[425] Owens, D.H. and Raya, A., Robust stability of Smith predictor controllers for time-delay systems, *IEE Proceedings, Part D*, Vol. 129, 1982, pp. 298-304.

[426] Palmor, Z.J. and Halevi, Y., On the design and properties of multivariable dead time compensators, *Automatica*, Vol. 19, 1983, pp. 255-264.

[427] Chu, Y.T. and Wu, W.-T., On modelling error characterisation of multiple dead time systems, *IEEE Transactions on Automatic Control*, Vol. AC-31, 1986, pp. 157-159.

[428] Feng, W., On practical stability of linear multivariable feedback systems with time-delays, *Automatica*, Vol. 27, 1991, pp. 389-394.

[429] Luo, X., Sun, X. and Zhou, C., Time delay structure of a multiple input, multiple output system and its factorisation and compensation, *Industrial and Engineering Chemistry Research*, Vol. 31, 1992, pp. 1418-1421.

[430] Wu, W.-T. and Tseng, C.-G., Robust and adaptive control of a multi-variable system, *Transactions of the Institute of Measurement and Control*, Vol. 14, 1992, pp. 204-211.

[431] Maciejowski, J.M., Robustness of multivariable Smith predictors, *Journal of Process Control*, Vol. 4, 1994, pp. 29-32.

[432] Furukawa, T. and Shimemura, E., Predictive control for systems with time delay, *International Journal of Control*, Vol. 37, 1983, pp. 399-412.

[433] De Paor, A.M., A modified Smith predictor and controller for unstable processes with time delay, *International Journal of Control*, Vol. 41, 1985, pp. 1025-1036.

[434] De Paor, A.M., On the control of unstable time-delayed processes: approaches based on a modified Smith predictor and on a Luenberger observer, Presentation to *Institute of*

Electrical and Electronics Engineers, UKRI Section, Control Systems Chapter, University of Ulster at Jordanstown, Northern Ireland, April 1989.

[435] De Paor, A.M. and Egan, R.P.K., Observer based sampled-data control of unstable process with time delay, *International Journal of Control*, Vol. 51, 1990, pp. 341-352.

[436] Lilja, M., Least squares fitting to a rational transfer function with time delay, Proceedings of the *IEE Control Conference*, 1988, pp. 143-146.

[437] Rad, A.B., Self-tuning control of systems with unknown time delay: a continuous-time approach, *Control - Theory and Advanced Technology*, Vol. 10, 1994, pp. 479-497.

[438] Szita, G. and Sanathanan, C.K., Robust design for disturbance rejection in time delay systems, *Journal of the Franklin Institute*, Vol. 334B, 1997, pp. 611-629.

[439] Prasad, C.C. and Krishnaswamy, P.R., Control of pure time delay processes, *Chemical Engineering Science*, Vol. 30, 1975, pp. 207-215.

[440] Liu, G.P. and Wang, H., An adaptive controller for continuous-time systems with unknown varying time-delay, Proceedings of *Control 85 - IEE International Control Conference*, 1985, pp. 1084-1088.

[441] Kocijan, J. and Korba, R., An approach to robust multivariable combustion control design, Proceedings of *the 6th Mediterranean Electronics Conference*, Ljubljana, Slovenia, Vol. 2, 1991, pp. 864-867.

[442] Perng, M.H. and Ju, J.S., Optimally decoupled robust control of MIMO plants with multiple delays, *IEE Proceedings - Control Theory and Applications*, Vol. 141, 1994, pp. 25-32.

[443] Agamennoni, O.E., Desages, A.C. and Romagnoli, J.A., A multivariable delay compensator scheme, *Chemical Engineering Science*, Vol. 47, 1992, pp. 1173-1185.

[444] Dahlin, E.B., Designing and tuning digital controllers, *Instruments and Control Systems*, Vol. 41, No. 6, 1968, pp. 77-83.

[445] Gautam, R. and Mutharasan, R. A general direct digital control algorithm for a class of linear systems, *AIChE Journal*, Vol. 24, No. 2, 1978, pp. 360-364.

[446] Krivoshein, K.D. and Corripio, A.B., A study of ringing and dead-time compensation in Dahlin's digital control algorithm, Proceedings of the *ISA Conference and Exhibition. Advances in Instrumentation*, Houston, Texas, U.S.A., Vol. 35(1), 1980, pp. 43-56.

[447] Qi, L.-W. and Corripio, A.B., A refractometer dead time compensation method for supersaturation control of sugar crystalization in a vacuum pan, Proceedings of the *ISA/85 International Conference and Exhibition. Advances in Instrumentation*, Philadelphia, Penn., U.S.A., Vol. 40(1), 1985, pp. 363-372.

[448] Leffew, K.W., Stiso, M.J. and Langhorst, H., Application of digital control techniques to a laboratory extrusion process, Proceedings of the *American Control Conference*, Minneapolis, Minnesota, U.S.A., 1987, pp. 1002-1007.

[449] Dumont, G.A., Control techniques in the pulp and paper industries, C.T. Leondes (Ed.), *Control and Dynamic Systems. Advances in Theory and Applications*, Academic Press Inc., Vol. 37, 1990, pp. 65-114.

