Control of Integral Processes with Dead Time

Part I: A Disturbance Observer-based 2DOF Control Scheme*

Qing-Chang Zhong†
Faculty of Mechanical Engineering
Technion-Israel Institute of Technology
Technion City, Haifa, 32000
Israel
E-mail: *zhongqc@ic.ac.uk*

Julio E. Normey-Rico
Departamento de Automação e Sistemas
Universidade Federal de Santa Catarina
Florianopolis-SC, 88040-900
Brazil
E-mail: *julio@lcmi.ufsc.br*

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Abstract

This paper reveals that a disturbance observer-based control scheme is very effective in controlling integral processes with dead time. The controller can be designed to reject ramp disturbances as well as step disturbances, even arbitrary disturbances. Only two parameters are left to tune when the plant model is available . One is the time constant of the setpoint response and the other is the time constant of the disturbance response. The latter is tuned according to the compromise between disturbance response and robustness. This control scheme has a simple, clear, easy-to-design, easy-to-implement structure and good performances. It is compared to the best results (so far) using some simulation examples.

Index Terms: Dead-time compensator, robustness, integral processes, disturbance observer, Smith predictor, 2DOF IMC

1 Introduction

During the last decade, more specifically, after the paper [1] written by Prof. K.J.Åström *et al.* was published, the control of integral processes with dead time has become very active. There have been at least five papers on this topic published by *IEEE Trans. on Automatic Control*. Why are there so many researchers interested in such a simple process?

Such a process is a special case of unstable processes with dead time. As is known, Smith predictor (SP) has been served as an effective control scheme for stable processes with dead time. However, the disturbance response of the classical SP is sometime not satisfactory. When the process has an integral mode, a constant load disturbance results in a steady-state error. Hence, many modifications were proposed to improve the disturbance performance. Watanabe and Ito [2] presented a method,

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†Qing-Chang Zhong is currently at Imperial College, London, UK. *Tel*: 44-20-7594 6295, *Fax*: 44-20-7594 6282, *Email*: zhongqc@ic.ac.uk, *URL*: http://come.to/zhongqc

called *process model control,* for general unstable processes with dead time. Åström *et al.* [1] proposed a novel structure to decouple the disturbance response from the setpoint response and hence the setpoint response and the disturbance response can be designed separately. After that, a series of papers have been published on this subject. Zhang and Sun [3] presented a simple tuning formula for the control scheme proposed by Åström *et al.* in [1]. Matausek and Micic presented a modified SP by introducing a minor loop to stabilize the process with a proportional gain [4] and another scheme with a high-pass filter [5]. Normey-Rico and Camacho [6] analyzed the robustness of a modified structure of Watanabe-Ito's and obtained quite good results. Majhi and Atherton [7] presented another scheme for such a system as well as stable/unstable processes with dead time. However, there still exists a delay element in the characteristic equations of the disturbance response in the schemes studied in [4, 5, 7]. This dominates and seriously slows down the disturbance response when the dead time is long. Comparative studies [8] have shown that the result obtained in [6] is so far the best.

Disturbance observer, originally presented by Ohnishi [9, 10], is an excellent approach to handling disturbances in motion control. It uses the inverse of the nominal model to observe the disturbances and then directly to cancel the effect of disturbances in the control signal. As a result, the closed loop is forced to act as the nominal plant. Umeno and Hori [11] refined it and applied it to the robust control of DC servo motors. Endo *et al.* [12] and Kempf and Kobayashi [13] applied it to control the high-speed direct-drive positioning table. In these literature, the dead time in the process was not included or only included using the Pade approximation in the nominal model [14] in continuous domain. Hong and Nam [15] explicitly considered the measurement delay in the load torque observer. However, they only used the structure to improve the stability and hence the significance of such a structure was under-estimated.

This paper applies the disturbance observer with an explicitly considered delay element [15] to control integral processes with dead time and reveals its advantages over the existing modified Smith predictor. In fact, this is a version of 2DOF internal model control [16], due to which this control scheme also has the property to decouple the disturbance response from the setpoint response like the modified Smith predictor proposed in [1]. The robust stability of the closed-loop system is quite easy to be guaranteed graphically. The low-pass filter $Q(s)$ is designed according to the compromise between disturbance response and robustness. Comparative studies show that this control scheme has the same robustness as the scheme in [6] but has a simpler, clearer, easier-to-design and easier-to-implement structure. It has already been shown that the disturbance response obtained in this control scheme is sub-ideal [17].

