Multi-Controller Scheme for Load Rejection and Set-Point Tracking

Bingjun Guo and Arthur Jutan*

Department of Chemical and Biochemical Engineering, The University of Western Ontario, London, ON N6A 5B9, Canada

To acheive complete compensation for loads, a novel multi-controller scheme with feedforward control is proposed. This scheme has four controllers, a set-point controller, two load controllers, and a feedforward controller. This results in the separation of the load response from the set-point response in a closed-loop system. These four controllers can then be designed independently to achieve good system performance for both set-point tracking and load rejection. One of the load controllers can be chosen as a proportional controller; this guarantees physical realizability and provides excellent compensation. The results of simulation and real time control show that the proposed multi-controller scheme is superior to a double-controller system and a Smith predictor in the presence of large uncertainty in process dynamics especially for load disturbances.

Pour réaliser une compensation complète des charges, on propose un nouveau schéma à contrôleurs multiples avec un contrôle anticipé. Ce schéma possède quatre contrôleurs, un contrôleur à points de consigne, deux contrôleurs de charge et un contrôleur anticipé. Cela aboutit à la séparation de la réponse aux charges de la réponse aux points de consigne dans le système à boucle fermée. Ces quatre contrôleurs peuvent alors être conçus séparément pour une bonne performance du système que ce soit pour le suivi des points de consigne ou le rejet de la charge. L'un des contrôleurs de charge peut être choisi comme contrôleur proportionnel, ce qui garantit la faisabilité physique et fournit une excellente compensation. Les résultats de la simulation et du contrôle en temps réel montrent que le schéma à contrôleurs multiples est supérieur à un système à double contrôleur et à un prédicteur de type Smith en présence d'une grande incertitude dans la dynamique des procédés en particulier pour les perturbations de charge.

Keywords: process control, multi-controller, set-point tracking, load rejection, dominant time delay, Smith predictor, feedforward control.

Set-point tracking, load rejection, and system robustness are three major objectives in designing a control system. These objectives are, however, often conflicting. In a conventional feedback control system, a single controller is expected to meet these conflicting requirements. If set-point changes and load disturbances are both likely to occur, a performance compromise has to be made. A compromise between set-point tracking and load rejection is often accompanied by a sacrifice of the system performance.

Zhang et al. (1998) have proposed a two degree-of-freedom Smith predictor for processes with time delay for decoupling between the set-point response and the load response. In their scheme the set-point response and load response can be tuned by two adjustable parameters. But their scheme only marginally improves the control performance. A double-controller scheme has been proposed by Tian and Gao (1998a). But in order to improve the robustness of the control system, the load controller is tuned to be insensitive to the model structure and parameters to accommodate large model uncertainty and results in a sluggish load response, as shown later.

A multi-controller scheme is proposed in this paper to improve the control performance of the load rejection when controlling processes with small time delay and dominant time delays. The scheme consists of four controllers, a set-point controller, two load controllers, a feedforward controller and a process model. Both the set-point controller and one load controller have been chosen to be of the PI type for simplicity. A second load controller and the feedforward controller can be chosen to be a proportional controller. With the multi-controller scheme, the set-point and load responses of the closed-loop system are decoupled, similar to the double-controller scheme. As a result, the set-point controller and one load controller can be designed independently. Predictive errors due to the model mismatch are fed back to the load controllers and compensated as additional load disturbances, which, if measurable, can be completely compensated by a feedforward controller. Extensive simulations show that the proposed control scheme can accommodate large model mismatch errors.