[450] Elnagger, A., Dumont, G.A. and Elshafei, A.-L., Adaptive control with direct delay estimation, Proceedings of the *Conference on Control Systems*, Whistler, U.S.A., 1992, pp. 13-17.

[451] Elnagger, A., Dumont, G.A. and Elshafei, A.-L., Adaptive control with direct delay estimation, Proceedings of the *12th IFAC World Congress*, Sydney, Australia, Vol. 9, 1993, pp. 19-23.

[452] Dumont, G.A., Elnagger, A. and Elshafei, A., Adaptive predictive control of systems with time-varying time delay, International *Journal of Adaptive Control and Signal Processing*, Vol. 7, 1993, pp. 91-101.

[453] Teng, F.C., Ledwich, G.F. and Tsoi, A.C., Extension of the Dahlin-Higham controller to multivariable systems with time delays, *International Journal of System Science*, Vol. 25, 1994, pp. 337-350.

[454] Cohen, I., Adaptive and self-tuning controllers for processes with internal perturbations, time delay, non-minimum phase and hard non-linearity, Proceedings of the *IFAC Identification and System Parameter Estimation Conference*, York, U.K., 1985, pp. 329-334.

[455] Astrom, K.J. and Hagglund, T., A new auto-tuning design, Proceedings of the *Second International IFAC Symposium on the Adaptive Control of Chemical Processes*, Copenhagen, Denmark, 1988, pp. 141-146.

[456] Wellstead, P.E. and Zarrop, M.B., *Self-tuning systems*. John Wiley and Sons, 1991.

[457] Kristinsson, K. and Dumont, G.A., System identification and control using genetic algorithms, *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 22, 1992, pp. 1033-1046.

[458] Gendron, S., Perrier, M., Barrette, J., Amjad, M., Holko, A. and Legault, N., Deterministic adaptive control of SISO processes using model weighting adaptation, *International Journal of Control*, Vol. 58, 1993, pp. 1105-1123.

[459] Astrom, K.J., Hagglund, T. and Wallenborg, A., Automatic tuning of digital controllers with applications to HVAC plants, *Automatica*, Vol. 29, 1993, pp. 1333-1343.

[460] Jansen, L.B. and Corripio, A.B., A computer control algorithm for feedback composition control using off-line analysis, *Computers and Chemical Engineering*, Vol. 17, 1993, pp. 1031-1039.

[461] Chen, G.P., Malik, O.P. and Hope, G.S., Generalised discrete control system design method with control limit considerations, *IEE Proceedings - Control Theory and Applications*, Vol. 141, 1994, pp. 39-47.

[462] Kotob, S., Badran, M., Al-Atiqi, I. and Juraidan, M., Analysis and applications of self-tuning controls in a refining process: case study, *Automatica*, Vol. 30, 1994, pp. 1663-1675.

[463] Lundh, M. and Astrom, K.J., Automatic initialisation of a robust self-tuning controller, *Automatica*, Vol. 30, 1994, pp. 1649-1662.

[464] Keviczky, L., Combined identification and control: another way, *Control Engineering Practice*, Vol. 4, 1996, pp. 685-698.

[465] Chai, T.Y., A multivariable generalised self-tuning decoupling controller and application, Proceedings of the *American Control Conference*, Seattle, Washington, U.S.A., Vol. 2, 1986, pp. 739-744.

[466] Wellstead, P.E., Prager, D. and Zanker, P., Pole assignment self-tuning regulator, *IEE Proceedings*, Vol. 126, 1979, pp. 781-787.

[467] Vogel, E.F. and Edgar, T.F., Application of an adaptive pole-zero placement controller to chemical processes with variable dead time, Proceedings of the *American Control Conference*, 1982, pp. 536-544.

[468] Prasad, C.C., Hahn, V., Unbehauen, H. and Keuchel, U., Adaptive control of a variable dead time process with an integrator, Proceedings of the *IFAC Workshop on Adaptive Control of Chemical Processes*, Frankfurt am Main, Germany, 1985, pp. 71-75.

[469] Delapasse, J.S., Behbehani, K., Tsui, K. and Klein, K.W., Accommodation of time delay variations in automatic infusion of sodium nitroprusside, *IEEE Transactions on Biomedical Engineering*, Vol. 41, 1994, pp. 1083-1091.

[470] Prager, D.L. and Wellstead, P.E., Multivariable pole assignment self-tuning regulators, *Proceedings of the IEE, Part D*, Vol. 128, 1980, pp. 9-18.

[471] Vogel, E.F. and Edgar, T.F., An adaptive pole placement controller for chemical processes with variable dead time, *Computers and Chemical Engineering*, Vol. 12, 1988, pp. 15-26.

[472] Mo, L. and Bayoumi, M.M., Adaptive pole placement control of MIMO systems, *IEEE Transactions on Automatic Control*, Vol. 38, 1993, pp. 967-970.

[473] Stahl, H. and Hippe, P., Design of pole placing controllers for stable and unstable systems with pure time delay, *International Journal of Control*, Vol. 45, 1987, pp. 2173-2182.