The rest of the paper is organized as follow. The control scheme is shown in Section 2. The Q-filter is designed in Section 3, trading-off the disturbance rejection response and the robustness. Comparison to and some disadvantages of the scheme studied in [6] are shown in Section 4 and some illustrative examples are given in Section 5. Finally, conclusions are made in Section 6.

2 Control Structure

Consider the following integral process with dead time:

$$G(s) = G_p(s)e^{-\tau s} = \frac{G_{p0}(s)}{s}e^{-\tau s}, \tag{1}$$

where $\tau > 0$ is a pure dead time and $G_{p0}(s)$ is a strictly proper Hurwitz, minimum-phase transfer function with $G_{p0}(0) \neq 0$.

The control scheme, induced from [15], is shown in Figure 1(a), where τ_m is the estimated dead time and $G_m(s)$ is a low order approximation of $G_p(s)$. c, d, n and y are the command, the disturbance, the measurement noise and the output respectively. $\widehat{d}$ is the estimated disturbance. The low-pass filter $Q(s)$ (known as Q-filter in disturbance observers) is designed to trade-off the robustness and the performance to reject the disturbance and the measurement noise. $C(s)$ is designed according to the delay-free part $G_m(s)$ so that $\frac{C(s)G_m(s)}{1+C(s)G_m(s)}e^{-\tau_m s}$ meets the desired setpoint response. The whole controller consists of two parts: one is the loop $C(s) \sim G_m(s)$ and the other is the disturbance observer of the process. The former serves as a pre-filter and the latter as a feedback loop. The former forms the setpoint response and the latter forms the disturbance response. This control scheme falls into the category of a 2DOF internal model control scheme [16]. The original structure in Figure 1(a) is not causal and sometimes not internally stable. An equivalent structure shown in Figure 1(b) is causal and internally stable provided that the relative degree of $Q(s)$ is high enough and the low-pass filter $F(s)$ has a proper relative degree. In the sequel, the controller is designed according to Figure 1(a) but should be implemented according to Figure 1(b), where $F(s)$ is used to make the controller proper. It is also necessary to non-dynamically implement the finite-impulse-response block in $\frac{F(s)}{G_m(1-Qe^{-\tau_m s})}$ to avoid possible pole-zero cancellations between controller and plant [18, 19].

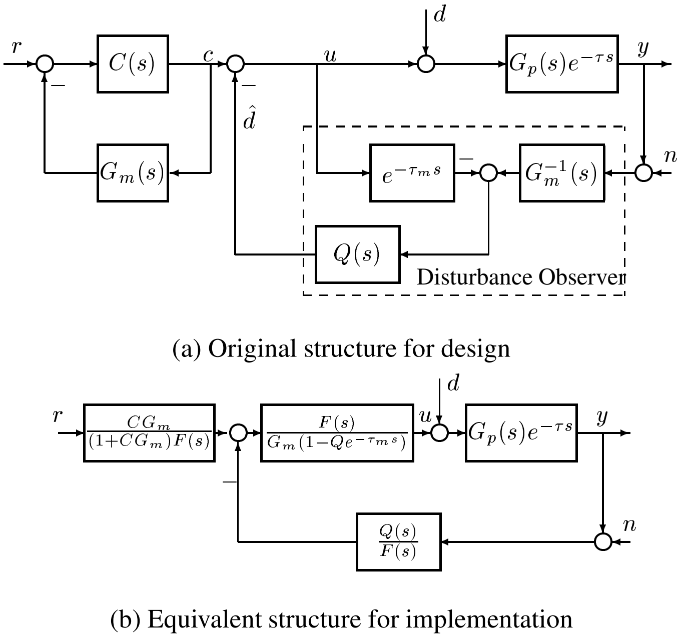

Figure 1: Disturbance observer-based control scheme

Under nominal conditions, *i.e.* $G_m(s) = G_p(s)$ and $\tau_m = \tau$, the transfer functions from reference command r, disturbance d, and measurement noise n to output y are respectively:

$$G_{yr}(s) = \frac{C(s)G_m(s)}{1 + C(s)G_m(s)}e^{-\tau_m s}, \tag{2}$$

$$G_{yd}(s) = G_m(s)e^{-\tau_m s}\left(1 - Q(s)e^{-\tau_m s}\right), \tag{3}$$

$$G_{yn}(s) = Q(s)e^{-\tau_m s}. \tag{4}$$

Obviously, the Smith principle is satisfied and the dead time is not included in the closed-loop characteristic equation. In addition, $G_{yd}(s) \to 0$ at low frequencies and $G_{yn}(s) \to 0$ at high frequencies for a low-pass filter $Q(s)$. The system has good performances to reject disturbances and measurement noises. More importantly, the setpoint response is determined by $C(s)$ and the disturbance response is determined by $Q(s)$. In other words, they are *entirely* decoupled from each other.

In general, $C(s)$ may be designed as a proportional controller

$$C(s) = \frac{1}{T_c} \tag{5}$$

to obtain the desired setpoint response.

3 Design of $Q(s)$ to Reject Ramp/Step Disturbances

First of all, in order to guarantee the causality of $\frac{Q(s)}{G_m(s)}$ in Figure 1(a), the relative degree of $Q(s)$ should be no less than that of $G_m(s)$.

The well-known *internal-model principle* shows that if a disturbance with some modes should be rejected, then the model of the disturbance should be included in the controller. In the proposed controller, $Q(s)$ can be designed to guarantee the rejection of a known disturbance. Assume that the disturbance polynomial can be represented by $d_d(s)$ with degree n_d and that it has m_d disturbance modes λ_{dk} ($1 \leq k \leq m_d$) with multiplicity r_{dk} ($\sum_{k=1}^{m_d} r_{dk} = n_d$). It is possible [20] to design $Q(s)$ to reject arbitrary disturbances provided that the disturbance modes λ_{dk} ($1 \leq k \leq m_d$) are also the zeros of $1 - Q(s)e^{-\tau_m s}$. In other words, the disturbance polynomial has to be included in the controller (*implicitly* but not *explicitly*).

In practice, ramp disturbances ($d_d(s) = s^2$) are often used to represent slowly varying disturbances. In this case, pole $s = 0$ in the disturbance response (3) is of 3 multiplicities. In other words, $Q(s)$ must be tuned to meet the following conditions:

$$\begin{cases} 1 - Q(s)e^{-\tau_m s}\big|_{s=0} = 0 \\ \frac{d}{ds}\left(1 - Q(s)e^{-\tau_m s}\right)\Big|_{s=0} = 0 \\ \frac{d^2}{ds^2}\left(1 - Q(s)e^{-\tau_m s}\right)\Big|_{s=0} = 0 \end{cases}, \tag{6}$$

equivalently

$$\begin{cases} Q(0) = 1, \\ \dot{Q}(0) = \tau_m, \\ \ddot{Q}(0) = \tau_m^2. \end{cases} \tag{7}$$

In other words, any low-pass filter with a high enough relative degree that meets the above conditions can be used to reject ramp disturbances. The simplest $Q(s)$ that can meet these conditions is:

$$Q(s) = \frac{1 + \mu s + \beta s^2}{(\lambda s + 1)^{d_r + 2}}, \tag{8}$$

where

$$\mu = (d_r + 2)\lambda + \tau_m,$$
$$\beta = \frac{\tau_m^2 + \lambda(d_r + 2)((d_r + 1)\lambda + 2\tau_m)}{2}$$

and d_r is the relative degree of the delay free model $G_m(s)$ and λ is a tuning parameter to trade-off disturbance response and robustness. When implemented as Fig. 1(b), $F(s)$ may be chosen as $\frac{1}{(\lambda s+1)^{d_r}}$ to guarantee that $\frac{F(s)}{G_m(s)}$ and $\frac{G_m(s)}{F(s)}$ are proper.