Double-Controller Scheme

To obtain fast set-point tracking and good load rejection simultaneously, a double-controller scheme was proposed by Tian and Gao (1998a), as shown in Figure 1a. Let $G_{c1}(s)$ and $G_{c2}(s)$ denote the set-point controller and the load controller respectively, as shown in Figure 1a. The process

*Author to whom correspondence may be addressed. E-mail address: ajutan@uwo.c

and its model are represented by $P(s)$ and $P^*(s)$. The overall transfer function of the double-controller scheme shown in Figure 1 for set-point changes is:

$$Y(s)\,/\,R(s) = H_r(s) = \left(\frac{G_{c1}(s)P(s)}{1+G_{c1}(s)P^*(s)}\right)\left(\frac{1+G_{c2}(s)P^*(s)}{1+G_{c2}(s)P(s)}\right) \tag{1}$$

The overall transfer function for load changes is:

$$Y(s)\,/\,L(s) = H_l(s) = \frac{P(s)}{1+G_{c2}(s)P(s)} \tag{2}$$

Equation (2) clearly indicates that the load response of the closed-loop system is determined only by the load controller $G_{c2}(s)$ and has been separated from the set-point response. Therefore, the load controller can be designed independently to achieve good load rejection performance.

From Equation (1), with a good process model, i.e., $P^*(s) \approx P(s)$, the set-point response becomes:

$$H_r(s) = \frac{G_{c1}(s)G_p(s)}{1+G_{c1}(s)P^*(s)} \tag{3}$$

The above equation implies that the set-point response is independent of the load controller and is determined only by the set-point controller. As a result, the set-point controller can also be designed independently. The primary design objective of the set-point controller is to obtain good set-point tracking performance.

The control of dominant time delay processes remains an important problem in process control. One control scheme that tries to address the problem is the double-controller scheme for dominant delay processes proposed by Tian and Gao (1998b),

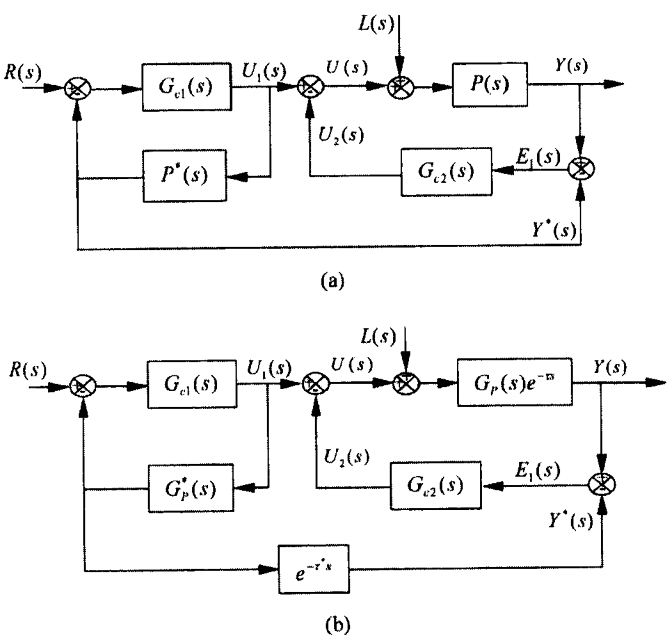

Figure 1. The double-controller scheme (a) with for non-delay processes and (b) with for dominant delay processes [Tian et al. (1998a)]

as shown in Figure 1b. In this structure, the set-point control loop does not contain any time delay and therefore can be designed to have fast set-point tracking. The delay may also be included in the set-point control loop without significant performance deterioration if the delay is not dominant.

Let $P(s) = G_p(s)e^{-\tau s}$ and $P^*(s) = G^*_p(s)e^{-\tau^* s}$, where $G_p(s)$ and $G^*_p(s)$ do not contain any delay and τ^* is an estimate of the delay τ. The overall transfer function of the double-controller scheme shown in Figure 1b for set-point changes is:

$$Y(s)\,/\,R(s) = H_r(s) = \left(\frac{G_{c1}(s)G_p(s)e^{-\tau s}}{1+G_{c1}(s)G_p^*(s)}\right)\left(\frac{1+G_{c2}(s)G_p^*(s)e^{-\tau^* s}}{1+G_{c2}(s)G_p(s)^{-\tau s}}\right) \tag{4}$$

The overall transfer functions of Figures 1a and 1b for load changes are the same as Equation (2). Therefore, the schemes of Figures 1b and 1a have the same load rejection performance.