[474] De Souza, C.E., Goodwin, G.C., Mayne, D.Q. and Palaniswami, M., An adaptive control algorithm for linear systems having unknown time delay, *Automatica*, Vol. 24, 1988, pp. 327-341.

[475] Salgado, M.E., De Souza, C.E. and Goodwin, G.C., Issues in time delay modelling, Proceedings of the *Eighth IFAC/IFORS*

Symposium on Identification and System Parameter Estimation, Beijing, China, 1988, pp. 549-554.

[476] Bartolini, G. and Ferrara, A., Discrete-time adaptive control of linear plants with uncertain time delay, Proceedings of the *31st Conference on Decision and Control*, Tucson, Arizona, U.S.A., 1992, pp. 3554-3558.

[477] Tsai, J.S.H., Wei, C.-P. and Shieh, L.S., Design of a stable digital output feedback controller for continuous-time input-delay plants, *International Journal of Systems Science*, Vol. 25, 1994, pp. 2187-2206.

[478] Lang, S.-J., Gu, X.-Y. and Chai, T.-Y., A multivariable generalised self tuning controller with decoupling design, *IEEE Transactions on Automatic Control*, Vol. AC-31, 1986, pp. 474-477.

[479] Kinneart, M., Hanus, R. and Henrotte, J.-L., A new decoupling precompensator for indirect adaptive control of multivariable linear systems, *IEEE Transactions on Automatic Control*, Vol. AC-32, 1987, pp. 455-459.

[480] Kinneart, M. and Hanus, R., Adaptive control of multiple-input, multiple-output linear systems, *Journal A*, Vol. 29, 1988, pp. 9-16.

[481] Nagarajan, R. and Sajed, K.A., Application of front end control in time-delayed plants, *Proceedings of the Institute of Mechanical Engineers, Part 1: Journal of Systems and Control Engineering*, Vol. 208, 1994, pp. 71-78.

[482] Gawthrop, P.J., Some interpretations of the self-tuning controller, *Proceedings of the Institute of Electrical Engineers - Control & Science*, 1977, Vol. 124, pp. 889-894.

[483] Brown, L.J., Meyn, S.P. and Weber, R.A., Adaptive dead-time compensation with application to a robotic welding system, *IEEE Transactions on Control Systems Technology*, Vol. 6, 1998, pp. 335-349.

[484] Isermann, R., Lachmann, K.-H. and Matko, D., *Adaptive Control Systems*, Prentice-Hall International Series in Systems and Control Engineering, 1992.

[485] Barthal, J.W. and Shin, Y.C., Adaptive control of nonminimum phase processes with application to the end milling process, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 2449-2454.

[486] Meyn, S.P. and Brown, L.J., Model reference adaptive control of time-varying and stochastic systems, *IEEE Transactions on Automatic Control*, Vol. 38, 1993, pp. 1738-1753.

[487] Kimura, J., Nishimura, Y., Yonezawa, Y. and Saeki, M., A design method of discrete time MRACS for an unstable and nonminimum phase system with unknown time delay, Proceedings of the *Asian Control Conference*, Tokyo, Japan, 1994, pp. 291-294.

[488] Mizuno, N. and Fujii, S., Discrete time multivariable adaptive control for non-minimum phase plants with unknown dead time, Proceedings of the *IFAC Adaptive Systems in Control and Signal Processing*, San Francisco, California, U.S.A., 1983, pp. 363-368.

[489] Manitius, A.Z. and Olbrot, A.W., Finite spectrum assignment problem for systems with delays, *IEEE Transactions on Automatic Control*, Vol. AC-24, 1979, pp. 541-553.

[490] Manitius, A.Z., Feedback controllers for a wind tunnel model involving a delay: analytical design and numerical simulation, *IEEE Transactions on Automatic Control*, Vol. AC-29, 1984, pp. 1058-1068.

[491] Ichikawa, K., Frequency domain pole assignment and exact model-matching for delay systems, *International Journal of Control*, Vol. 41, 1985, 1015-1024.

[492] Watanabe, K. and Ouchi, T., An observer of systems with delays in state variables, *International Journal of Control*, Vol. 41, 1985, pp. 217-229.

[493] Ortega, R. and Lozano, R., Globally stable adaptive controller for systems with delay, *International Journal of Control*, Vol. 47, 1988, pp. 17-23.

[494] Wang, S.-S. and Chen, B.-S., Optimal model-matching control for time-delay systems, *International Journal of Control*, Vol. 47, 1988, pp. 883-894.

[495] Wang, Q.-G., Sun, Y.X. and Zhou, C.H., Finite spectrum assignment for multivariable delay systems in the frequency domain, *International Journal of Control*, Vol. 47, 1988, pp. 729-734.

[496] Wang, Q.-G., Lee, T.H. and Hang, C.C., Frequency domain finite-spectrum assignment for delay systems with multiple poles, *International Journal of Control*, Vol. 58, 1993, pp. 735-738.

[497] Wang, Q.-G., Lee, T.H. and Tan, K.K., Automatic tuning of finite spectrum assignment controllers for delay systems, *Automatica*, Vol. 31, 1995, pp. 477-482.