For step disturbances, pole $s = 0$ in the disturbance response (3) is of 2 multiplicities. In this case, only the first two conditions in (7) should be met. The simplest $Q(s)$ that can meet the conditions is:

$$Q(s) = \frac{\mu s + 1}{(\lambda s + 1)^{d_r+1}} \tag{9}$$

with

$$\mu = (d_r + 1)\lambda + \tau_m. \tag{10}$$

When the nominal model is $G_m(s) = \frac{k_m}{s}$ then $d_r = 1$. This provides a low-pass filter

$$Q(s) = \frac{(2\lambda + \tau_m)s + 1}{(\lambda s + 1)^2} \tag{11}$$

and then $F(s)$ can be chosen as $\frac{1}{\lambda s+1}$ without introducing a new parameter. The free parameter λ is left to compromise disturbance response and robustness.

The loop transfer function of the nominal system is

$$L(s) = \frac{Q(s)e^{-\tau_m s}}{1 - Q(s)e^{-\tau_m s}} \tag{12}$$

and the complementary transfer function is

$$T(s) = \frac{L(s)}{1 + L(s)} = Q(s)e^{-\tau_m s}. \tag{13}$$

Hence, for a multiplicative uncertainty $\Delta(s) \in H_\infty$, the system is robustly stable if $\|Q(s)\|_\infty < \frac{1}{\|\Delta(s)\|_\infty}$, *i.e.* the magnitude frequency response of $Q(s)$ stays beneath that of $\frac{1}{\Delta(s)}$. This can be easily used to guarantee the robust stability using a graphic method.

4 Comparison to the Scheme Studied in [6]

As shown in Introduction, the result in [6] is so far the best result. Some comparative studies to it are given below.

For the reader's convenience, the control scheme studied in [6] (noted as N-C scheme hereafter) is shown in Figure 2, where

$F(s) = \frac{1+\alpha T_i s}{1+T_i s}$ $(\alpha < 1)$, $C(s) = \frac{k_c(1+T_i s)}{T_i s}$, $G_1(s) = \frac{k_m(1-\tau_m s)}{s}$ and $G_m(s) = \frac{k_m}{s}$. The control parameters tuned in [6] are

$$\begin{cases} T_i = 2T_0 + \tau_m \\ k_c = \frac{2T_0+\tau_m}{k_m(T_0+\tau_m)^2} \end{cases} \tag{14}$$

where T_0, the only tuning parameter (after identified τ_m and k_m), is the desired time constant of the closed-loop system. The setpoint response and the disturbance response under the nominal case are respectively,

$$G_r(s) = \frac{F(s)C(s)G_m(s)}{1+C(s)G_1(s)}e^{-\tau_m s} = \frac{1+\alpha T_i s}{(T_0 s+1)^2}e^{-\tau_m s}, \tag{15}$$

$$\begin{aligned} G_d(s) &= G(s)(1 - \frac{C(s)G_m(s)}{1+C(s)G_1(s)}e^{-\tau_m s})e^{-\tau_m s} \\ &= \frac{k_m}{s}(1 - \frac{1+T_i s}{(T_0 s+1)^2}e^{-\tau_m s})e^{-\tau_m s}. \end{aligned} \tag{16}$$

The complementary sensitivity transfer function is

$$T_n(s) = \frac{C(s)G_m(s)}{1+C(s)G_1(s)}e^{-\tau_m s} = \frac{(2T_0+\tau_m)s+1}{(T_0 s+1)^2}e^{-\tau_m s}. \tag{17}$$

Obviously, equation (17) is exactly the same as equation (13) in the case of $G_m(s) = \frac{k_m}{s}$ except different notations used. In other words, these two control schemes possess the same robust property.

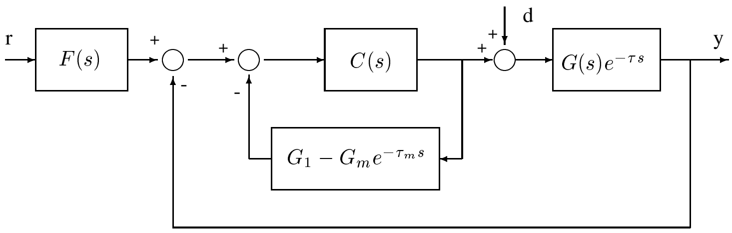

Figure 2: The control scheme in [6]

However, the N-C scheme cannot be directly applied to high order integral processes with dead time. One possible solution is to reduce the original process to $\frac{k_m}{s}e^{-\tau_m s}$, as studied in [6]. This introduces *additional* uncertainties and hence decreases the allowable uncertainty bound and degrades the closed-loop performance. Another possible solution, which was not discussed in [6], is to implement $G_1(s)$ according to the state-space realization of the high order process and then *re-design* and *re-tune* the controller. This is quite involved [18].