From Equation (4), with a good process model, i.e., $G_p(s)e^{-\tau s} \approx G_p^*(s)e^{-\tau^* s}$, the set-point response becomes:

$$H_r(s) = \frac{G_{c1}(s)G_p(s)e^{-\tau s}}{1+G_{c1}(s)G_p^*(s)} \tag{5}$$

Equation (5) does not contain any delay in its denominator, implying that the time delay has been compensated, thus we can achieve good set-point tracking performance more easily.

From Equation (2), in spite of the fact that the load controller can be designed independently, this equation still contains delay in its denominator. It will thus be difficult to obtain good load rejection performance for dominant delay processes, since this delay will have to be approximated.

On the other hand, because any errors resulting from the inevitable mismatch between the model and the process can be viewed as additional load disturbances, that is:

$$E_1(s) = Y(s) - Y^*(s) \tag{6}$$

$E_1(s) \neq 0$, the errors signal enters the load control loop, and is compensated for by the load controller. Therefore the load controller must be tuned to be insensitive to the model structure and parameters, to accommodate large model uncertainty, which results in a sluggish load response, as shown later. Clearly, the load controller should generally have integral action to eliminate the errors in steady state.

In order to improve this load rejection performance, a novel multi-controller scheme is proposed here.

Multi-Controller Scheme

A novel multi-controller scheme is shown in Figure 2a. The control scheme has four controllers, a set-point controller, two load controllers, and a feedforward controller. From Figure 2a we see that two additional controllers, a load controller and feedforward controller are added. Both these controllers can be selected as proportional controllers.

From Figure 2a, the closed-loop transfer function for set-point changes is:

$$Y(s)\,/\,R(s) = H_r(s) = \left(\frac{G_{c1}(s)P(s)}{1+G_{c1}(s)P^*(s)}\right)\left(\frac{1+[G_{c2}(s)+G_{c3}(s)]P^*(s)}{1+[G_{c2}(s)+G_{c3}(s)]P(s)}\right) \tag{7}$$

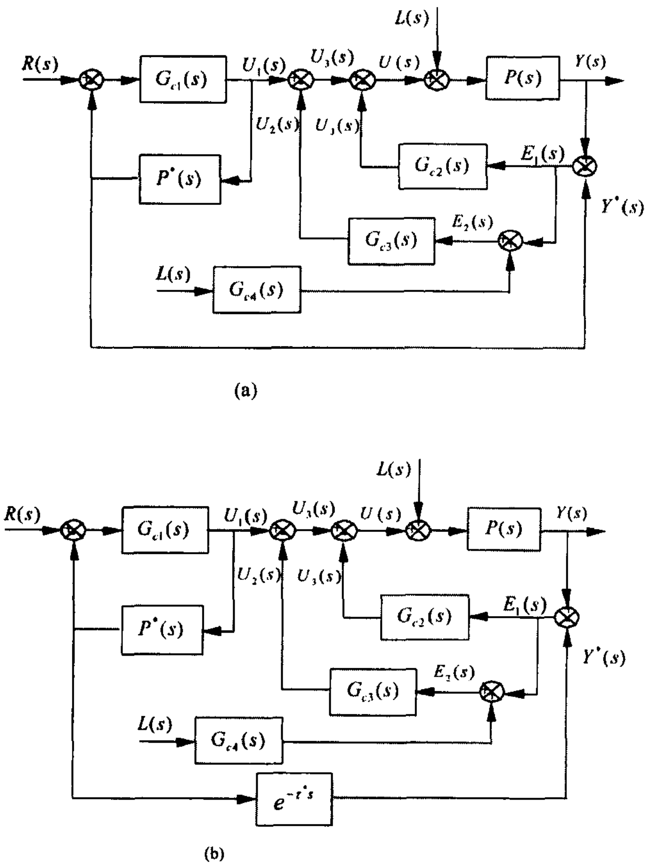

Figure 2. The novel multi-controller scheme (a) with non-delay processes and (b) with dominant delay processes.

and the closed-loop transfer function for load changes is:

$$Y(s)/L(s) = H_l(s) = \frac{[1 - G_{c3}(s)G_{c4}(s)]P(s)}{1 + [G_{c2}(s) + G_{c3}(s)]P(s)} \tag{8}$$

(Notice that the load $L(s)$ enters the sytem at two points.) From Equation (7), with a good process model, the set-point response becomes Equation (3). That is, the set-point responses are the same as the double-controller scheme.