[498] Furutani, E., Araki, M., Sakamoto, T. and Maetani, S., Blood pressure control during surgical operations, *IEEE Transactions on Biomedical Engineering*, Vol. 42, 1995, pp. 999-1006.

[499] Yao, Y.X., Zhang, Y.M. and Kovacevic, R., Parameterisation of observers for time delay systems and its application to observer design, *IEE Proceedings - Control Theory and Applications*, Vol. 143, 1996, pp. 225-231.

[500] Yao, Y.X., Zhang, Y.M. and Kovacevic, R., Functional observer and state feedback for input time-delay systems, *International Journal of Control*, Vol. 66, 1997, pp. 603-617.

[501] Tan, K.K., Wang, Q.-G. and Lee, T.H., Relay-tuned finite spectrum assignment control of time delay processes, *ISA Transactions*, Vol. 37, 1998, pp. 123-131.

[502] Tan, K.K., Wang, Q.-G. and Lee, T.H., Finite spectrum assignment control of unstable time delay processes with relay tuning, *Industrial Engineering Chemistry Research*, Vol. 37, 1998, pp. 1351-1357.

[503] Slater, G.L. and Wells, W.R., On the reduction of optimal time-delay systems to ordinary ones, *IEEE Transactions on Automatic Control*, 1972, pp. 154-155.

[504] Grimble, M.J., The solution of finite-time optimal control problems with control time delays, *Optimal Control Applications and Methods*, Vol. 1, 1980, pp. 263-277.

[505] Palanisamy, K.R., Balachandran, K. and Ramasamy, R.S., Optimal control of linear time-varying delay systems via single-term Walsh series, *IEE Proceedings, Part D*, Vol. 135, 1988, page 332.

[506] Anderson, B.D.O. and Moore, J.B., *Optimal Control Linear Quadratic Methods*, Prentice-Hall, 1989.

[507] Dadebo, S. and Luus, R., Optimal control of time-delay systems by dynamic programming, *Optimal Control Applications and Methods*, Vol. 13, 1992, pp. 29-41.

[508] Dadebo, S.A. and McAuley, K.B., Minimum energy control of time delay systems via iterative dynamic programming, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 1261-1265.

[509] Chyung, D.H., Tracking controller for output feedback linear time delay systems, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 512-515.

[510] Paraskevopoulos, P.N. and Samiotakis, S.E., State space analysis and optimal control of time delay systems via Taylors series, Proceedings of the *IEE International Conference on Control*, 1994, pp. 70-74.

[511] Semino, D. and Scali, C., A method for robust tuning of linear quadratic optimal controllers, *Industrial and Engineering Chemistry Research*, Vol. 33, 1994, pp. 889-895.

[512] Lin, J.-S. and Hwang, C., Optimal control of time-delay systems by forward iterative dynamic programming, *Industrial Engineering Chemistry Research*, Vol. 35, 1996, pp. 2795-2800.

[513] Kurz, H. and Goedecke, W., Digital parameter-adaptive control of processes with unknown dead time, *Automatica*, Vol. 17, 1981, pp. 245-252.

[514] 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.

[515] Astrom, K.J. and Wittenmark, B., *Adaptive Control*, Addison Wesley, 1989.

[516] Allidina, A.Y., Hughes, F.M. and Tahmassebi, T., An implicit self-tuning controller for variable time-delay systems, Proceedings of the *IFAC Identification and System Parameter Estimation Conference*, York, U.K., 1985, pp. 1779-1785.

[517] Clough, D.E. and Park, S.J., A novel dead-time adaptive controller, Proceedings of the *IFAC Workshop on Adaptive Control of Chemical Processes*, Frankfurt am Main, Germany, 1985, pp. 21-26.

[518] Liu, K. and Gertler, J., An intelligent adaptive scheme for biomedical control, Proceedings of the *IEEE International Symposium on Intelligent Control*, Philadelphia, Pennsylvania, U.S.A., 1987, pp. 377-382.

[519] Koivo, H., Virtanen, P. and Pusenius, M., A self-tuning controller for processes with time varying delay: application to a paper machine head box, Proceedings of the *IFAC Adaptive Control of Chemical Processes Conference*, Copenhagen, Denmark, 1988, pp. 125-128.

[520] Hu, X., Ng, T.S. and Xu, H., Robust self tuner for variable time delay systems, Proceedings of the *Eighth IFAC/IFORS Symposium on Identification and System Parameter Estimation*, Beijing, China, 1988, pp. 245-249.

[521] Xu, H., Robust protection-time delay tracing adaptive control and its application, Proceedings of the *Eighth IFAC/IFORS Symposium on Identification and System Parameter Estimation*, Beijing, China, 1988, pp. 769-774.

[522] Voss, G.I., Chizeck, H.J. and Katona, P.G., Self-tuning controller for drug delivery systems, *International Journal of Control*, Vol. 47, 1988, pp. 1507-1520.

[523] Chen, H.-F. and Zhang, J.-F., Identification and adaptive control for systems with unknown orders, delay and coefficients, *IEEE Transactions on Automatic Control*, Vol. 35, 1990, pp. 866-877.