The second disadvantage is that it is quite difficult to design a controller in [6] to reject arbitrary disturbances.

The disturbance response of N-C scheme is mainly determined by T_0 as shown in (16). Hence, the third disadvantage of the N-C scheme is that the setpoint response and the disturbance response all relate to T_0. In other words, the setpoint response is not decoupled from the disturbance response although the N-C scheme has two degree-of-freedoms.

There exists a zero $s = -\frac{1}{\alpha T_i}$ in the setpoint response of N-C scheme. Hence, the fourth disadvantage is that there exists overshoot in the setpoint response when $0 < T_0 < \frac{\alpha}{1-2\alpha}\tau_m$, which may tend to the positive infinity even when $\alpha = 0.4$ if $T_0 \to \frac{\alpha}{1-2\alpha}\tau_m$ from the left side. Further research shows that a better choice of α is $\alpha = \frac{2.55T_0}{2T_0+\tau_m}$ (which will ensure the overshoot less than 5%) but not $\alpha = 0.4$ as given in [6]. By the way, the control scheme in [7] for such a process also results in overshoot in the setpoint response although it is tuned by minimizing the standard ISTE criterion.

The studied control scheme is advantageous over the N-C scheme from the above aspects, although the last two disadvantages of N-C scheme may be overcome with a different filter $F(s) = \frac{(1+T_0 s)^2}{(1+T_i s)(1+T_1 s)}$ [8], in which T_1 is the time constant of the setpoint response $\frac{1}{1+T_1 s}e^{-\tau_m s}$.

5 Examples

As stated in Introduction, the result obtained in [6] is so far the best. Hence, the simulations below are only compared to the N-C scheme.

5.1 Example 1: to reject step disturbances

Consider the following process studied in [6, 4]:

$$G_p(s) = \frac{1}{s(s+1)(0.5s+1)(0.2s+1)(0.1s+1)}, \tau = 5\text{sec}.$$

The proposed controller may be designed according to the exact process. This results in a high order controller. However, the controller proposed in [6] has to be designed according to a reduced model, for example, $\frac{1}{s}e^{-6.5s}$ given in [6].

Here, the proposed controller is designed according to a nominal model $G_m(s) = \frac{1}{s(s+1)(0.5s+1)}$ and $\tau_m = 5.3$ sec, where the short time constants are estimated with a dead time equal to their sum [4]. Hence, $Q(s) = \frac{(4\lambda+5.3)s+1}{(\lambda s+1)^4}$, where λ is chosen to trade-off robustness and disturbance response. Here, $\lambda = 1.3$. $C(s)$ is designed as a proportional controller $C(s) = \frac{1}{5}$ to obtain almost the same time constant of the setpoint response in [6] where $T_0 = 5$sec. The unit step responses are shown in Figure 3 where a step disturbance $d(t) = -0.1$ acts at $t = 70$ sec. There exists overshoot in the response of N-C scheme (noted as N-C in figures hereafter) but there is no overshoot in the response of the proposed scheme. Moreover, the disturbance response of the proposed scheme is much faster.

When the dead time varies to $\tau = 5.5$sec, the responses under the same controller are shown in Figure 4. The performance of the proposed scheme is still much better.

5.2 Example 2: to reject ramp disturbances

Consider the same process as in Example 1. In order to obtain a simpler controller, the proposed controller is designed according to the reduced model $\frac{1}{s}e^{-6.5s}$ as in the case of N-C scheme. The filter is then designed as $Q(s) = \frac{1+\mu s+\beta s^2}{(\lambda s+1)^3}$ with $\lambda = 5$ to meet the robust-stability condition for the additional uncertainty. The system is affected by a ramp disturbance $d(t) = 0.003(t-50)\cdot 1(t-50) - 0.003(t-150)\cdot 1(t-150)$. The responses are shown in Figure 5. The proposed system has an