For dominant delay processes, the corresponding multi-controller scheme is shown as Figure 2b. Again, $P(s) = G_p(s)e^{-\tau s}$, and consequently $P^*(s) = G^*_p(s)e^{-\tau^* s}$. In contrast to the control systems in Figure 1b and 2a, we can show that the overall transfer function of the multi-controller scheme shown in Figure 2b for set-point changes is:

$$H_r(s) = \left(\frac{G_{c1}(s)G_p(s)e^{-\tau s}}{1 + G_{c1}(s)G_p^*(s)}\right)\left(\frac{1 + [G_{c2}(s) + G_{c3}(s)]G_p^*(s)e^{-\tau^* s}}{1 + [G_{c2}(s) + G_{c3}(s)]G_p(s)e^{-\tau s}}\right) \tag{9}$$

The overall transfer functions of Figures 2a and 2b for load changes are the same as in Equation (8). Therefore, the schemes of Figures 2a and 2b have the same load rejection performance. From Equation (9), if the process model is a good description of the process, then the overall transfer function for set-point changes is the same as Equation (5), that is, the closed-loop control responses for set-point changes for multi-controller scheme and double-controller scheme are the same.

Provided the load can be measured, feedforward control is a good choice for load rejection. One can see from Equation (8), that the load can be completely compensated if we choose:

$$G_{c3}(s)G_{c4}(s) = 1 \tag{10}$$

To eliminate offset, the load controller $G_{c2}(s)$ should have integral action, but we are free to choose the load controller $G_{c3}(s)$ and feedforward controller $G_{c4}(s)$ to be simple proportional controllers. This guarantees the realizability of the feedforward controller and complete compensation of the measured load.

Tuning of the Multi-Controller Scheme

The tuning of the multi-controller scheme is simple and straightforward, due to the decoupled structures as discussed previously. Of course, it is based on the assumption that the process model is a good description of the process dynamics. The set-point controller $G_{c1}(s)$ and load controller $G_{c2}(s)$ are designed, for simplicity, to be of the PI type, taking the form:

$$G_{cj}(s) = K_{cj}\left(1 + \frac{1}{T_{ij}s}\right), \quad j = 1,2 \tag{11}$$

where K_{cj} and T_{ij} are controller gain and integral time, respectively, for controllers $j = 1, 2$. The load controller $G_{c3}(s)$ and feedforward controller $G_{c4}(s)$ are designed, as described above, to be of the P type, taking the form:

$$G_{cj}(s) = K_{cj}, \quad j = 3,4 \tag{12}$$

where K_{cj} are controller gains, respectively, for controllers $j = 3, 4$.

For simplicity, suppose that the process is governed by a first-order plus delay transfer function as:

$$P(s) = G_p(s)e^{-\tau s} = \frac{K_p^*}{T_p s + 1}e^{-\tau s} \tag{13}$$

where K_p, and T_p are the process gain and the time constant, respectively. Correspondingly, a first-order plus delay process model is chosen to approximate the process dynamics:

$$P^*(s) = G_p^*(s)e^{-\tau^* s} = \frac{K_p^*}{T_p^* s + 1}e^{-\tau^* s} \tag{14}$$

where K^*_p, T^*_p and τ^* are the estimates of K_p, T_p and τ, respectively. The assumption of the first-order plus delay is reasonable as many industrial processes can be approximated by this form.

As the closed-loop characteristic equation for the set-point design does not contain the dominant delay term, when the process model is a good approximation, the set-point controller can be designed as if the process does not contain any dominant time delay. The direct synthesis method is adopted for the set-point controller tuning as shown in Figures 2b and 1b. Assume that the desired closed-loop transfer function $H_{re}(s)$ for set-point changes is:

$$H_{re}(s) = \frac{1}{T_e s + 1}e^{-\tau s} \tag{15}$$

where T_e is the desired closed loop time constant. Letting $H_r(s) = H_{re}(s)$ leads to the PI set-point controller settings as:

$$K_{c1} = \frac{T_p^*}{T_e K_p^*}, \quad T_{c1} = T_p^* \tag{16}$$

This setting rule was proposed by Tian and Gao (1998b). In determining the closed-loop time constant, T_e, we suggest selecting T_e to be equal to, or slightly larger than T^*_p in order to avoid instability and physically unachievable performance.