[524] Landau, I.D., *System Identification and Control Design*, Prentice-Hall Inc., 1990.

[525] 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*, Vol. 138, 1991, pp. 445-452.

[526] Ren, W., Stochastic adaptive control of multiple delay systems, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 2195-2199.

[527] Al-Chalabi, L.A. and Khalil, F.F., Dahlin minimum variance self-tuning controller, *International Journal of Control*, Vol. 60, 1994, pp. 747-766.

[528] Pratt, P. and Downing, C.J., LQG regulation of a thermal process - an alternative formulation, *Proceedings of the Irish DSP and Control Colloquium*, Dublin City University, Dublin 9, Ireland, 1994, pp. 177-184.

[529] Weerasooriya, S. and Phan, D.T., Discrete time LQG/LTR design and modeling of a disk drive actuator tracking servo system, *IEEE Transactions on Industrial Electronics*, Vol. 42, 1995, pp. 240-247.

[530] Borison, U., Self-tuning regulators for a class of multivariable systems, *Automatica*, Vol. 15, 1979, pp. 209-215.

[531] El-Bagoury, M.A. and Bayoumi, M.M., Multivariable self tuning augmented regulator, Proceedings of an *International Symposium on Methods and Applications in Adaptive Control*, Bochum, Germany, 1980, pp. 41-53.

[532] Dugard, L., Goodwin, G.C. and Xianya, X., The role of the interactor matrix in multivariable stochastic adaptive control, *Automatica*, Vol. 20, 1984, pp. 701-709.

[533] Scattolini, R., A multivariable self-tuning controller with integral action, *Automatica*, 1986, Vol. 2, pp. 619-627.

[534] Chai, T.Y., A self-tuning decoupling controller for a class of multivariable systems and global convergence analysis, *IEEE Transactions on Automatic Control*, Vol. 33, 1988, pp. 767-771.

[535] Chai, T.Y., Direct adaptive decoupling control for general stochastic multivariable systems, *International Journal of Control*, Vol. 51, 1990, pp. 885-909.

[536] Chai, T.-Y. and Ma, Z., A multivariable self tuning decoupling controller with consistent parameter estimates, Proceedings of the *11th triennial World Congress of the International Federation of Automatic Control*, Tallinn, Estonia, Vol. 2, 1990, pp. 279-284.

[537] Chai, T.Y. and Wang, G., Globally convergent multivariable adaptive decoupling controller and its application to a binary distillation column, *International Journal of Control*, Vol. 55, 1992, pp. 415-429.

[538] Tade, M.O., Bayoumi, M.M. and Bacon, D.W., Self-tuning controller design for systems with arbitrary time delays. Part 1: Theoretical development, *International Journal of System Science*, Vol. 19, 1988, pp. 1095-1115.

[539] Tade, M.O., Bayoumi, M.M. and Bacon, D.W., Self-tuning controller design for systems with arbitrary time delays. Part 2: Algorithms and simulation examples, *International Journal of System Science*, Vol. 19, 1988, pp. 1117-1141.

[540] Chen, H.-F., Guo, L. and Zhang, J.-F., *Identification and adaptive control for ARMAX systems*, Lecture Notes in Control and Information Sciences, Vol. 161, 1991, pp. 216-241.

[541] Yin, K. and Asbjornson, O.A., Application of MIMO adaptive control to a binary distillation process, *Chemical Engineering Communications*, Vol. 124, 1993, pp. 115-130.

[542] Joshi, S. and Kaufman, H., Digital adaptive controllers using second order models with transport lag, *Automatica*, Vol. 11, 1975, pp. 129-139.

[543] Knobbe, E.J., Optimal control of linear stochastic systems with process and observation time delays, C.T. Leondes (Ed.), *Control and Dynamic Systems. Advances in Theory and Applications*. Vol. 31, Part 1 of 3, Academic Press Inc., 1989, pp. 185-192.

[544] Ha, C., Ly, U.-L. and Vagners, J., Optimal digital control with computation time-delay: a w-synthesis method, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 2626-2630.

[545] Nilsson, J., Bernhardsson, B. and Wittenmark, B., Stochastic analysis and control of real-time systems with random time delay, *Automatica*, Vol. 34, 1996, pp. 57-64.

[546] Ray, W.H. and Soliman, M.A., The optimal control of processes containing pure time delays - I. Necessary conditions for an optimum, *Chemical Engineering Science*, Vol. 25, 1970, pp. 1911-1925.

[547] Kwon, W.H., Lee, G.W. and Kim, S.W., Delayed state feedback controllers for the stabilization of ordinary systems, Proceedings of the *American Control Conference*, Pittsburgh, Pennsylvania, U.S.A., Vol. 1, 1989, pp. 292-297.

[548] Grimble, M.J., LQG controllers for discrete-time multivariable systems with different transport delays in signal channels, *IEE Proceedings - Control Theory and Applications*, Vol. 145, No. 5, 1998, pp. 449-462.

[549] Latour, P.R., Koppel, L.B. and Coughanowr, D.R., Time-optimum control of chemical processes for set-point changes, *Industrial and Engineering Chemistry Process Design and Development*, Vol. 6, 1967, pp. 452-460.