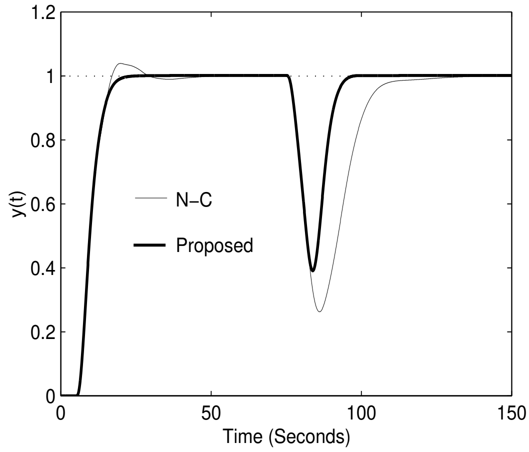

Figure 3: Responses without dead-time uncertainty: Step disturbance

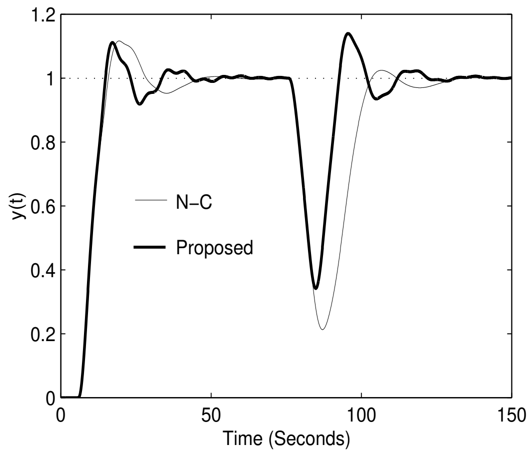

Figure 4: Responses with dead-time uncertainty: Step disturbance

excellent capability to reject the *ramp disturbance* while the scheme in [6] cannot reject the ramp disturbance. As a matter of fact, it is quite difficult to design a controller $C(s)$ so that N-C scheme has such a capability. When the dead time becomes 5.5sec, the responses using the same controller are shown in Figure 6. The response of the proposed control scheme is still much better.

5.3 Example 3

Consider the following widely studied process [2],[5],[6]:

$$G_m(s) = \frac{1}{s} \text{ and } \tau_m = 5\,\text{sec}, \tag{18}$$

where an uncertainty $0 \leq \tau_\Delta \leq 0.5\,\text{sec}$ exists in dead time $\tau = \tau_m + \tau_\Delta$.

Here, $Q(s) = \frac{(2\lambda+5)s+1}{(\lambda s+1)^2}$ is selected in the form of (11). In order to obtain a robustly stable closed-loop system the bandwidth of $Q(s)$ could not be larger than 3 rad/sec, as shown in Figure 7, where three possible candidates of $Q(s)$ with $\lambda = 2.1$, $\lambda = 4$ and $\lambda = 8$ are shown. The robust performance does not degrade considerably for $\lambda = 8$ but the disturbance

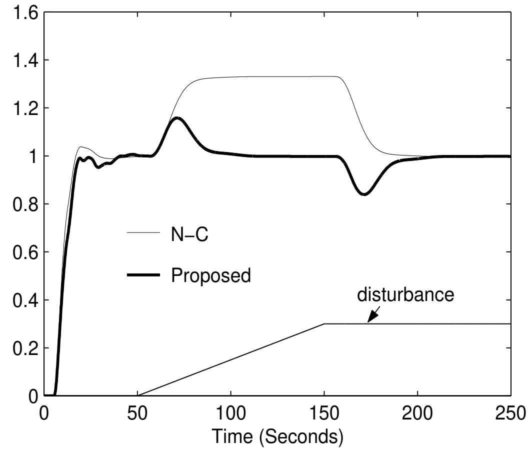

Figure 5: Responses without dead-time uncertainty: Ramp disturbance

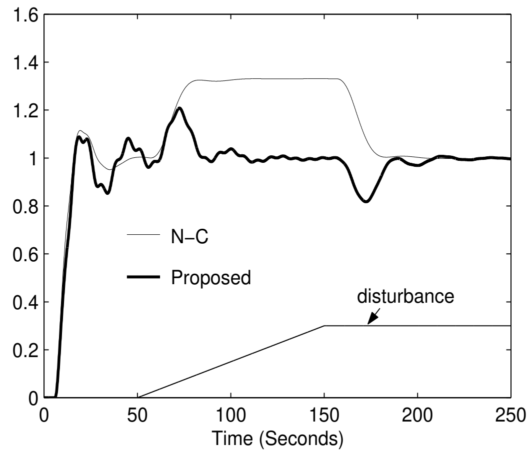

Figure 6: Responses with dead-time uncertainty: Ramp disturbance

response is sluggish, as shown in Figures 8 and 9.