A different method is adopted to tune the load PI controller $G_{c2}(s)$ as shown in Figures 1 and 2, and the set-point controller $G_{c1}(s)$ as shown in Figures 1a, and 2a. Simulations indicate that the PI tuning rule proposed by Haalman (1965) results in acceptable performance. For a process that can be approximated by a first-order plus delay model, Haalman's tuning formulae are:

$$K_c = \frac{2T_p^*}{3K_p^*\tau^*}, \quad T_i = T_p^* \tag{17}$$

These formulae are, however, conservative for processes with dominant delay. Therefore, Haalman's formulae are modified. A common factor α is introduced to provide more or less responsive controller tuning;

$$K_c = \frac{2\alpha T_p^*}{3K_p^*\tau^*}, \quad T_i = \alpha T_p^* \tag{18}$$

With $\alpha = 1$, the modified Haalman's tuning formulae of (18) reduce to the original Haalman's formulae of Equation (17).

According to the above tuning rule, we can determine the load controllers $G_{c2}(s)$ and $G_{c3}(s)$, as shown in Figure 2b. The load controller $G_{c3}(s)$ is a proportional controller, which we can easily tune.

From Equation (10), the feedforward controller $G_{c4}(s)$ is calculated as:

$$K_{c4} = \frac{1}{K_{c3}} \tag{19}$$

where $G_{c4}(s)$ is also a proportional controller, as described above.

Simulation

To illustrate the effectiveness of the proposed multi-controller scheme, a high-order plus delay process with an unstable zero, is considered in the simulations. The process is governed by:

$$P(s) = \frac{1-1.4s}{(s+1)^3} e^{-3.5s} \tag{20}$$

To implement the proposed multi-controller scheme, the high-order process is approximated by a first-order plus delay model as:

$$P(s) = \frac{1-1.4s}{(s+1)^3} e^{-3.5s} \approx \frac{1}{1.84s+1} e^{-6s} \tag{21}$$

Using the above tuning rules, the settings of the set-point controller, the load controllers, and the feedforward controller are tabulated in Table 1 for this process. Because the process is a dominant time delay process, we will apply the multi-controller scheme as shown in Figure 2b to control the process and use the orignal Haalman formulae to tune the controllers.

Table 1. The process with the tuned controller settings.

	Process
Process	$P(s) = (1-1.4s)e^{-3.5s}/(s+1)^3$
Model	$e^{-6s}/(1.84s+1)$
$G_{c1}(s)$	$K_{c1} = 1$, $T_{i1} = 1.84$
α factor	$\alpha = 1.75$
$G_{c2}(s)$	$K_{c2} = 0.1578$, $T_{i2} = 3.22$
$G_{c3}(s)$	$K_{c3} = 0.2$
$G_{c4}(s)$	$K_{c4} = 5$

The load controllers $G_{c2}(s)$ and $G_{c3}(s)$ are tuned by the modified Haalman's tuning formulae ($\alpha = 1.75$). In contrast to the double-controller system, the set-point controller in the double-controller scheme is the same as in the multi-controller scheme. The load controller $G_{c2}(s)$ in the double-controller scheme is equivalent to the sum of the load controllers $G_{c2}(s)$ and $G_{c3}(s)$ in the multi-controller system. Therefore, the multi-controller system and the double-controller system have the same robustness, as shown later. As excitation signal, a positive unit step in set-point and a negative unit step change in load are introduced to the sysems at $t = 0$ and $t = 100$, respectively. The simulation results are compared to that of the double-controller scheme and the Smith predictor, which are also tuned by the direct synthesis method.