[550] Hiratsuka, S. and Ichikawa, A., Optimal control of systems with transportation lags, *IEEE Transactions on Automatic Control*, Vol. AC-14, 1969, pp. 237-247.

[551] Lin, Y.-I., Beard, J.N. and Melsheimer, S.S., Model-independent algorithms for time-optimal control of chemical processes, *AIChE Journal*, Vol. 39, 1993, pp. 979-988.

[552] Song, H.K., Fisher, D.G. and Shah, S.L., Experimental evaluation of a robust self-tuning PID controller, *The Canadian Journal of Chemical Engineering*, Vol. 62, 1984, pp. 755-763.

[553] Ozbay, H. and Peery, T.E., On fixed order controllers for delay systems: discrete time case, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 1030-1031.

[554] Lublinsky, B. and Fradkov, A., A comparison of adaptive and nonadaptive feedback for discrete-time plants with dead time, *IEEE Transactions on Automatic Control*, Vol. 38, 1993, pp. 492-495.

[555] Dym, H., Georgiou, T.T. and Smith, M.C., Direct design of optimal controllers for delay systems, *Proceedings of the IEEE Conference on Decision and Control*, Vol. 4, 1993, 3821-3823.

[556] Yen, N.-Z. and Wu, Y.-C., Multirate robust servomechanism controllers of linear delay systems using a hybrid structure, *International Journal of Control*, Vol. 60, 1994, pp. 1265-1281.

[557] Dym, H., Georgiou, T.T. and Smith, M.C., Explicit formulas for optimally robust controllers for delay systems, *IEEE Transactions on Automatic Control*, Vol. 40, 1995, pp. 656-669.

[558] Rosenwasser, Y.N., Polyakov, K.Y. and Lampe, B.P., Frequency-domain method for H_2 optimisation of time-delayed sampled-data systems, *Automatica*, Vol. 33, 1997, pp. 1387-1392.