The controller for the setpoint response is designed as a P controller $C(s) = 0.5$. The nominal responses of the three cases are shown in Figure 8. The system is disturbed by a step disturbance $d_0 = -0.1$ at $t = 50s$. The disturbance response is the best when $Q(s)$ has the broadest bandwidth ($\lambda = 2.1$).

When the dead time varies to the worst case ($\tau = 5.5$sec), the responses under the same controller are shown in Figure 9. There exists a limit cycle when $\lambda = 2.1$ and the best robustness is obtained when $\lambda = 8$. Trading-off the disturbance response and the robustness, the best choice of $Q(s)$ can be made as $\lambda = 4$.

6 Conclusions

A disturbance observer-based control scheme, in fact, a 2DOF internal model control structure, is revealed to be a very effective way to control integral processes with dead time (IPDT). The main advantages of this scheme are: It has a simple, clear, easy-to-design and easy-to-implement structure; it decouples the set-point response from the disturbance response and has only two tuning parameters if the model has been identified; it can be designed to reject arbitrary disturbances. Comparative studies

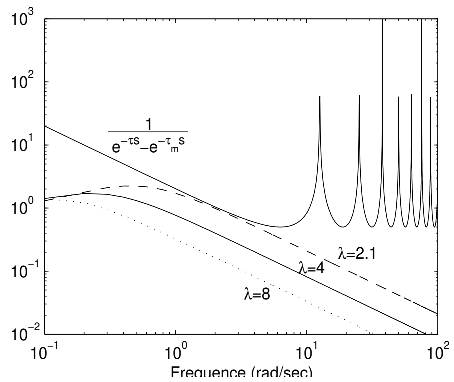

Figure 7: Design of $Q(s)$

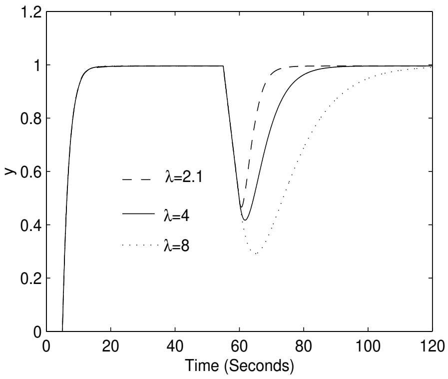

Figure 8: Nominal responses of Example 3

to the best results so far show that this control scheme obtains better performances. Some simulation examples are given to illustrate the comparative analysis and the advantages of the proposed control scheme.

Although the control schemes proposed in some of the cited papers and this paper are different, many of them offer the same disturbance response. It has been shown that this disturbance response is sub-ideal [17]. This fact motivated the research in Part II [21]: the quantitative analysis of the robust stability regions, the achievable specifications of the disturbance response and the stability of the controller itself. As a result, the controller can be quantitatively designed. Another fact that all the above-mentioned disturbance responses are of infinite impulse responses. This motivated the research in Part III [22] to obtain a dead-beat disturbance response.

References

[1] Åström , K.J.; Hang, C.C.; Lim, B.C. A new Smith predictor for controlling a process with an integrator and long dead-time. *IEEE Trans. Automat. Contr.* **1994**, vol.39, pp.343-345.

[2] Watanabe, K.; Ito, M. A process- model control for linear systems with delay. *IEEE Trans. Automat. Contr.* **1981**, vol.26, pp.1261-1269.

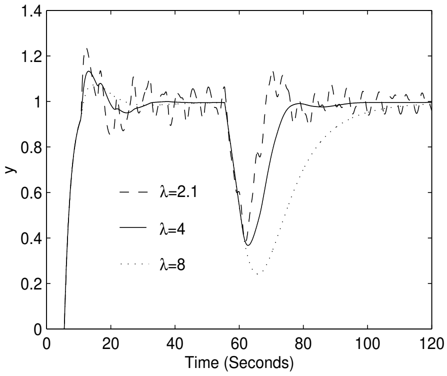

Figure 9: Robust responses of Example 3

[3] Zhang, W.D.; Sun, Y.X. Modified Smith predictor for controlling integrator/time delay processes. *Ind. Eng. Chem. Res.* **1996**, vol.35.pp.2769-2772.