The ideal case, with no perturbations in the process dynamics, is simulated first. In designing controllers, the process is often approximated by a first-order plus delay model. This leads to a small model mismatch with the true process. Figure 3 gives the responses of the multi-controller system, the double-controller system and the Smith predictor. As expected, the multi-controller system, the double-controller system and the Smith predictor have similar set-point tracking responses. The load disturbances is completely compensated in the multi-controller system, while the load response of the double-controller system is slightly slower than that of the Smith predictor in the ideal case.

In the following simulations, the approximated first-order plus delay model and all the controllers settings are kept constant, while the process dynamics are changed, to test the robustness of the multi-controller system. The deviations of the delay time, τ, from its original value $\tau = 3.5$ are considered first.

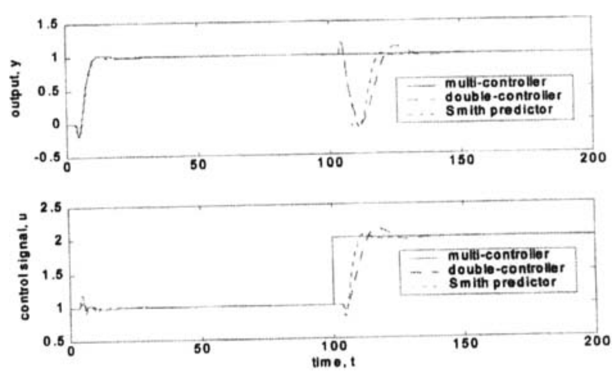

Figure 3. Responses of the multi-controller system, the double-controller system and the Smith predictor for process, with a good process model approximation of first-order plus delay.

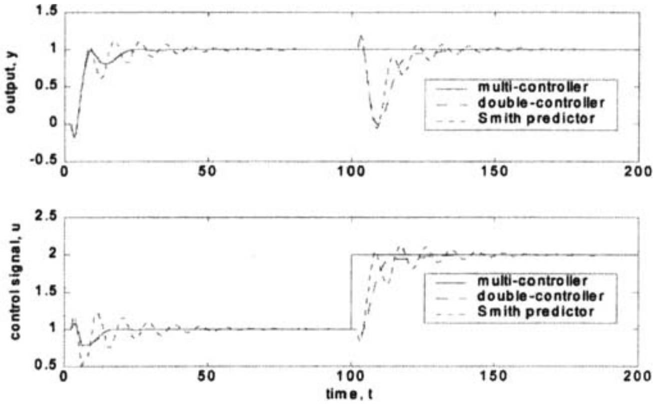

Figure 4. Responses of the multi-controller system, the double-controller system and the Smith predictor for process, with a change of τ from 3.5 to 2.

Figure 4 gives the responses of the multi-controller system, the double-controller system and the Smith predictor, for τ changing to 2. Excellent performances of the multi-controller system are clearly seen from the figure in both set-point tracking and load rejections. Simulations show that the Smith predictor is unstable if $\tau < 1.3$ or $\tau > 6.1$. In contrast, the multi-controller scheme and the double-controller scheme still are stable for $0 < \tau < 12$.

Significant changes of the process dynamics in zero, poles (or time constants), and delay time do not affect the performance of the multi-controller system significantly. The Smith predictor is, however, sensitive to these changes. Figure 5 gives the responses of the multi-controller system, the double-controller system and the Smith predictor for $P(s) = e^{-3s}(1-2s)/(0.84s + 1)^3$. The multi-controller system is clearly superior to the double-controller system and the Smith predictor for load rejection, but has the same performance as the double-controller system for set-point tracking. Clearly the multi-controller system and the double-controller system are more robust than the Smith predictor.