[559] Qin, S.J., Control performance monitoring - a review and assessment, *Computers and Chemical Engineering*, Vol. 23, 1998, pp. 173-186.
[560] Kwon, W.H., Advances in predictive control: theory and applications, Proceedings of the *Asian Control Conference*, Tokyo, Japan, 1994.
[561] Pike, A.W., Grimble, M.J., Johnson, M.A., Ordys, A.W. and Shakoor, S., Predictive control, *The Control Handbook*, Editor: W. Levine, CRC/IEEE Press, 1996, pp. 805-813.
[562] Rani, K.Y. and Unbehauen, H., Study of predictive controller tuning methods, *Automatica*, Vol. 33, 1997, pp. 2243-2248.
[563] Clark, D.W., Mohtadi, C. and Tuffs, P.S., Generalised predictive control - part I. The basic algorithm, *Automatica*, Vol. 23, 1987, pp. 137-148.
[564] Clark, D.W., Mohtadi, C. and Tuffs, P.S., Generalised predictive control - part II. The basic algorithm, *Automatica*, Vol. 23, 1987, pp. 149-160.
[565] Demircioglu, H. and Gawthrop, P.J., Continuous-time generalised predictive control (CGPC), *Automatica*, Vol. 27, 1991, pp. 55-74.
[566] Camacho, E.F. and Bordons, C., Implementation of self-tuning generalised predictive controllers for the process industry, *International Journal of Adaptive Control and Signal Processing*, Vol. 7, 1993, pp. 63-73.
[567] Bordons, C. and Camacho, E.F., A generalised predictive controller for a wide class of industrial processes, *IEEE Transactions on Control Systems Technology*, Vol. 6, 1998, pp. 372-387.
[568] Jolly, T., Bentsman, J. and Ross, D., Generalized predictive control with dynamic filtering for process control applications, Proceedings of the *American Control Conference*, San Francisco, California, U.S.A., 1993, pp. 1741-1745.
[569] Unbehauen, H. and Kramer, K., Application of adaptive predictive control to a shaker conveyor for transportation of plastic beads, *International Journal of Adaptive Control and Signal Processing*, Vol. 11, 1997, pp. 217-230.
[570] Chan, C.C., Rad, A.B. and Wong, Y.K., Comparison of GPC controller and a PID auto-tuner for a heating plant, *International Journal of Electrical Engineering Education*, Vol. 34, 1997, pp. 316-325.
[571] Tsai, C.-C. and Lu, C.-H., Multivariable self-tuning temperature control for plastic injection moulding process, *IEEE Transactions on Industry Applications*, Vol. 34, 1998, pp. 310-318.
[572] Ydstie, B.E., Extended horizon adaptive control, Proceedings of the *9th IFAC World Congress*, Budapest, Hungary, 1984, pp. 911-915.
[573] Zevros, C.C. and Dumont, G.A., Deterministic adaptive control based on Laguerre series representation, *International Journal of Control*, Vol. 48, 1988, pp. 2333-2359.
[574] Chisci, L. and Mosca, E., Adaptive predictive control of ARMAX plants with unknown deadtime, Proceedings of the *IFAC Symposium on Adaptive Systems in Control and Signal Processing*, Vol. 8, 1993, pp. 221-226.
[575] Jerome, N.F. and Ray, W.H., Model-predictive control of linear multivariable systems having time delays and right-half-plane zeroes, *Chemical Engineering Science*, Vol. 47, 1992, pp. 763-785.
[576] Liu, J.Z., Pieper, J.K. and Surgenor, B.W., Deadtime compensation and zero frequency decoupling of a thermal hydraulic process, *Transactions of the ASME. Journal of Dynamic Systems, Measurement and Control*, Vol. 114, 1992, pp. 527-531.
[577] Rad, A.B. and Lo, W.L., Predictive PI controller, *International Journal of Control*, Vol. 60, 1994, pp. 953-975.
[578] Rangaiah, G.P. and Krishnaswamy, P.R., Effective implementation of conservative model based control algorithm, *Chemical Engineering Communications*, Vol. 128, 1994, pp. 135-141.
[579] Maiti, S.N., Kapoor, N. and Saraf, D.N., Adaptive dynamic matrix control of pH, *Industrial Engineering Chemistry Research*, Vol. 33, 1994, pp. 641-646.
[580] Austin, P.C., Park, S. and Delich, J., Model-based predictive control in the process industries, Proceedings of the *Irish DSP and Control Colloquium*, Dublin City University, Dublin 9, Ireland, 1994, pp. 159-168.
[581] Wojsznis, W.K., Variable horizon predictor, Proceedings of the *33rd Conference on Decision and Control*, Lake Buena Vista, Florida, U.S.A., 1994, pp. 3032-3035.
[582] Huang, H.-P. and You, H.-S., New robust state analytical predictor design for a general class of deadtime processes, *International Journal of Control*, Vol. 62, 1995, pp. 651-683.
[583] Dunia, R.H. and Edgar, T.F., An improved generic model control algorithm for linear systems, *Computers in Chemical Engineering*, Vol. 20, 1996, pp. 1003-1016.
[584] Maitelli, A.L. and Yoneyama, T., Suboptimal dual adaptive control for blood pressure management, *IEEE Transactions on Biomedical Engineering*, Vol. 44, 1997, pp. 486-492.
[585] Shridhar, R. and Cooper, D.J., A tuning strategy for unconstrained SISO model predictive control, *Industrial Engineering Chemistry Research*, Vol. 36, 1997, pp. 729-746.
[586] Shridhar, R. and Cooper, D.J., A novel tuning strategy for multivariable model predictive control, *ISA Transactions*, Vol. 36, No. 4, 1998, pp. 273-280.
[587] Wang, J., Richalet, J. and Vitte, E., PFC-CAD/Modicon. First order system with a pure time delay, *Technical paper*, Adersa Ltd., Palaiseau, France, 1997.
[588] Wang, J.C., Estival, J.L. and Richalet, J., Predictive functional control for 1st order system (ModPFC1), *Technical paper*, Adersa Ltd., Palaiseau, France, 1998.
[589] Wang, J.C., Estival, J.L. and Richalet, J., Predictive feedforward compensation for 1st order system of measured disturbance (ModFFC1), *Technical paper*, Adersa Ltd., Palaiseau, France, 1998.
[590] Wang, J.C., Estival, J.L. and Richalet, J., PFC's in cascade control systems for 1st order systems, *Technical paper*, Adersa Ltd., Palaiseau, France, 1998.
[591] Uraz, A. and Ozturk, N., Predictor control of multivariable processes with time delays, Proceedings of the *IEE Control Conference*, 1985, pp. 648-653.
[592] Richalet, J., Observations on model-based predictive control, *Control Engineering*, August, 1992, pp. 39-41.
[593] Astrom, K.J., Assessment of achievable performance of simple feedback loops, *International Journal of Adaptive Control and Signal Processing*, Vol. 5, 1991, pp. 3-19.
[594] Astrom, K.J., Hang, C.C., Persson, P. and Ho, W.K., Towards intelligent PID control, *Automatica*, Vol. 28, 1992, pp. 1-9.
[595] Rao, A.S. and Perdikaris, G.A., Computer aided compensator design, *IEEE Transactions on Education*, Vol. 31, 1988, pp. 221-224.
[596] Newell, R.B. and Lee, P.L., *Applied process control - a case study*, Prentice-Hall, 1989.
[597] Shah, S., Iwai, Z., Mizumoto, I. and Deng, M., Simple adaptive control of processes with time-delay, *Journal of Process Control*, Vol. 7, 1997, pp. 439-449.
[598] Chou, J.-H., Horng, I.-R. and Chen, B.-S., Dynamical feedback compensator for uncertain time-delay systems containing saturating actuator, *International Journal of Control*, Vol. 49, 1989, pp. 961-968.
[599] Lee, J.H., Kim, S.W. and Kwon, W.H., Memoryless H_∞ controllers for state delayed systems, *IEEE Transactions on Automatic Control*, Vol. 39, 1994, pp. 159-162.
[600] Choi, H.H. and Chung, M.J., Memoryless H_∞ controller design for linear systems with delayed state and control, *Automatica*, Vol. 31, 1995, pp. 917-919.
[601] Shyu, K.-K. and Chen, Y.-C., Robust tracking and model following for uncertain time-delay systems, *International Journal of Control*, Vol. 62, 1995, pp. 589-600.
[602] Zwart, H., Curtain, R. and Bakema, J., Robust controllers for dead-time systems, Proceedings of *EURACO 1995: Recent results in robust and adaptive control*, Florence, Italy, 1995, pp. 233-251.
[603] Toffner-Clausen, S. and Anderson, P., μ synthesis - a non-conservative methodology for design of controllers with robustness towards dynamic and parametric uncertainty, Proceedings of *EURACO Workshop: Recent results in robust and adaptive control*, Florence, Italy, 1995, pp. 269-303.
[604] Jeung, E.T., Oh, D.T., Kim, J.H. and Park, H.B., Robust controller design for uncertain systems with time delays: LMI approach, *Automatica*, Vol. 32, 1996, pp. 1229-1231.