[4] Matausek, M.R.; Micic, A.D. A modified Smith predictor for controlling a process with an integrator and long dead-time. *IEEE Trans. Automat. Contr.* **1996**. vol.41, no.8. pp.1199-1203.

[5] Matausek, M.R.; Micic, A.D. On the modified Smith predictor for controlling a process with an integrator and long dead-time. *IEEE Trans. Automat. Contr.* **1999**. vol.44, no.8. pp.1603-1606.

[6] Normey-Rico, J.E.; Camacho, E.F. Robust tuning of dead-time compensators for process with an integrator and long dead-time. *IEEE Trans. Automat. Contr.* **1999**, vol.44, no.8. pp.1597-1603.

[7] Majhi, S.; Atherton, D.P. Modified Smith predictor and controller for processes with time delay. *IEE Proc-Control Theory Appl*. **1999**, vol.146, no.5. pp.359-366.

[8] Normey-Rico, J.E.; Camacho, E.F.Smith predictor and modifications: a comparative study. Proc. of the European Control Conference ECC'99. Karlsruhe, Germany. 1999,9.

[9] Ohnishi, K. *et al*. Microprocessor-controlled DC motor for load-insensitive position servo system. *IEEE Trans. Ind. Electron*. **1987**, vol.34,pp.44-49.

[10] Ohnishi, K. A new servo method in mechantronics. *Trans. Jpn. Soc. Elec. Eng.* **1987**. vol.107-D, pp.83-86.

[11] Umeno, T.; Hori, Y. Robust speed control of DC servomotors using modern two degrees-of-freedom controller design. *IEEE Trans. Ind. Electron.* **1991**,vol.38, no.5, pp.363-368.

[12] Endo, S. *et al*. Robust digital tracking controller design for high-speed positioning systems. *Control Engineering Practice*. **1996**, vol.4, no.4, pp.527-536.

[13] Kempf, C. J.; Kobayashi, S. Disturbance observer and feedforward design for a high-speed direct-drive positioning table. *IEEE Transactions on Control Systems Technology*. **1999**, vol.7, no.5. pp.513-526.

[14] Kempf, C. J.; Kobayashi, S. Discrete- time disturbance observer design for systems with time delay. *International Workshop on Advanced Motion Control Proceedings*. **1996**, vol.2, pp.332-337.

[15] Hong, K. ; Nam, K. A load torque compensation scheme under the speed measurement delay. *IEEE Trans. on Industrial Electronics*. **1998**, vol 45., pp.283-290.

[16] Morari, M.; E. Zafiriou. Robust Process Control. Prentice-Hall, Inc. 1989.

[17] Mirkin, L.; Zhong, Q.-C. Coprime parametrization of 2DOF controllers to obtain sub-ideal disturbance response for processes with dead-time. *Proc. of the 40th IEEE Conf. on Decision & Control*. Orlando, USA. 2001.

[18] Palmor, Z.J. Time-delay compensation — Smith predictor and its modifications, in *The Control Handbook*, S.Levine, Ed., pp. 224–237. CRC Press, 1996.

[19] Zhong, Q.-C. and Li, H.-X. Two-Degree-of-Freedom PID-Type Controller with Smith Principle for Processes with Dead-Time. *Ind. Eng. Chem. Res.* **2002**, 41, 2448-2454.

[20] Tsypkin, Y.Z. Robust internal model control. *50th Anniversary Issue of DSCD, ASME Transactions*, **1993**, vol.115, no.2(B), pp.419-425.

[21] Zhong, Q.-C. and L. Mirkin, Control of integral processes with dead time (Part II: Quantitative analysis). IEE Proc. Control Theory Appl., **2002**, in press.

[22] Zhong, Q.-C. and H.-X. Li, Control of integral processes with dead time (Part III: Dead-beat disturbance response). Submitted to *IEEE Trans. Automat. Contr.*, **2002**.