Simulation results show that the performance of the multi-controller scheme for unmeasurable loads is the same as the double-controller scheme. While the compensation is not

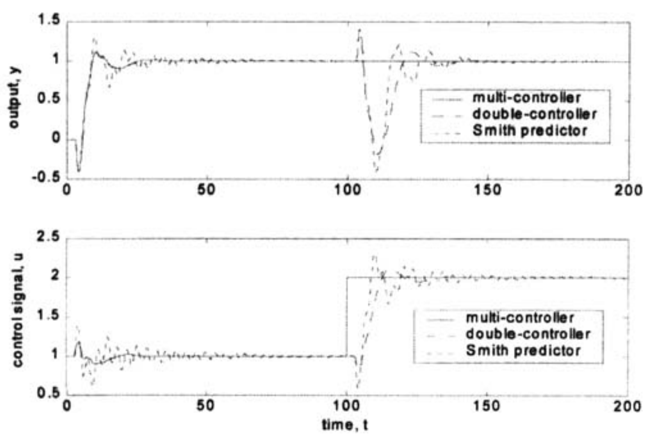

Figure 5. Responses of the multi-controller system, the double-controller system and the Smith predictor for process 3, with significant changes in zero, poles (time constant) and delay time.

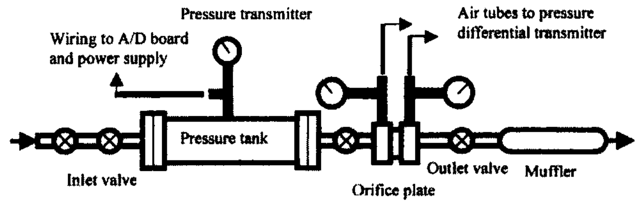

Figure 6. Experimental pressure system.

complete, suitable control is achieved. This is further verified in the experimental realtime control study below. The simulation results are not shown for this case to save space.

Experimental Studies

Pressure Tank Control

The system used here is a pressure tank (Figure 6) through which air flows from a regulated supply. Control valves are installed on both the inlet and the outlet of the tank. The pressure in the tank and the outlet flow rate are measured and transmitted to a computer. Data collection and system control are accomplished by use of a micro-computer with an input–output (I/O) interface board.

We considered the pressure as a controlled variable and the inlet valve opening as a manipulated variable. We fixed the outlet valve opening at 50%. This is also a somewhat nonlinear system. Not only is the valve nonlinear, but there is also severe hysteresis in the valves themselves. Because of this valve hysteresis and sticking, model identification is difficult, since the operating point is not easily reproducible, leading to poor repeatability in the dynamic data.

First we selected white noise as an input signal based on the fixed inlet valve opening of 50%, and a sample interval of 1 s. We identified a suitable pressure model as follows:

$$P(z) = \frac{0.1079z^{-1} + 0.02871z^{-2} + 0.0978z^{-3}}{1 - 0.9833z^{-1} - 0.055z^{-2} + 0.076z^{-3}} \tag{22}$$

We can see that the pressure plant model does not contain any time delay.

Control Results

We applied the multi-controller scheme to this real time plant. Because as shown above, the controlled plant doesn't contain time delay, the control structure of Figure 2a and the ITAE PI type of control law is adopted. First, the set-point controller and the load controller were tuned by the ITAE criterion, since the inlet valve opening range is 0% to 100%, that is, the manipulated variable contains a constraint condition. The tuning parameters of the controllers were chosen by trial and error as follows:

$$G_{c1}(z) = \frac{0.105 - 0.1z^{-1}}{1 - z^{-1}} \tag{23}$$

$$G_{c2}(z) = \frac{0.1067 - 0.1z^{-1}}{1 - z^{-1}} \tag{24}$$

$$G_{c3}(z) = 0.05 \tag{25}$$

$$G_{c4}(z) = 20 \tag{26}$$

where the controllers $G_{c1}(z)$ and $G_{c2}(z)$ are digital PI controllers.

The setpoint was changed from 176.9 kPa to 211.4 kPa and then back to 176.9 kPa. This was intended to test the performance of the control scheme over different operating ranges. For comparison, an experimental run was made under the double-controller scheme as shown in Figure 1a. The set-point controller of the double-controller scheme was the same as one in the Equation (26), and the load controller was the equivalent to the sum of the load controllers $G_{c2}(z)$ and $G_{c3}(z)$ in the multi-controller system. Figure 7 shows the variations of process output and process input with time. At 600 s we added a disturbance in inlet valve of 20%. This nonlinear process was well controlled, despite the wide changes in the operating range. Clearly, the disturbance was completely compensated.