[605] Man, K.F., Tang, K.S., Kwong, S. and Halang, W., *Genetic algorithms for control and signal processing*, Springer-Verlag, 1996.

[606] Yu, L., Chu, J. and Su, H., Robust memoryless H_∞ controller design for linear time-delay systems with norm-bounded time-varying uncertainty, *Automatica*, Vol. 32, 1996, pp. 1759-1762.

[607] Moheimani, S.O.R. and Petersen, I.R., Optimal quadratic guaranteed cost control of a class of uncertain time delay systems, *IEE Proceedings - Control Theory and Applications*, Vol. 144, 1997, pp. 183-188.

[608] Nagpal, K.M. and Ravi, R., H_∞ control and estimation problems with delayed measurements: state space solutions, *SIAM Journal of Control and Optimization*, Vol. 35, 1997, pp. 1217-1243.

[609] Smith, B.E., Kravaris, C., Wright, R.A., Wassick, J.M. and Camp, D.T., A notion of set-based control and its application to robust deadtime compensation, *Chemical Engineering Science*, Vol. 53, No. 13, 1998, pp. 2299-2318.

[610] Shi, P., Robust control of linear continuous time-delay systems with finite discrete jumps and norm-bounded uncertainties, *International Journal of Systems Science*, Vol. 29, No. 12, 1998, pp. 1381-1392.

[611] Sun, D. and Hoo, K.A., A robust transition control structure for time delay systems, *International Journal of Control*, Vol. 72, No. 2, 1999, pp. 150-163.

[612] Dawson, J.G. and Gao, Z., Fuzzy logic control of variable time delay systems with a stability safe guard, Proceedings of the *4th IEEE Conference on Control Applications*, 1995, pp. 347-353.

[613] Chen, S. B., Wu, L. and Wang, Q.L., Self-learning fuzzy neural networks for control of uncertain systems with time delays, *IEEE Transactions on Systems, Man and Cybernetics - Part B: Cybernetics*, Vol. 27, 1997, pp. 142-148.

[614] Ishida, M. and Zhan, J., Control of a process with time delay by a policy-and- experience driven neural network, *Journal of Chemical Engineering of Japan*, Vol. 25, 1992, pp. 763-766.

[615] Ishida, M. and Zhan, J., Neural network control for a MIMO process with time delay, *Journal of Chemical Engineering of Japan*, Vol. 26, 1993, pp. 337-339.

[616] Omatu, S., Khalid, M. and Yusof, R., *Neuro-control and its applications*, Springer-Verlag, 1995.

[617] Ng, G.W. and Cook, P.A., Neural networks in control of systems with unknown and varying time delays, Proceedings of the *UKACC International Conference on Control*, 1996, pp. 188-193.

[618] Zheng, F., Cheng, M. and Cao, W.-B., Variable structure control of time-delay systems with a simulation study on stabilising combustion in liquid propellant rocket motors, *Automatica*, Vol. 31, 1995, pp. 1031-1037.

[619] El-Khazali, R., Variable structure robust control of uncertain time delay systems, *Automatica*, Vol. 34, 1998, pp. 327-332.

[620] Drakunov, S.V. and Utkin, V.I., Sliding mode control in dynamic systems, *International Journal of Control*, Vol. 55, 1992, pp. 1029-1037.

[621] Oucheriah, S., Robust sliding mode control of uncertain dynamic delay systems in the presence of matched and unmatched uncertainties, *Transactions of the ASME. Journal of Dynamic Systems, Measurement and Control*, Vol. 119, 1997, pp. 69-72.

[622] Camacho, O.E., Smith, C. and Chacon, E., Toward an implementation of sliding mode control to chemical processes, Proceedings of the *IEEE International Symposium on Industrial Electronics*, Vol. 3, 1997, pp. 1101-1105.

[623] Zhendong, X., Shengli, X. and Yongqing, L., Decentralised sliding mode controller for interconnected distributed parameter systems with time delay, Proceedings of the *UKACC International Conference on Control*, Swansea, Wales, Vol. 1, 1998, pp. 375-379.

[624] Wong, Y.H., Rad, A.B. and Wong, Y.K., Qualitative modeling and control of dynamic systems, *Engineering Applications of Artificial Intelligence*, Vol. 10, No. 5, 1997, pp. 429-439.