From the results it is clear that both multi-controller scheme and double-controller scheme can satisfactorily control this nonlinear process and the multi-controller scheme can completely compensate for measurable loads.

Conclusions

A multi-controller scheme has been proposed to acheive complete compensation for measurable loads. The scheme consists of four controllers: a set-point controller, two load controllers, a feedforward controller and an approximate process model. With this scheme, the set-point response and the load response are no longer coupled ant thus can be compensated for independently.

Simulations and real time controlled results have shown that the multi-controller system outperforms the double-controller system in load rejection, and the Smith predictor in the presence of process uncertainties. This controller is applied to a realtime pressure tank system, which has nonlinearitiies and significant unmeasured noise, and is shown to perform very well under these conditions. A proportional feedforward controller is all that is required to achieve complete compensation for measurable loads. Predictive errors resulting from model mismatch can be viewed as additional loads. These additional loads together with unmeasurable loads are compensated for by the load controllers. The controlled performace of the multi-controller system for unmeasurable loads is the same as the double-controller system. In the new multi-controller scheme, the load rejection loop does not contain the process model, and therefore can accommodate large model mismatches. The set-point controller and one load controller were chosen as PI controllers for simplicity. The control scheme is not restricted to this choice and more sophisticated control algorithms may well provide further improvements.

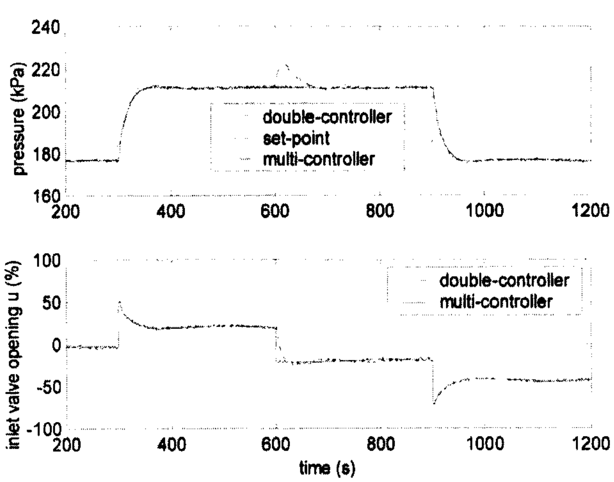

Figure 7. Tank pressure and inlet valve changes under multi-controller scheme and double-controller scheme.

Nomenclature

E_1	error between output and output estimation
G_{c1}	set-point controller
G_{c2}	load controller
G_{c3}	load controller
G_{c4}	feedforward controller
H_l	overall transfer function for load changes
H_r	overall transfer function for set-point changes
L	load disturbance
K	gain
P	process
R	set-point
s	Laplace operator
T	time constant
Y	output
z	z-operator

Greek Symbols

α	common factor
τ	time delay

Subscripts

*	estimation

Superscripts

1	controller 1
2	controller 2
3	controller 3
4	controller 4
p	process
e	desired

References

Haalman, A., "Adjusting Controllers for Deadtime Processes", Control Engineering **12**, 71–73 (1965).

Smith, O.J.M., "Closer Control of Loops with Dead Time", Chem. Eng. Prog. **53**(5), 217–219 (1957).

Zhang, W.D., Y. Sun and X. Xu, "Two Degree-of-Freedom Smith Predictor for Processes with Time Delay", Automatica **34**, 1279–1282 (1998).

Tian, Y.C. and F. Gao, "Double-Controller Scheme for Separating Load Rejection from Set-Point Tracking", Transactions of the Institute of Chemical Engineers, Part A **76**, 445–450 (1998a).

Tian, Y.C. and F. Gao, "Double-Controller Scheme for Control of Processes with Dominant Delay", IEE Proceedings: Control Theory Application **145**, 479–484 (1998b).

Zhu, Z.X. and A. Jutan, "Model Identification and Optimal Stochastic Control of a Multivariable Pressure Tank System", Transactions of the Institute of Chemical Engineers, Part A **72**, 64–71 (1994).

Manuscript received April 17, 2000; revised manuscript received May 14, 2001; accepted for publication May 30, 2001.